IEEE: Models and Technologies for ITS

Capacity and Delay Analysis of Arterials with Mixed Autonomous and Human-Driven Vehicles

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Introduction

- **Goal:**
  - **Assessment of performance of mixed stream of human-driven (N) and autonomous vehicles (AV) at signalized intersections**

MOEs: capacity, and delay

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

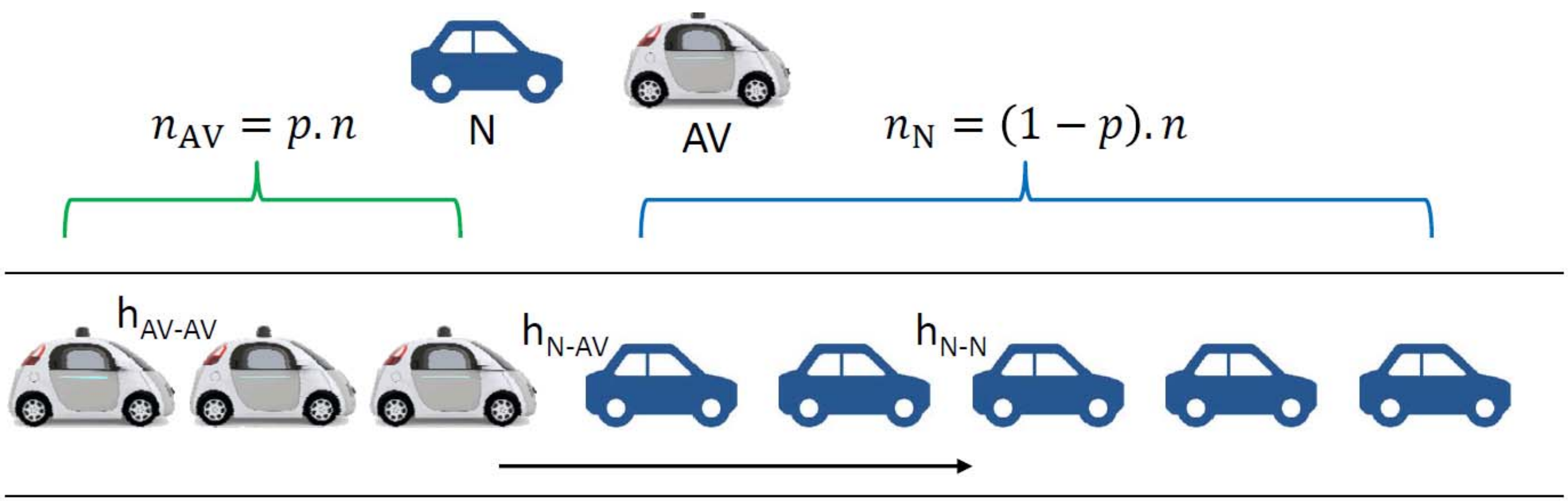
N-AV

