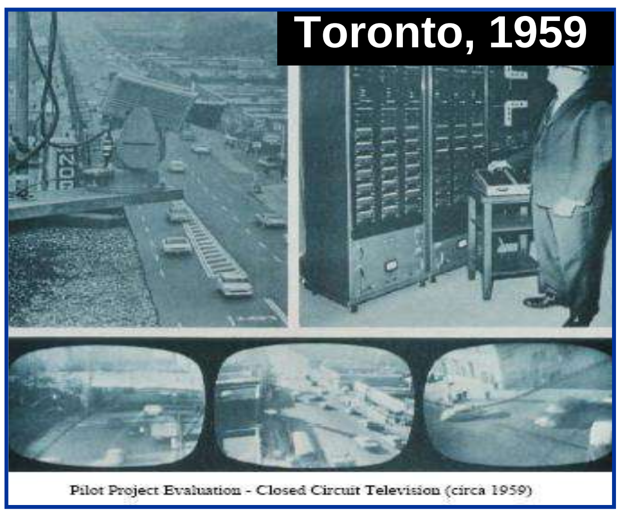
NTUA Seminar

Connected and Automated Vehicles (CAVs): Challenges and Opportunities for Traffic Operations



Alexander Skabardonis

NTUA 1977, University of California, Berkeley

Athens, May 31, 2018

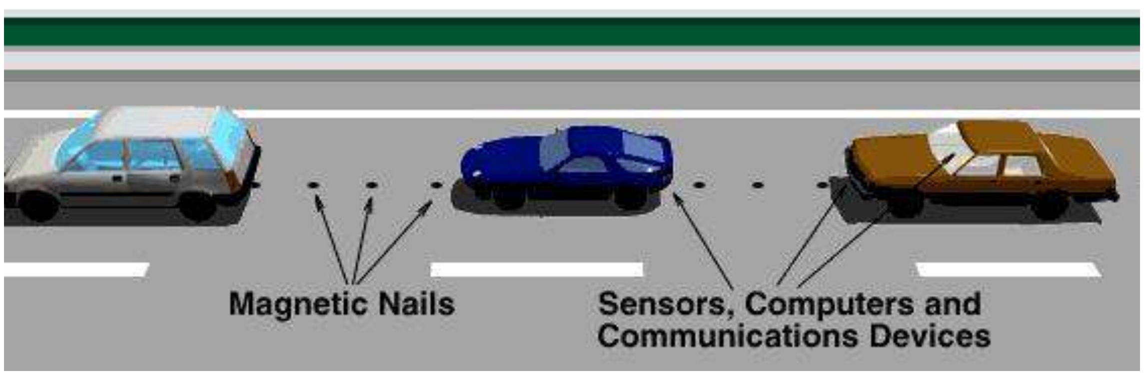
History of Automated Driving (pre-Google)*

- 1939 – General Motors “Futurama” exhibit
- 1949 – RCA technical explorations begin
- 1950s – GM/RCA collaborative research
- 1950s – GM “Firebird II” concept car
- 1964 – GM “Futurama II” exhibit
- 1964-80 – Research by Fenton at Ohio State University
- 1960s – Kikuchi and Matsumoto wire following in Japan
- 1970s – Tsugawa vision guidance in Japan
- 1986 – California PATH and PROMETHEUS programs start
- 1980s – Dickmanns vision guidance in Germany
- 1994 – PROMETHEUS demo in Paris
- 1994-98 – National AHS Consortium (Demo ‘97)
- 2003 – PATH automated bus and truck demos
- *(2004 - 2007 – DARPA Challenges)*

***Source: Steven Shladover, PATH**

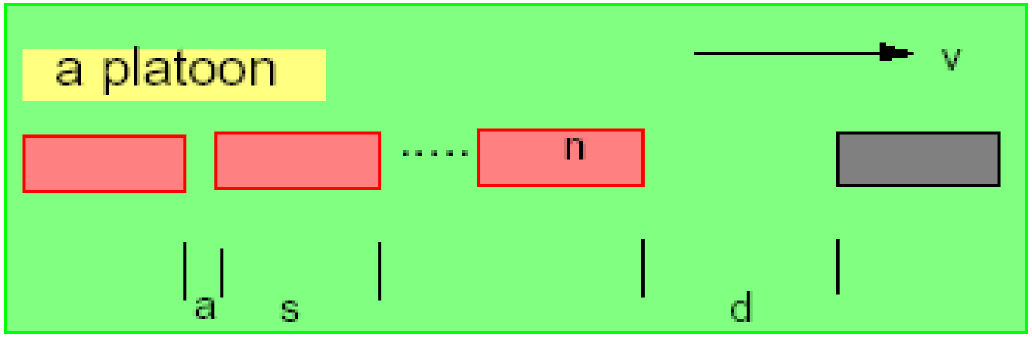
Background: AHS Implementation

- Dedicated AHS lanes
- Automated Check-in
- Automated Check-out
- Lateral and Longitudinal Controls
- Automated merging/diverging
- Malfunction Management & Analysis



AHS Demo: San Diego 1997

Capacity of AHS Lane



Capacity = C = v . n / [ns + a(n - 1) + d] veh / lane / hour

Assume v = 72 k/h, s = 5m. Then

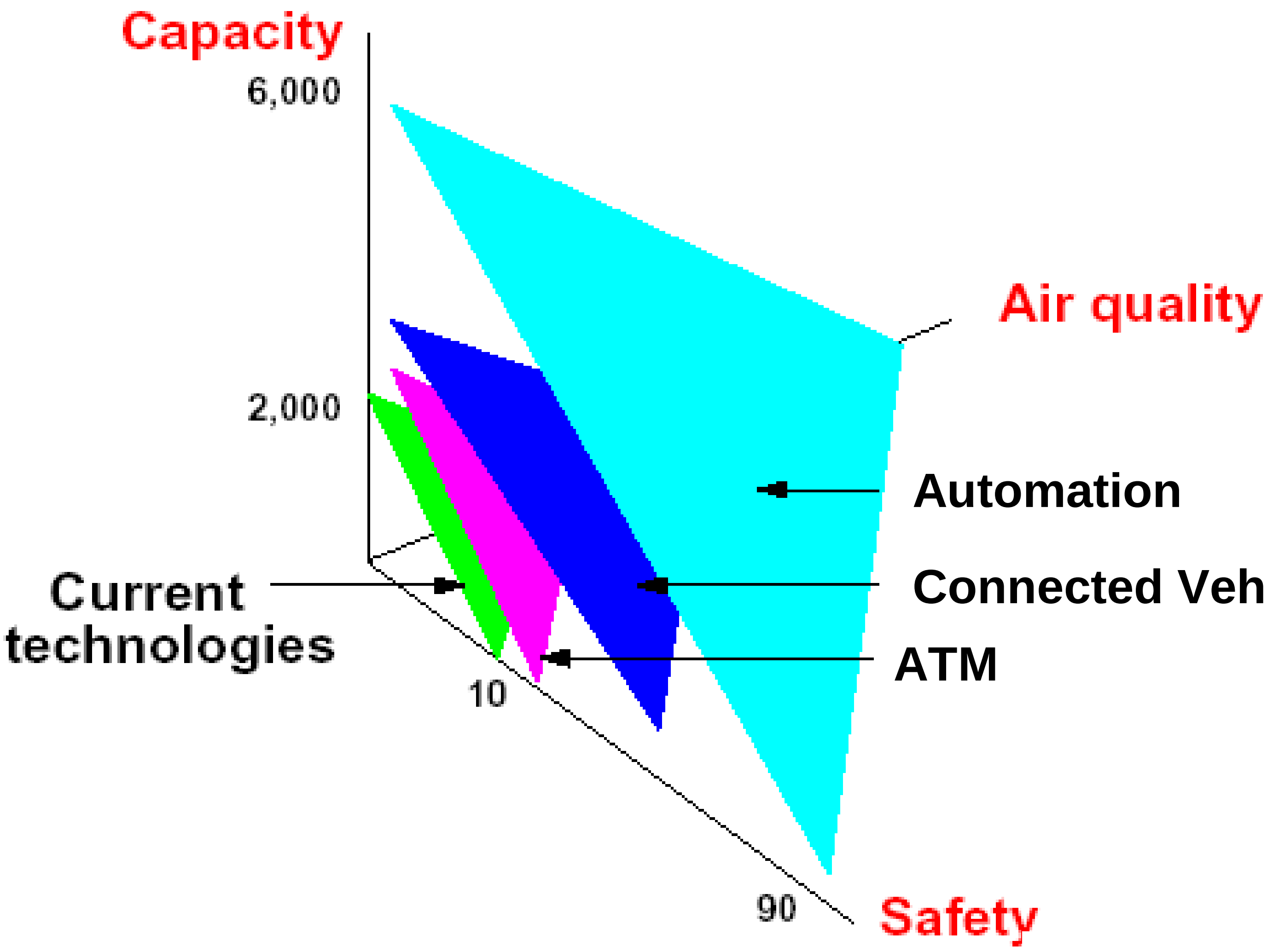
n	a	d	C
1	-	30	2,100
5	2	60	3,840
15	2	60	6,600
20	1	60	8,000

Notes

n=20 yields nearly 4 times today's capacity

capacity proportional to speed

The Promise..


Capacity
6,000
2,000
Air quality
Automation
Connected Veh
ATM
Current technologies
10
90
Safety

Levels of Automation (1)

Levels of Automation (2)

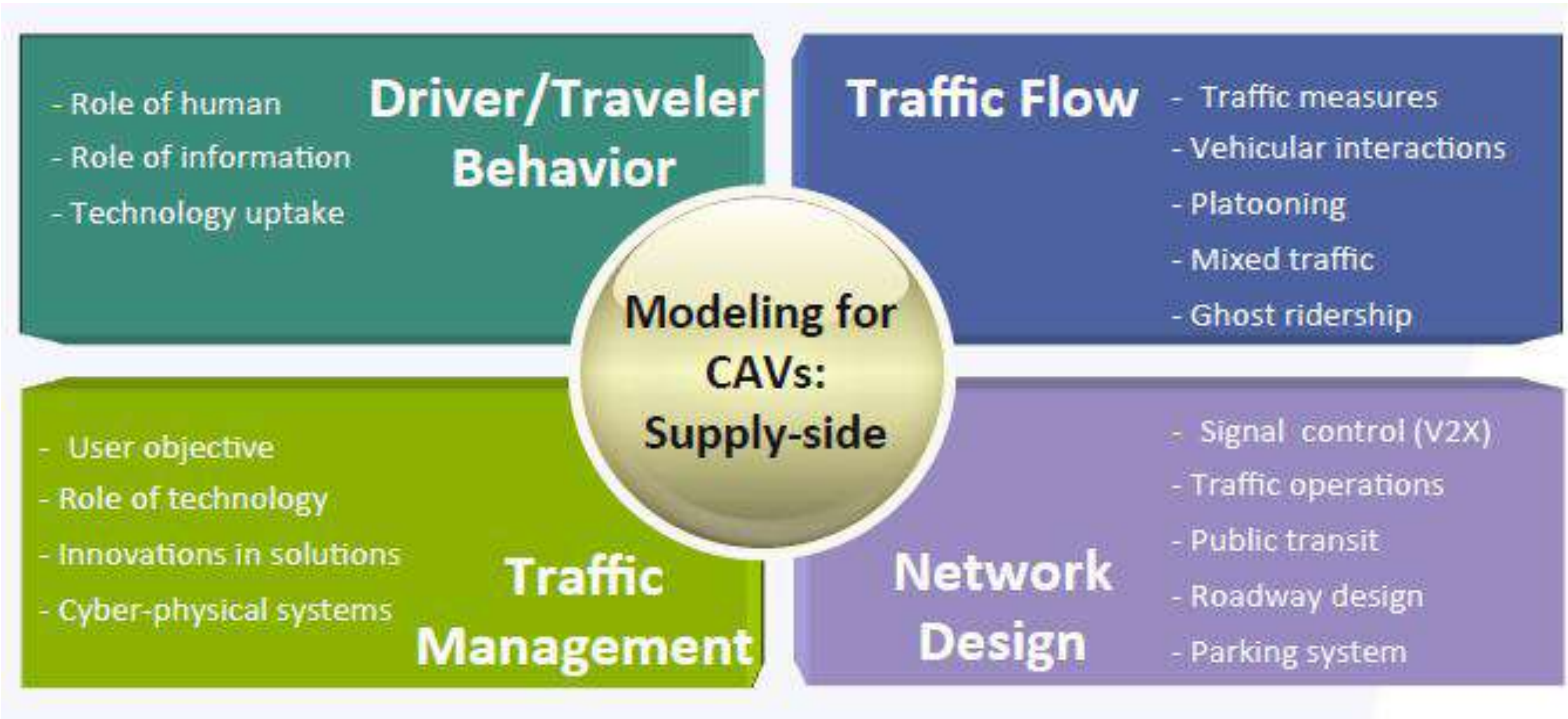
Example Systems at Each Automation Level

(based on SAE J3016 - http://standards.sae.org/j3016_201609/)

Level	Example Systems	Driver Roles
1	Adaptive Cruise Control OR Lane Keeping Assistance	Must drive other function and monitor driving environment
2	Adaptive Cruise Control AND Lane Keeping Assistance Highway driving assist systems (Mercedes, Tesla, Infiniti, Volvo…) Parking with external supervision	Must monitor driving environment (system nags driver to try to ensure it)
3	Freeway traffic jam "pilot"	May read a book, text, or web surf, but be prepared to intervene when needed
4	Highway driving pilot Closed campus "driverless" shuttle "Driverless" valet parking in garage	May sleep, and system can revert to minimum risk condition if needed
5	Ubiquitous automated taxi Ubiquitous car-share repositioning	Can operate anywhere with no drivers needed

CALIFORNIA PATH

CAVs: Modeling Needs



Source: Srinivas Peeta Workshop ISTTT22, 2017

CAVs: Modeling Challenges

Models: Challenges and Opportunities (1)

- **Existing Traffic Models Luck Features to Account for Changes due to CAVs**

  Simplified assumptions on CAVs car-following, lane changing models

  Car-following model for mixed traffic

  Interactions with manual driven vehicles

  Macroscopic traffic flow relationships

- **New Models Needed to Leverage Technological capabilities, and Capture Emergent Interactions**

  Operational and communication protocols

  Modeling platoon streams for CAVs

  Platoon stability

  Impacts of latency

Models: Challenges and Opportunities (2)

- **Modeling of CAVs and Technology Integration (V2X)**
  Traffic signal control
  ATM strategies on freeways
  Highway design for mixed and purely autonomous vehicles

- **Modeling Incidents/Re-routing**
  Diversion strategies under cooperation and real-time information available to CAVs

- **Model Calibration**
  Data sources?
  Framework?

