UFLTI Seminar

Capacity and Delay Implications of Connected and Automated Vehicles at Signalized Intersections

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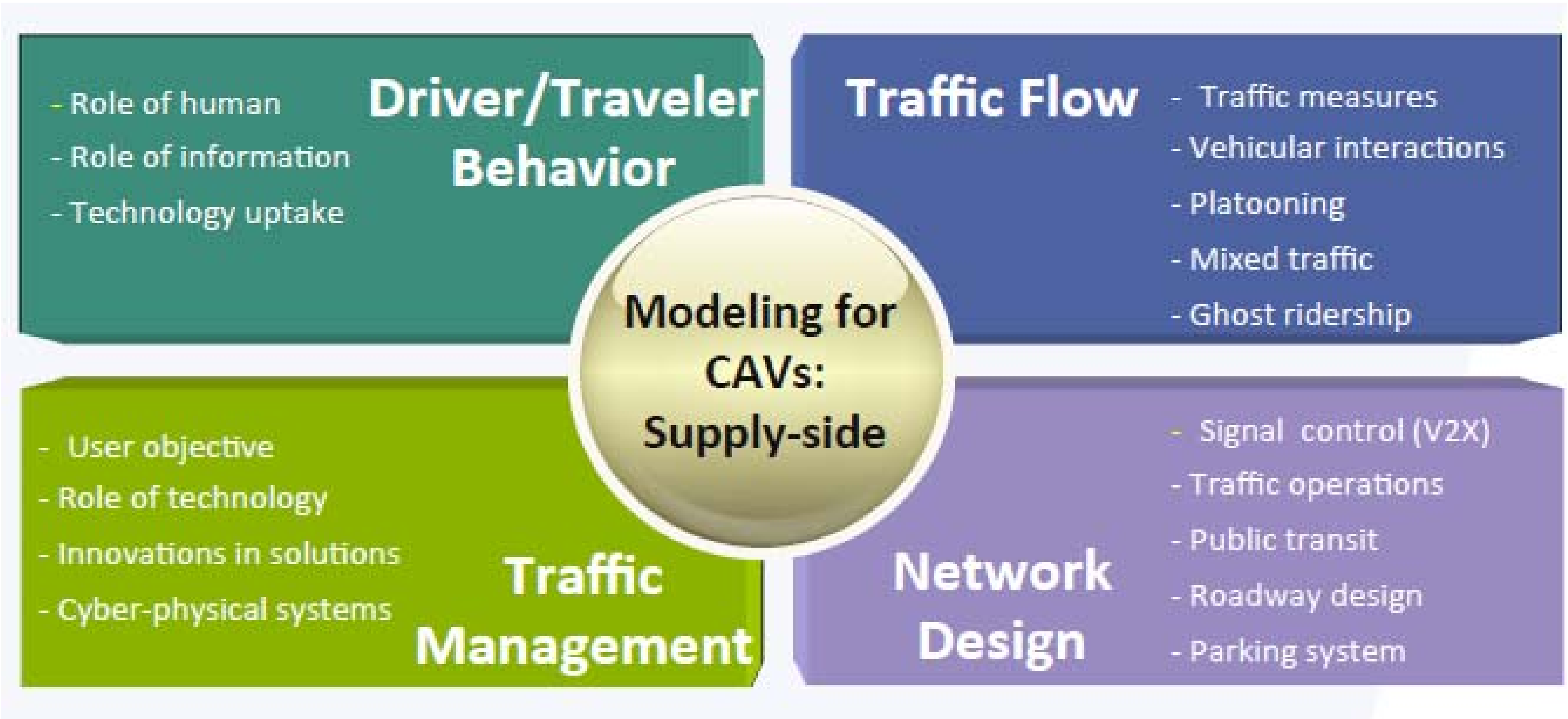
Abstract

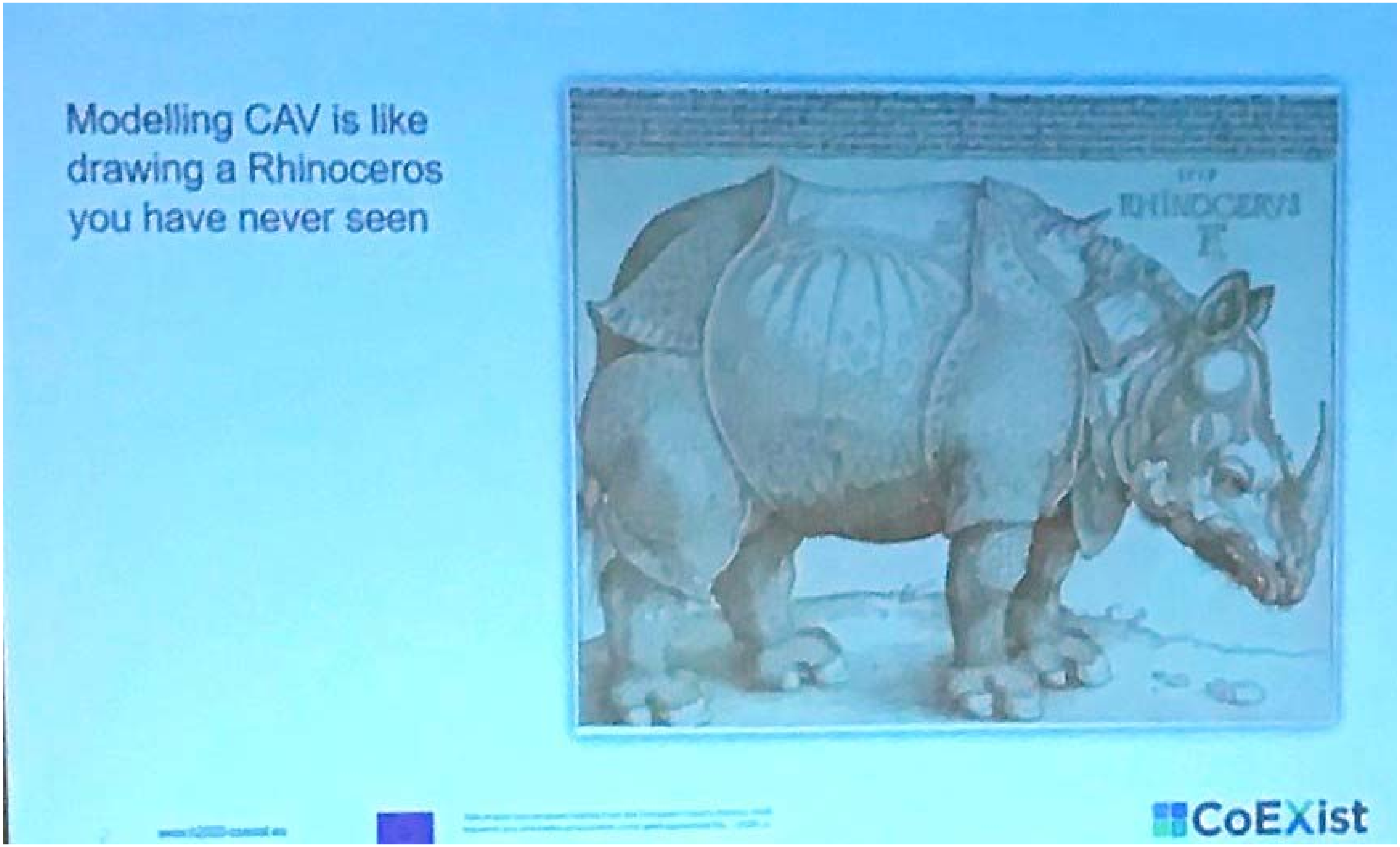
The deployment of connected and automated vehicles (CAVs) brings significant challenges and opportunities to the operation and management of highway facilities. We present work in progress on investigating the traffic flow characteristics of mixed stream of and human-driven vehicles at signalized intersections and obtain estimates of saturation flows and delays through analysis and simulation. The role of CAVS in control and design strategies is explored (e.g., multimodal transit priority, dynamic lane allocation). We also discuss the modeling challenges because of the lack of field data on CAV operation and performance, the dependence of predictions on CAVs penetration rate, which will change over time, and the potential intersection capacity decrease because of security concerns.

