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TRANSPORTATION RESEARCH BOARD

Capacity Impacts of Connected and Autonomous Vehicles

September 29, 2020

@NASEMTRB
#TRBwebinar

PDH Certification Information:

- 1.5 Professional Development Hour (PDH) – see follow-up email for instructions
- You must attend the entire webinar to be eligible to receive PDH credits
- Questions? Contact Reggie Gillum at RGillum@nas.edu

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RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

#TRBwebinar

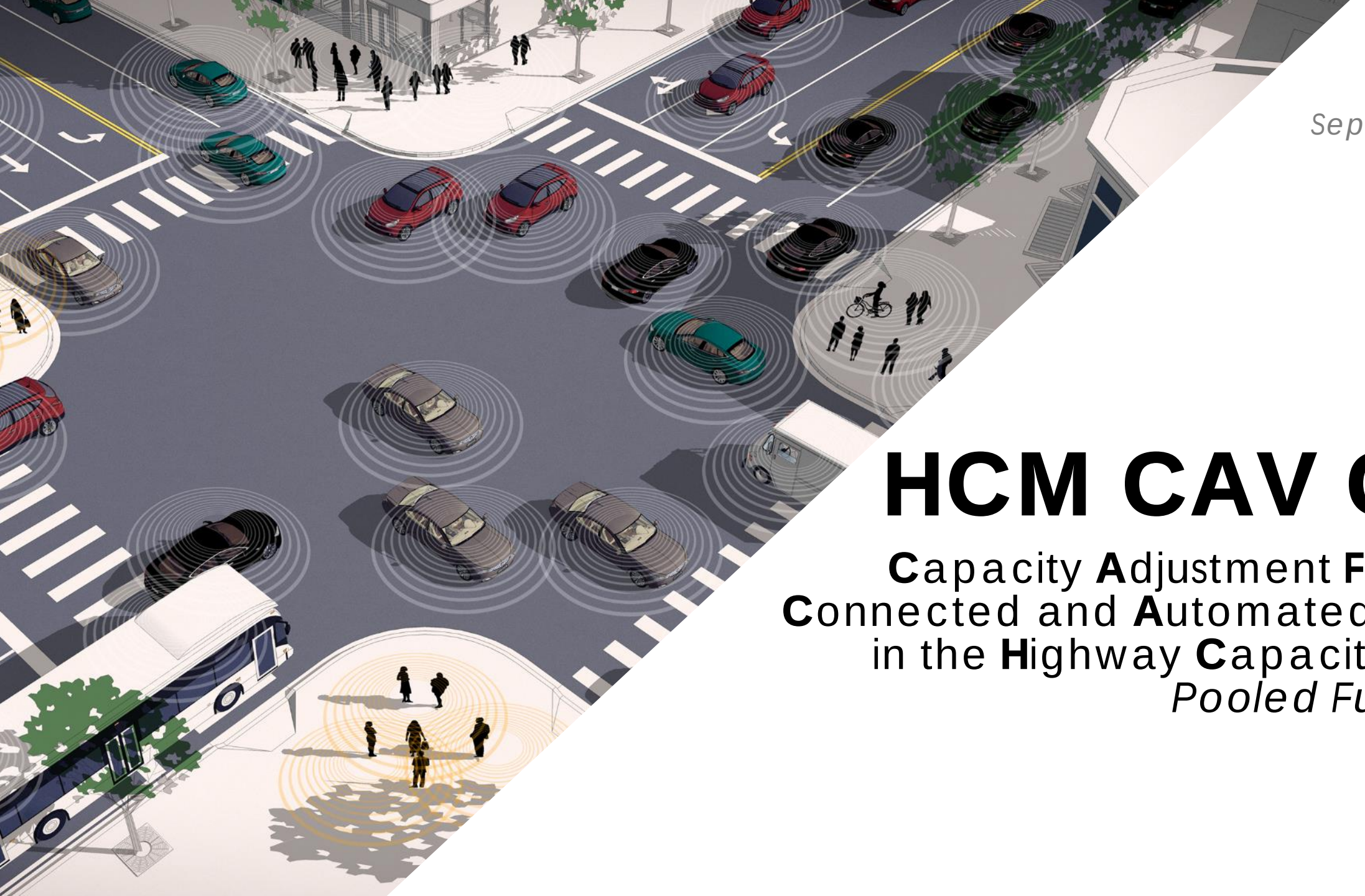
Learning Objectives

1. Identify the assumptions involved in CAV technology and adoption timelines

2. Estimate capacity impacts of CAVs on freeways and arterials

3. Use the HCM to plan for a connected and automated future

#TRBwebinar



TRB Webinar
September 2020

HCM CAV CAFs

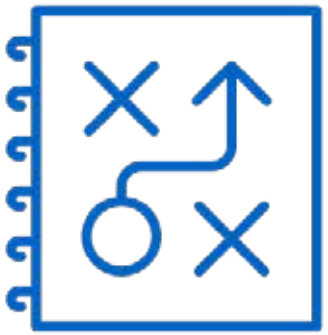
Capacity **A**djustment **F**actors for
Connected and **A**utomated **V**ehicles
in the **H**ighway **C**apacity **M**anual
Pooled Fund Study

HCM CONTEXT

- Highway Capacity Manual (HCM) traditionally used for long-range planning applications
- Agencies looking to answer questions about the impacts of connected and automated vehicles (CAVs) on future capacities
- Results from this study are expected to become official part of the next HCM
- HCM Version 6.1 expected to be available in early 2021
- TRB is planning for an electronic release (e-book and PDF), in addition to print option

Project Motivation

Brian Dunn
Oregon DOT



Modeling Approach

Abby Morgan
Kittelson

Results

Abby and Bastian
Kittelson

Implementation

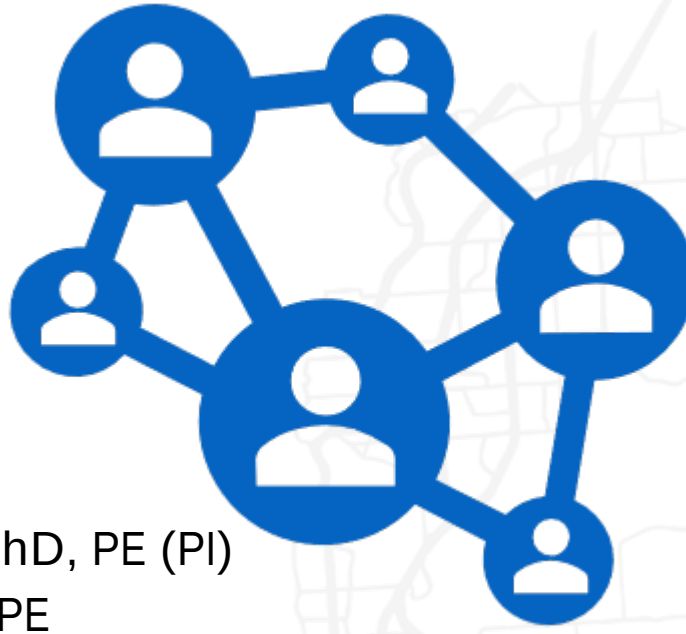
Bastian Schroeder
Kittelson

AGENDA

Introduction and Motivation

Brian Dunn – Oregon DOT

ACKNOWLEDGMENTS



TECHNICAL ADVISORY COMMITTEE (TAC)

- **Brian Dunn, Oregon DOT**
- **Tony Knudson, Oregon DOT**
- Peter Calcaterra, Connecticut DOT
- Grant Farnsworth, Utah DOT
- Joe Hummer, NCDOT
- Jessie Jones, Arkansas DOT
- Jim Mahugh, Washington State DOT
- Bill Knowles, TXDOT
- Subrat Mahapatra, MDOT SHA
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  - Abby Morgan, PhD, PE
  - Paul Ryus, PE
  - Burak Cesme, PhD
  - Lee Rodegerdts, PE
  - Apoorba Bibeka
- UCLA
  - Jiaqi Ma, PhD

POOLED FUND STUDY OVERVIEW

Objectives

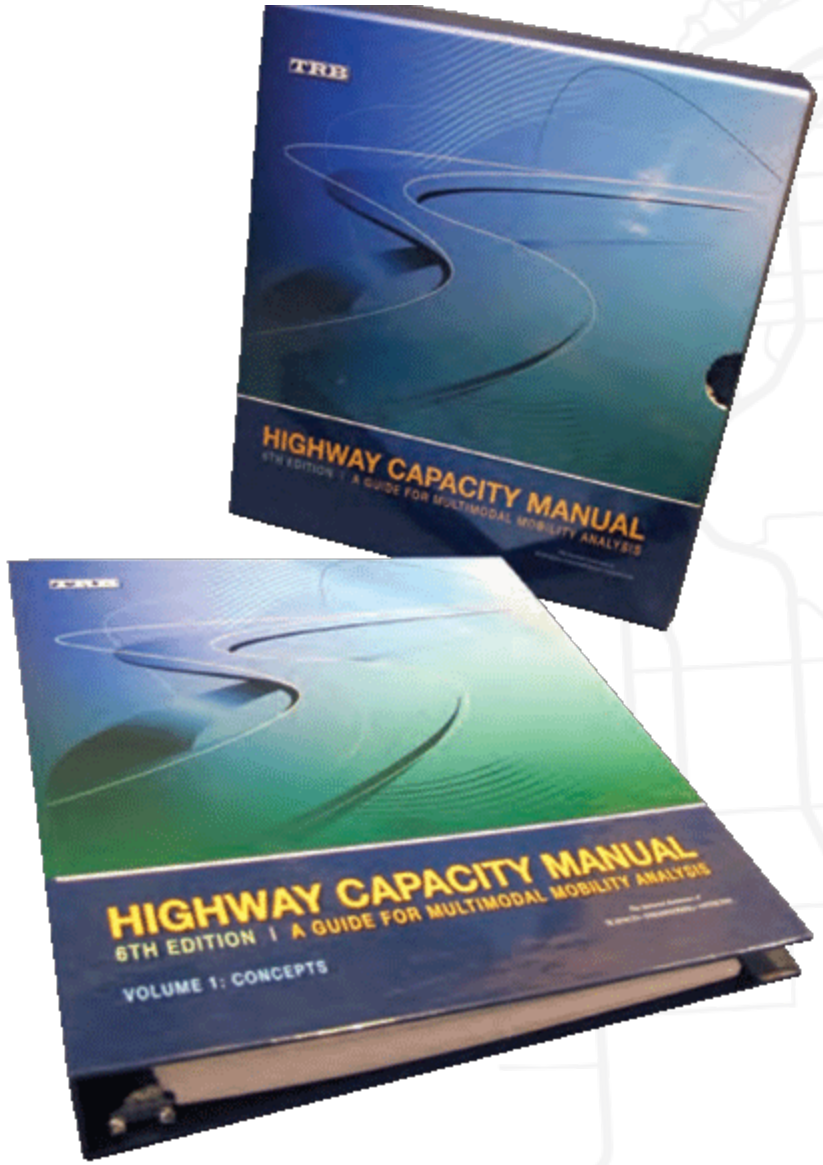
Develop capacity adjustments for CAVs at different levels of volume and market penetration

Agent-Based Approach

Vehicle and driver behavior fully customizable for simulation scenarios

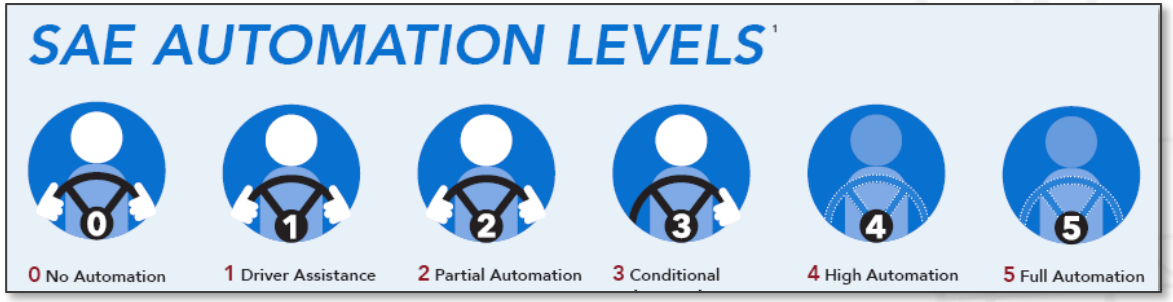
What is Capacity?