Data Opportunities-Challenges

CAVs can be used as mobile sensors

CAVs provide data for trajectory construction

- **Current TMC systems are not equipped to handle CAV data**

  Minimizing data transmission/processing costs while maintaining accuracy and timeliness requirements

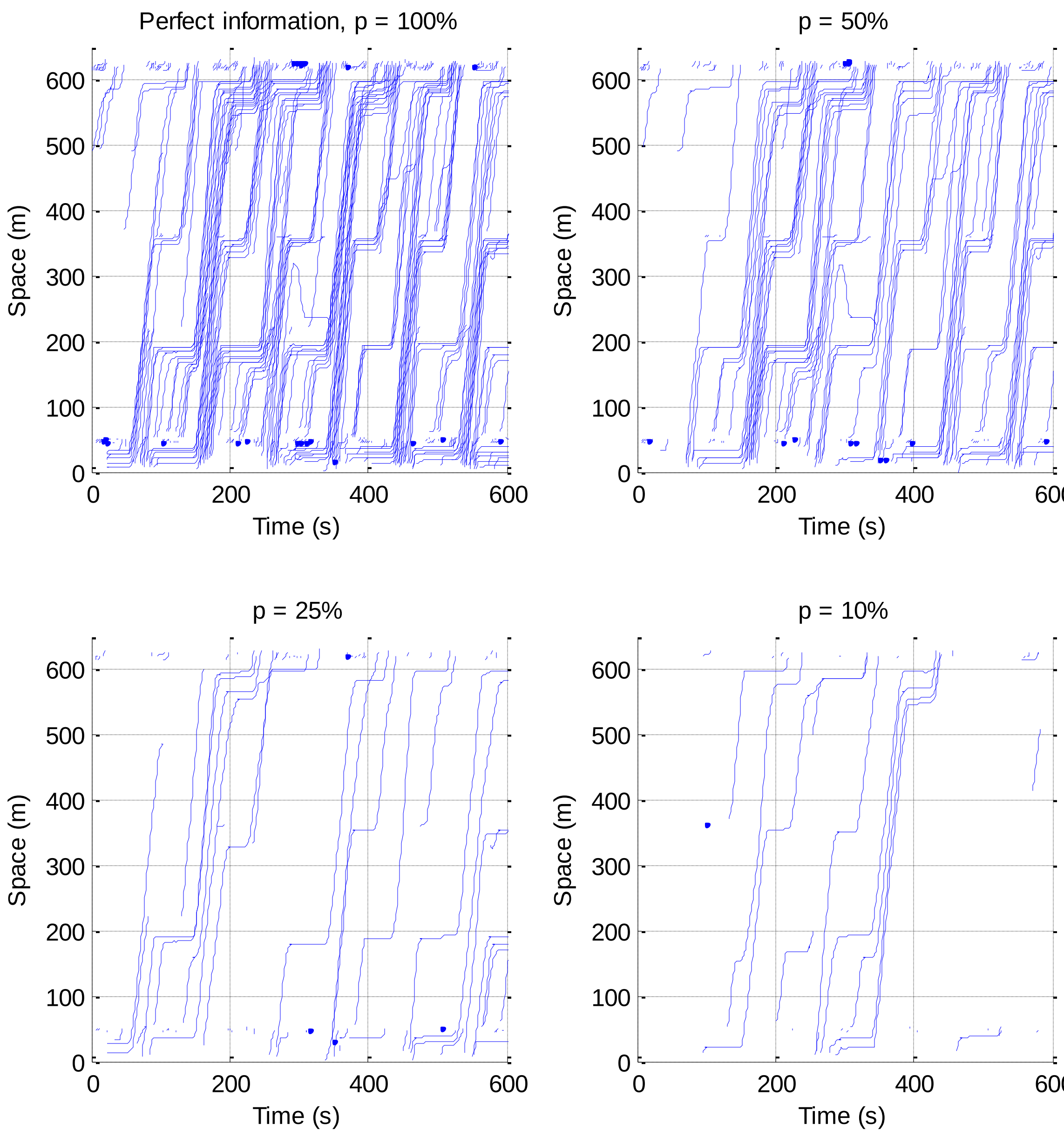
- **No standards/procedures exist for collecting, processing integrating CAV data into existing operations**

- **CAV Operational Characteristics not yet determined**

- **Effect of advance information on CAVs is unknown until tested**

- **Impacts on intersection capacity and performance depend on CAVs penetration rate (*will change over time*)**

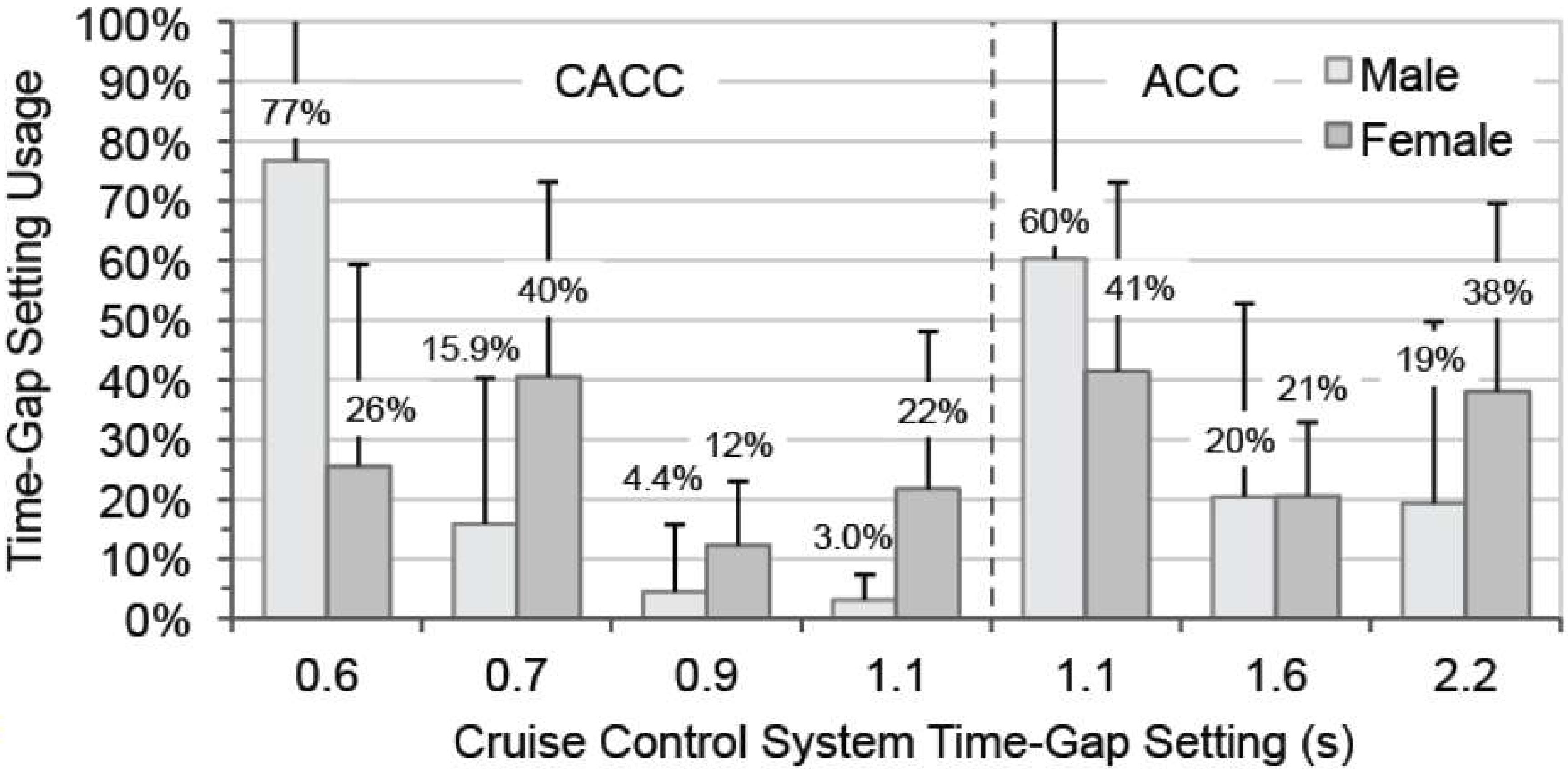
Impact of Penetration Rates*



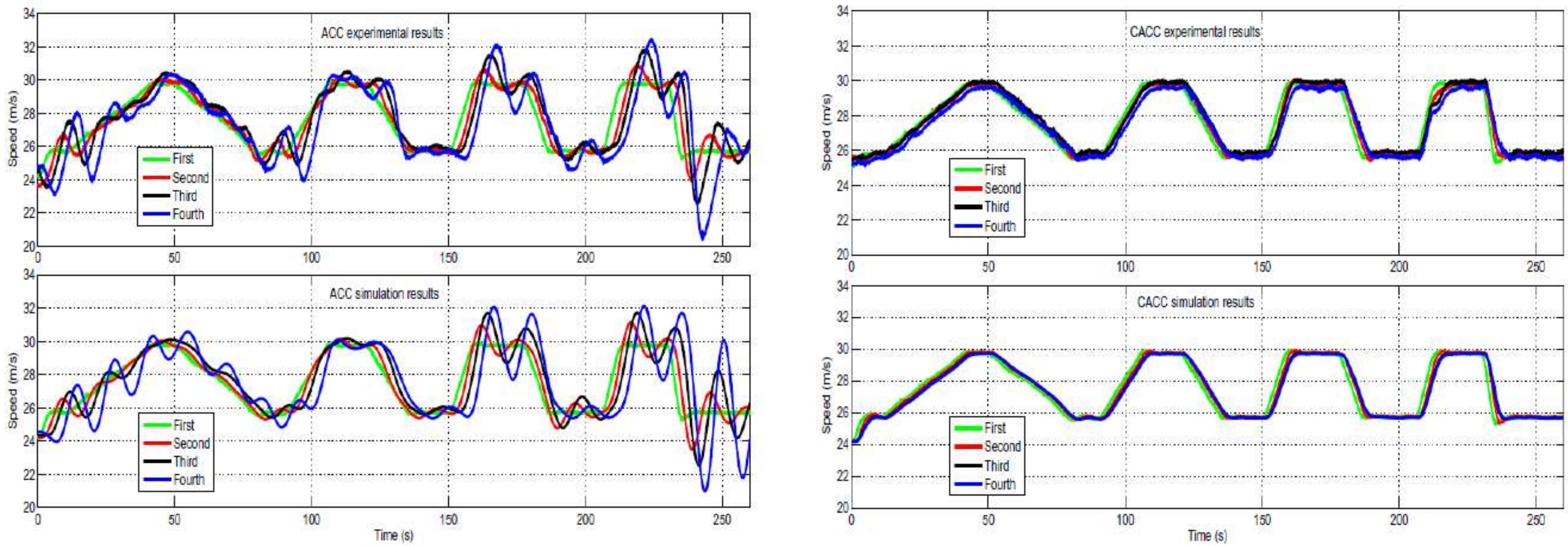
*NGSIM Data

Cooperative Adaptive Cruise Control (CACC)

- Field Experiments
- CACC Users accept short gaps



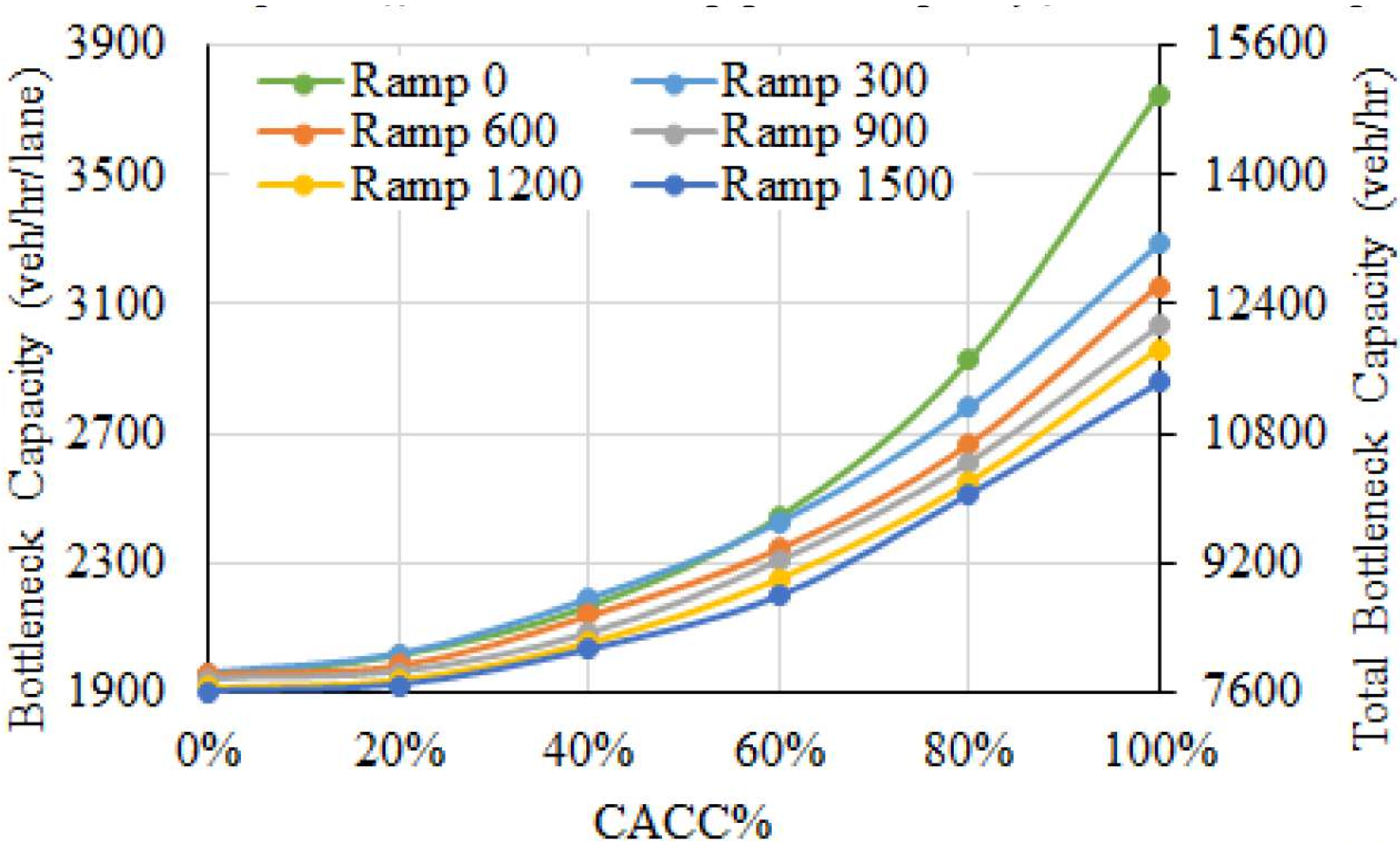
Modeling ACC/CACC Vehicles*



- **Field Data on ACC and CACC operation**
- **Improved Car Following Lane Changing Models**
- **Reproduce Accurately Field Conditions**