CAVs: Modeling Needs



Source: Srinivas Peeta Workshop ISTTT22, 2017

CAVs: Modeling Challenges



Models: Challenges and Opportunities (1)

- **Existing models need to be updated/modified/discarded to account for changes due to CAVs**
  Simplified assumptions on car-following, lane changing
  macroscopic traffic flow relationships/models

- **New models to leverage new technological capabilities, and capture emergent interactions**
  Operational and communication protocols
  Modeling platoon streams for CAVs
  Platoon stability
  Impacts of latency

- **Modeling challenges in the transition period**
  Dedicated lanes for CAVS
  Interactions with manually driven vehicles
  Car-following model for mixed traffic

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 trajectory data

Data available from mobility service providers

- **Operational Characteristics**
  - ***Lost time reduction***
  - ***Increased saturation flow rate***
- **Control Strategies**
  - **Multimodal adaptive control**
  - ***Dynamic lane allocation***
  - ***Eco Driving***
  - ***Signal-Free Intersections***

Challenges

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

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

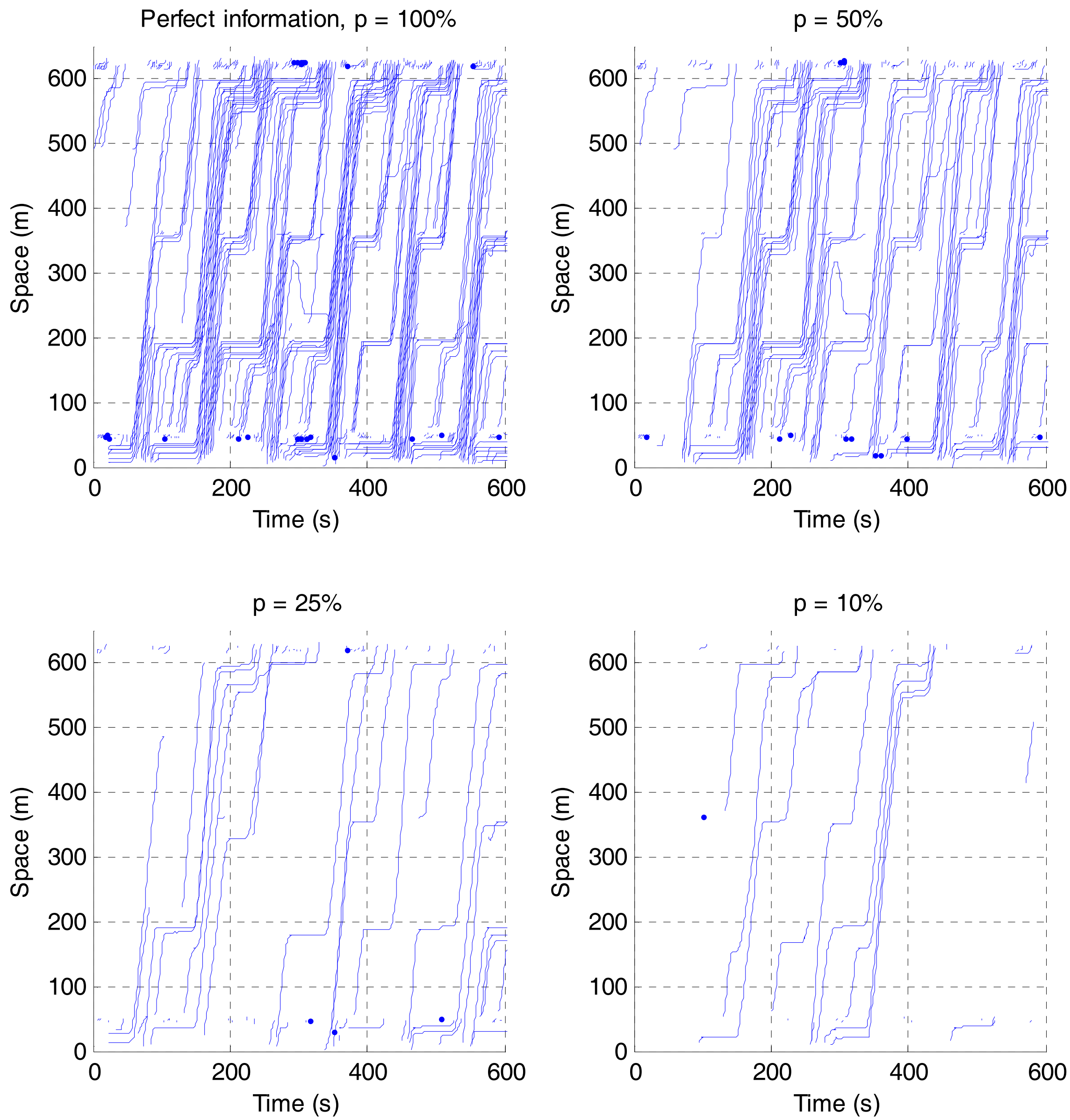
- **No standards/procedures exist for collecting, processing integrating CAV data into existing operations**

- **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



CAVS: Capacity & Delay at Traffic Signals

- 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.