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

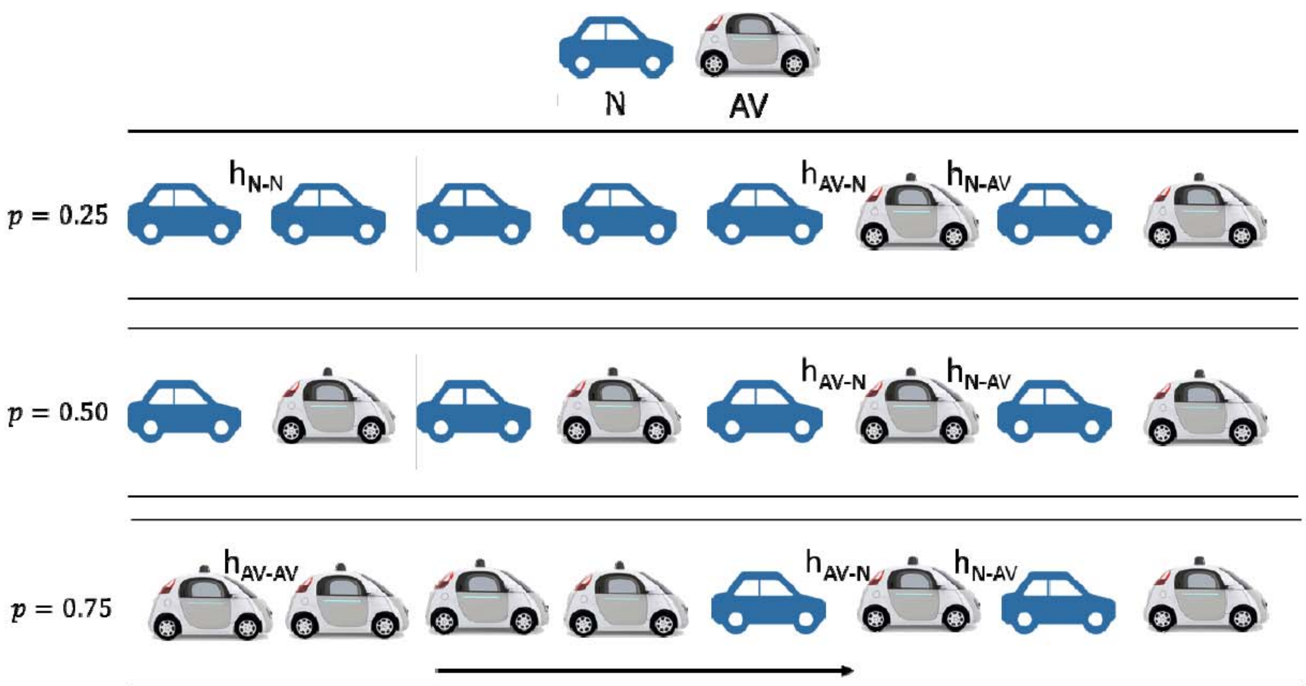
▪ Lower Bound Vehicle Headway



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

Headway Analysis (2)

Upper Bound of Vehicle Headway



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

5

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:

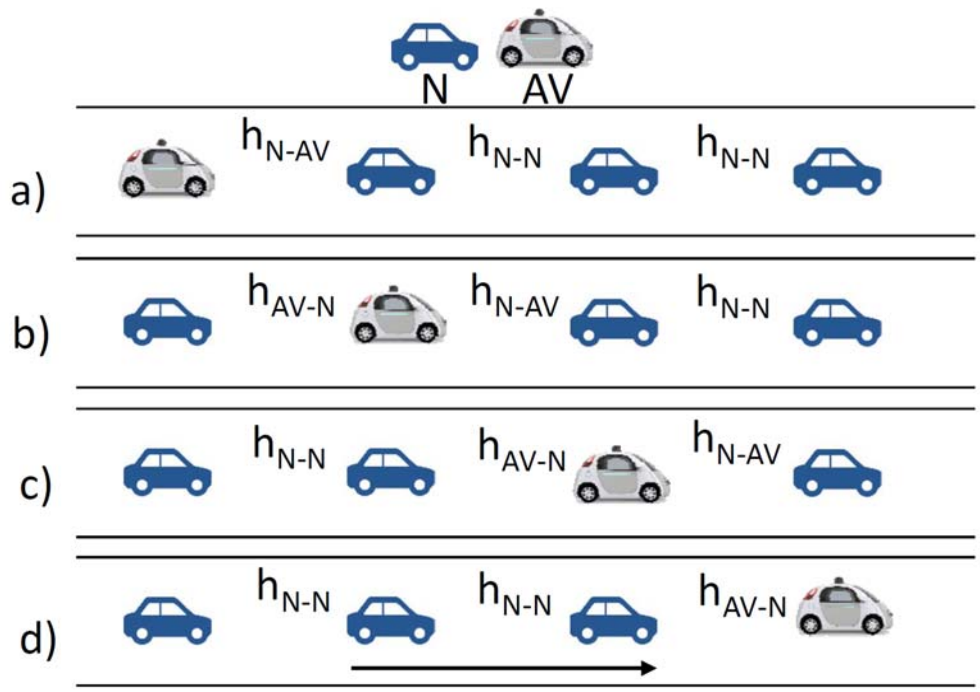
- $k = 0$ (only N)
- $k = 1$
- $k = 2$
- $k = 3$
- $k = 4$ (only AV)