***PATH, US DOE & FHWA Research**

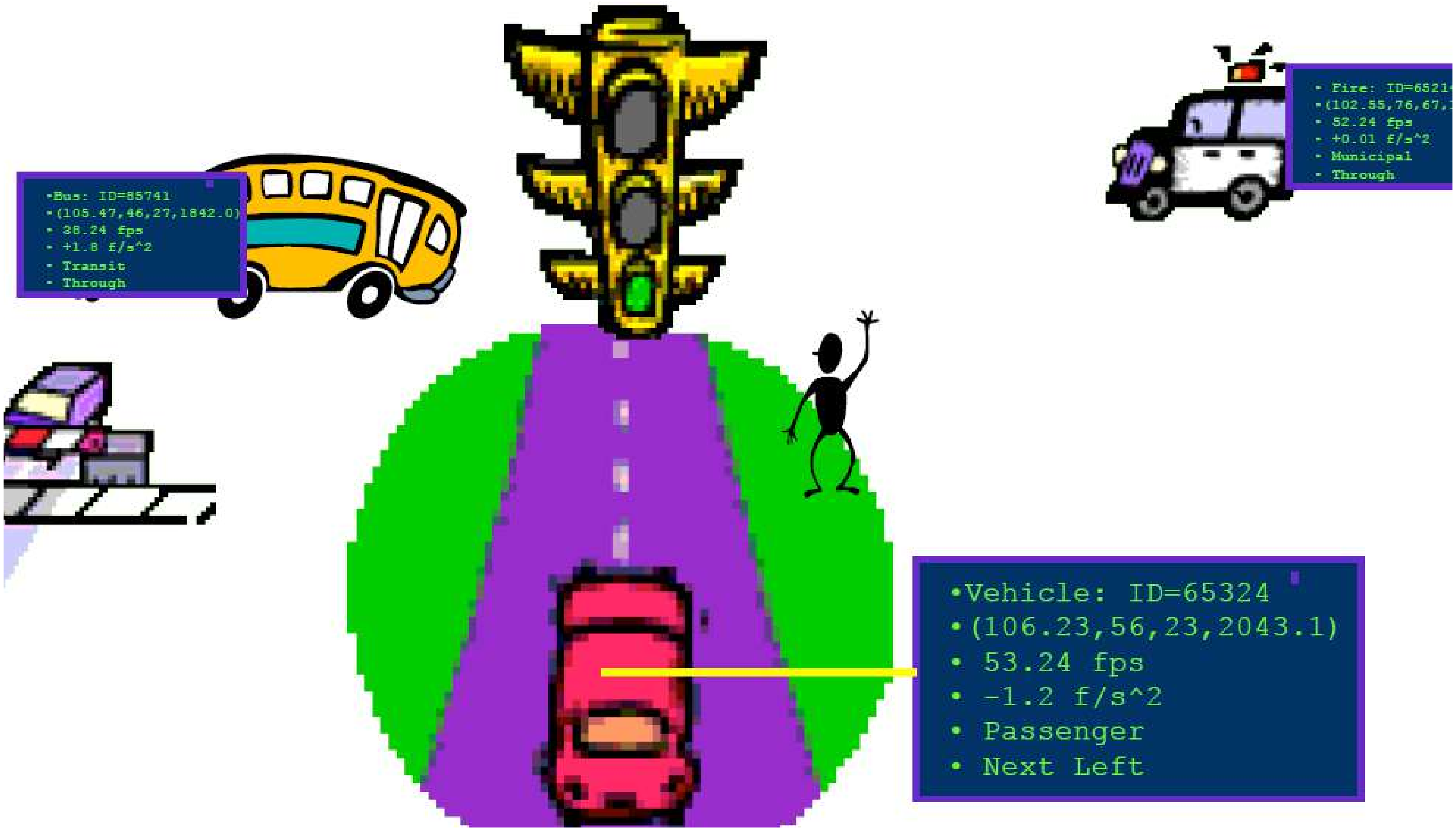
Merging Throughput with CACC



CAV Applications: Traffic Signals (1)

V: Each vehicle a sensor

Here I am



CAV Applications: Traffic Signals (2)

V2I

V: vehicles – here I am

I: intersection: SpaT Message

- **Operational Characteristics**

  Lost time reduction

  Increased saturation flow rate

- **Control Strategies**

  Multimodal adaptive control

  Dynamic lane allocation

  Eco Driving

  Signal-Free Intersections

CAVs: Capacity & Delay at Traffic Signals

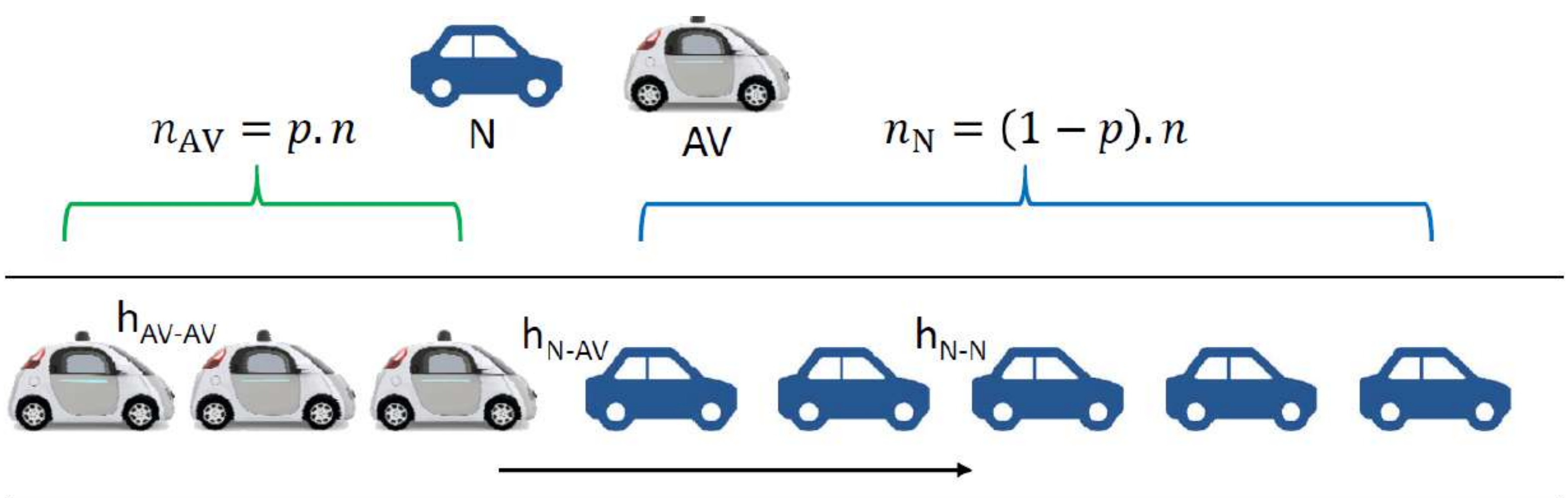
- **Issues:**
  - **CAVs Penetration Rate**
  - **Differences in driving behaviour of (N) and (CAV)**
  - **Relative Position of N and CAV**
  - **Complicated dynamics of car following situations**

Ramezani, M., J.A. Machago, A. Skabardonis, N. Geroliminis, "Capacity and Delay Analysis of Arterials with Mixed Autonomous and Human-Driven Vehicles," 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, Napoli, Italy, June 2017.

CAVs: Saturation Headway (1)

- **Given the penetration rate of AV, $0 \leq p \leq 1$**
- **The expected headway of a mixed platoon depends on the relative locations of AV in the platoon**

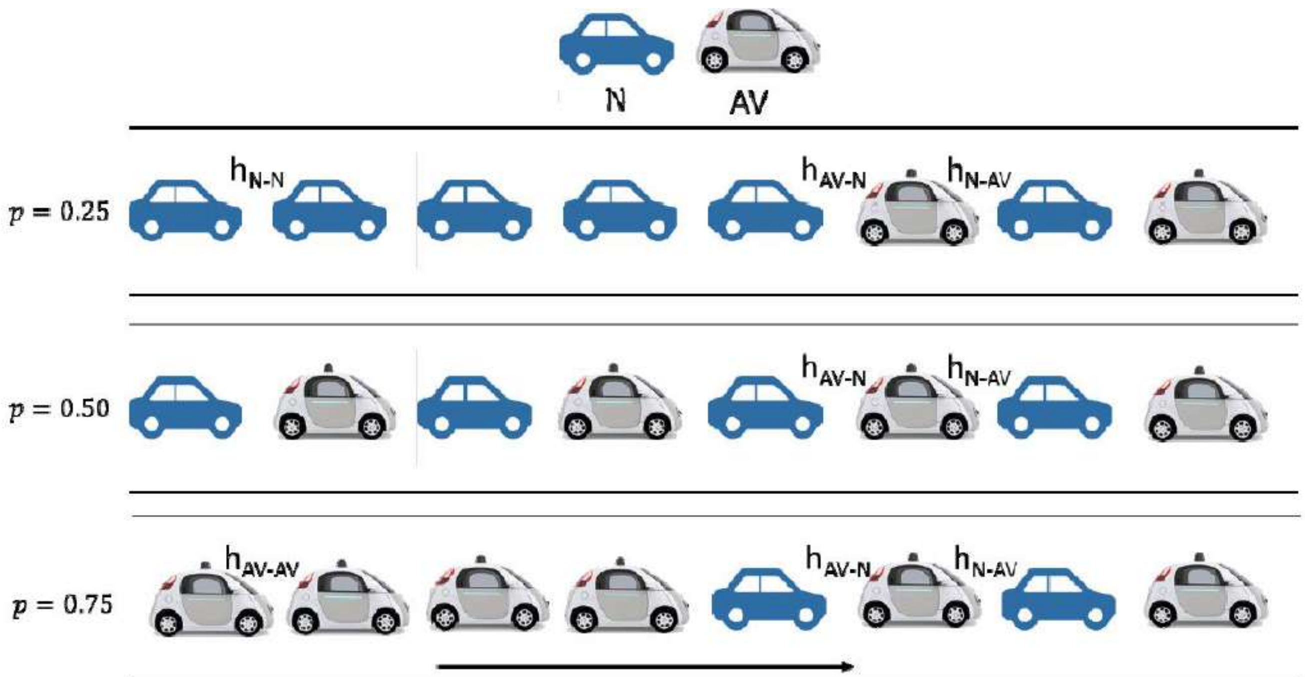
▪ Lower Bound Vehicle Headway



$$\bar{h} = \frac{(n_{\mathrm{N}} - 1) \cdot h_{\mathrm{N-N}} + (n_{\mathrm{AV}} - 1) \cdot h_{\mathrm{AV-AV}} + h_{\mathrm{N-AV}}}{n - 1}$$

CAVs: Saturation Headway (2)

Upper Bound of Vehicle Headway



$$\bar{h} = \begin{cases} \dfrac{n_{AV} \cdot h_{AV-N} + (n_{AV} - 1) \cdot h_{N-AV} + (n_N - n_{AV}) \cdot h_{N-N}}{n-1} & \text{if } p < 0.5 \\ \dfrac{n/2 \cdot h_{AV-N} + (n/2 - 1) \cdot h_{N-AV}}{n-1} & \text{if } p = 0.5 \\ \dfrac{n_N \cdot h_{AV-N} + n_N \cdot h_{N-AV} + (n_{AV} - n_N - 1) \cdot h_{AV-AV}}{n-1} & \text{if } p > 0.5 \end{cases}$$

CAVs: Saturation Headway (3)

Expected Vehicle Headway

$$\bar{h} = \sum_{k=0}^{n} \bar{h}_k \cdot \mathcal{P}(X = k); \quad \mathcal{P}(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$$

- $n =$ *number of vehicles*
- $k =$ *number of AV vehicles*
- $p =$ *penetration rate*

Example:

$n = 4\ [veh];\ p = 0.25$

Possible scenarios:

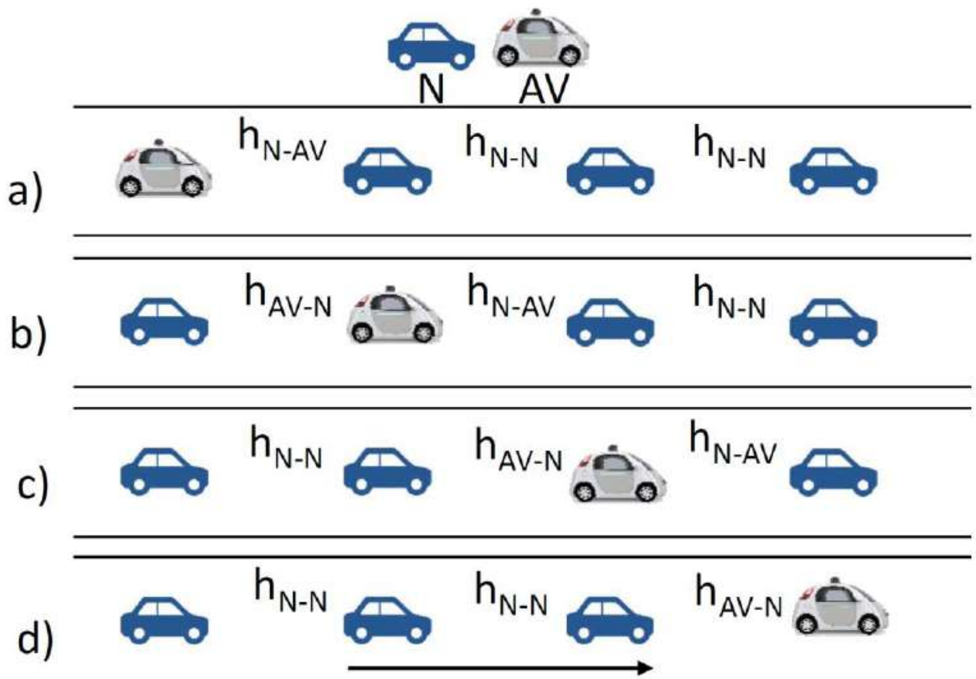
- $k = 0$ (only N)
- $k = 1$
- $k = 2$
- $k = 3$
- $k = 4$ (only AV)