Implications for Operation of Highway Facilities

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

AV-AV

AV-N

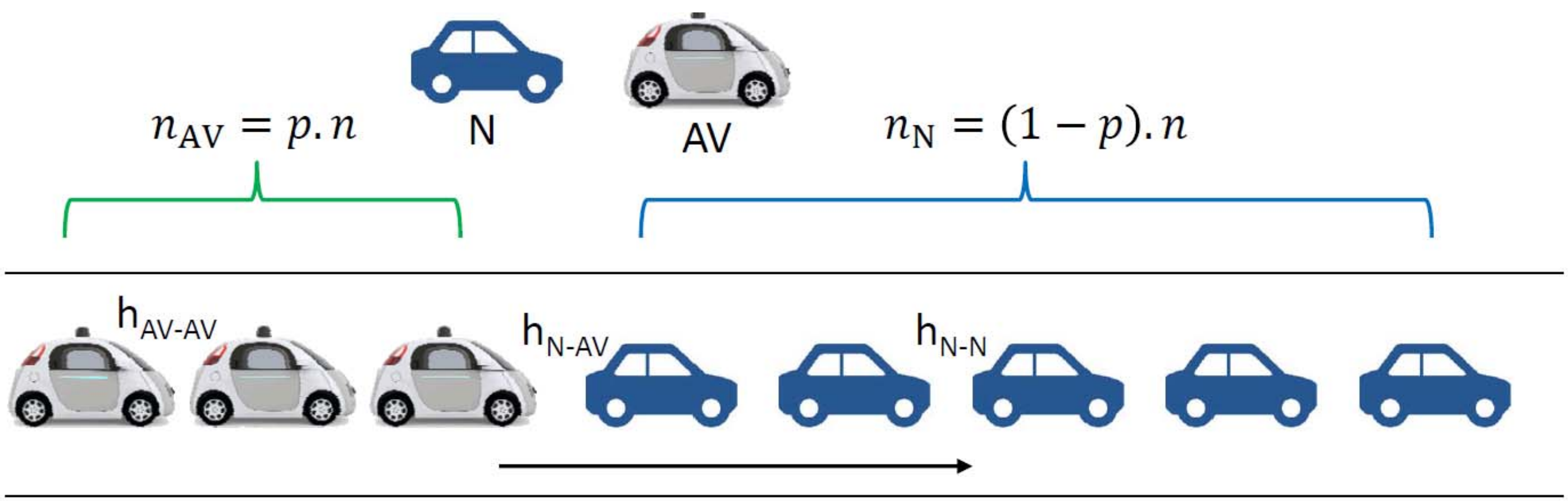
N-AV

N-N

Headway Analysis (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



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

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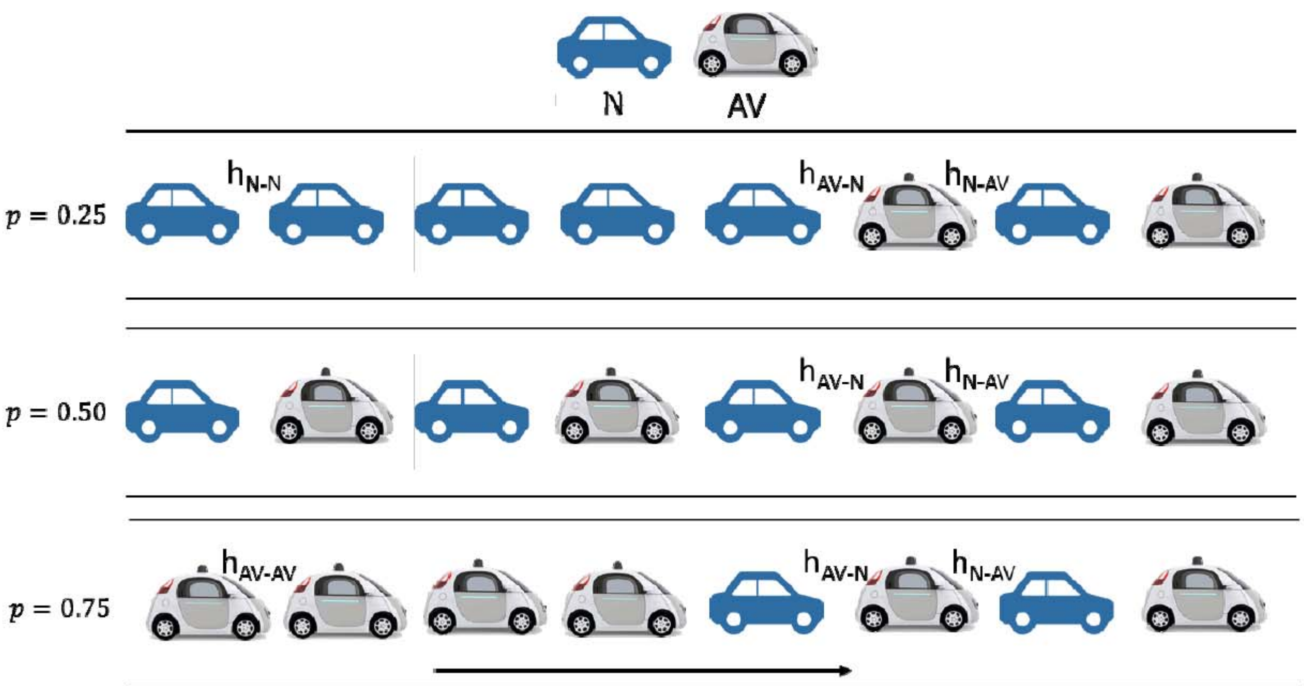
Headway Analysis (2)

Upper Bound of Vehicle Headway



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

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Headway Analysis (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:

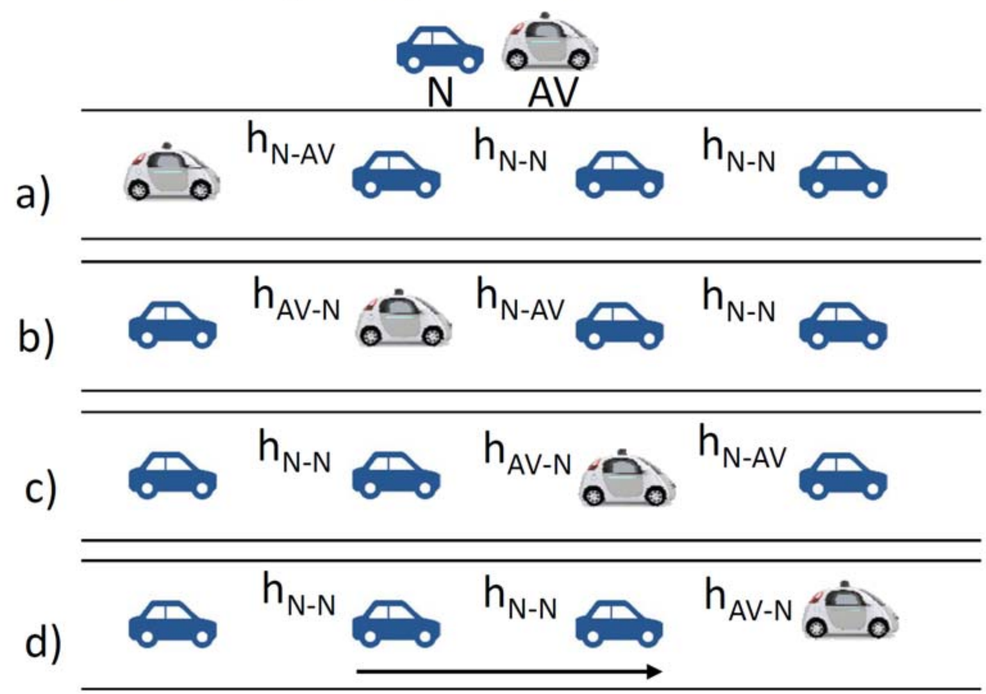
- $k = 0$ (only N)
- $k = 1$
- $k = 2$
- $k = 3$
- $k = 4$ (only AV)

Headway Analysis (3)

Expected Vehicle Headway – Example (*cont.)*

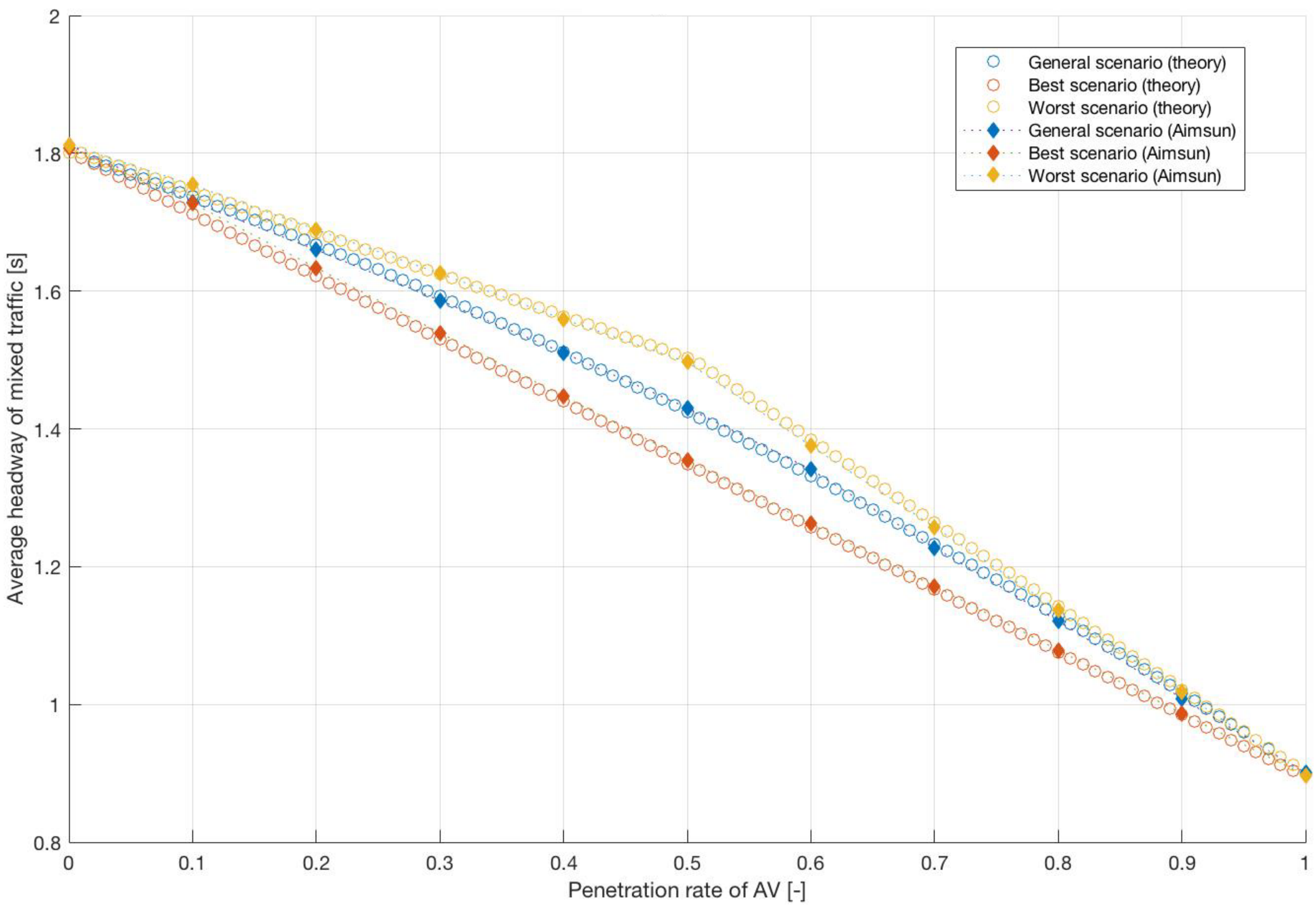
$$h_{\mathrm{N-N}} = 1.8\ [s];\ h_{\mathrm{AV-AV}} = 0.9\ [s];\ h_{\mathrm{N-AV}} = 1.2\ [s];\ h_{\mathrm{AV-N}} = 1.8\ [s]$$