- "The **maximum sustainable flow rate** at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions…" (HCM)
- Typically expressed in units of
  - Vehicles per hour per lane (vphpln)



CAV ADOPTION TIMELINE

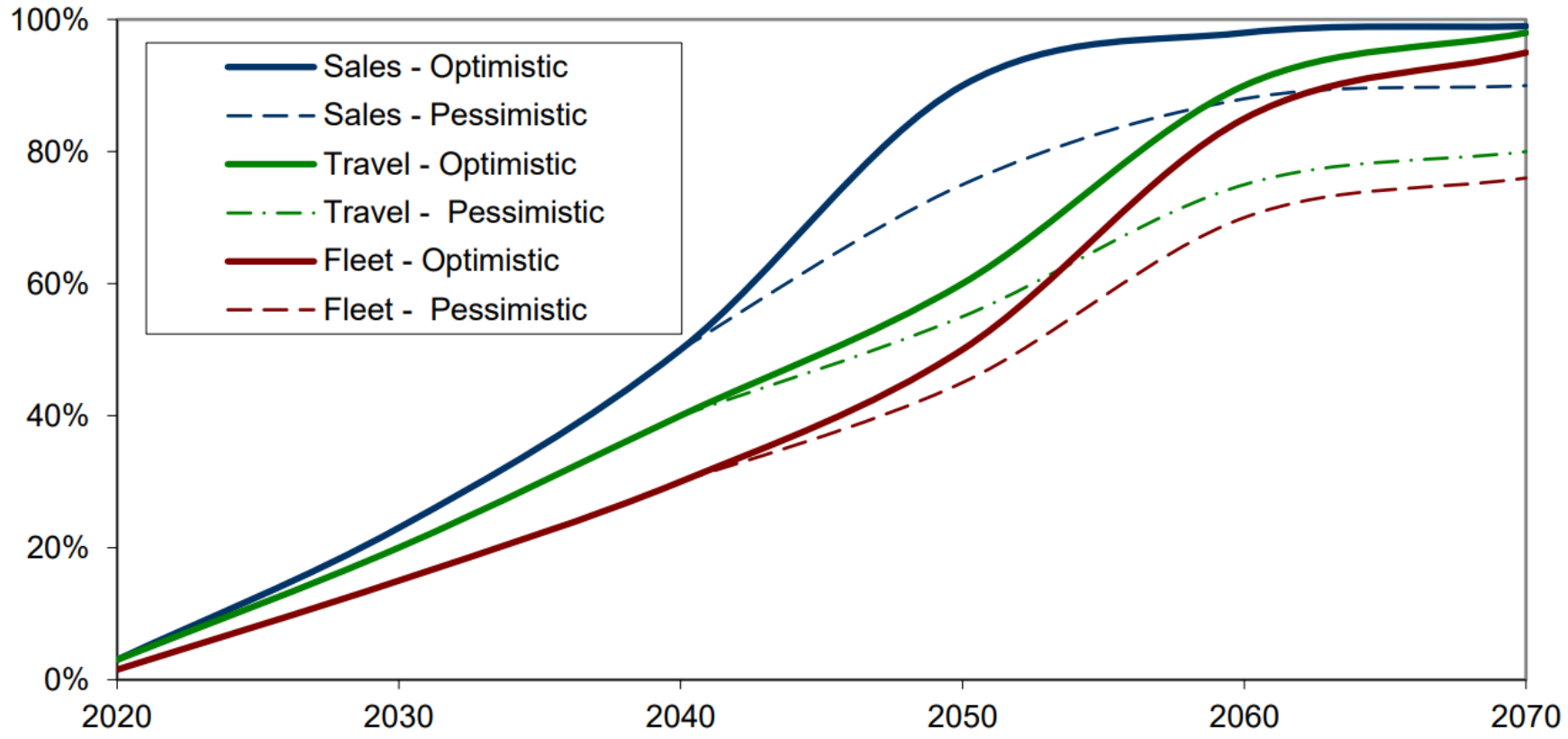
- **U.S. Light Duty Fleet Turnover Rate: 14.8 years**
- **Technology availability:**
  - Partial Automation (Levels 1-2): 2017-2019
  - Conditional Automation (Level 3): 2020 (limited operational design domains)
  - High/Full Automation (Levels 4-5): 2025-2030



- **Market Penetration:**
  - Once technology is perfected, it will take another 13 years for 50% market penetration and 27 years for 90% market penetration

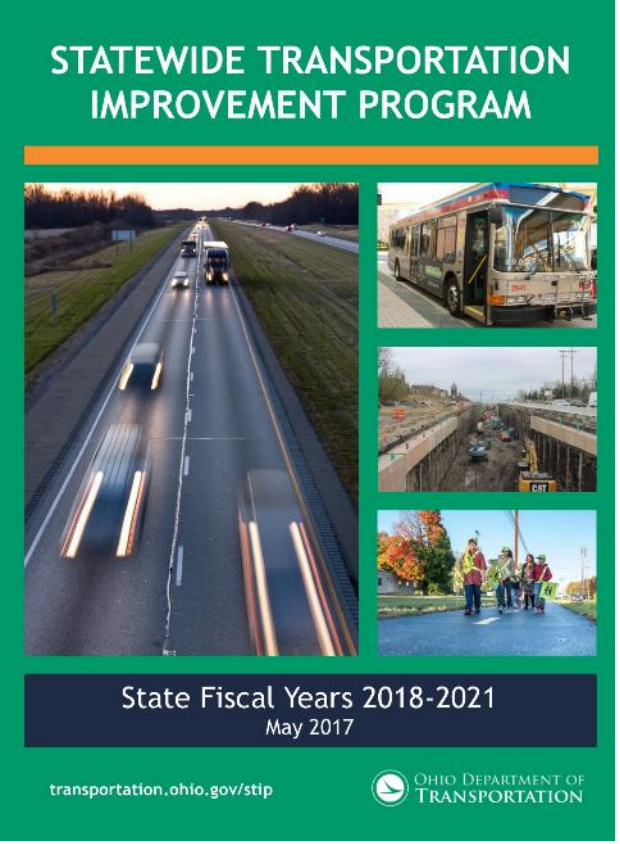
CAV ADOPTION TIMELINE

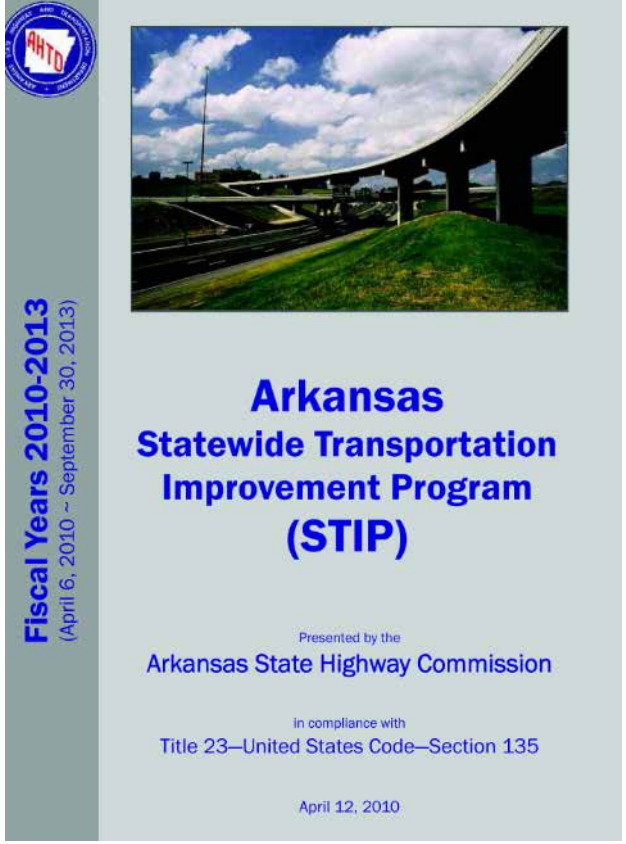
Exhibit 14 **Autonomous Vehicle Sales, Fleet and Travel Projections** (Based on Exhibit 13)

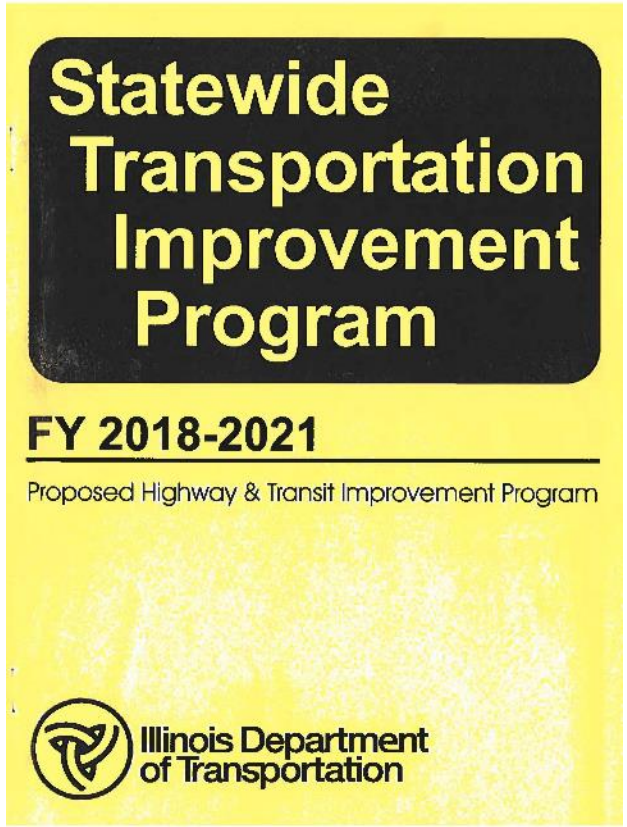


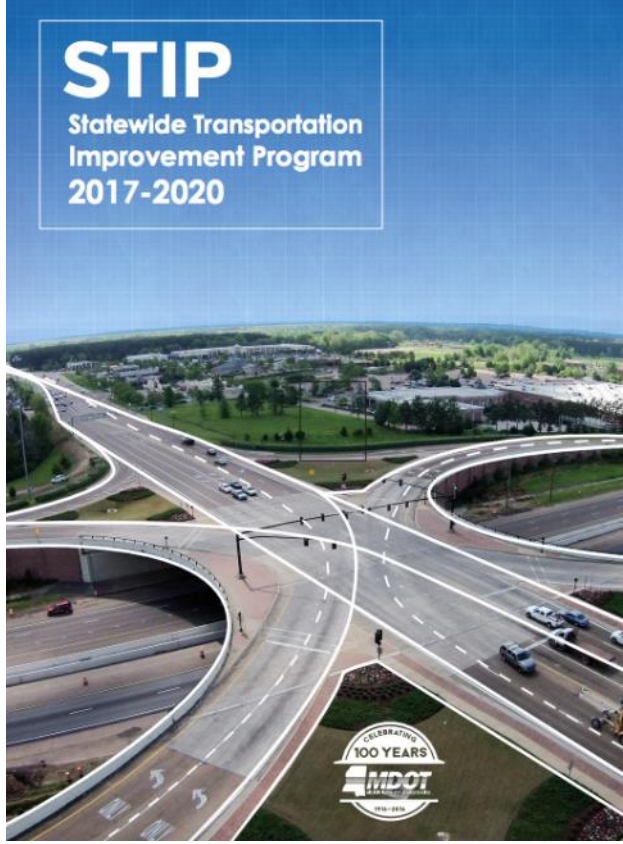
If they follow previous vehicle technologies autonomous vehicles it will take one to three decades to dominate vehicle sales, and one or two more decades to dominate vehicle travel, and even at saturation a significant portion of vehicle travel may continue to be human operated, indicated by the dashed lines.

Source: Litman, Todd, 2018. Autonomous Vehicle Implementation Predictions. https://www.vtpi.org/avip.pdf



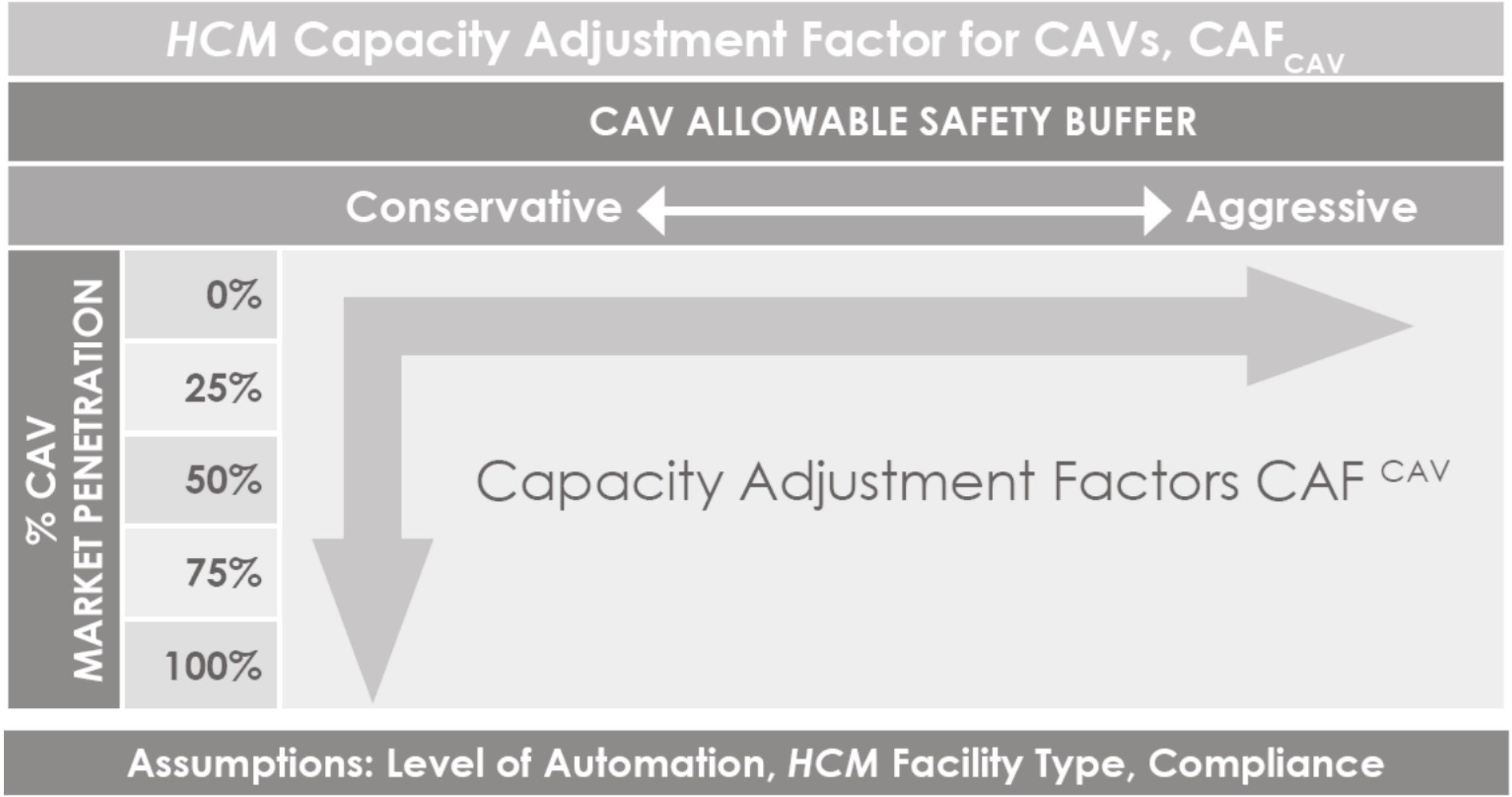






Why this study is needed?