CAVs: Saturation Headway (4)

Expected Vehicle Headway – Example (*cont.*)

$h_{\mathrm{N-N}} = 1.8\ [s];\ h_{\mathrm{AV-AV}} = 0.9\ [s];\ h_{\mathrm{N-AV}} = 1.2\ [s];\ h_{\mathrm{AV-N}} = 1.8\ [s]$

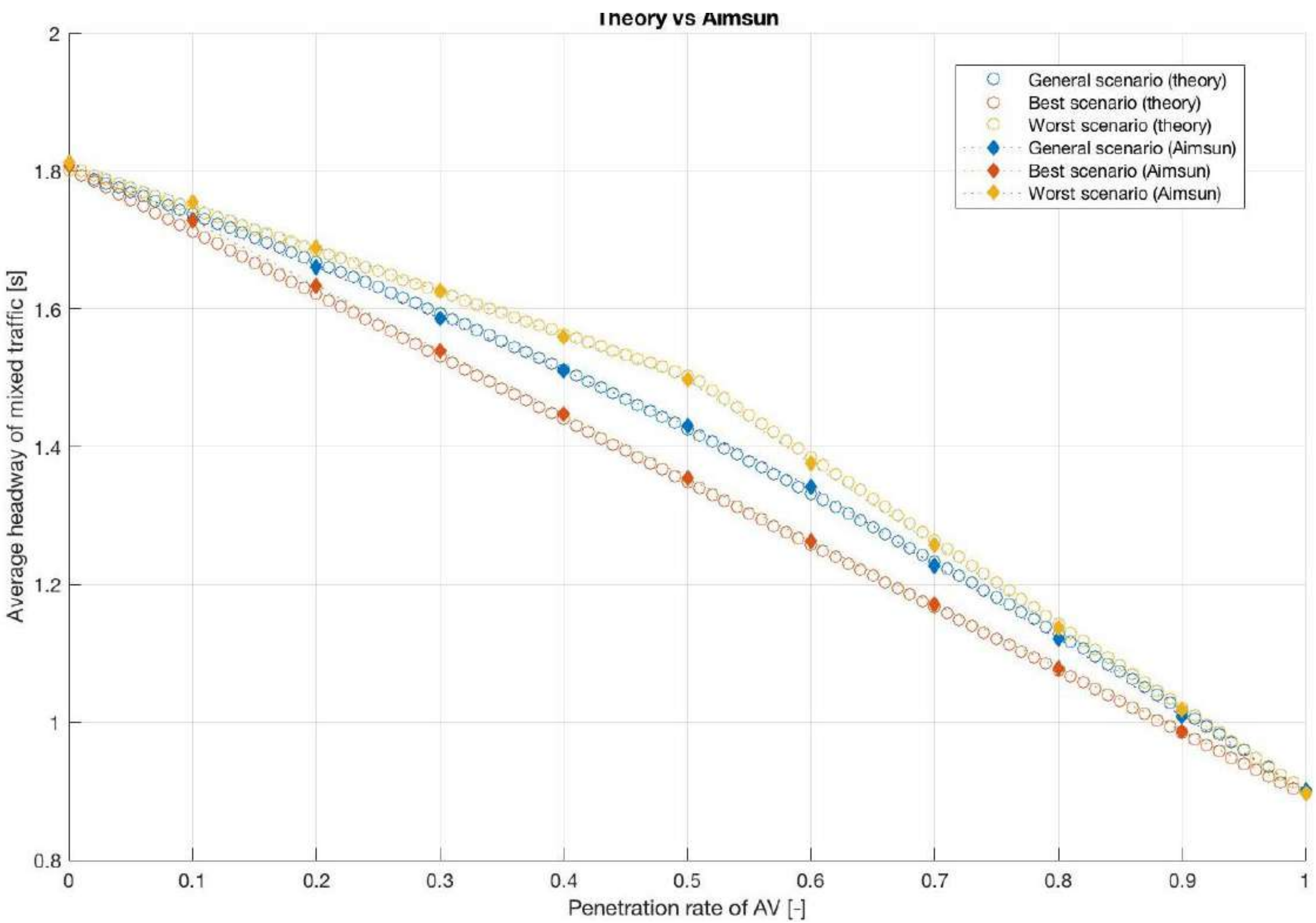
$k = 1 \qquad C_n^k = \binom{n}{k} = \frac{n!}{k!\,(n-k)!} = \frac{4!}{1!\,3!} = 4 \text{ combinations}$



$$\bar{h}_1 = \frac{6h_{\mathrm{N-N}} + 3h_{\mathrm{AV-N}} + 3h_{\mathrm{N-AV}}}{(n-1)} \times \frac{1}{C_n^1} = 1.65\ [s]$$

CAVs: Saturation Headway (5)

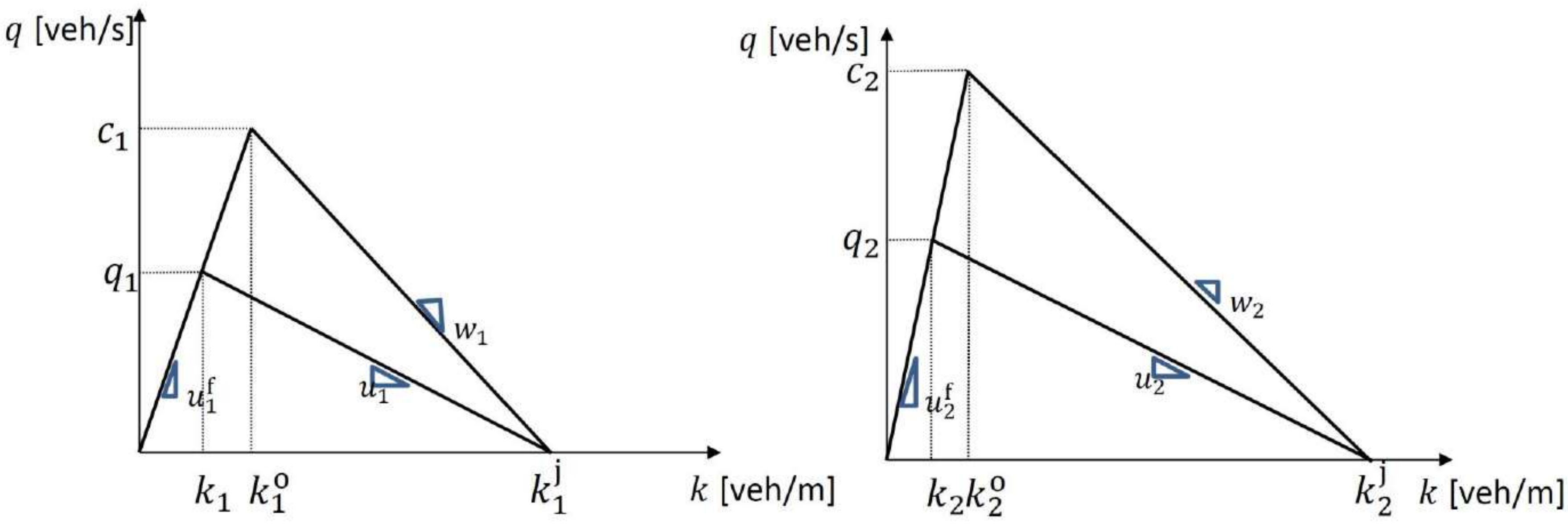
- **Expected, upper and lower bounds of mixed flow headway**
- **validation of theoretically obtained headways using microsimulation**



Delay at an Arterial Signalized Link (1)

Scenarios

i. mixed lanes
ii. dedicated lanes for AV and N
iii. one mixed lane and one AV dedicated lane
iv. one mixed lane and one N dedicated lane



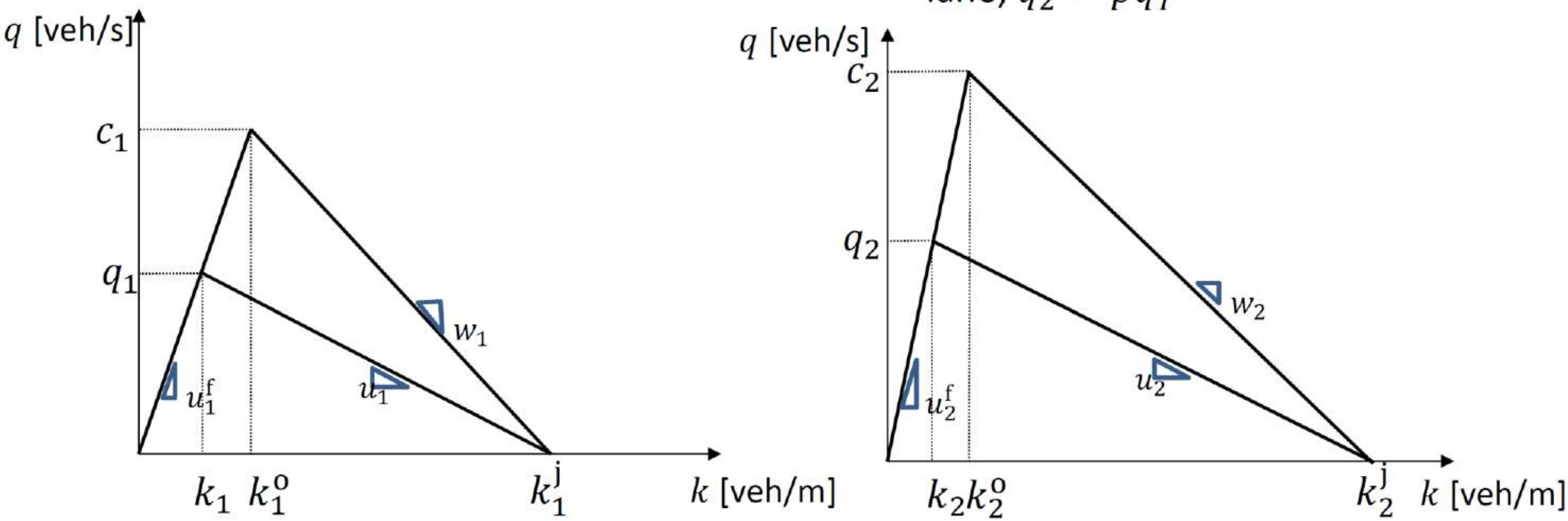
Delay at an Arterial Signalized Link (2)

i. dedicated lanes for AV and N (cont..)

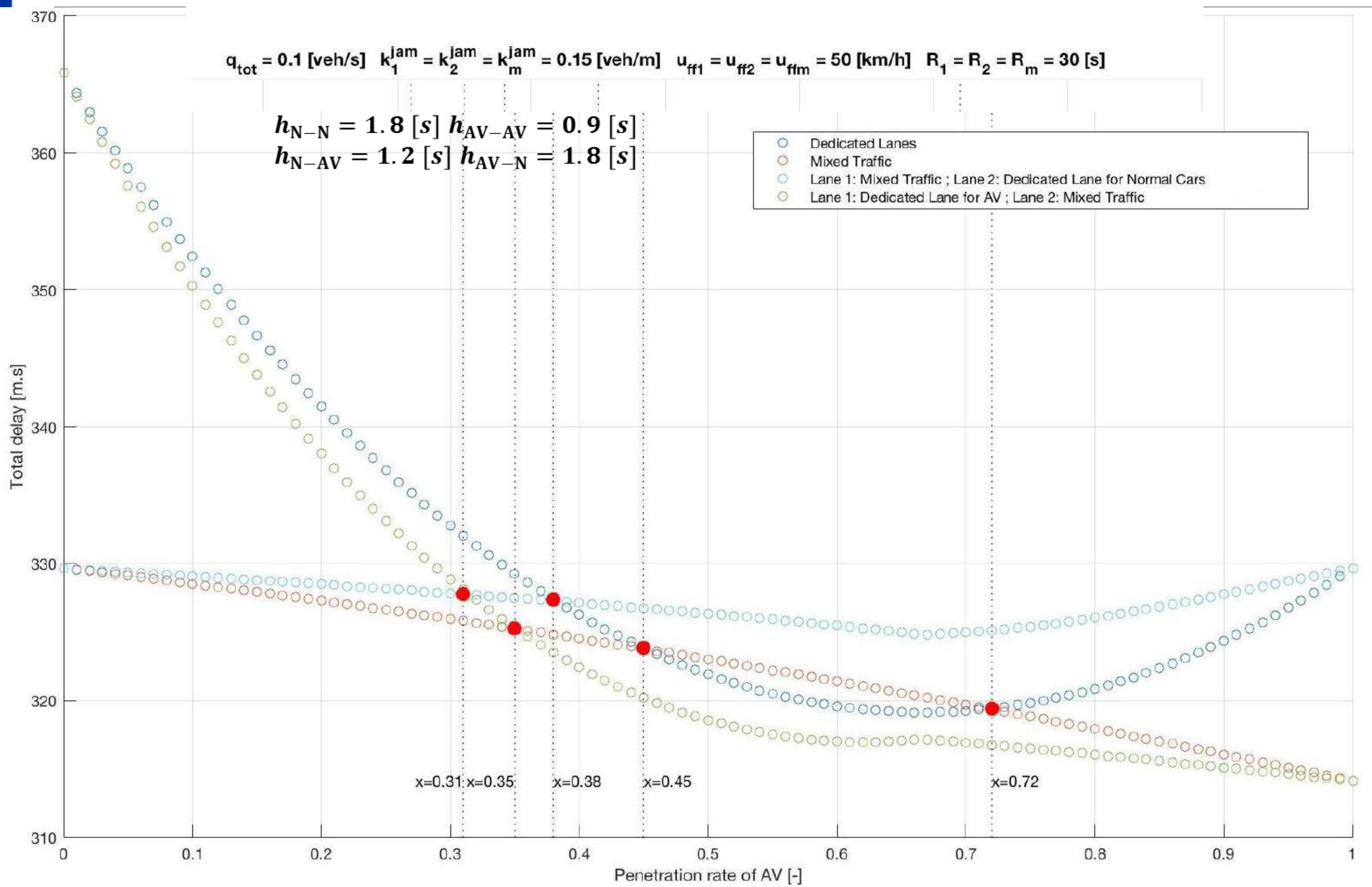
$$D_i = 0.5R_i^2 \cdot \left(\frac{w_i \cdot u_i}{w_i - u_i}\right)$$

$$D_{\mathrm{T}} = \sum_{i=1}^{2} 0.5R_i^2 \cdot \left(\frac{\frac{c_i}{k_i^{\mathrm{j}} - \frac{c_i}{u_i^{\mathrm{f}}}} \cdot \frac{q_i}{k_i^{\mathrm{j}} - \frac{q_i}{u_i^{\mathrm{f}}}}}{\frac{c_i}{k_i^{\mathrm{j}} - \frac{c_i}{u_i^{\mathrm{f}}}} - \frac{q_i}{k_i^{\mathrm{j}} - \frac{q_i}{u_i^{\mathrm{f}}}}}\right)$$