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



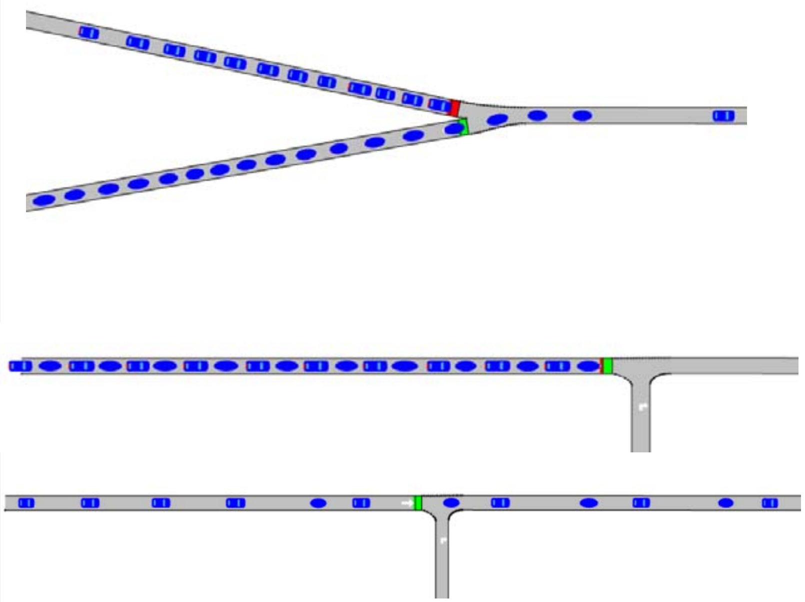
$$\bar{h}_1 = \frac{6h_{\mathrm{N-N}} + 3h_{\mathrm{AV-N}} + 3h_{\mathrm{N-AV}}}{(n-1)} \times \frac{1}{C_n^1} = 1.65\ [s]$$

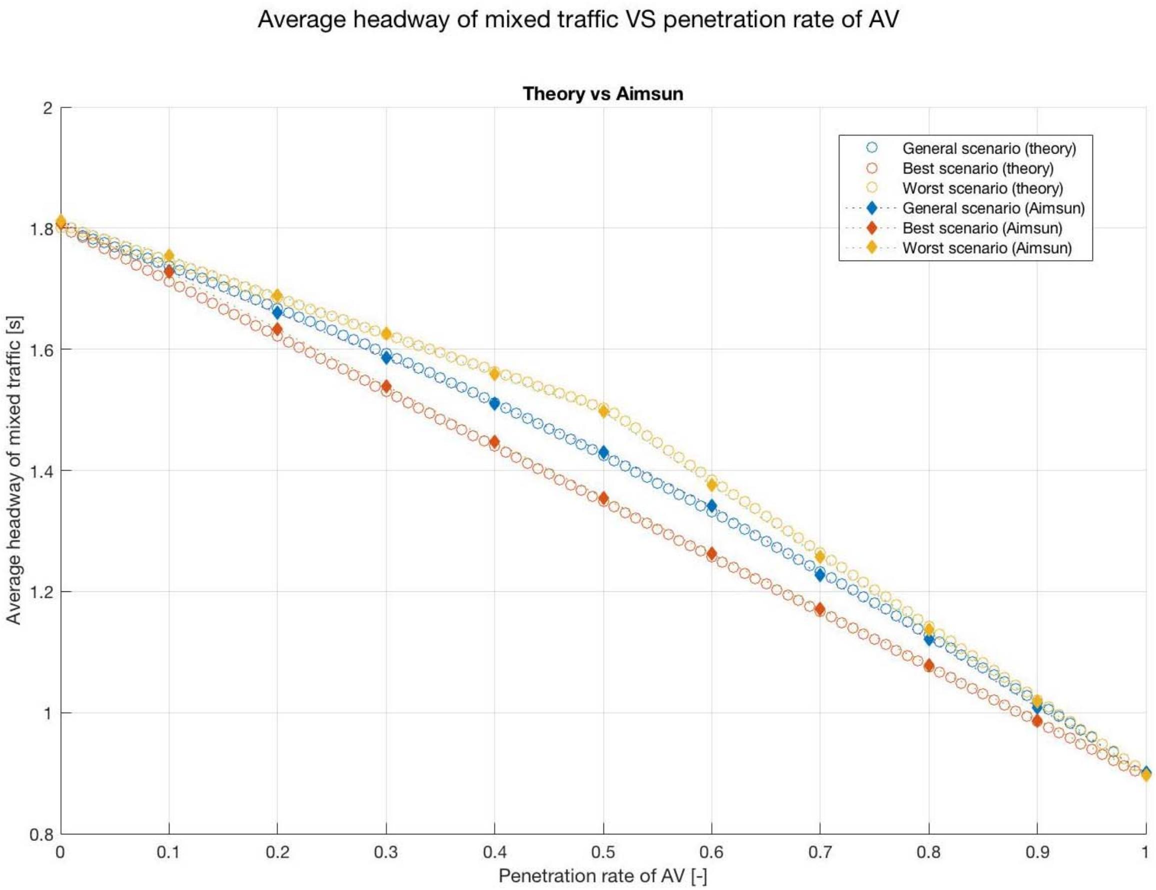
CAVs Saturation Headway



Headway Analysis-Summary

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





Delay at an Arterial Signalized Link (1)

Assumptions:

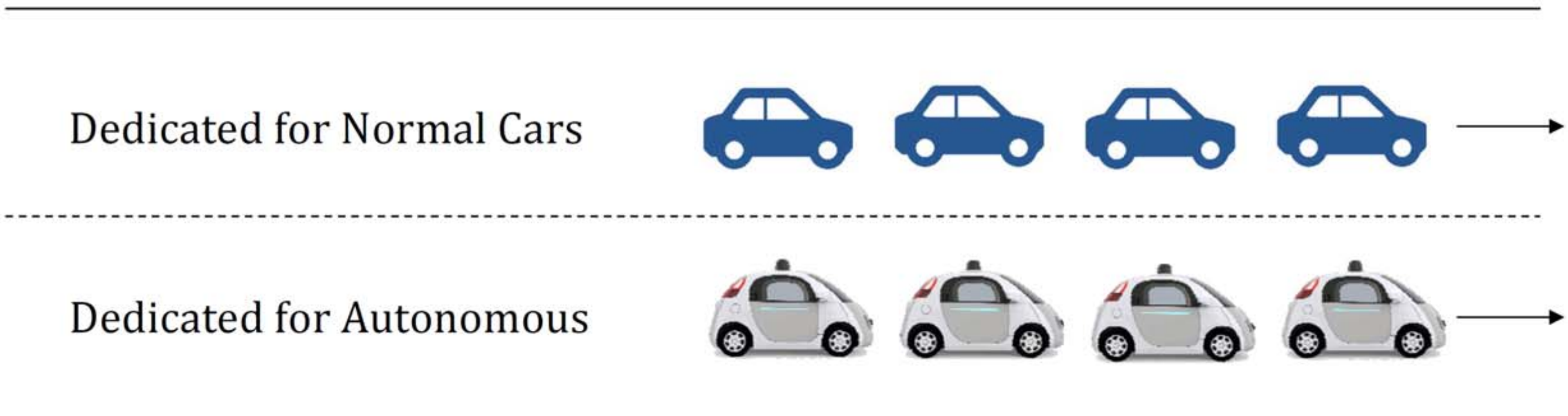
- **Two lane signalized arterial link**
- **Apply shockwave theory**
- **FD parameters (<u>capacity</u>, critical density jam density) for each flow condition**