Headway Analysis (3)

Expected Vehicle Headway – Example (*cont.*)

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

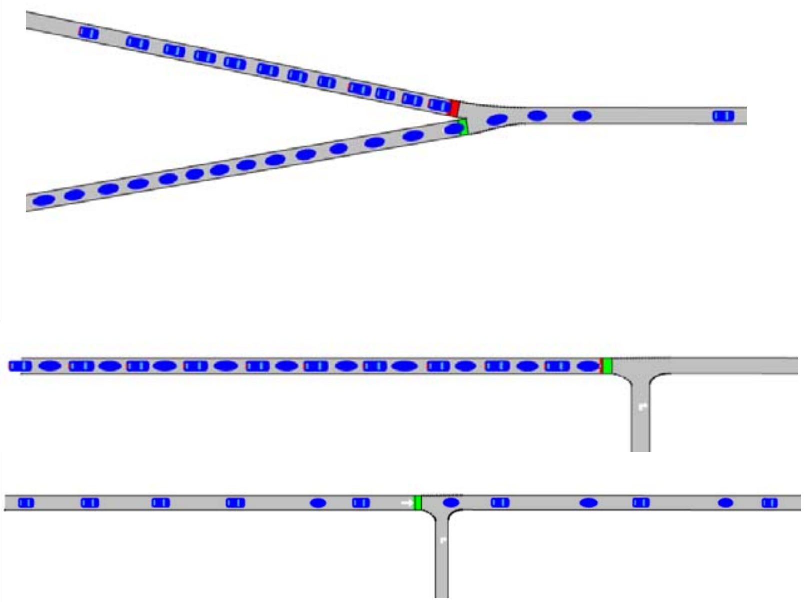
$$k = 1 \qquad C_n^k = \binom{n}{k} = \frac{n!}{k!\,(n-k)!} = \frac{4!}{1!\,3!} = 4 \text{ combinations}$$