- R_i: red duration
- q_T : total arrival flow to the link
- q_i : arrival flow of lane i
- q_1: arrival flow to the N dedicated lane; $q_1 = (1-p)q_T$
- q_2: arrival flow to the AV dedicated lane; $q_2 = pq_T$

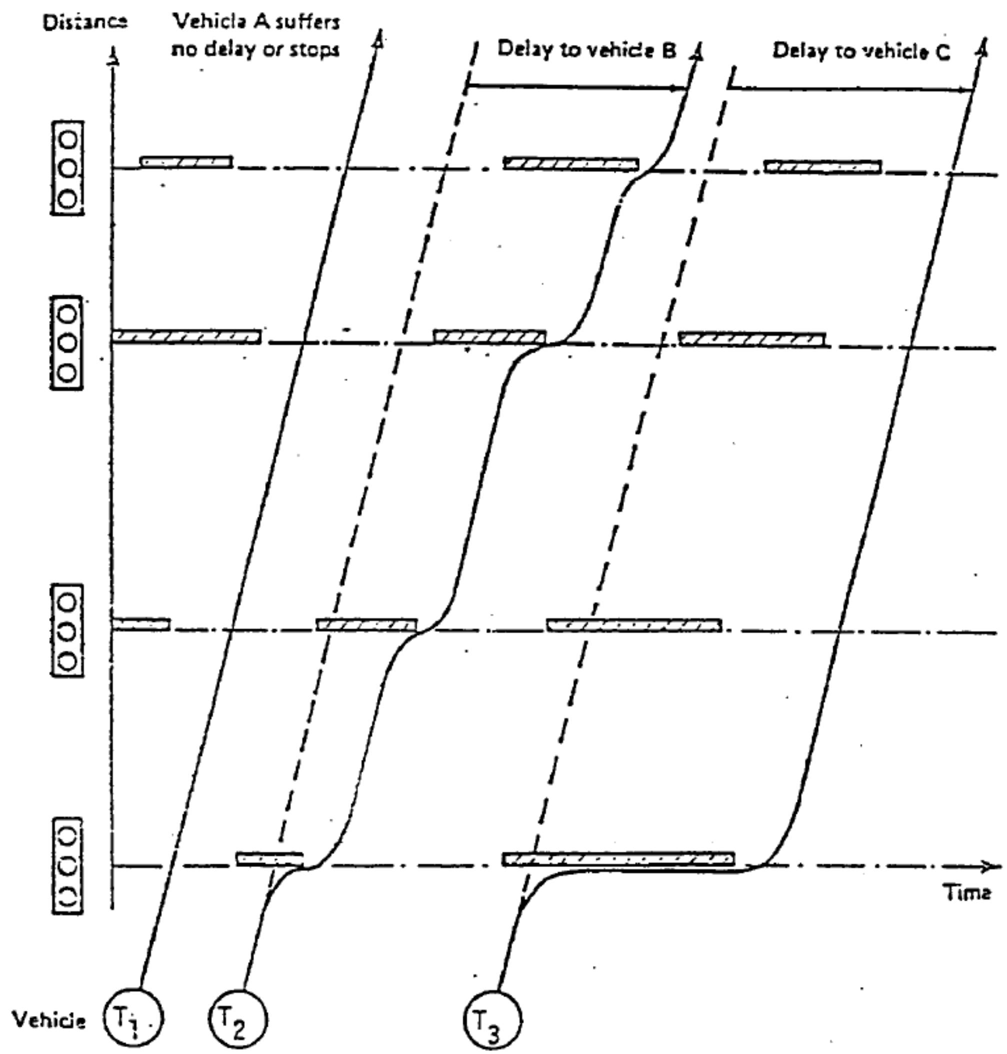


Delay at an Arterial Signalized Link (3)



Eco-Driving: Background (1)

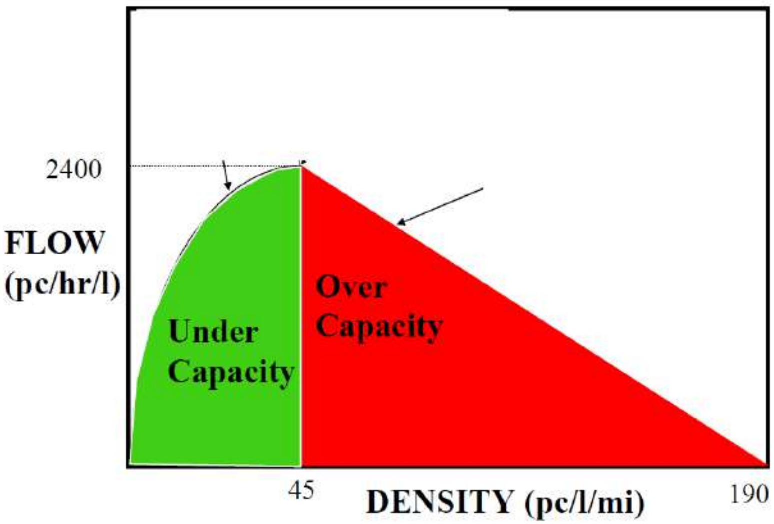
Importance of Vehicle Activity



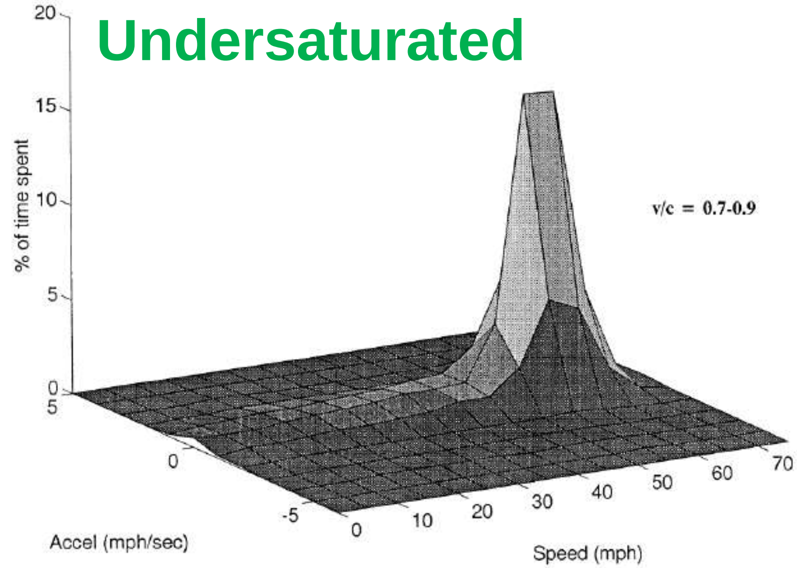
Modal vs. Average Speed based Emission/Fuel Estimates

Eco-Driving: Background (2)

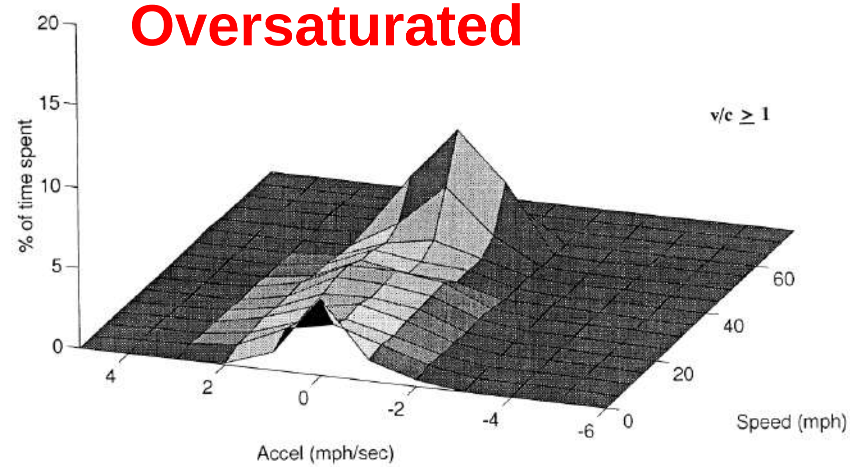
Impacts of Traffic Conditions & Operations



Undersaturated



Oversaturated



Uncertainty on CAVs Impacts on Energy & Emissions

Changes in traffic flows ⇒ Different Speeds

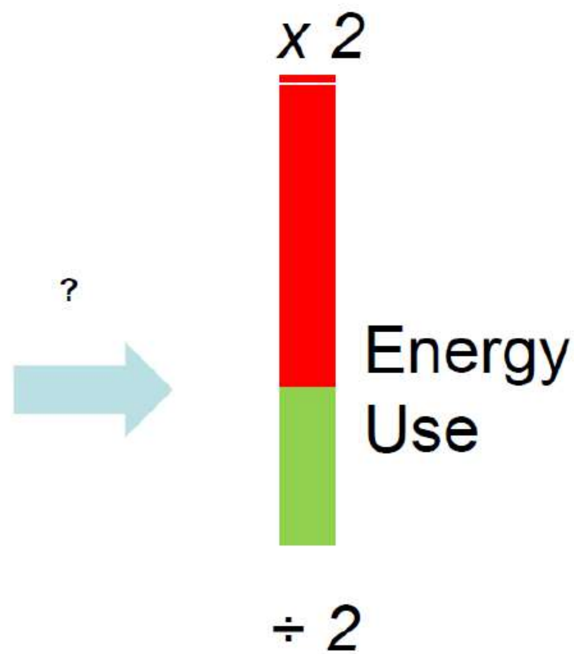
– Increased capacity
– Smoother speeds
– Potentially faster speeds
– Smart intersections

Travel behavior ⇒ +/- VMT

- Mode shifts (to/away from transit with automated shuttles)
- Increased access to mobility of underserved populations
- Changes in the value of time

Higher Vehicle Energy Efficiency

– Smoother driving
– Predictive energy management
– Reduced aero losses in platoons
– Downsizing (due to performance/safety)



+ Interaction with advanced powertrain technology!

US DOE Initiative

Evaluating new vehicle technologies, developing new vehicle controls	Developing controls for connected and automated vehicles	Analyzing the impact of new infrastructure, control and new forms of transportation

Single Vehicle

Eco-driving
Eco-Routing
Predictive Control

Small Network

Connected Intersections
V2X
ACC, CACC & Platooning

Entire Urban Area

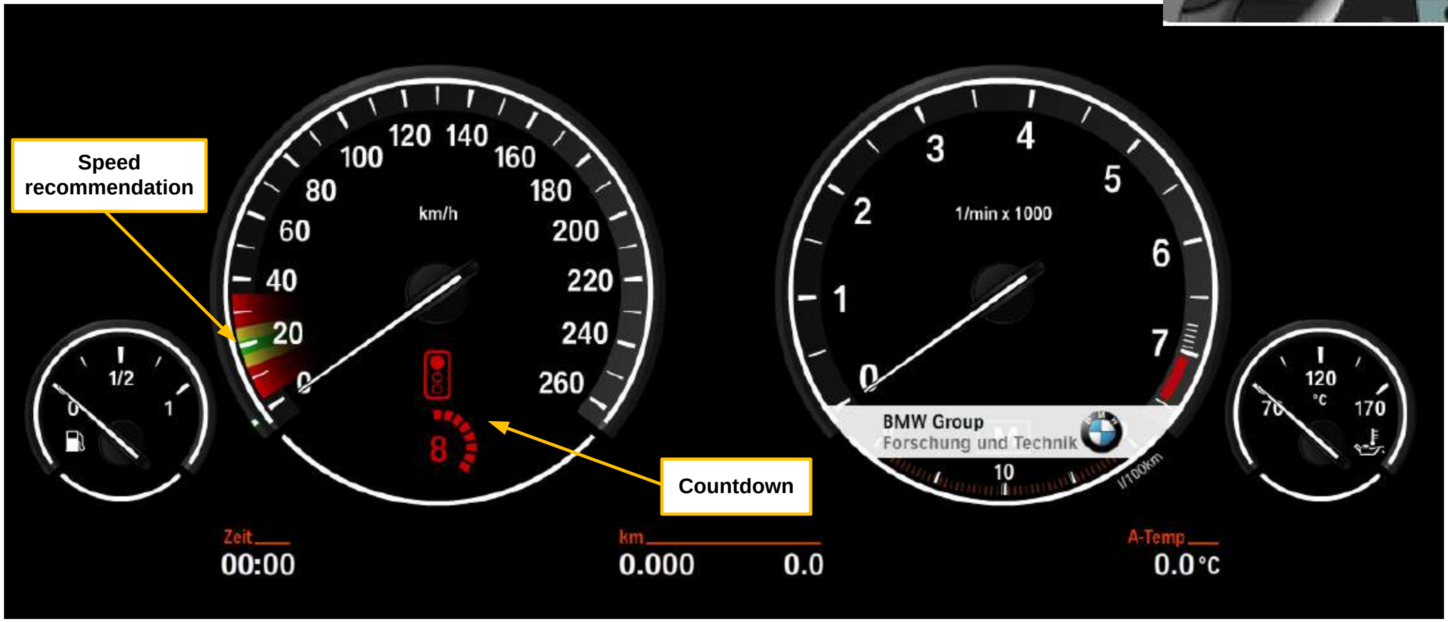
Connected Intersections
Platooning & Eco-lanes
Low-emission zones
VMT changes