- State Transportation Improvement Program (STIP)
  - *Multi-year capital improvement document which denotes the scheduling and funding of construction projects*
- Typical planning horizon of 25 years
  - **Funding decisions made for traffic in 2045-2050!**


HCM Capacity Adjustment Factor for CAVs, CAF CAV
CAV ALLOWABLE SAFETY BUFFER
Conservative
Aggressive
% CAV MARKET PENETRATION
0%
25%
50%
75%
100%
Capacity Adjustment Factors CAF CAV
Assumptions: Level of Automation, HCM Facility Type, Compliance

Methodology and Assumptions

Abby Morgan – Kittelson & Associates

AV – CV - CAV

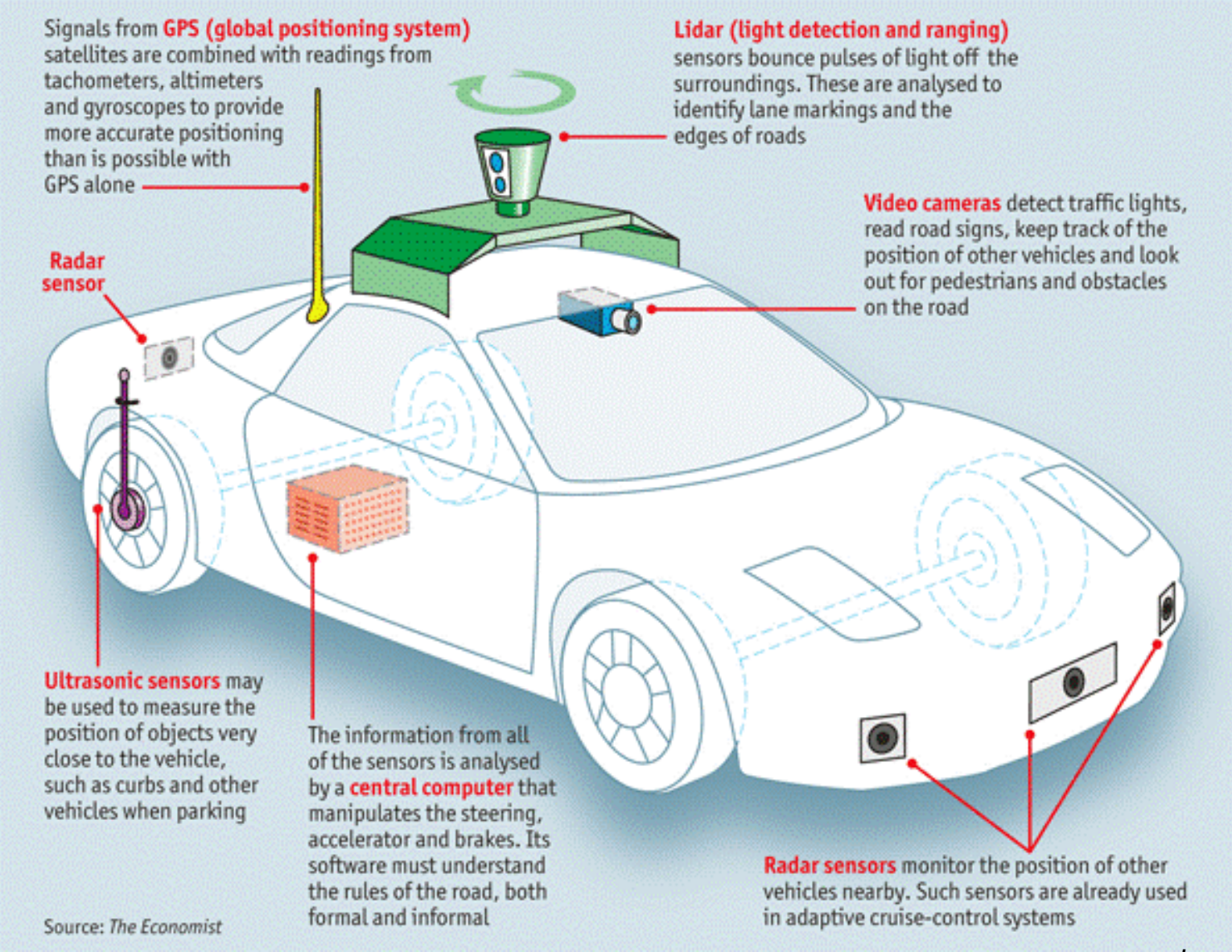


Image Credit: The Economist

Connected and Automated Vehicles (CAVs)

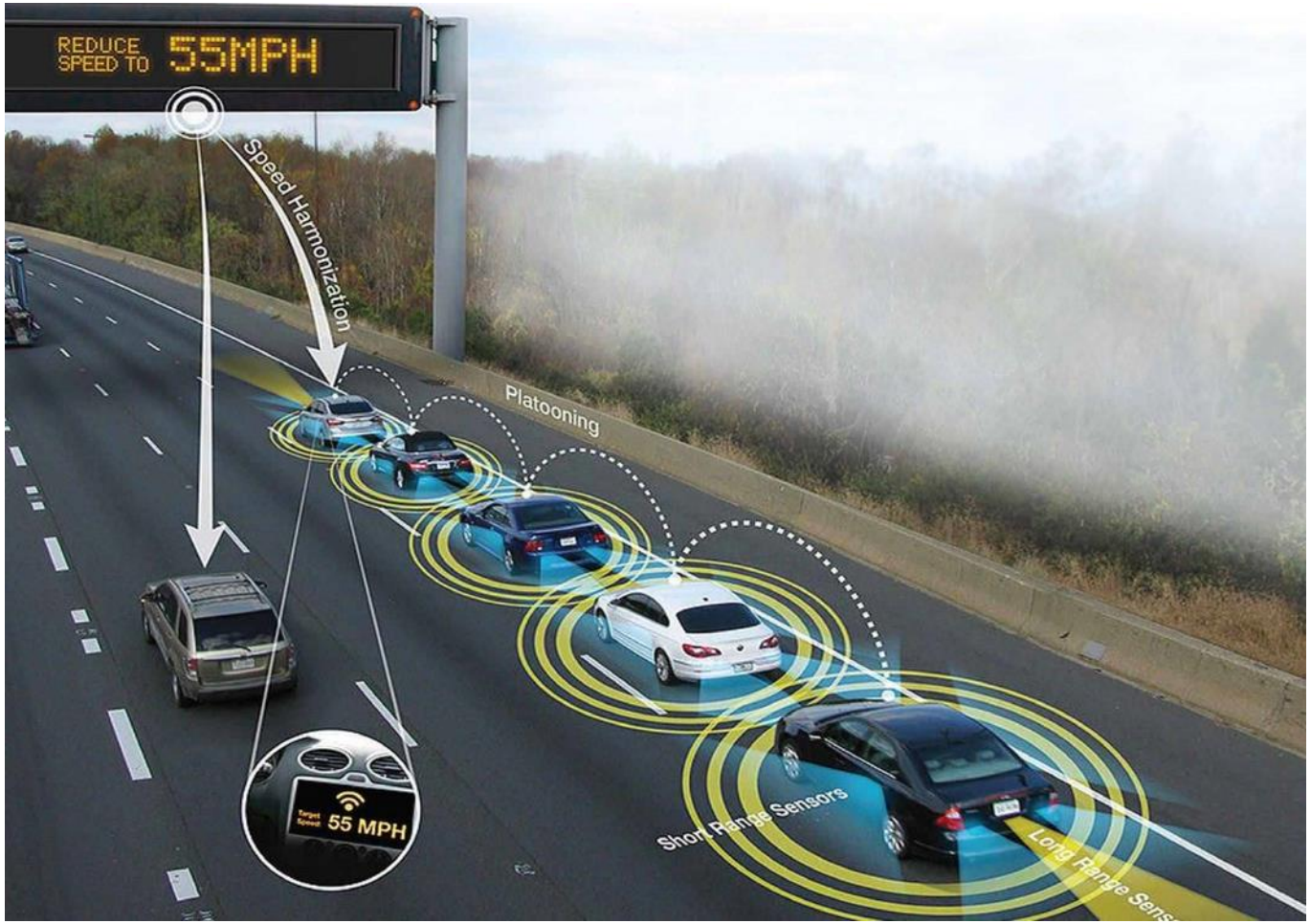
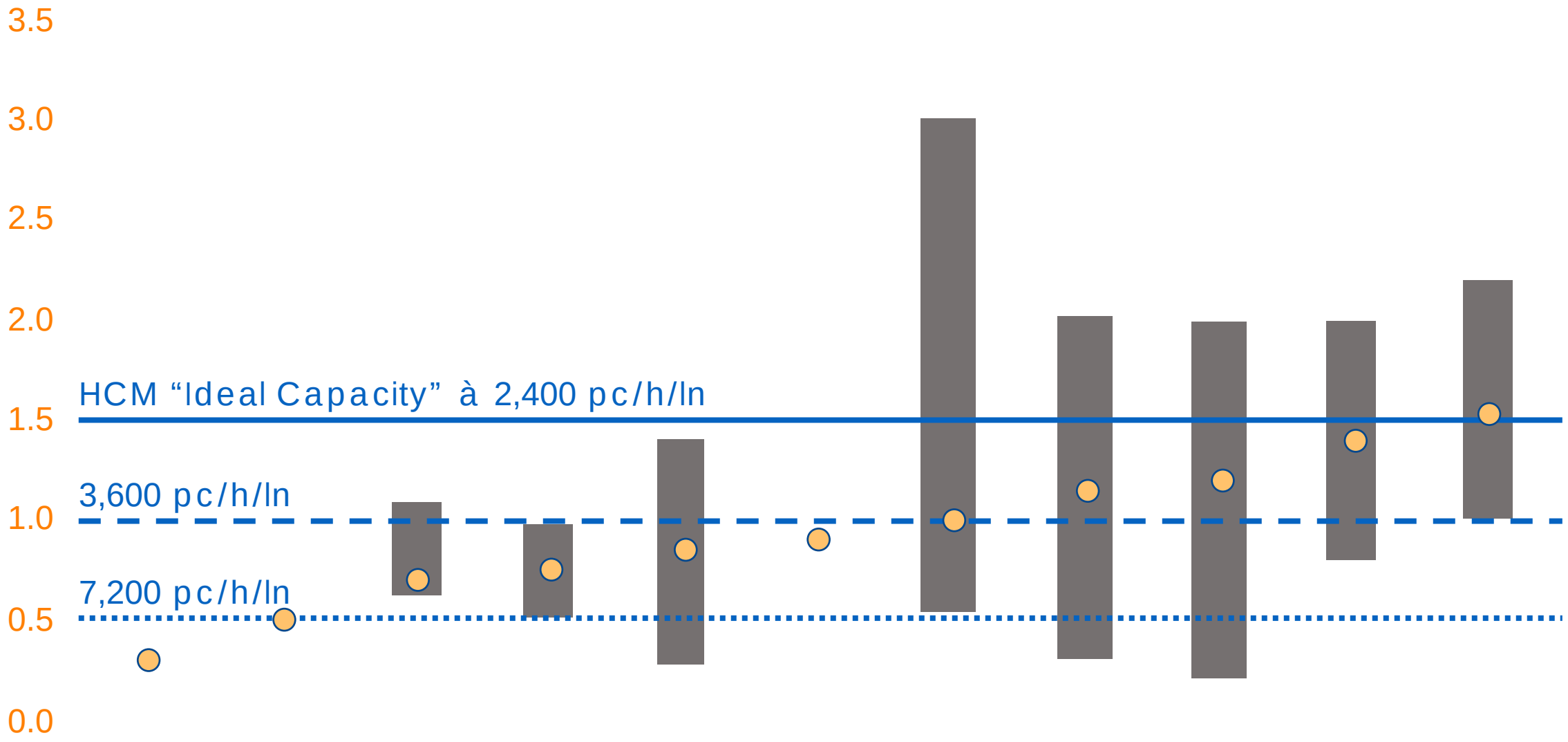
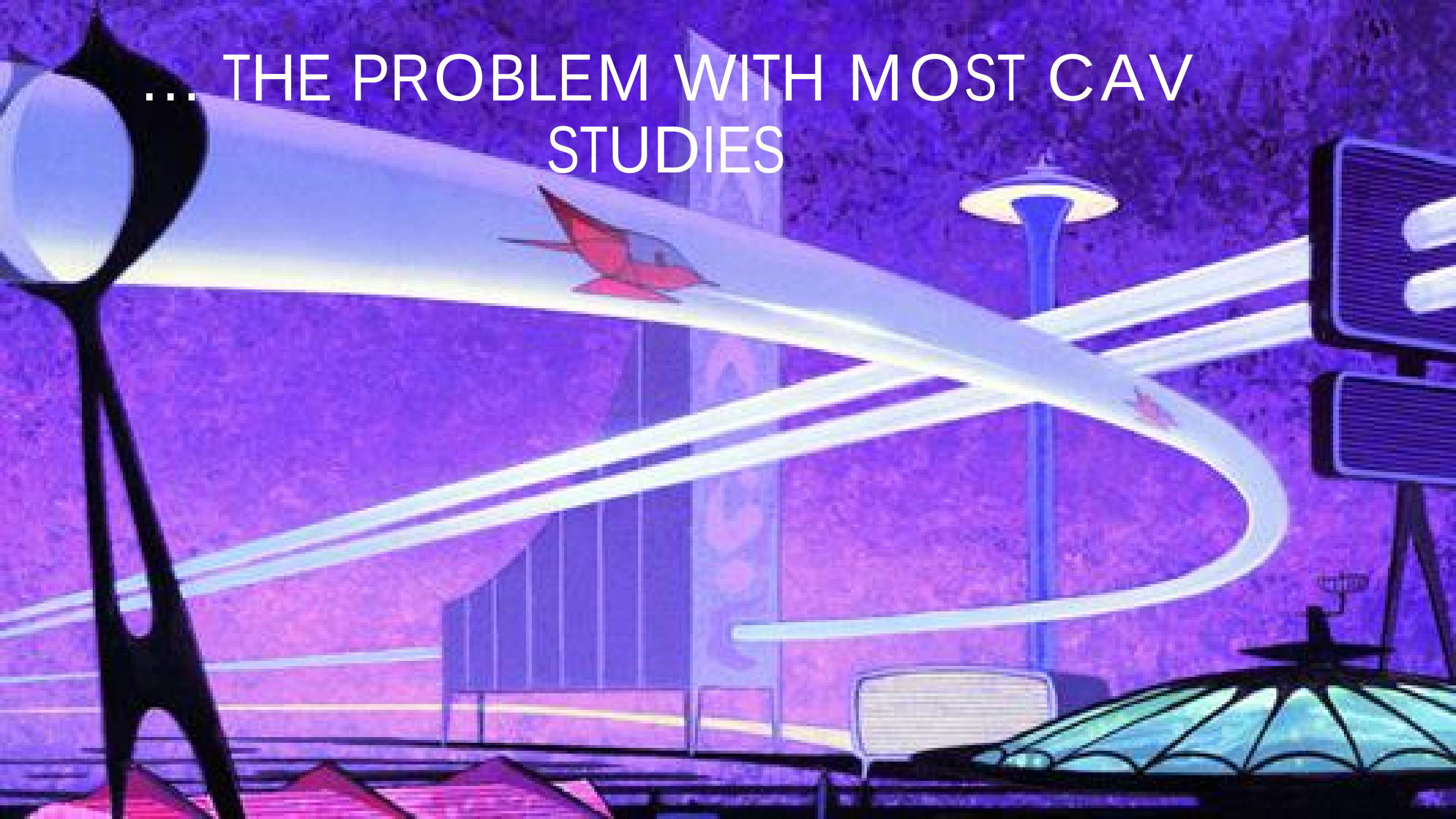