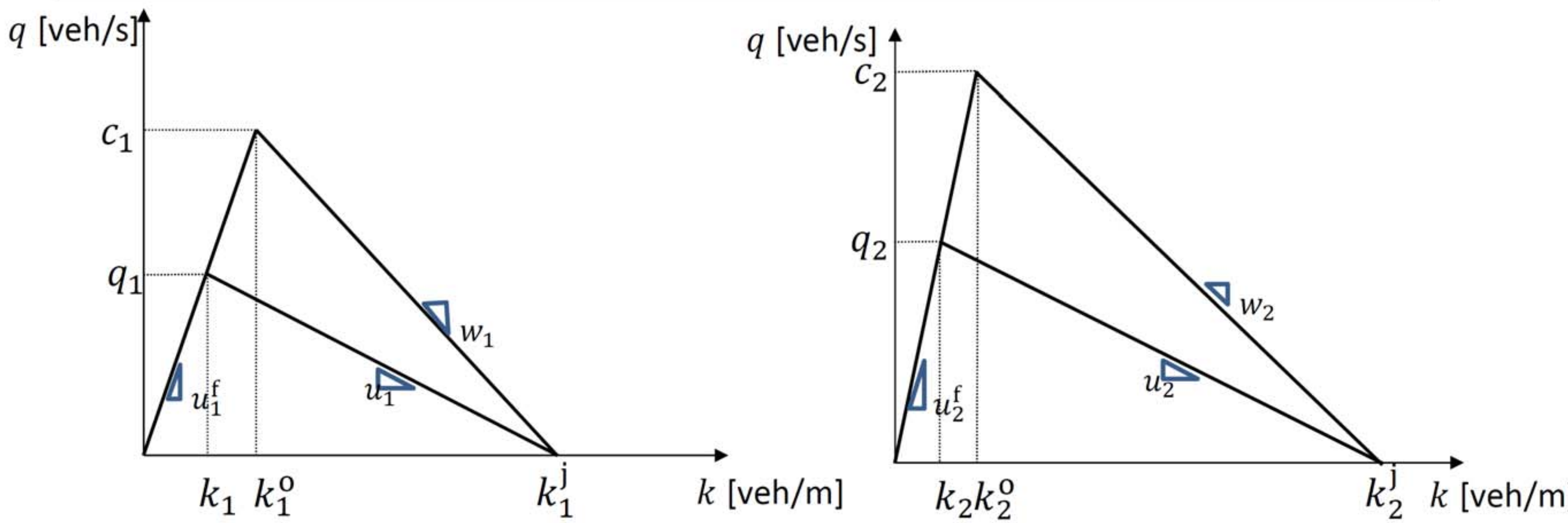
Scenarios

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





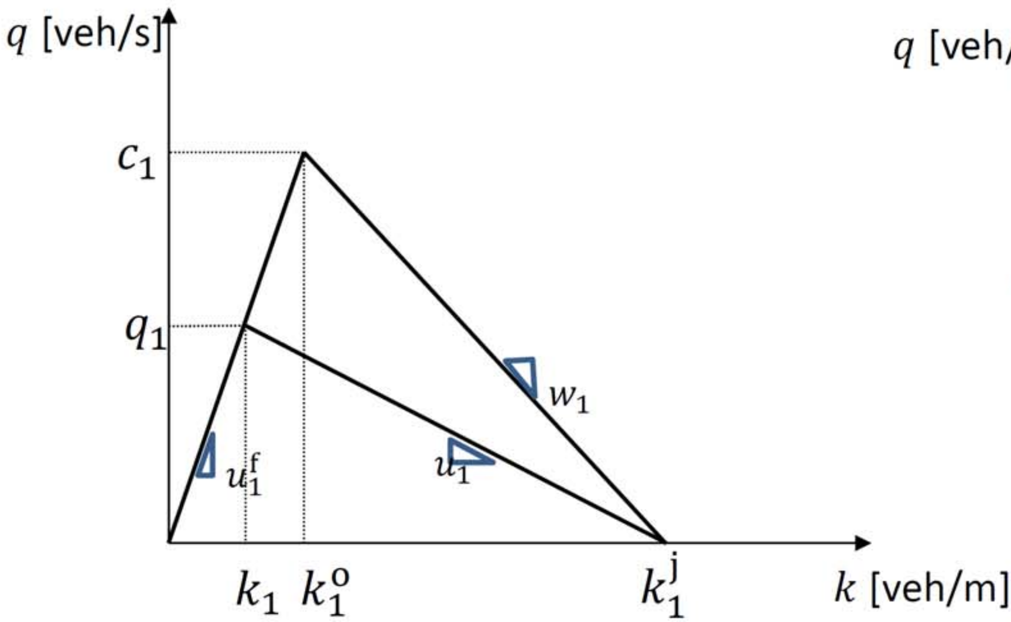
Delay at an Arterial Signalized Link (4)

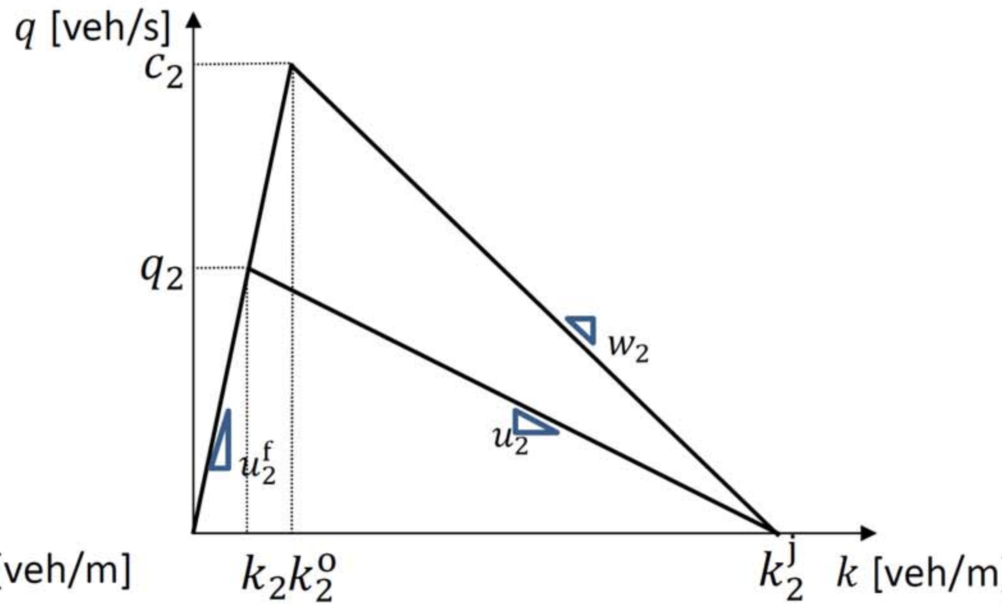
i. dedicated lanes for AV and N (cont..)

