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
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

\[
\tilde{h} = \frac{(n_N - 1) \cdot h_{N-N} + (n_{AV} - 1) \cdot h_{AV-AV} + h_{N-AV}}{n - 1}
\]
Upper Bound of Vehicle Headway

\[ \bar{h} = \begin{cases} 
\frac{n_{AV} \cdot h_{AV-N} + (n_{AV} - 1) \cdot h_{N-AV} + (n_N - n_{AV}) \cdot h_{N-N}}{n-1} & \text{if } p < 0.5 \\
\frac{n/2 \cdot h_{AV-N} + (n/2 - 1) \cdot h_{N-AV}}{n-1} & \text{if } p = 0.5 \\
\frac{n_N \cdot h_{AV-N} + n_N \cdot h_{N-AV} + (n_{AV} - n_N - 1) \cdot h_{AV-AV}}{n-1} & \text{if } p > 0.5 
\end{cases} \]
Headway Analysis (3)

Expected Vehicle Headway

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

- \( n = \text{number of vehicles} \)
- \( k = \text{number of AV vehicles} \)
- \( p = \text{penetration rate} \)

Example:

\( n = 4 \ [\text{veh}]; \ p = 0.25 \)

Possible scenarios:

- \( k = 0 \) (only N)
- \( k = 1 \)
- \( k = 2 \)
- \( k = 3 \)
- \( k = 4 \) (only AV)
Headway Analysis (3)

Expected Vehicle Headway – Example (cont.)

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

\[ k = 1 \quad C_n^k = \binom{n}{k} = \frac{n!}{k!(n-k)!} = \frac{4!}{1!3!} = 4 \text{ combinations} \]

\[ C_n^1 = 4 \]

\[ \overline{h}_1 = \frac{6h_{N-N} + 3h_{AV-N} + 3h_{N-AV}}{(n-1)} \times \frac{1}{C_n^1} = 1.65 \text{ [s]} \]
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 (capacity, 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

Dedicated for Normal Cars

Dedicated for Autonomous

\[
q \text{ [veh/s]}
\]

\[
k_1 \quad k_1^0 \quad k_1^j
\]

\[
k_2k_2^0 \quad k_2^j
\]
Delay at an Arterial Signalized Link (3)

i. dedicated lanes for AV and N

Dedicated for Normal Cars

Dedicated for Autonomous

$q \text{ [veh/s]}$

$k_1 \quad k_1^o \quad k_1^j \quad k \text{ [veh/m]}$

$q \text{ [veh/s]}$

$k_2 \quad k_2^o \quad k_2^j \quad k \text{ [veh/m]}$
Delay at an Arterial Signalized Link (4)

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

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

\[
D_T = \sum_{i=1}^{2} 0.5 R_i^2 \cdot \left( \frac{c_i}{k_i^j - \frac{c_i}{u_i}} - \frac{q_i}{k_i^j - \frac{q_i}{u_i}} \right)
\]

- \( R_i \): 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

\[ q_{\text{tot}} = 0.1 \text{ [veh/s]} \]
\[ k_{1}^{\text{jam}} = k_{2}^{\text{jam}} = k_{m}^{\text{jam}} = 0.15 \text{ [veh/m]} \]
\[ u_{\text{ff1}} = u_{\text{ff2}} = u_{\text{ffm}} = 50 \text{ [km/h]} \]
\[ R_{1} = R_{2} = R_{m} = 30 \text{[s]} \]

\[ h_{N-N} = 1.8 \text{ [s]} \]
\[ h_{N-AV} = 1.2 \text{ [s]} \]
\[ h_{AV-AV} = 0.9 \text{ [s]} \]

\[ h_{N-AV} = 1.2 \text{ [s]} \] \[ h_{AV-N} = 1.8 \text{ [s]} \]
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