Image Credit: PCQuest

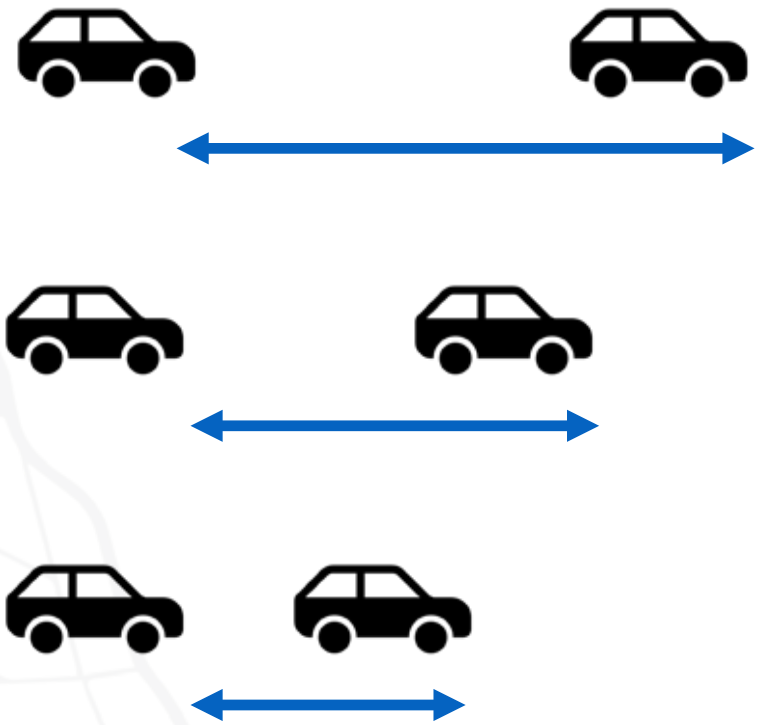
CAV Car-Following Headway (s/veh) Reported in Literature (Freeways)





… THE PROBLEM WITH MOST CAV STUDIES

… at 70 mi/h travel speed



2,400 pc/h/ln
à 1.5 seconds à 154 feet

3,600 pc/h/ln
à 1.0 seconds à 103 feet

7,200 pc/h/ln
à 0.5 seconds à 51 feet

WHAT IS CAPACITY?

- The inverse of following headway
- Function of:
  - Perception-Reaction Time
  - Physics
  - Level of Stress
- Lower at bottlenecks than basic segments

FACTORS THAT IMPACT CAPACITY

Geometry

Vehicle Composition

Truck Percentage

Driver Behavior

Other Factors Impacting Capacity

ASSUMPTIONS

- Headways and Oscillation
- Platooning
- Cooperation
- Market Penetration
- Number of Lanes
- Volume Mix
- Protected and Permissive Left Turns

Signalized Intersections with Protected Turns

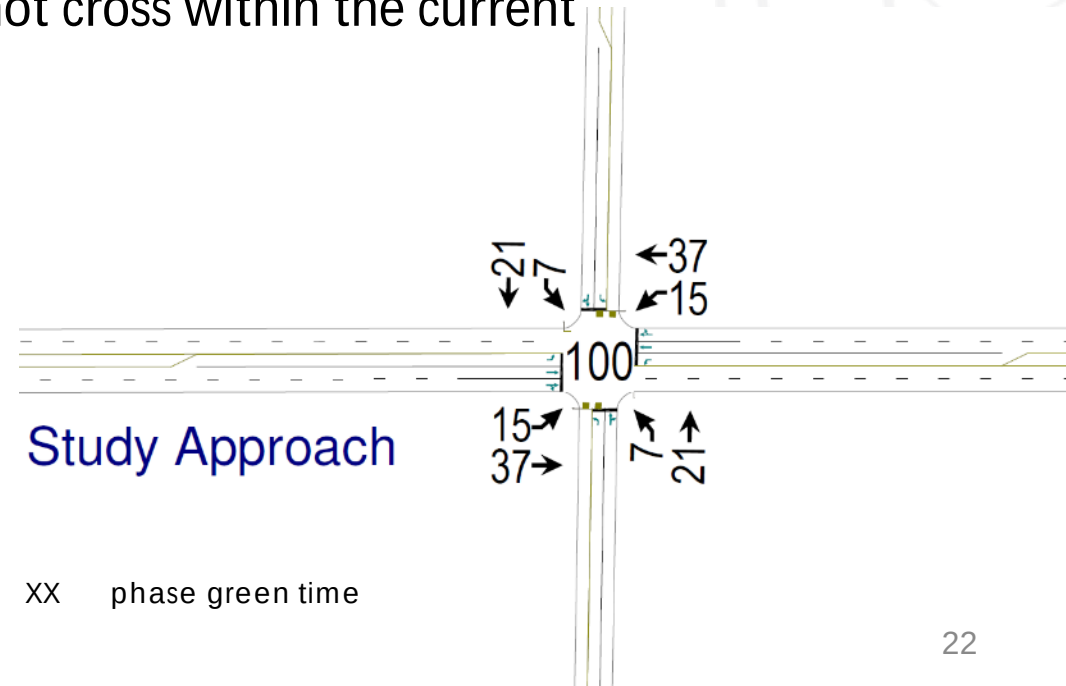
Abby Morgan – Kittelson & Associates

MODELING ASSUMPTIONS
SIGNALIZED INTERSECTIONS FOR **PROTECTED** MOVEMENTS

Assume Cooperative Adaptive Cruise Control (CACC):

- All vehicles implement early lane change behavior to avoid blocking through traffic
- CAVs have shorter start-up lost time due to implemented CACC behavior
- Follower will implement platoon-split function if it cannot cross within the current green phase
- Left turn CAVs keep CACC operations

Simplistic, but realistic signalized intersection



FACTORS THAT IMPACT CAPACITY

Capacity = saturation flow rate x effective green ratio

» Saturation flow rate: capacity if signal was always green

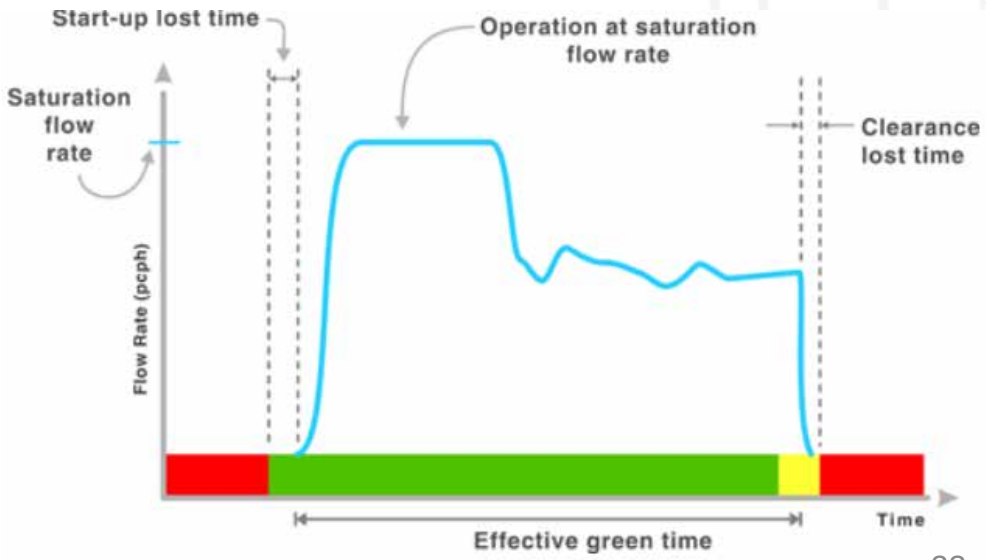
- Without CAVs, we assume:
  - Saturation flow rate: **1,800 veh/hr/lane**
  - Vehicle headway: **2 sec/veh**

} (3,600 sec/h) / (1,800 veh/h) = 2 sec/veh

» Effective green ratio: percent of signal cycle during which traffic may proceed

» Capacity could increase if we decrease:

- Vehicle headway
- Start-up lost time
- Clearance lost time



MODELING PERFORMANCE MEASURES
SIGNALIZED INTERSECTIONS WITH **PROTECTED** MOVEMENTS

Key Performance Measures

» **Capacity Adjustment Factor (CAF)** development
- Follow-up headway (directly related to saturation flow rate)
- Start-up lost time
- Green extension into yellow (or end lost time)

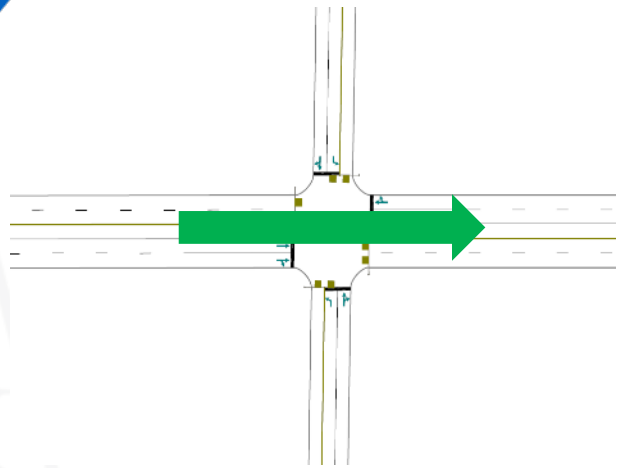
Key Variables

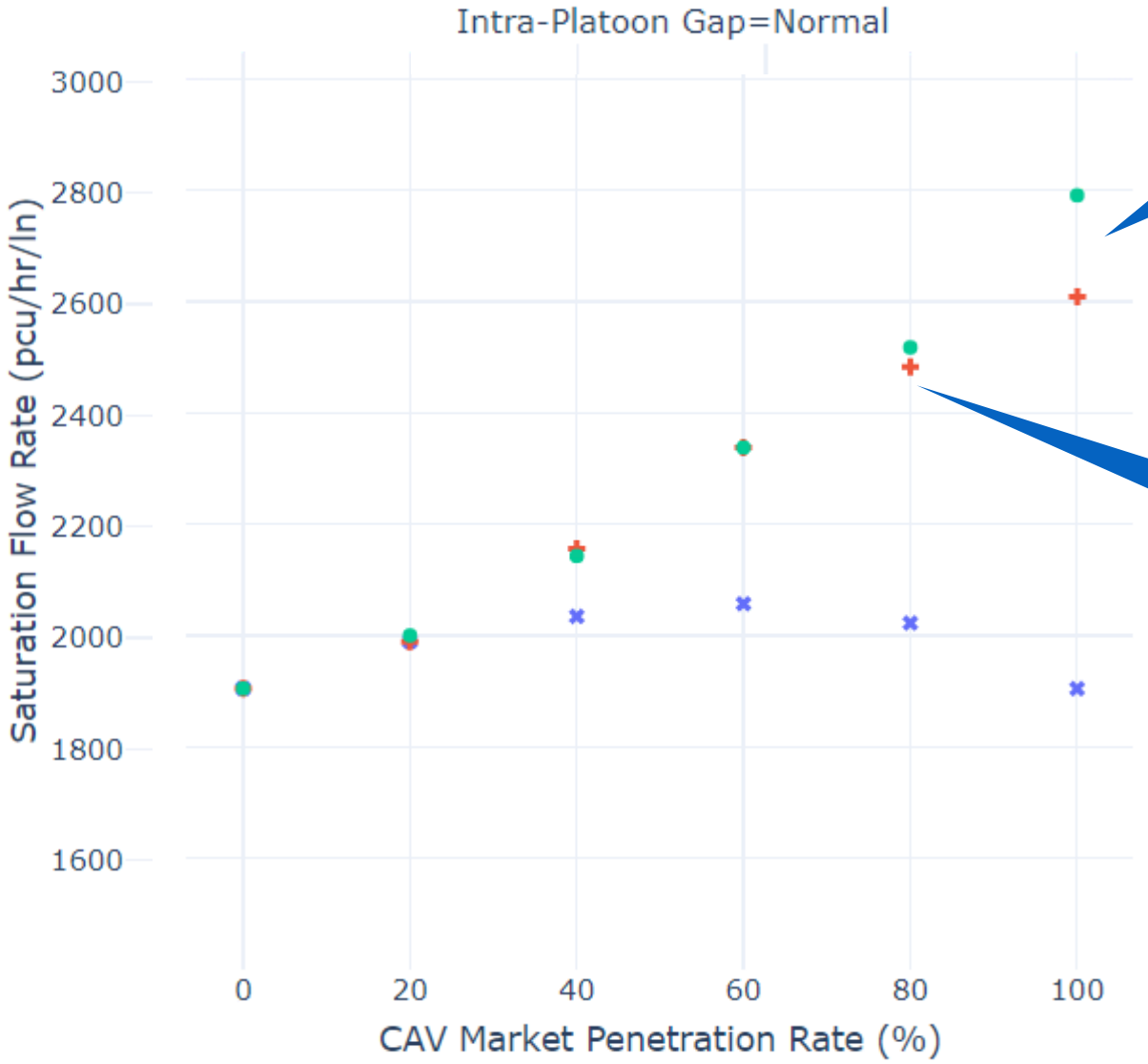
» Variation in CAV market penetration rates (0%, 20%, 40%, 60%, 80%, 100%)