Field Test: Eco-Driving at Intersections*

Inputs

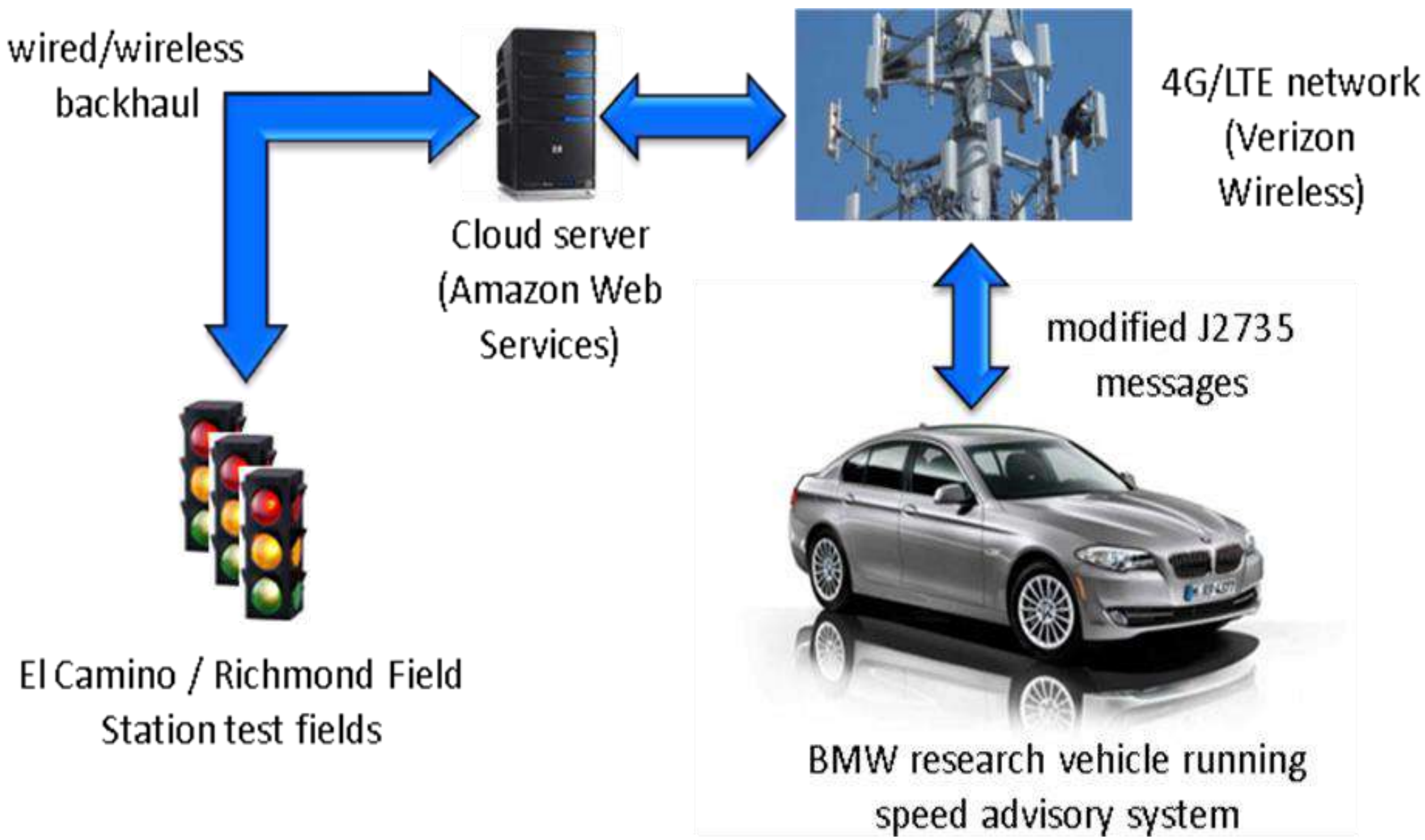
- "Here I am" V2I safety mesage
- Signal Phase & Timing (SPaT)

Dynamic Speed Advisory

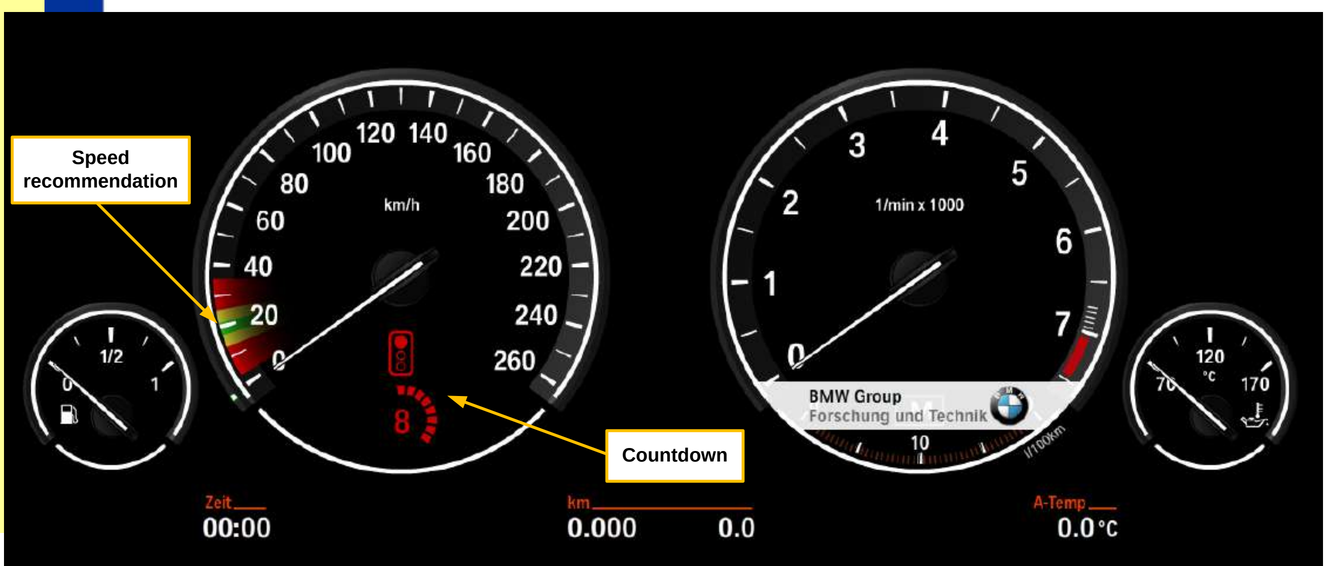


*PATH, FHWA Exploratory Advanced Research

Field Test: Communication System



BMW Research Vehicle



Field Test: Scenarios

1. Uninformed Driver (Baseline Scenario)

2. Informed Driver

    - Driver Follows speed-recommendation

3. Individual Vehicle Priority & Informed Driver

    - Driver Follows speed-recommendation

    - intersection adapts timing with individual vehicle priority

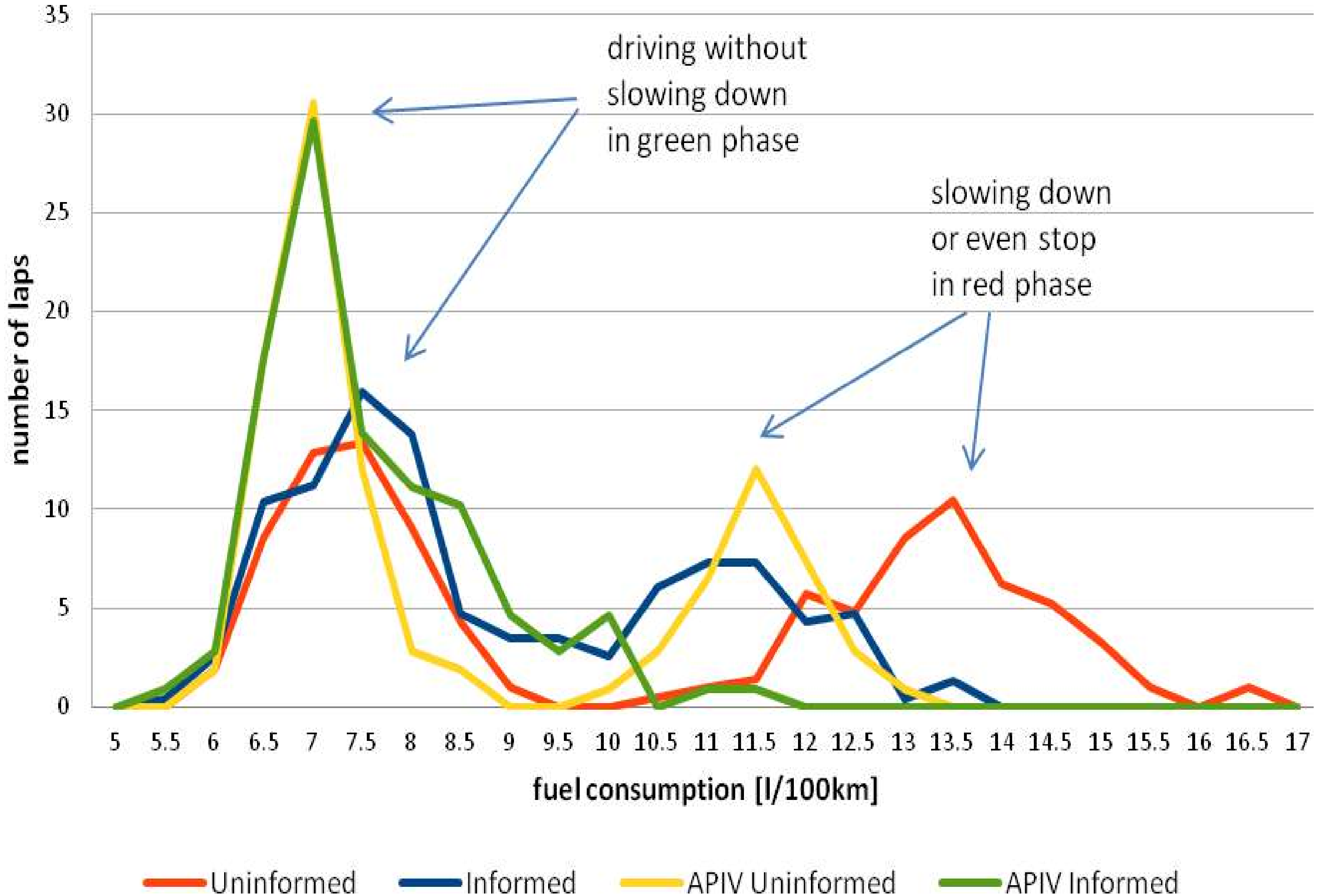
4. Individual Vehicle Priority & Uninformed Driver

    - intersection adapts timing with individual vehicle priority

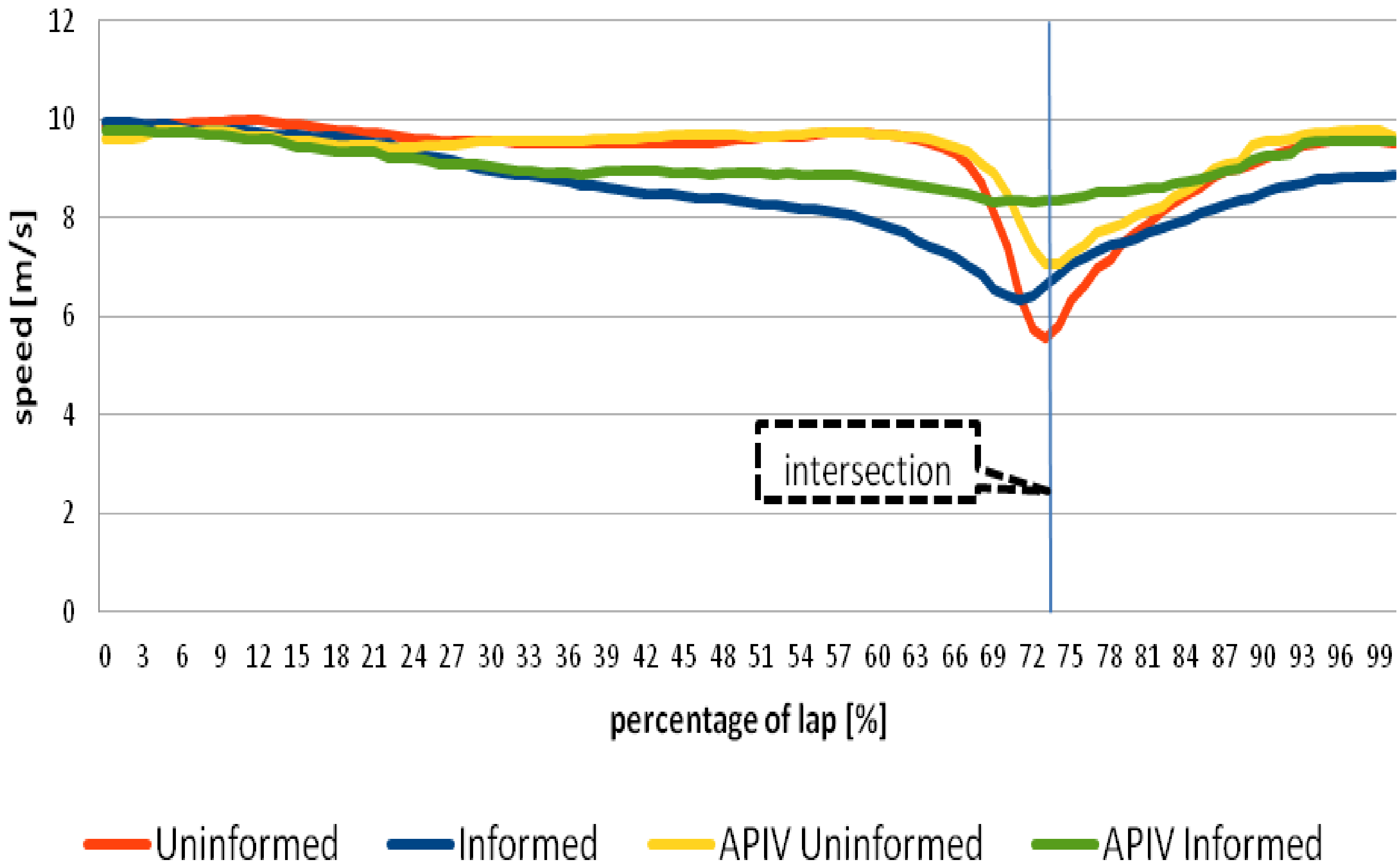
Field Test: Results (1)