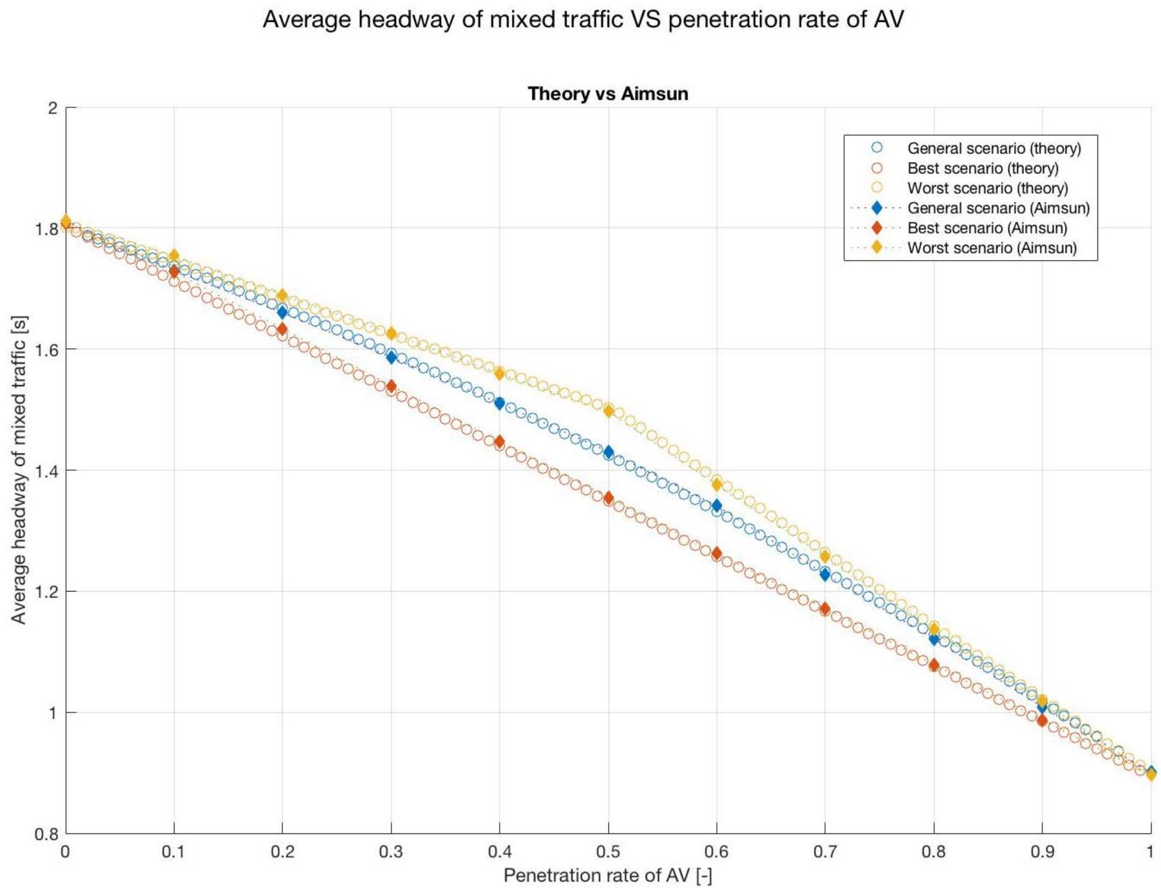


$$\bar{h}_1 = \frac{6h_{\mathrm{N-N}} + 3h_{\mathrm{AV-N}} + 3h_{\mathrm{N-AV}}}{(n-1)} \times \frac{1}{C_n^1} = 1.65\ [s]$$

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)

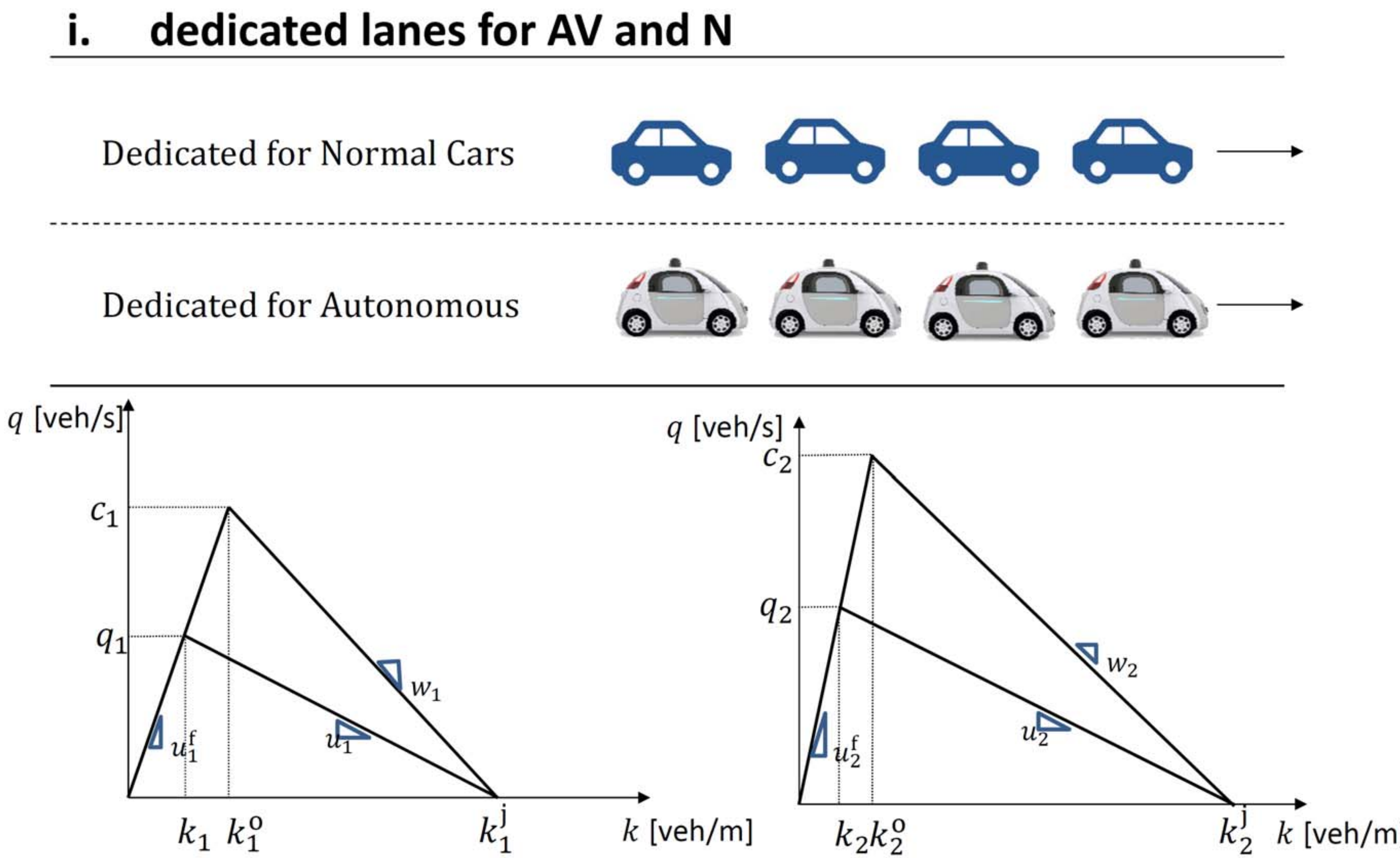
Assumptions:

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

Scenarios

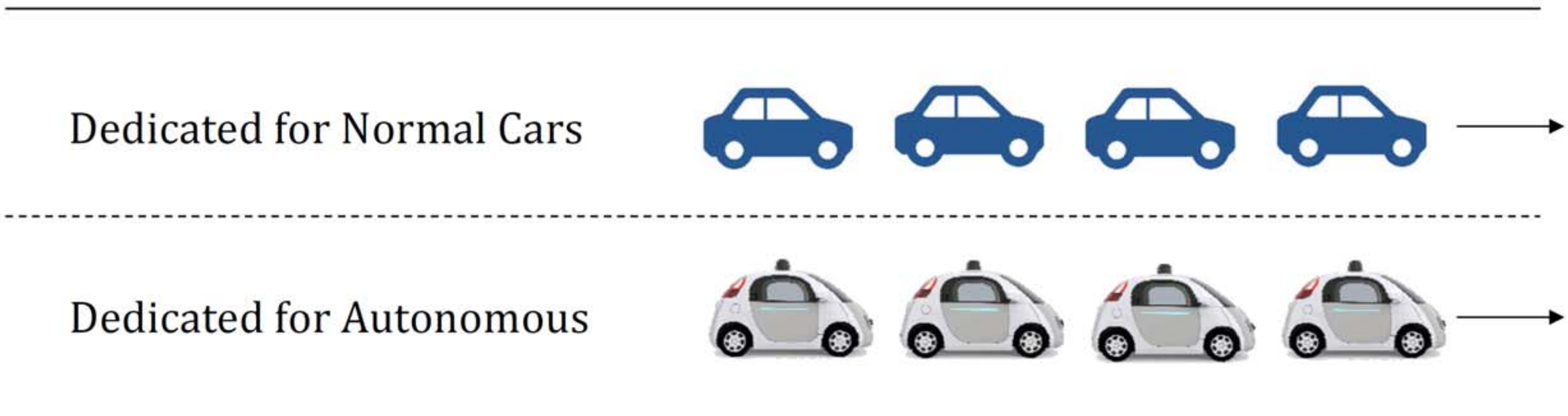
i.mixed lanes
ii.dedicated lanes for AV and N
iii.one mixed lane and one AV dedicated lane
iv.one mixed lane and one N dedicated lane