» Variation in CACC gap settings (*Conservative*, *Normal*, *Aggressive*)

» Variation in platoon size (1 vehicle (ACC), 5 vehicles, 8 vehicles)

Through Lane Saturation Flow Rate Results:
Sensitivity to MPR and Platoon Size





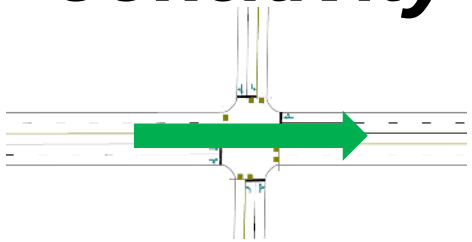
40-50% increase in saturation flow rate with 100% MPR

Platoon size has marginal benefits when MPR < 80%

Note: Intra-platoon gap is not relevant for ACC mode (Platoon Size = 1). Vehicles have a Desired Gap of 1.5 sec in ACC mode

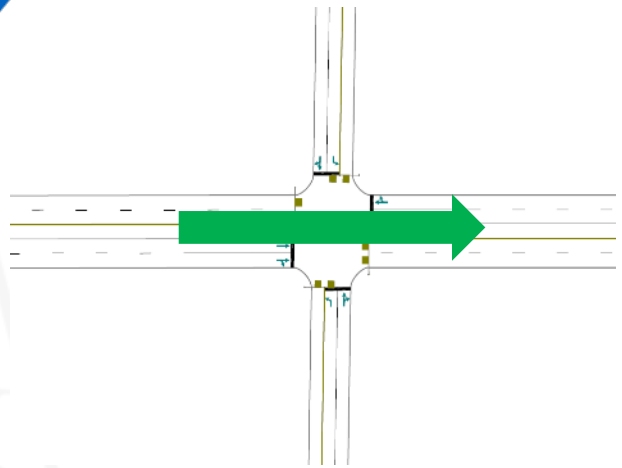
MPR = Market Penetration Rate

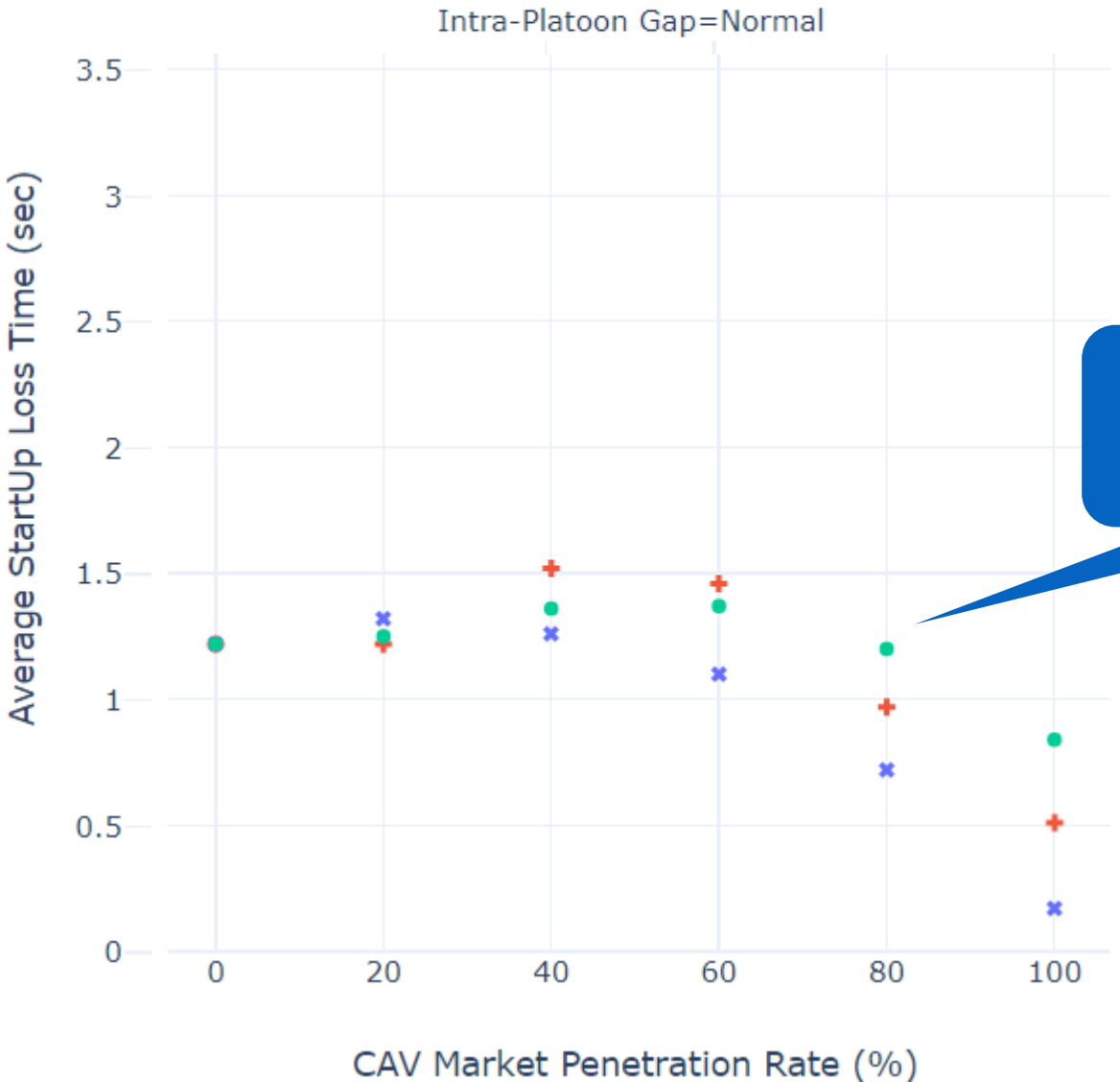
Through Lane Saturation Flow Rate Results:
Sensitivity to Intra-Platoon Gap



Intra-platoon gap is not relevant for ACC mode (Platoon Size = 1) in which vehicles have a Desired Gap of 1.5 seconds

Through Lane START-UP LOST TIME Results:
Sensitivity to MPR and Platoon Size

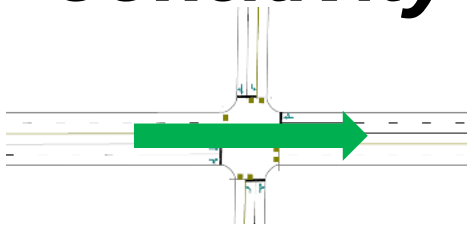




Marginal reductions in start-up lost time for all the scenarios

Note: Intra-platoon gap is not relevant for ACC mode (Platoon Size = 1). Vehicles have a Desired Gap of 1.5 sec in ACC mode

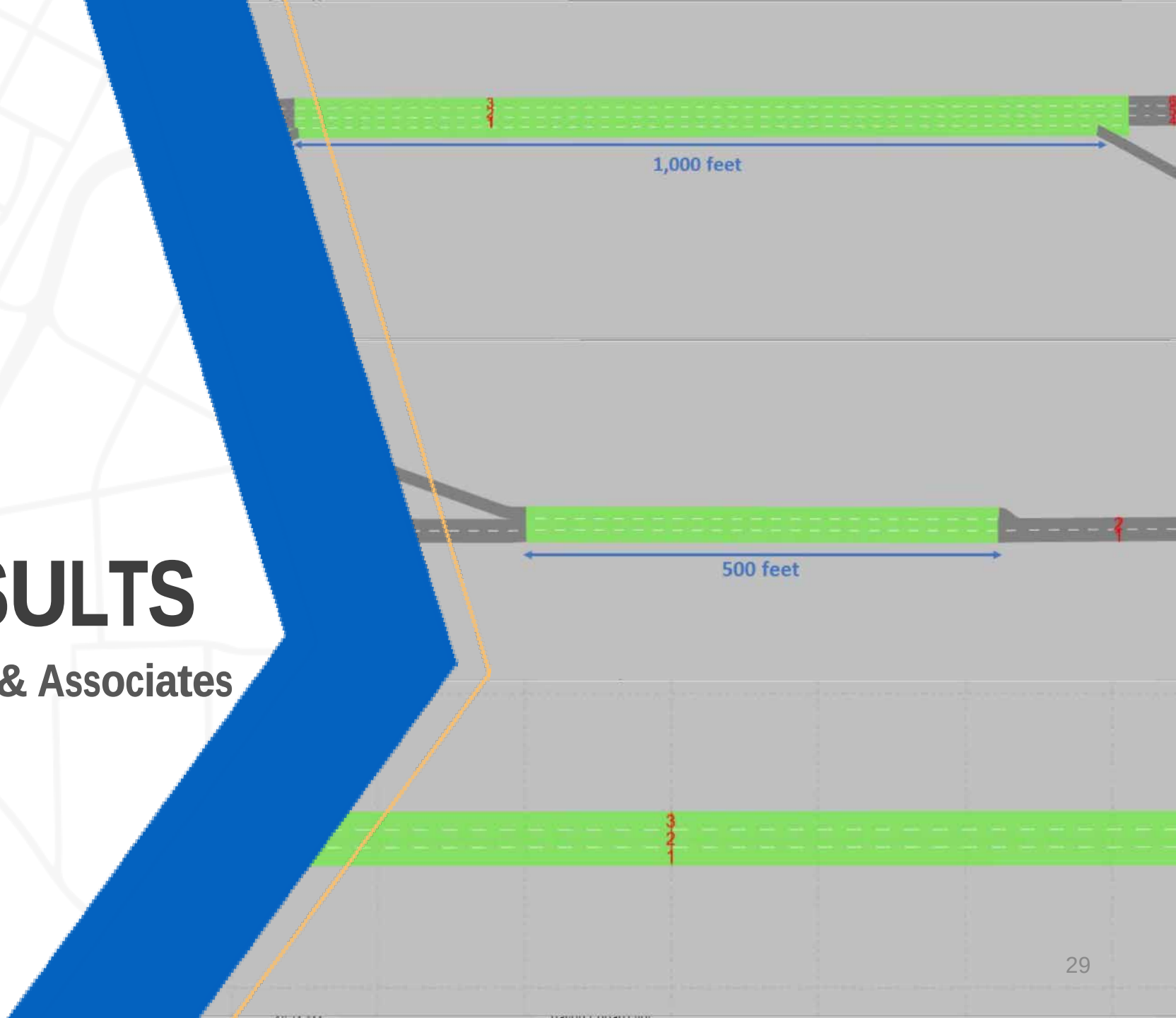
Through Lane End Lost Time Results:
Sensitivity to MPR/Platoon Size/Intra-Platoon Gap



End lost time remains almost identical in all the scenarios

FREEWAY RESULTS

Bastian Schroeder – Kittelson & Associates



MODELING FRAMEWORK (FREEWAYS)

Basic Freeway Segments

- 2-Lane vs. 3-Lane Segment
- ACC Only vs. CACC (platooning)
- Market Penetration Rate
- Parameter Sensitivity