	Uninformed Driver	Informed Driver	APIV Uninformed	APIV & Informed
Number of Test Runs	210	232	108	108
Stop Frequency (%)	48.57	30.60	14.81	0.93
% Change	-	-36.99%	-69.50%	-98.09%
Mean Stopped Time (sec)	15.77	10.49	5.56	2.00
% Change	-	-33.48%	-64.74%	-87.32%
Travel Time (sec/trip)	40.69	40.30	31.65	31.00
% Change	-	-0.96%	-22.22%	-23.81%
Fuel (l/100km)	10.2	8.8	8.3	7.3
% Change	-	-13.59%	-19.06%	-28.35%

Field Test: Results (2)

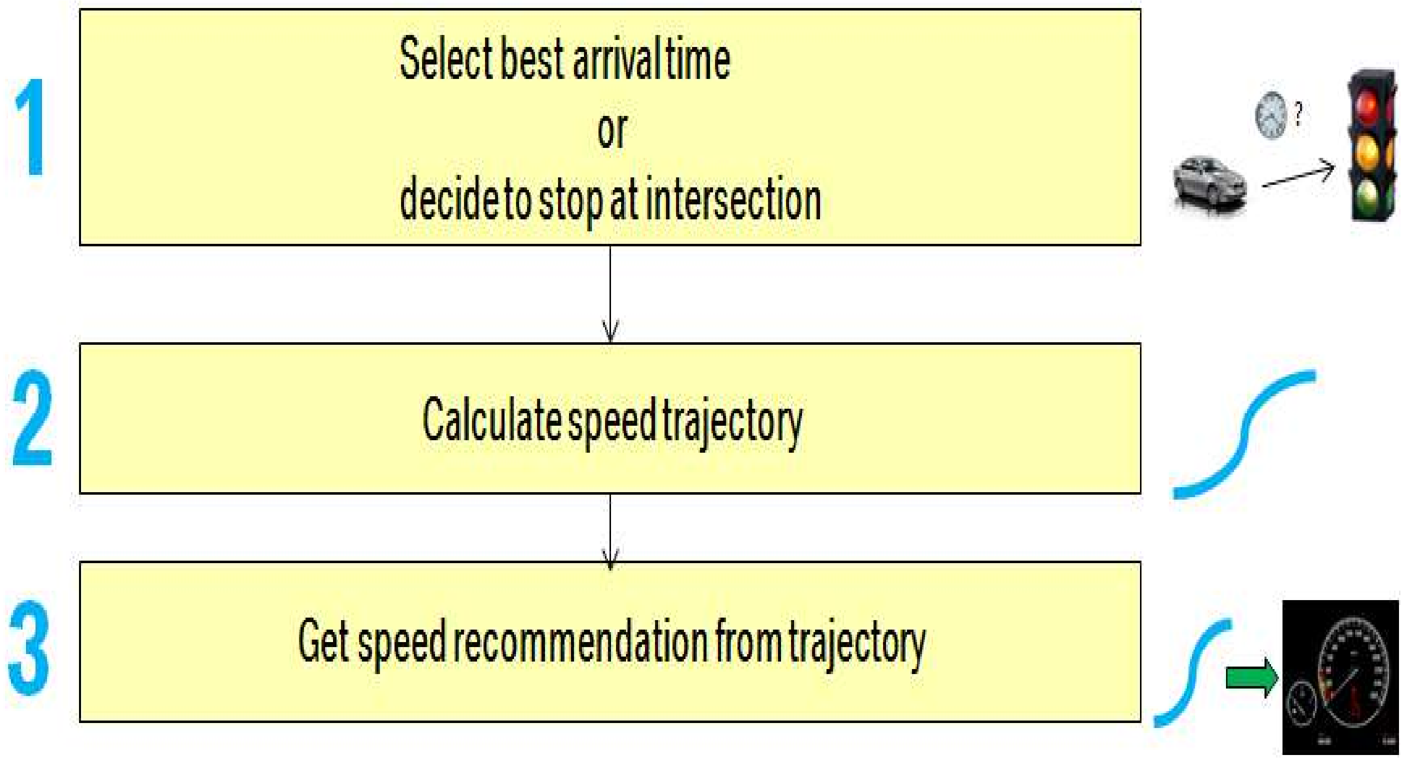


Field Test: Results (3)

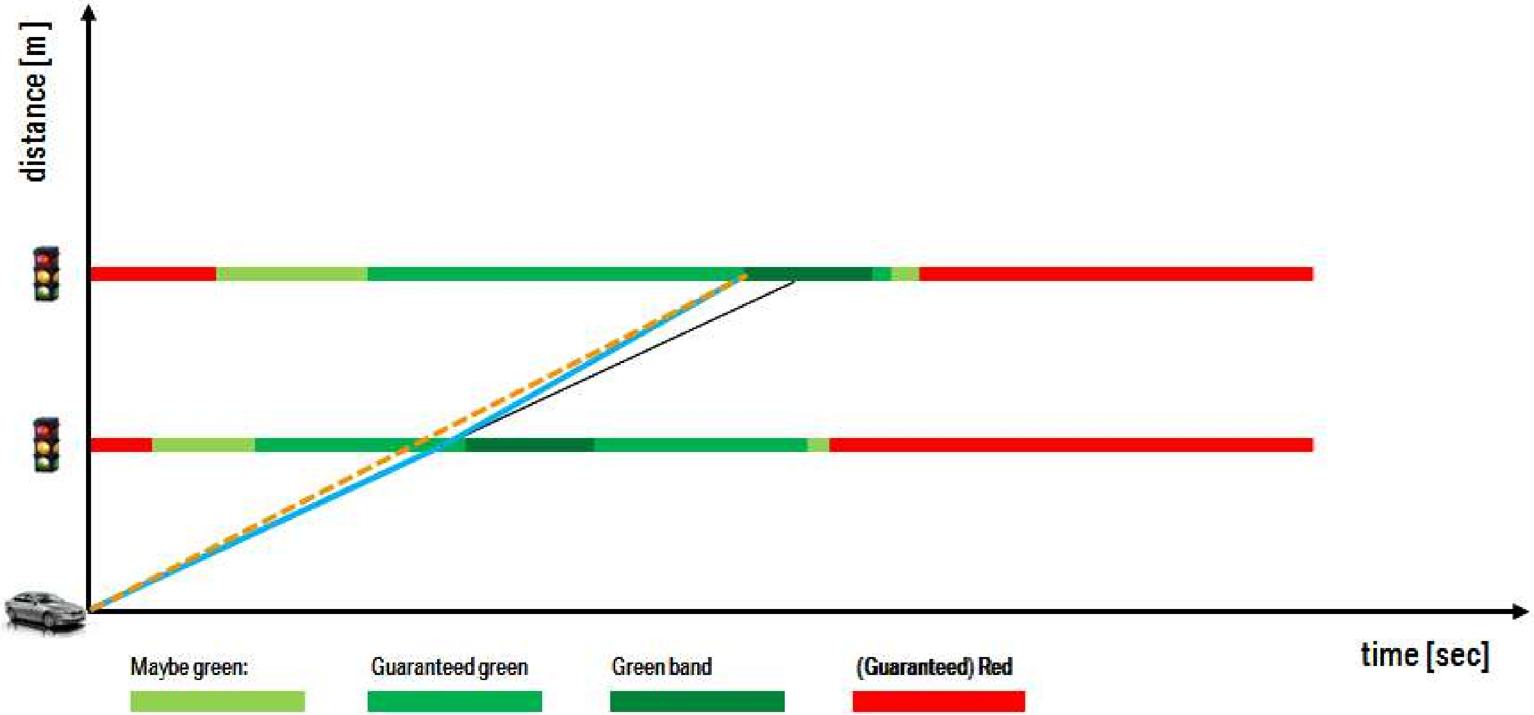


Arterial Field Test: El Camino Real

Algorithm Overview (1)



Implementation Challenges



- Green Window is not Fixed
- Need for Speed Prediction at successive Intersections
- Interactions with In-Informed Traffic
- Frequency of Speed Changes--Compliance

Dynamic Lane Allocation/Grouping (DLG)

- **Problem**

Given real-time O-D demands at a signalized intersection, determine the lane assignment in real-time to improve performance

- **Approach**

For each intersection leg find the optimum lane grouping

Minimize the max lane flow ratio y

(*y = flow/saturation flow*)

St:

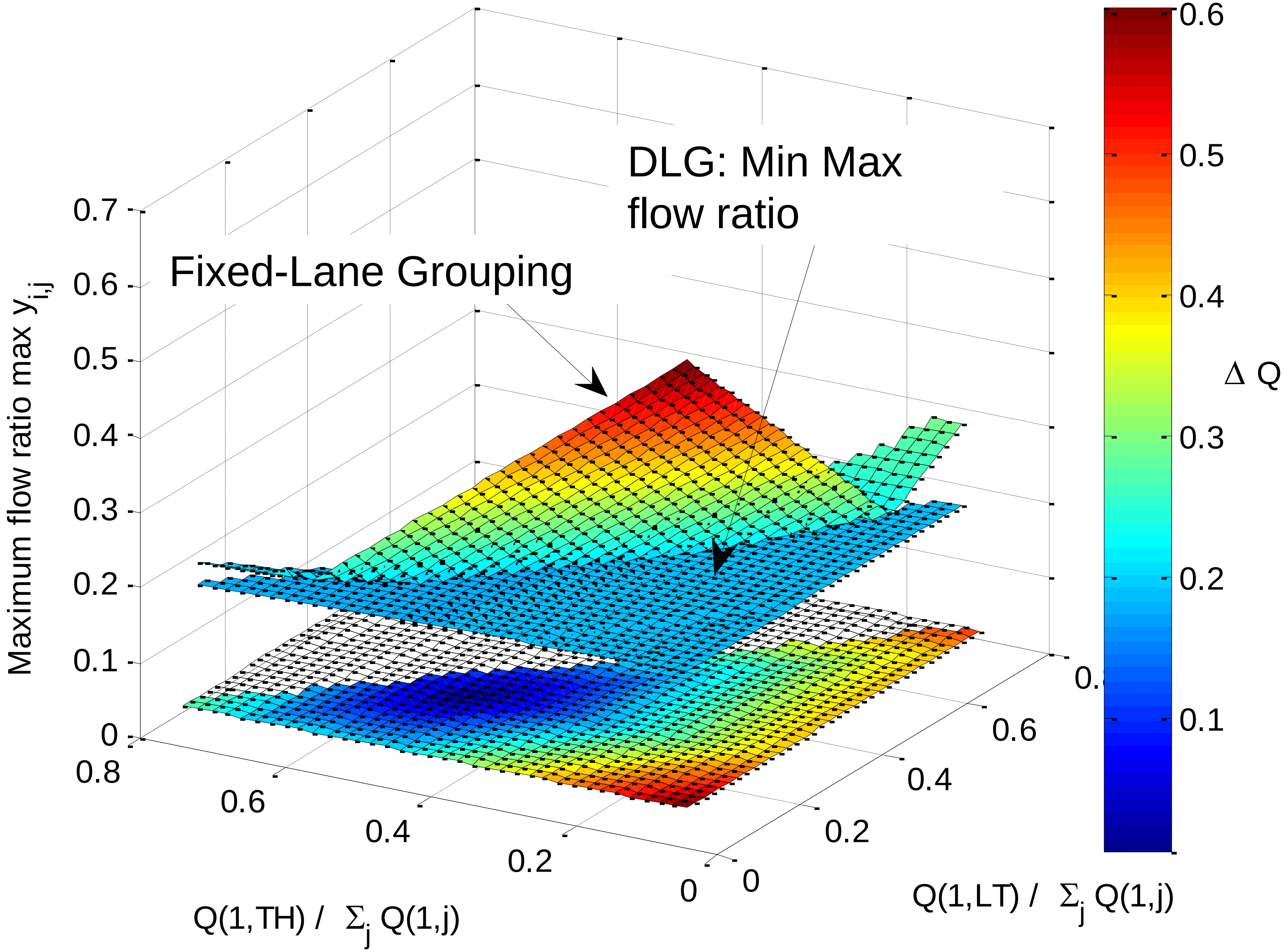
Allowable movements (safety constraints)

Sub-problem:

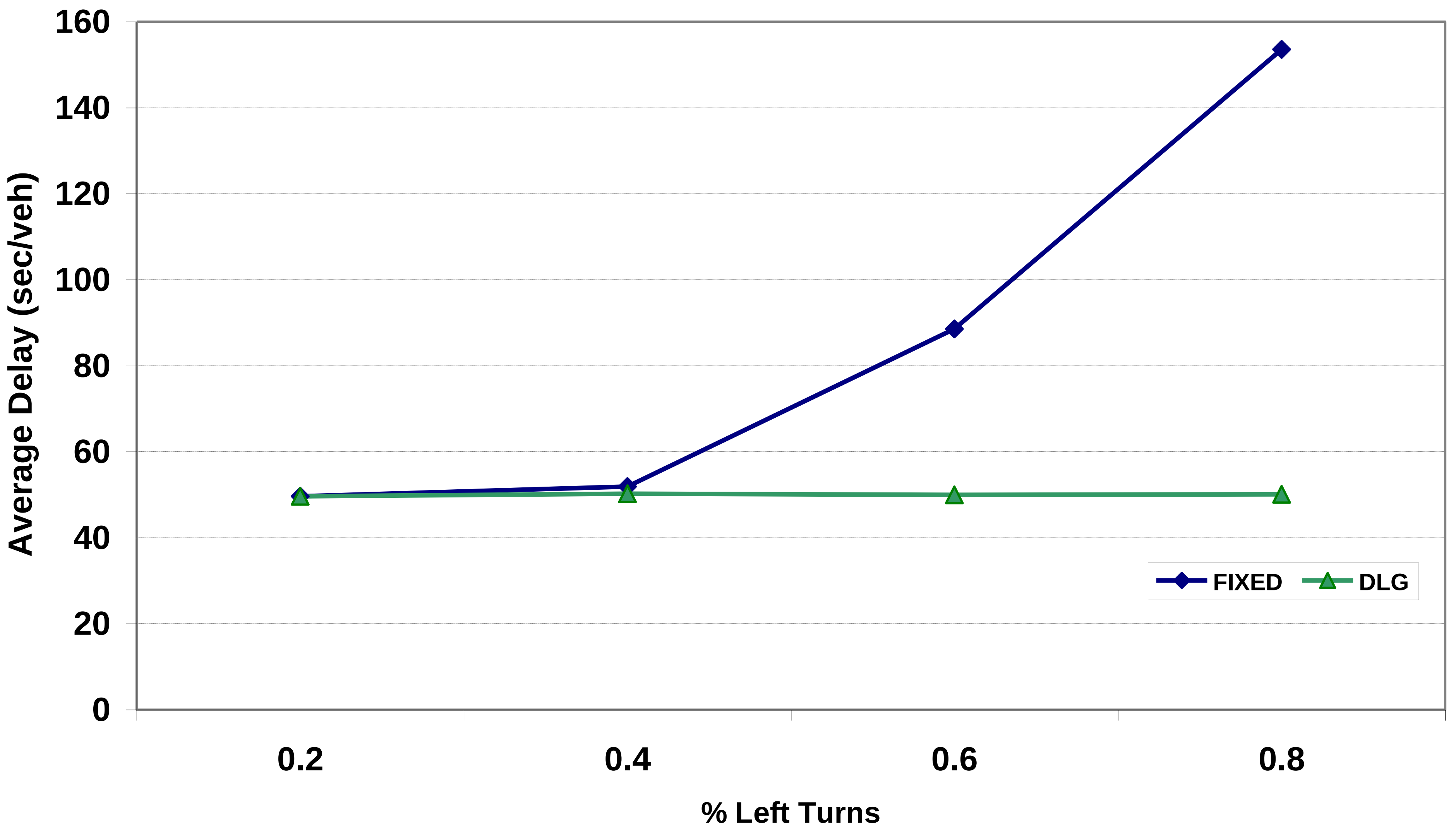
Determine the steady state traffic flow among lanes within each lane group also

DLG Impacts: Max Lane Flow Ratio/Lane

Under DLG, max lane flow ratio always keeps as low as 0.2



DLG Impacts: Average Delay



Public Agencies: Planning & Operations Analyses

- What link capacity to use in 2030 transpoartation plan?
- What are the impacts on operational performance (reliability)
- What will be the market penetration of CAVs?
- Do I need traffic lights?