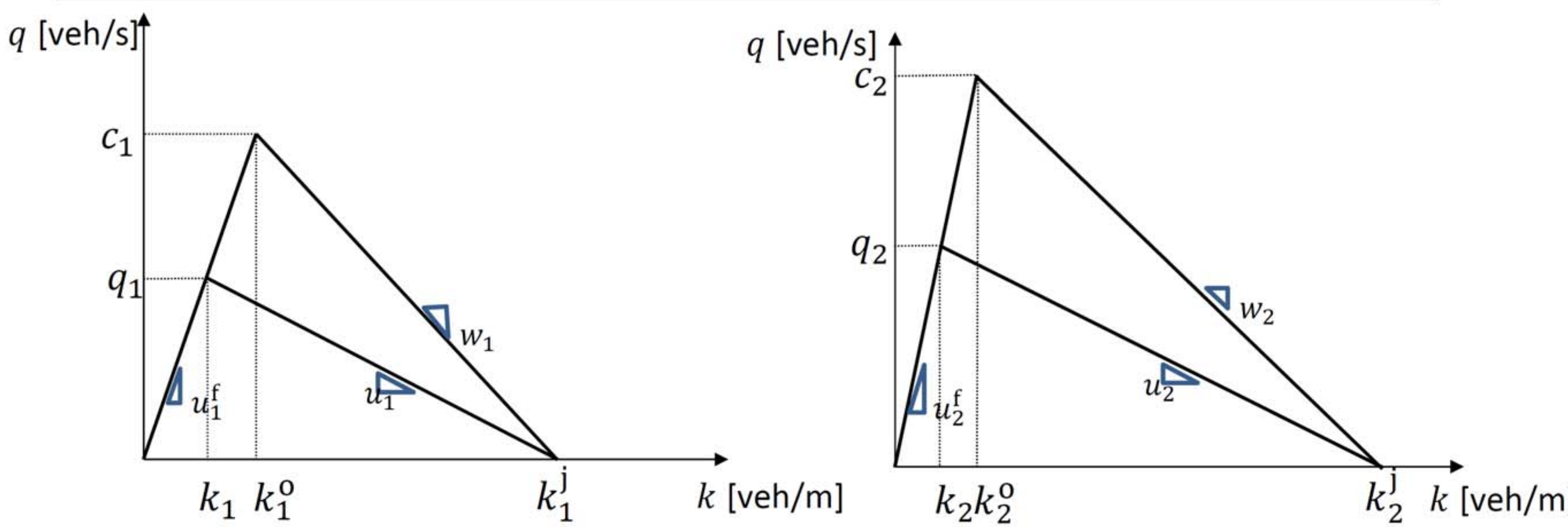
Delay at an Arterial Signalized Link (2)



Delay at an Arterial Signalized Link (3)

i. dedicated lanes for AV and N





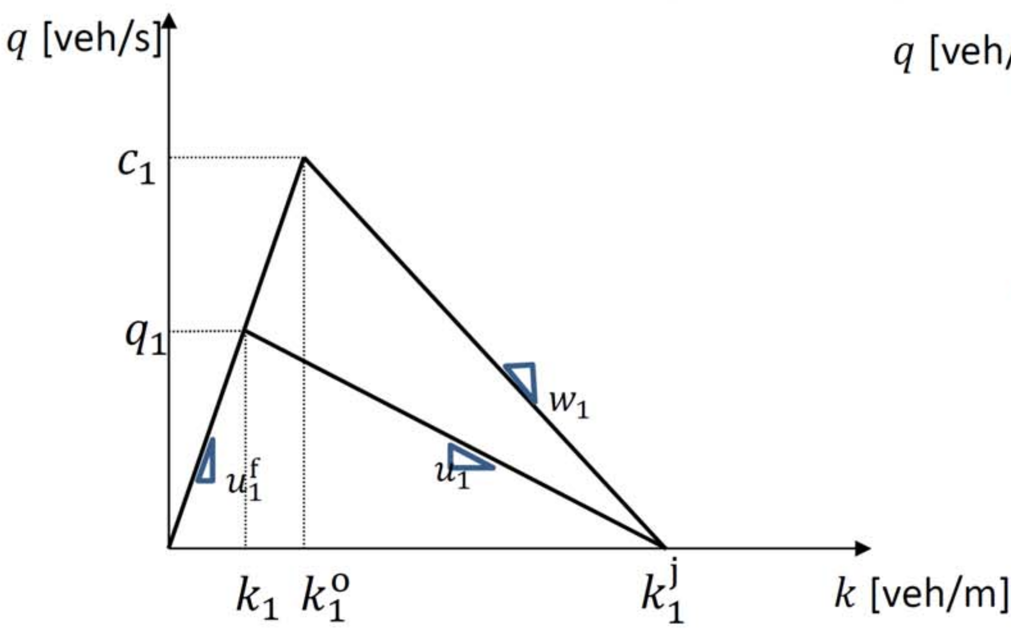
Delay at an Arterial Signalized Link (4)