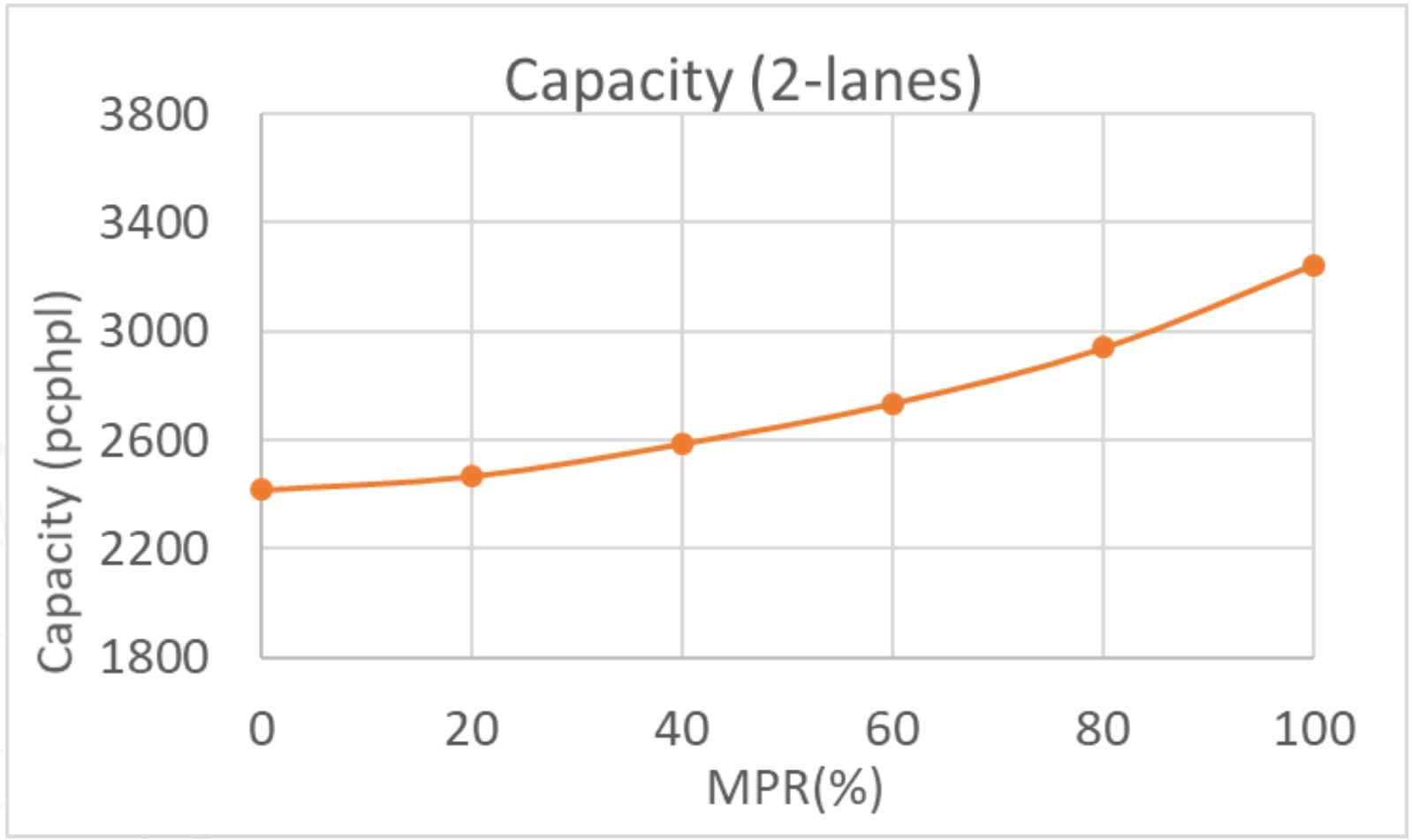
Freeway Merge Segments

- With and without Advanced Merge
- Market Penetration Rate
- Volume Balance

Freeway Weaving Segments

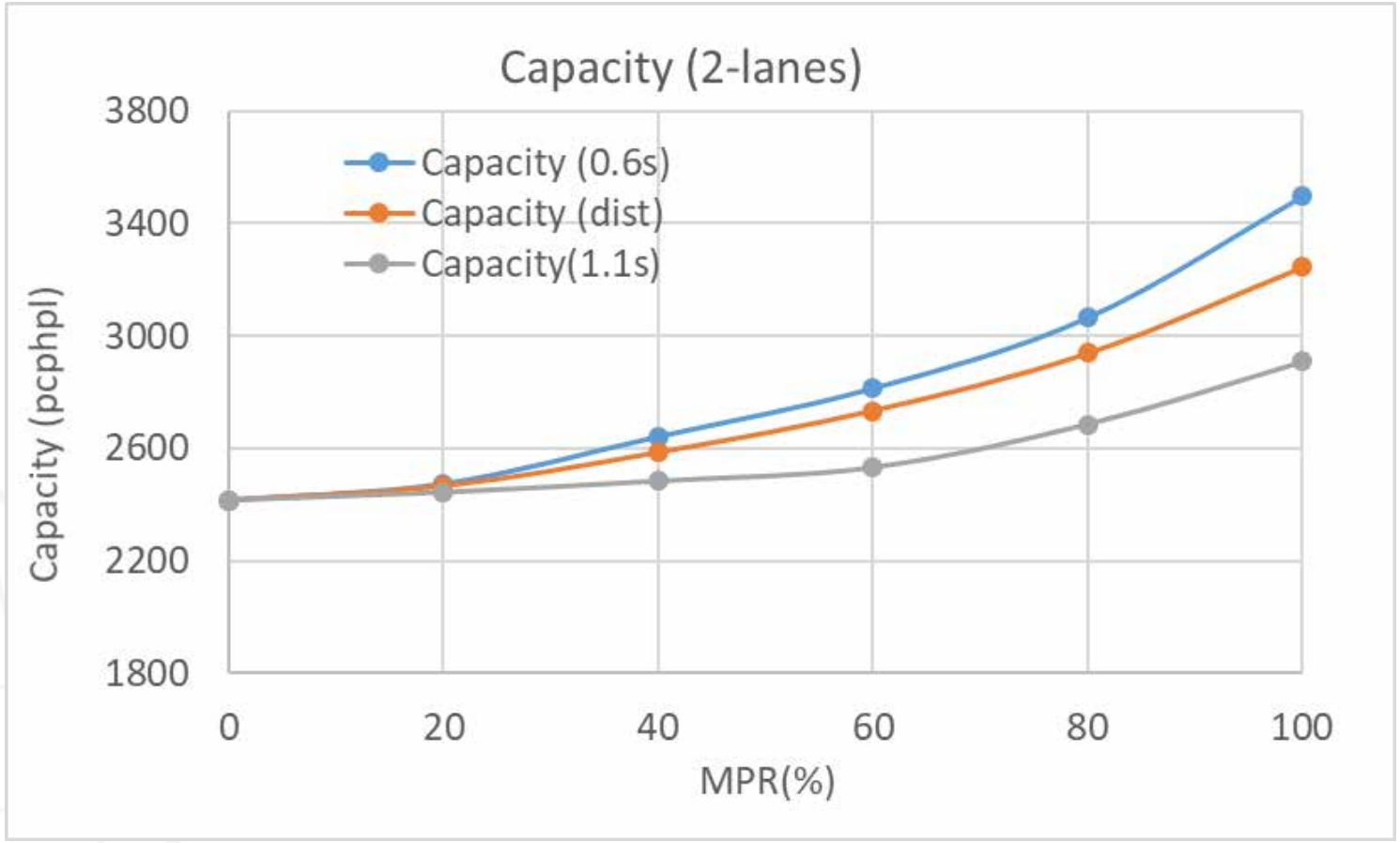
- With and without Advanced Merge
- Market Penetration Rate
- Weaving Intensity

Basic Freeway Segments à Effects of Market Penetration



Steady Increase in Capacity with Increasing Market Penetration

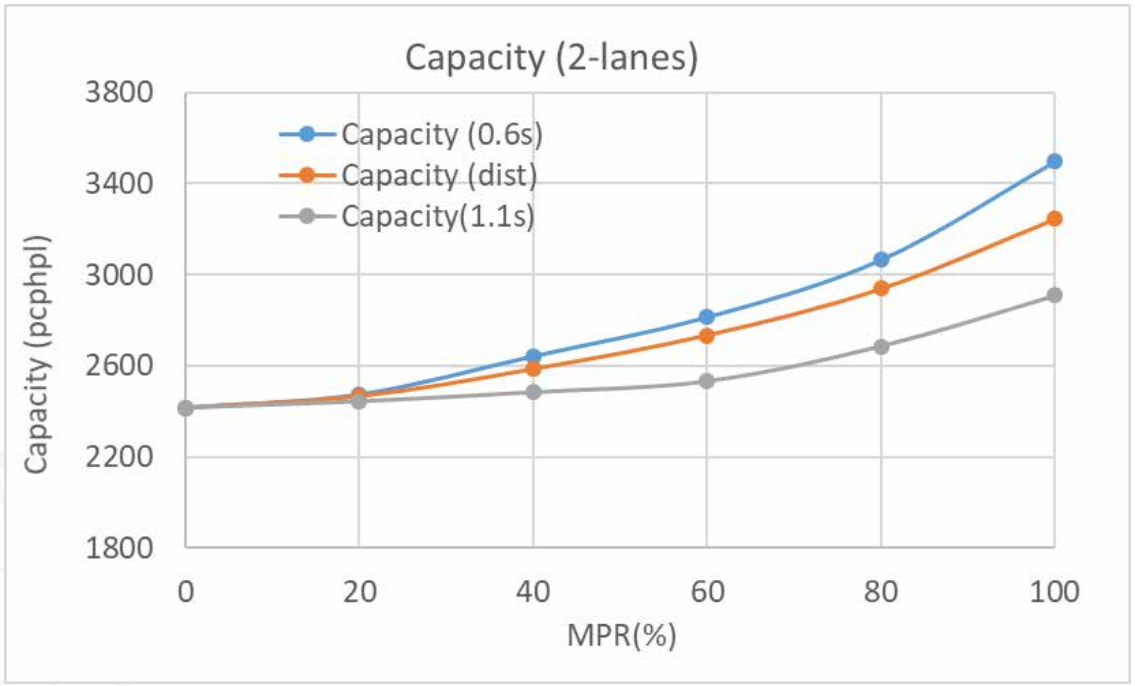
Basic Freeway Segments à Platooning Effects (Intra-platoon Gap)

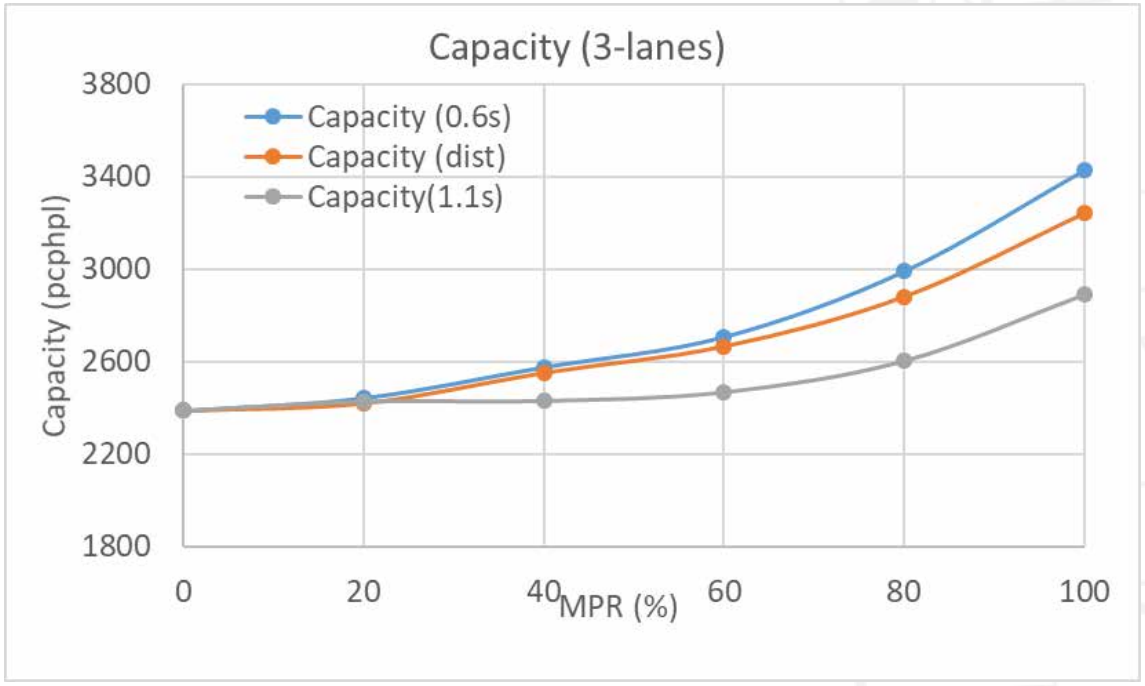


Capacity function of "Intra-Platoon Gap" Setting

à Average Distribution Used for Results

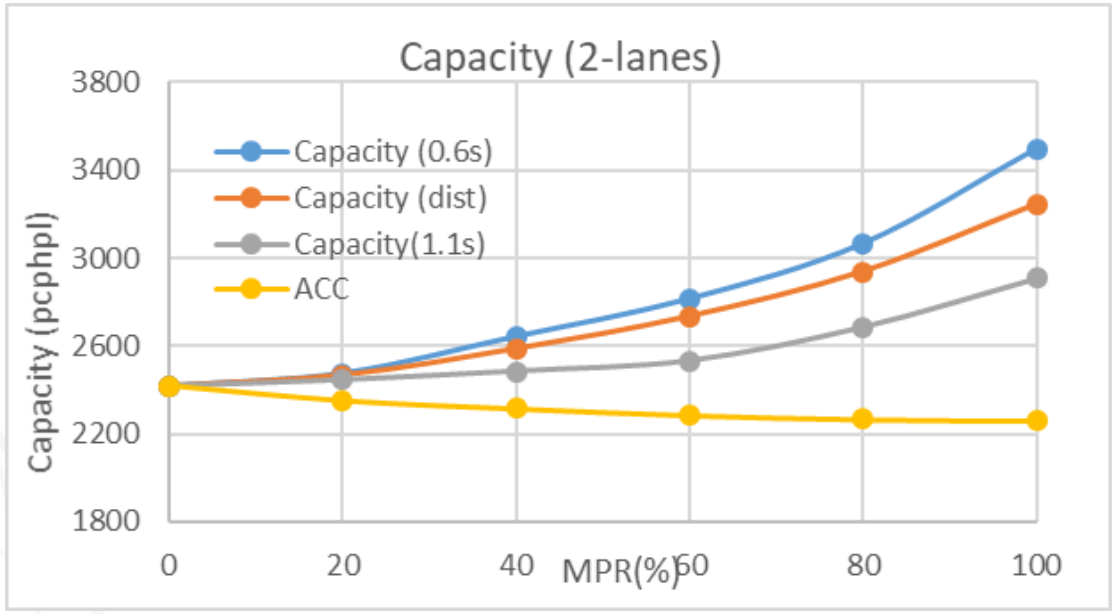
Basic Freeway Segments à 2-Lane vs. 3-Lane