- Highway Capacity Manual Procedures

  Use of "adjustment factors"

  Example: Critical Intersection control strategy improves intersection capacity by 7%

  Based on field data

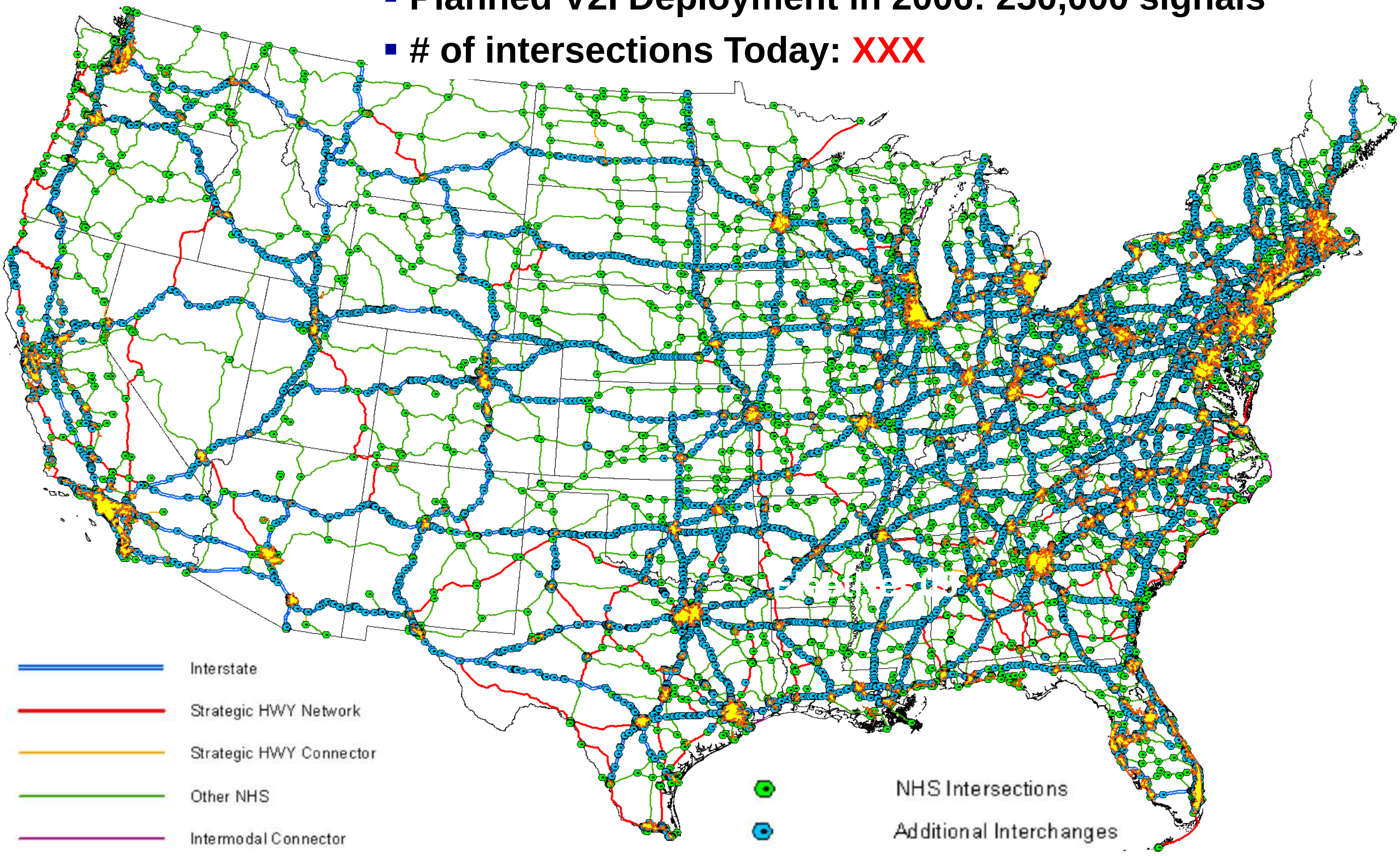
- Source of Factors

  Field data (not yet available)

  Simulation (assumptions)

Implementation Challenges
Background: Initial Deployment Plans

- **Planned V2I Deployment in 2006: 250,000 signals**
- **# of intersections Today: XXX**



The Safety Challenge

- **Human Drivers in the U.S (2015)**

  500,000 miles driven between crashes (approximately 1.9 years)

  1.8 million miles driven between injury crashes

  98 million miles driven between fatal crashes (approximately 370 years of operation between extreme failures)

- **Automated Vehicles**

  AV rate is 40K miles per accident

  Waymo rate is 5.5K miles per disengagement

Waymo accident (disengagement) rate is 13 (100) times worse than human drivers.

Disengagement: a failure of the technology is detected, or when the safe operation of the vehicle requires that the driver take over manual control.

US Legislation

STATE / CONTENT	Definitions / Committee on CAVs	Testing	Platooning	Public Operation	Liability Issues	Bill, Year
Alabama	X					SJR 81, 2016
Arkansas	X	X	X	X		HB 1754, 2017
California	X	X	X		X	SB 1298, 2012 / AB 1592, 2016 / AB 669, 2017 / AB 1444, 2017 / SB 145, 2017
Colorado	X	X			X	SB 213, 2017
Connecticut	X	X		X		SB 260, 2017
Florida	X	X	X	X	X	HB 1207, 2012 / HB 599, 2012 / HB 7027, 2016 / HB 7061, 2016
Georgia	X			X	X	HB 472, 2017 / SB 219, 2017
Illinois	X					HB 791, 2017
Louisiana	X					HB 1143, 2016
Michigan	X	X	X	X	X	SB 996, 2016 / SB 997, 2016 / SB 998, 2016 / SB 169, 2013 / SB 663,2013
Nevada	X	X	X	X	X	AB 511, 2011 / SB 140, 2011 / SB 313, 2013 / AB 69, 2017
New York	X	X				SB 2005, 2017
North Carolina	X		X	X		HB 469, 2017 / HB 716, 2017
North Dakota	X					HB 1065, 2015 / HB 1202, 2017
South Carolina	X		X			HB 3289, 2017
Tennessee	X	X	X	X	X	SB 598, 2015 / SB 2333, 2016 / SB 1561, 2016 / SB 676, 2017 / SB 151, 2017
Texas	X	X		X	X	HB 1791, 2017 / SB 2205, 2017
Utah	X	X				HB 373, 2015 / HB 280, 2016
Vermont	X					HB 494, 2017
Washington, D.C.				X	X	DC B 19-0931, 2012

USDOT Activities

USDOT Strategic Priorities

Safety
Infrastructure
Technology and Innovation
Reducing Regulatory Burden

Connected Vehicles Test Beds

Safety Pilot --Michigan
Mobility
Wyoming
Tampa
New York

Safety Pilot –2836 Vehicles

V2V

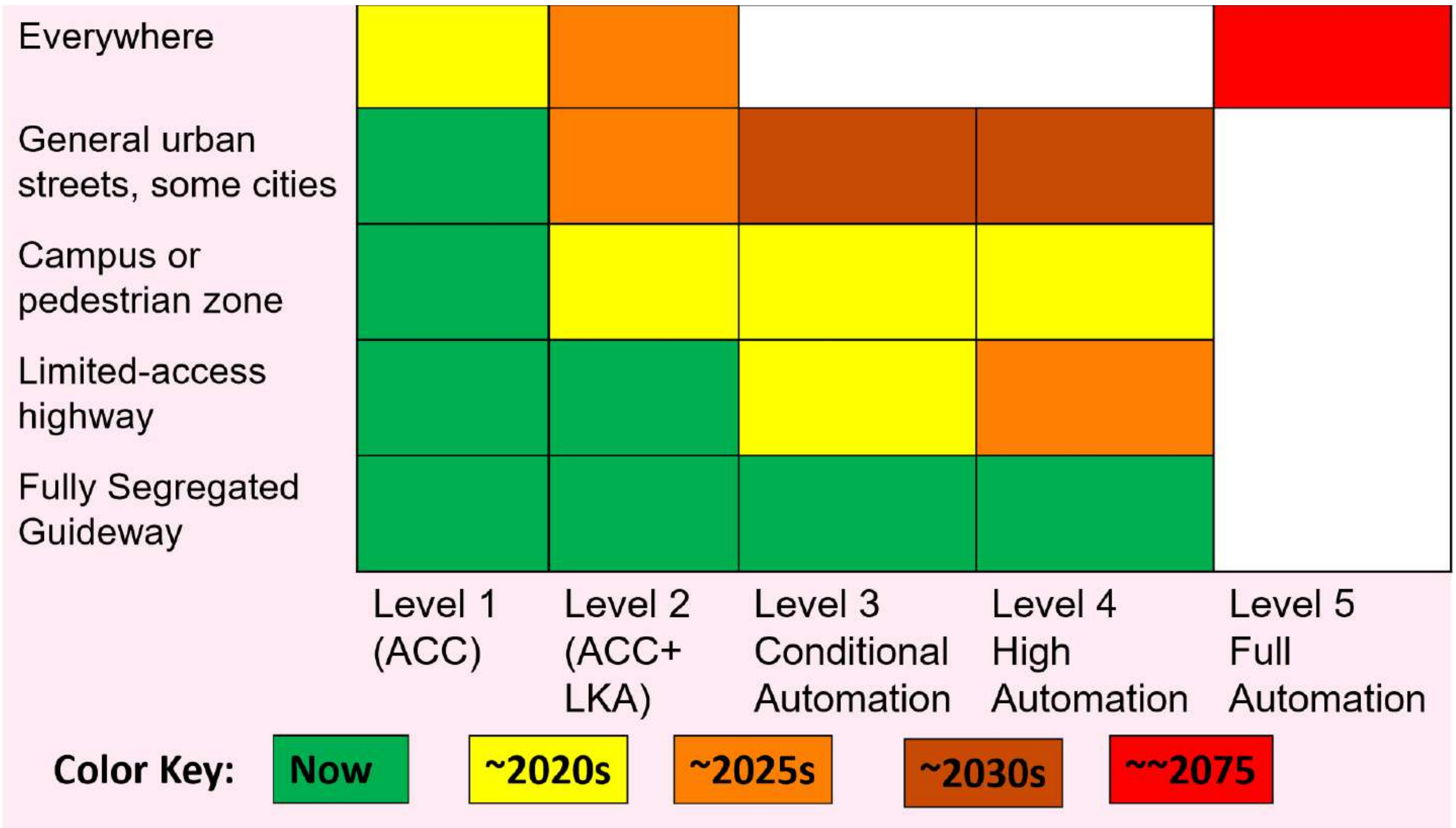
Forward Collision Warning
Emergency Electronic Brake Light
Intersection Movement Assist
Blind Spot Warning/Lane Change Warning
Do Not Pass Warning
Left Turn Across Path/ Opposite Direction
Right Turn in Front

V2I

Signal Phase and Timing
Curve Speed Warning
Railroad Crossing Warning
Pedestrian Detection

Informed NHTSA Decision February 2014

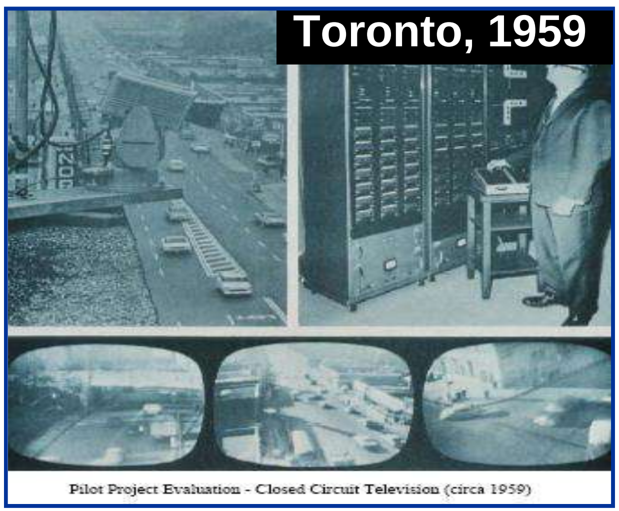
Estimate of Market Introduction*



*Steve Shladover, PATH Program

NTUA Seminar

Connected and Automated Vehicles (CAVs): Challenges and Opportunities for Traffic Operations



Alexander Skabardonis

NTUA 1977, University of California, Berkeley

Athens, May 31, 2018