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

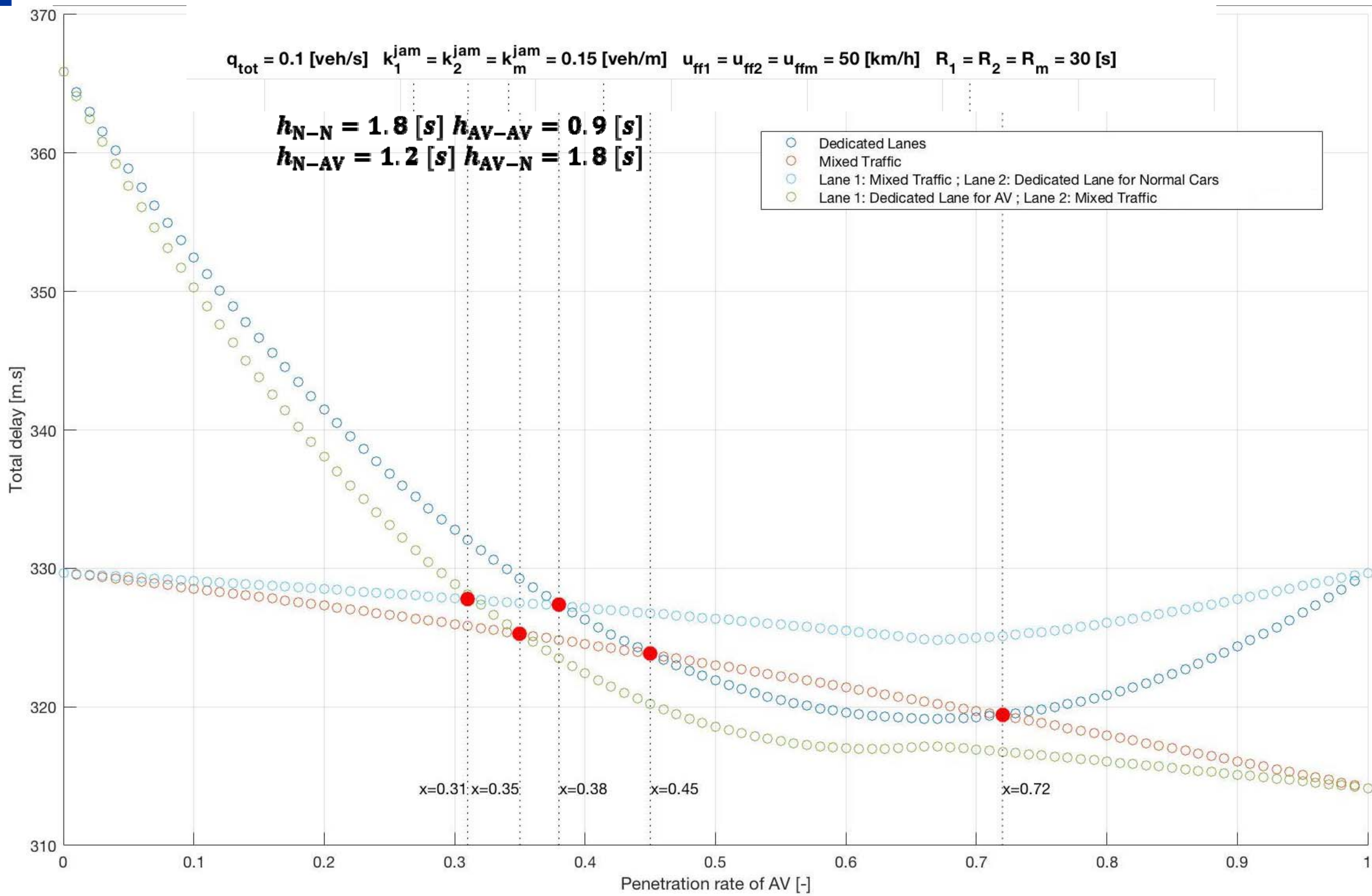
$$D_{\mathrm{T}} = \sum_{i=1}^{2} 0.5R_i^2 \cdot \left(\frac{\frac{c_i}{k_i^{\mathrm{j}} - \frac{c_i}{u_i^{\mathrm{f}}}} \cdot \frac{q_i}{k_i^{\mathrm{j}} - \frac{q_i}{u_i^{\mathrm{f}}}}}{\frac{c_i}{k_i^{\mathrm{j}} - \frac{c_i}{u_i^{\mathrm{f}}}} - \frac{q_i}{k_i^{\mathrm{j}} - \frac{q_i}{u_i^{\mathrm{f}}}}}\right)$$