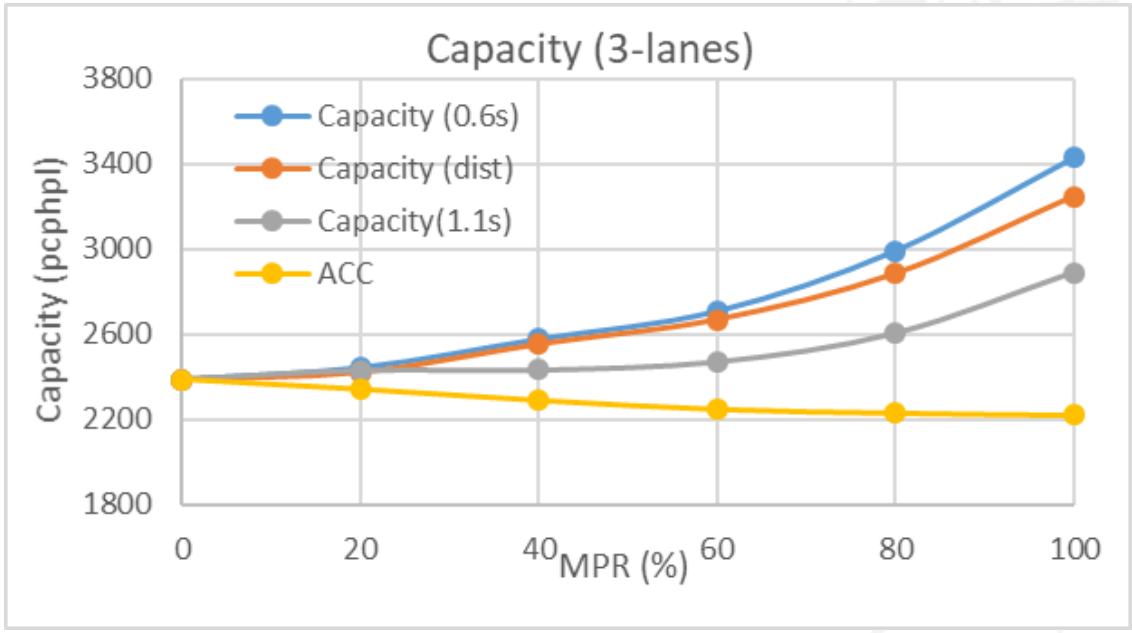




Capacity follows same trends for 2-lane and 3-lane Segments

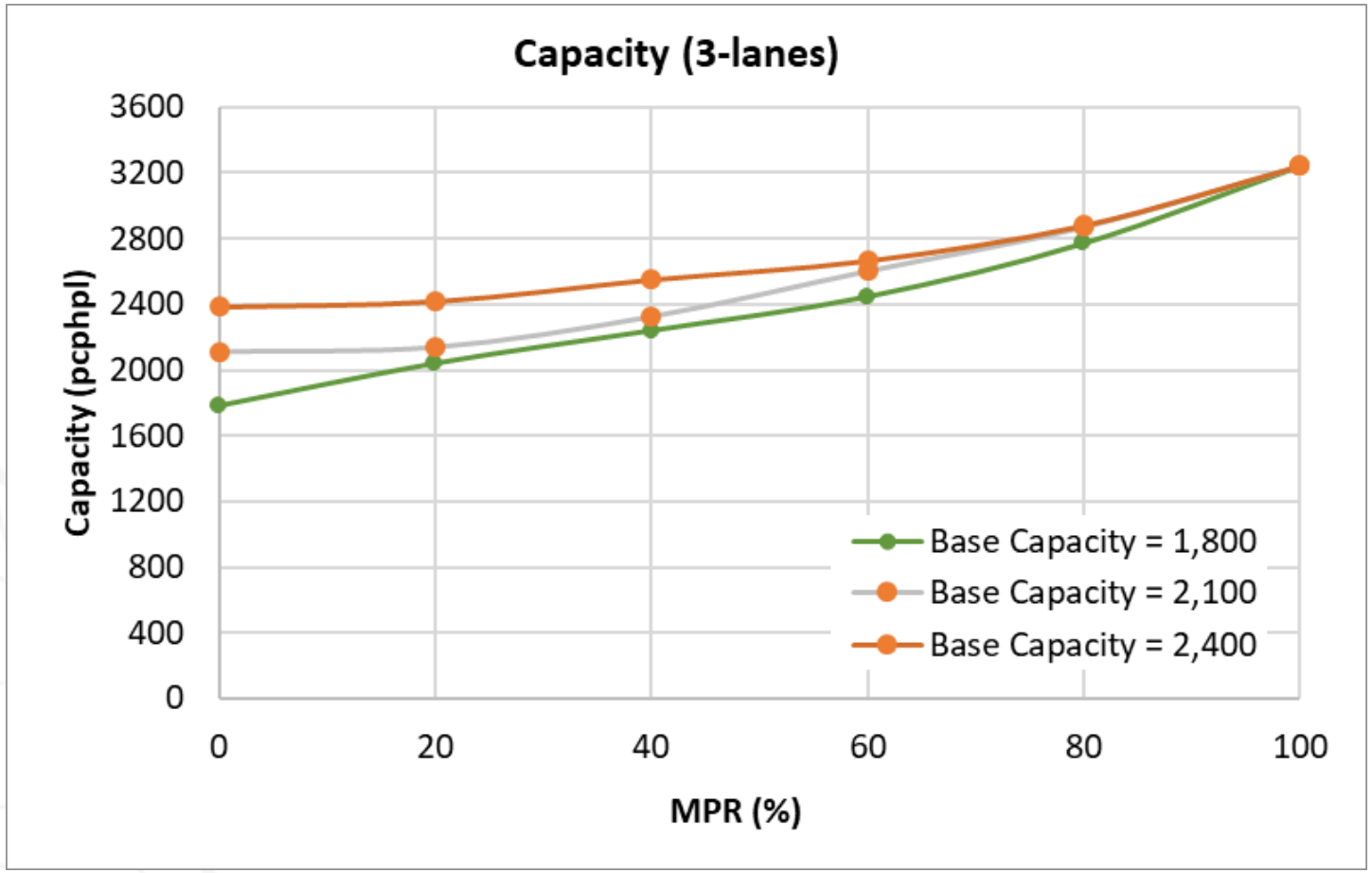
Basic Freeway Segments
à ACC vs. CACC





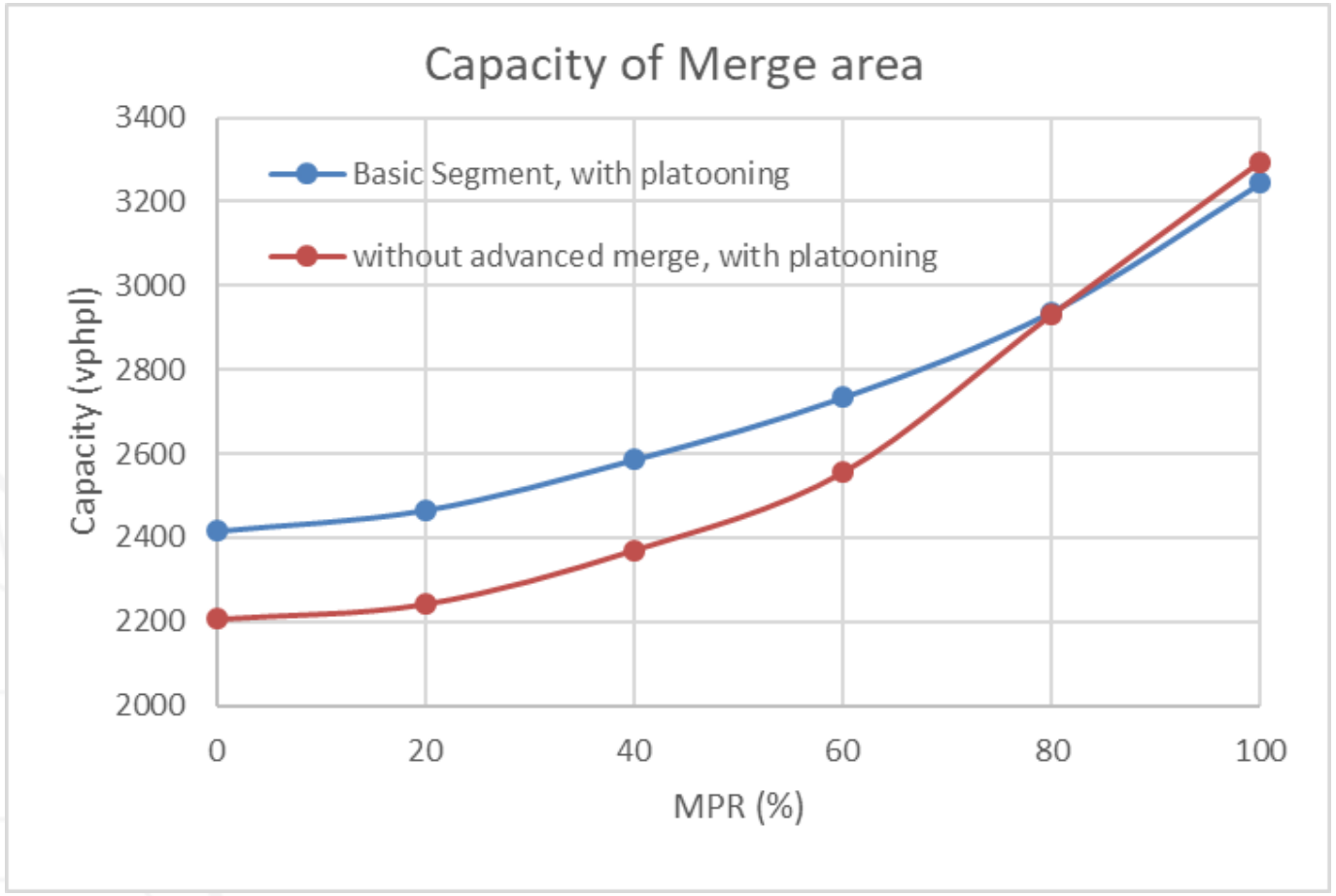
Capacity significantly lower with ACC (Autonomous Vehicles without Platooning)

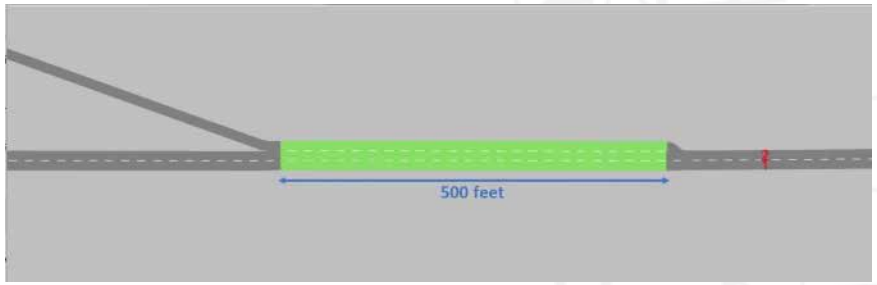
Basic Freeway Segments à Varying Base Capacity



Capacity converges at same point, despite varying calibrated base capacities (e.g. bottleneck capacities)