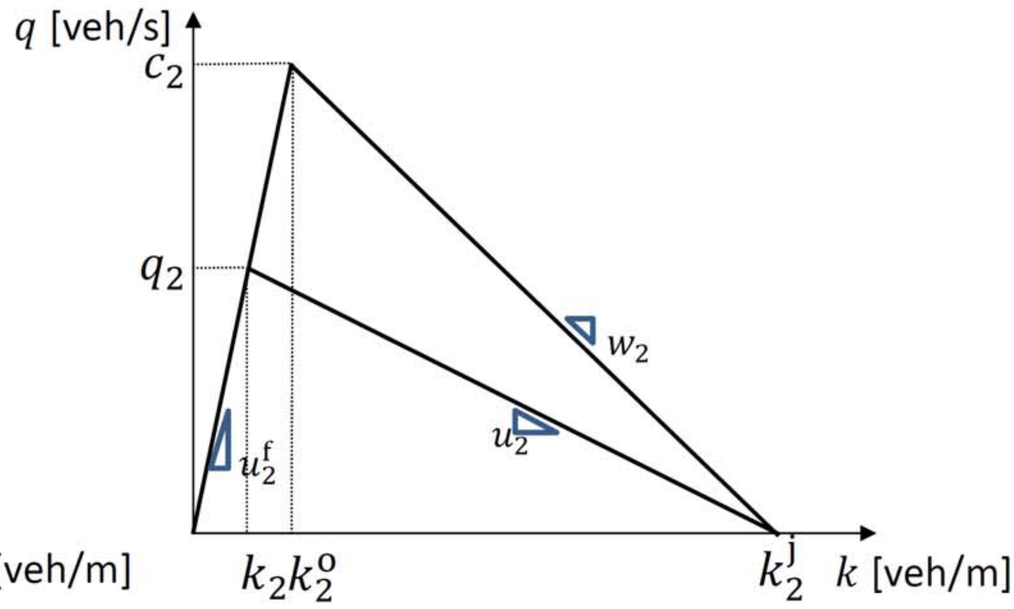
i. dedicated lanes for AV and N (cont..)