- 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; $q_2 = pq_T$

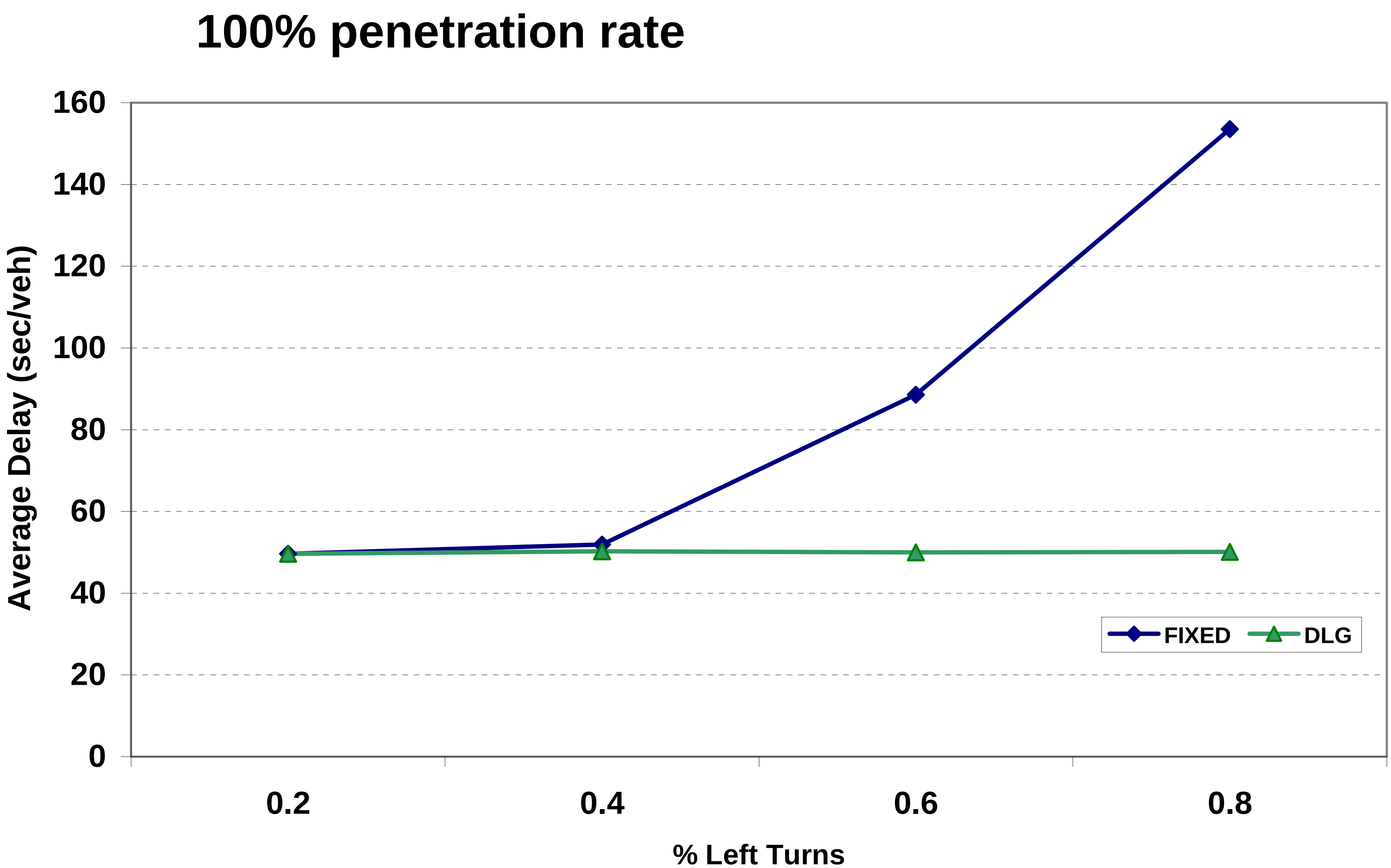




Delay at an Arterial Signalized Link-Summary



CAVs : Dynamic Lane Grouping



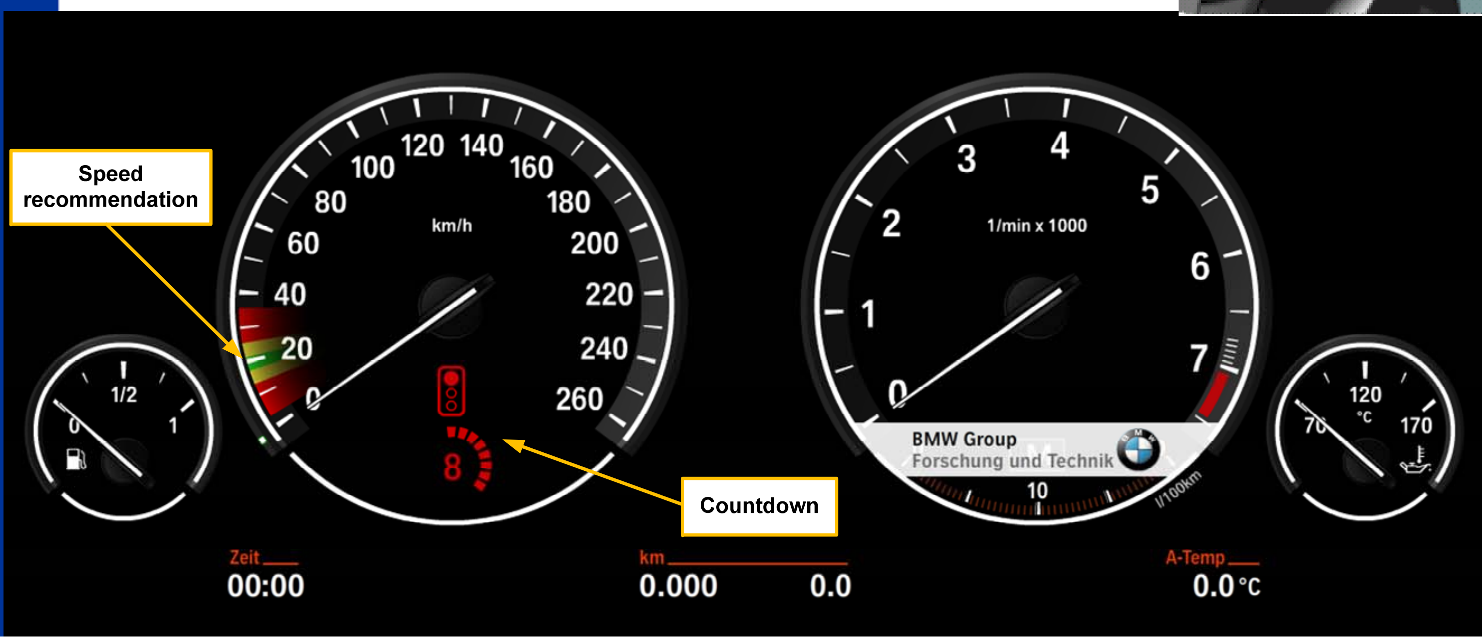
CAVs: Eco-Driving

Messages

“Here I am”

Signal Phase & Timing (SPaT)

Application: Dynamic Speed Advisory (source: UC & BMW)



14% Reduction in Fuel Use

Delay Savings

Real World (Public Agencies): Operational/Planning Analyses

What will be the capacity of freeway lane with CAVs?

What are the impacts on operational performance (reliability)

What link capacity to use in 2030 transportation plans?

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)