Freeway Merge Segments
à Effects of Market Penetration

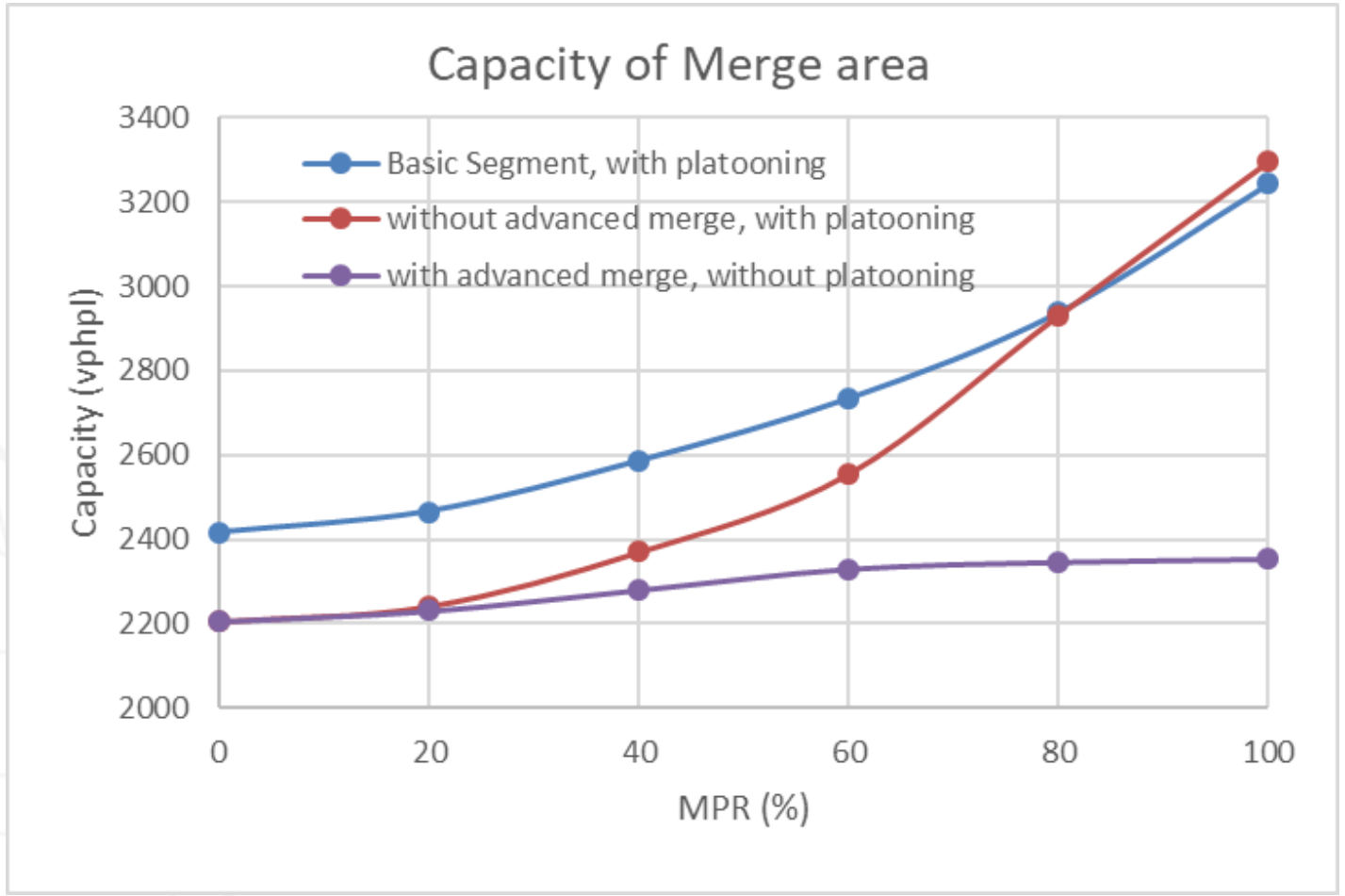


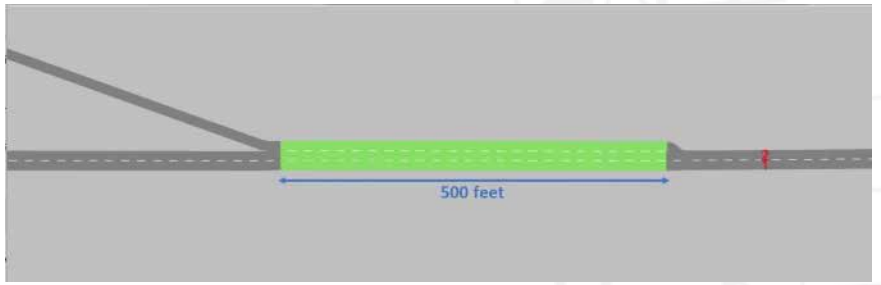


Merge capacity initially lower than basic segment

Converges at the same maximum 100% MPR

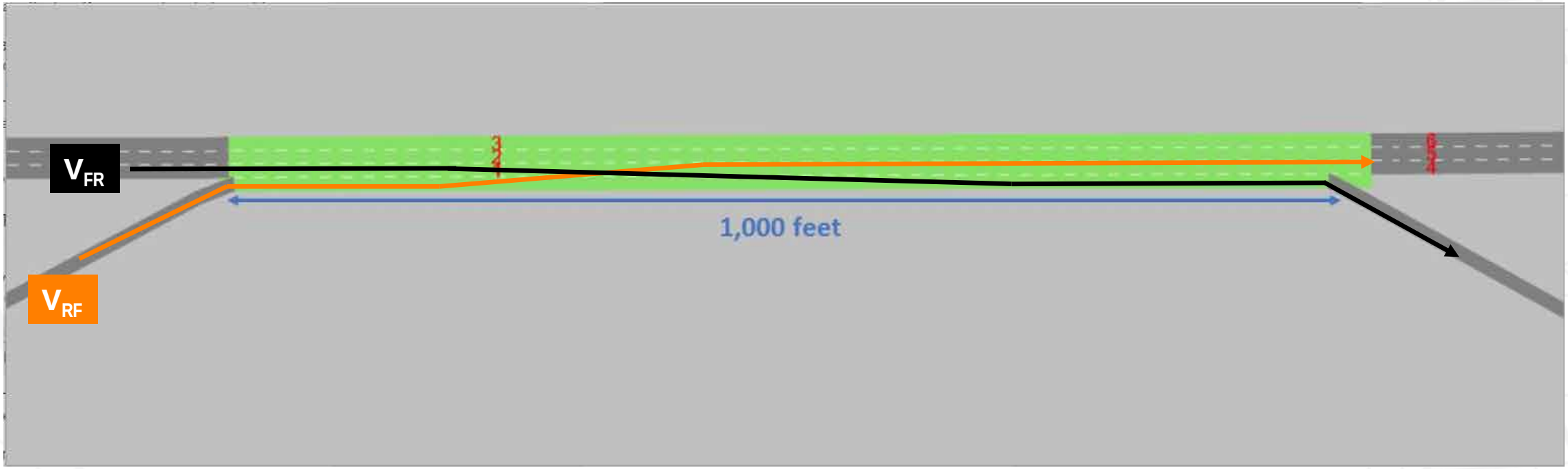
Freeway Merge Segments à Effects of Platooning





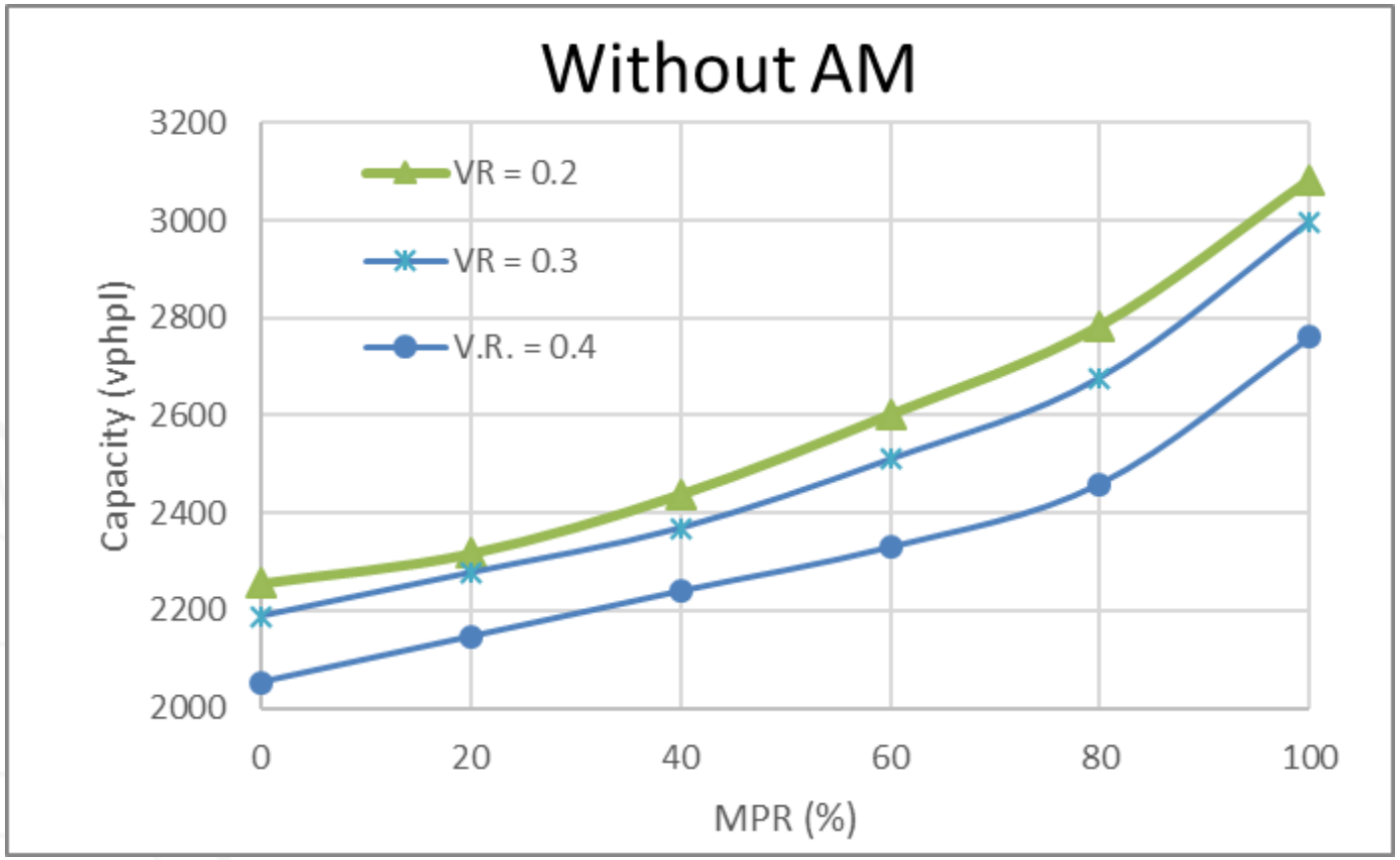
Platooning is essential to achieve merge area capacity benefits with CAVs

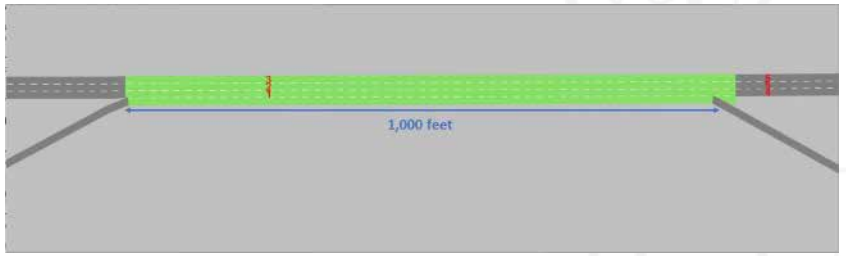
Freeway Weaving Segments
à Analysis under varying Volume Ratios (V.R.)



$$V.R. = \frac{V_{RF} + V_{FR}}{V_{RF} + V_{FR} + V_{FF} + V_{RR}}$$

Freeway Weaving Segments à Effects of Volume Ratios without Advanced Merge





Capacity decreases with higher volume ratio

MPR effects consistent across VRs (similar slopes)

Proposed HCM Implementation

Bastian Schroeder – Kittelson and Associates

(Examples shown for Freeways)

New Chapter 26 Section

will be available at www.hcmvolume4.org

Proposed

CHAPTER 26
FREEWAY AND HIGHWAY SEGMENTS: SUPPLEMENTAL

CONTENTS

Highway Capacity Manual: A Guide for Multimodal Mobility Analysis

CHAPTER 26
FREEWAY AND HIGHWAY SEGMENTS: SUPPLEMENTAL

CONTENTS

Chapter 26 – Draft Capacity Adjustment Factors (CAFs)

» Basic Freeway Segments

Proportion of CAVs in Traffic Stream	Adjusted Segment Capacity		
	2,400 pc/h/ln	2,100 pc/h/ln	1,800 pc/h/ln
0	1.00	1.00	1.00
20	1.02	1.02	1.15
40	1.07	1.10	1.27
60	1.13	1.25	1.40
80	1.22	1.37	1.60
100	1.33	1.52	1.78

Notes: CAV = connected and automated vehicle, defined here as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions and adjusted segment capacities.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to the given adjusted segment capacity.

Exhibit 26-15
Capacity Adjustment Factors for CAVs for Basic Freeway and Freeway Diverge Segments

Proposed

Chapter 26 – Draft Capacity Adjustment Factors (CAFs)

» Freeway Merge Segments

Exhibit 26-16
Capacity Adjustment Factors for CAVs for Freeway Merge Segments

Proposed

Proportion of CAVs in Traffic Stream	CAF_{CAV}
0	1.00
20	1.02
40	1.07
60	1.16
80	1.33
100	1.45

Notes: CAV = connected and automated vehicle, defined here as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions and adjusted segment capacities.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to 2,200 pc/h/ln.

Chapter 26 – Draft Capacity Adjustment Factors (CAFs)

» Freeway Weaving Segments

Exhibit 26-17
Capacity Adjustment Factors for CAVs for Freeway Weaving Segments

Proposed

Proportion of CAVs in Traffic Stream	Volume Ratio 0.2	0.3	0.4
0	1.00	1.00	1.00
20	1.03	1.04	1.05
40	1.08	1.08	1.09
60	1.15	1.15	1.13
80	1.23	1.22	1.20
100	1.37	1.37	1.34

Notes: CAV = connected and automated vehicle, defined here as a vehicle with an operating cooperative adaptive cruise control system.
Interpolate for other CAV proportions and volume ratios.
The volume ratio is the weaving demand flow rate divided by the total demand flow rate in the segment.
Assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to 2,200 pc/h/ln.

Chapter 26 – Draft Daily Service Volume Tables

Area Type	Terrain	Proportion of CAVs in Traffic Stream 0%	20%	40%	60%	80%	100%
Urban	Level	19,900	20,500	21,800	24,600	26,800	29,700
Urban	Rolling	19,000	19,900	21,400	24,500	26,800	29,700
Rural	Level	16,800	17,900	19,300	22,000	24,400	26,800
Rural	Rolling	15,200	17,200	19,100	21,600	24,400	26,800

Notes: CAV = connected and automated vehicle, defined here as a vehicle with an operating cooperative adaptive cruise control system.
Values represent the maximum annual average daily traffic per lane at LOS E.
Urban assumptions: Free-flow speed = 70 mph, 5% trucks, PHF = 0.94, *K*-factor = 0.09, *D*-factor = 0.60.
Rural assumptions: Free-flow speed = 70 mph, 12% trucks, PHF = 0.94, *K*-factor = 0.10, *D*-factor = 0.60.
CAV assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon qap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to 2,400 pc/h/ln.

Exhibit 26-18
Daily Maximum Service Volumes for Basic Freeway Segments with CAV Presence (2-way veh/day/ln)

Proposed

Chapter 26 – Draft Hourly Service Volume Tables

Area Type	Terrain	Proportion of CAVs in Traffic Stream 0%	20%	40%	60%	80%	100%
Urban	Level	2,150	2,210	2,350	2,660	2,900	3,200
Urban	Rolling	2,050	2,150	2,310	2,640	2,900	3,200
Rural	Level	2,010	2,140	2,310	2,640	2,900	3,200
Rural	Rolling	1,820	2,060	2,290	2,580	2,900	3,200

Notes: CAV = connected and automated vehicle, defined here as a vehicle with an operating cooperative adaptive cruise control system.
Values represent the maximum analysis hour volume per lane at LOS E.
Urban assumptions: Free-flow speed = 70 mph, 5% trucks, PHF = 0.94, *K*-factor = 0.09, *D*-factor = 0.60.
Rural assumptions: Free-flow speed = 70 mph, 12% trucks, PHF = 0.94, *K*-factor = 0.10, *D*-factor = 0.60.
CAV assumptions: Average intervehicle gap within CAV platoons = 0.71 s based on a distribution (see text), CAV interplatoon gap = 2.0 s, maximum CAV platoon size = 10 pc, human-driven vehicles operate with average gaps calibrated to 2,400 pc/h/ln.

Exhibit 26-19
Hourly Maximum Service Volumes for Basic Freeway Segments with CAV Presence (veh/h/ln)

Proposed

CLOSING THOUGHTS

- CAVs will likely increase capacities, but
  - … not as soon as you may think
  - … not as much as media may suggest
- Actual capacity is a function of many factors and assumptions
- Planning-level estimates can help inform decision-making, but agencies should understand modeling assumptions
- Results will be included in next *HCM* update (HCM 6.1)

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