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

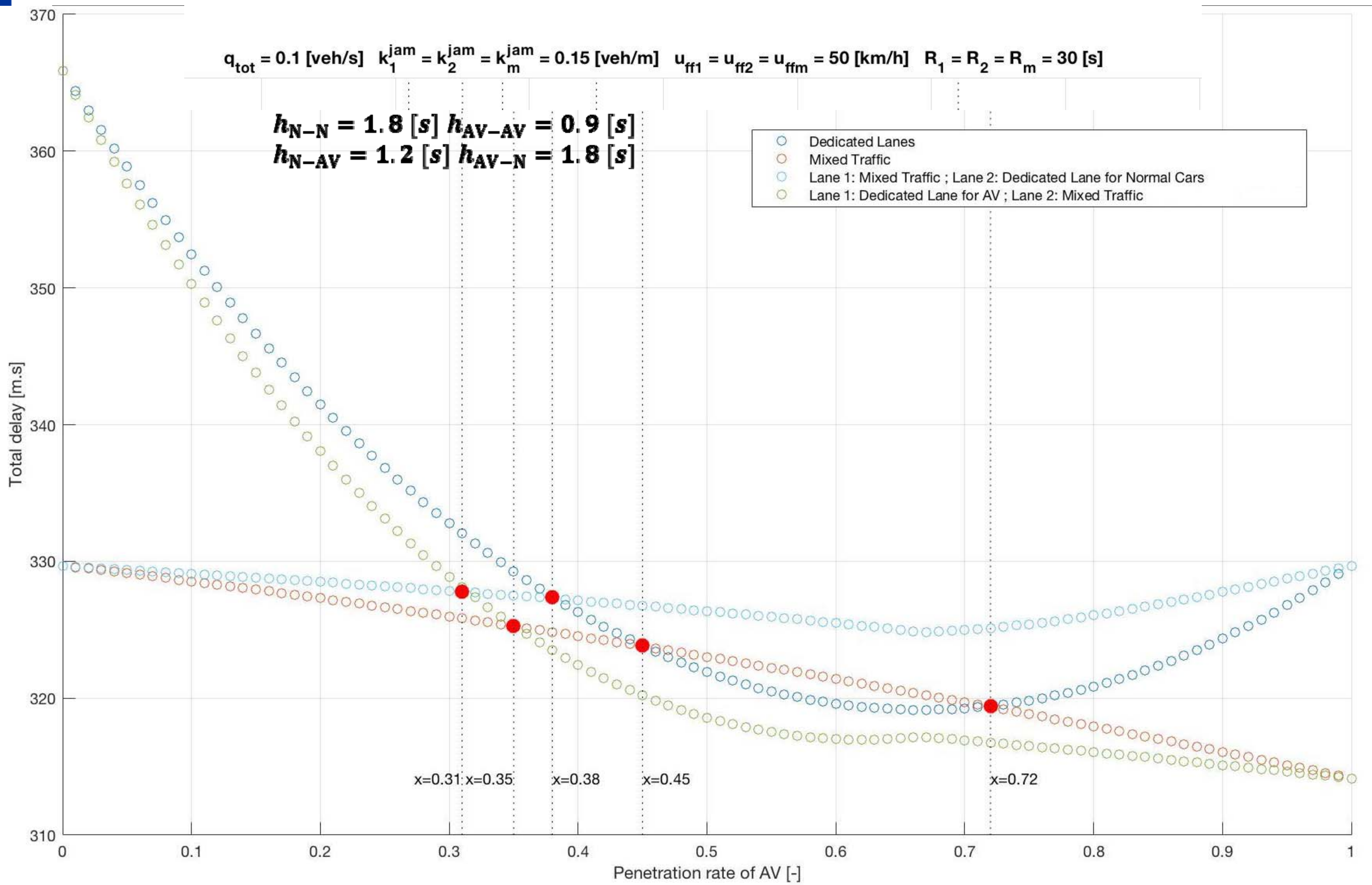
$$D_\mathrm{T} = \sum_{i=1}^{2} 0.5R_i^2 \cdot \left(\frac{\frac{c_i}{k_i^\mathrm{j} - \frac{c_i}{u_i^\mathrm{f}}} \cdot \frac{q_i}{k_i^\mathrm{j} - \frac{q_i}{u_i^\mathrm{f}}}}{\frac{c_i}{k_i^\mathrm{j} - \frac{c_i}{u_i^\mathrm{f}}} - \frac{q_i}{k_i^\mathrm{j} - \frac{q_i}{u_i^\mathrm{f}}}}\right)$$

- 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



Summary

- **Analytical expressions of upper and lower bounds of mixed flow headway**

- **validation of theoretical headways by microsimulation experiments**

- **Delay of a mixed flow at a signalized 2-lane arterial link for several lane utilization scenarios**

- **Trade-offs**

- **Dynamic Lane Allocation (left turning traffic, spillback)**
- **Signal Control Strategies**