Two Chapters on modelling and control of mixed traffic flow with CAVs

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Congestion cost US: more than **$120** billion in 2011

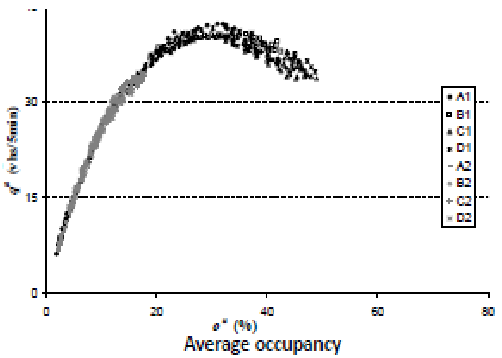
Congestion cost UK: £**20** billion per year

Congestion costs Europe about 1% of its GDP annually

Cost of Transport in Switzerland: **8.5** billion CHF in 2015

Congestion Cost Australia: **$16.5** billion in 2015

A holistic approach of mobility (3M)



MODELING

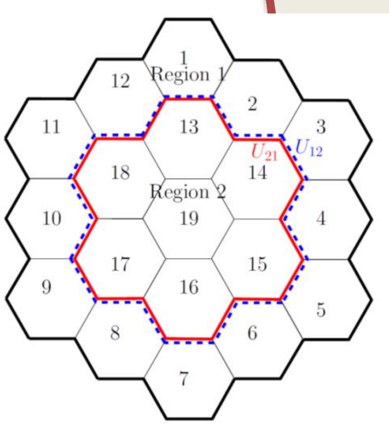
Micro vs. macroscopic

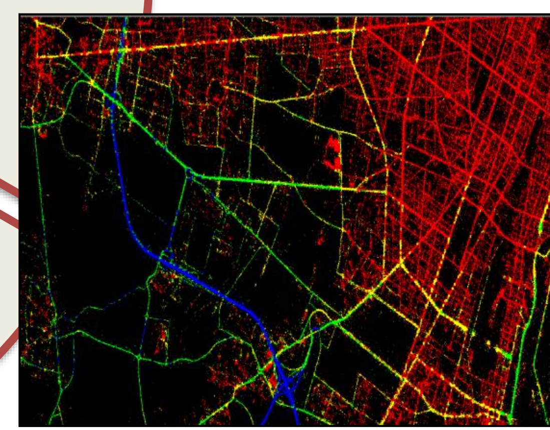
MONITORING

Massive data

MANAGEMENT

Hierarchical structure





Outline

- Chapter One: Modelling

  Characterizing traffic Flows with Mixed Autonomous and Human-driven Vehicles

    - Estimation of the saturation flow of the mixed traffic
    - Validation of the headway models
    - Estimation of the delay of a two-lane road
    - Validation of the delay models
    - Optimal lane management

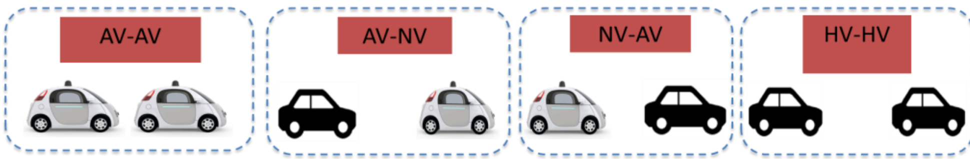
- Chapter Two: Control

  Lane density optimisation of autonomous vehicles for highway congestion control

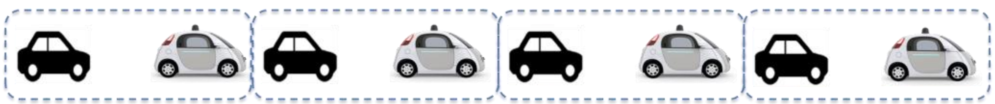
More Efficient Traffic Systems by CAVs

Estimation of the Saturation Flow

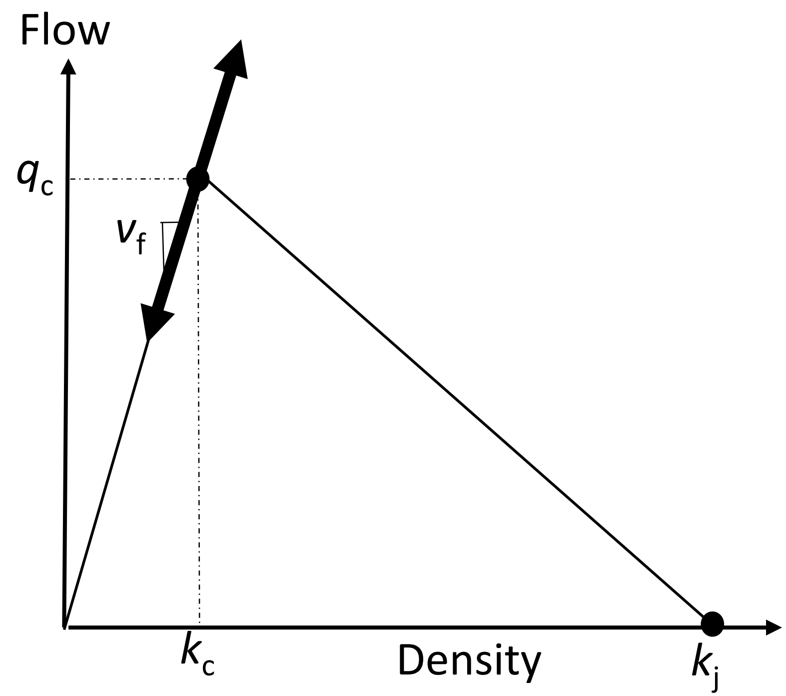
General arrangement:



Worst arrangement (lowest saturation flow)



Best arrangement (highest saturation flow)



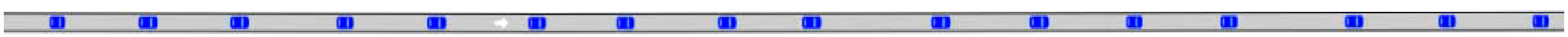
- AV Penetration rate?
- Order of vehicles?

❑ The number of AVs in the mixed traffic follows a binomial distribution

Estimation of the Saturation Flow

General arrangement of vehicles

Best arrangement of vehicles



Worst arrangement of vehicles

Estimation of the Saturation Flow

❑General random arrangement

$$\mathrm{E}[\bar{h}\,(k,n)] = \sum_{k=0}^{n} \bar{h}_k(n)\, P(X=k)$$

$$\overline{h_k}(n) = \frac{1}{n-1} A_k(n) H / C_n^k$$

Average headway of all possible platoon combinations

$$P(X=k) = C_n^k p^k (1-p)^{n-k}$$

$$C_n^k = \frac{n!}{(n-k)!\,k!}$$

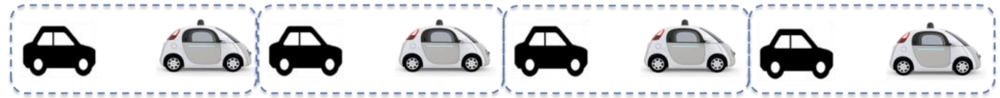
$$p = E[k/n]$$

$$\mathrm{E}\left[\bar{h}(k,n)\right] \approx \bar{h}_{\bar{k}}\ |_{\bar{k}=\lfloor np \rfloor}$$

Approximate formula

Estimation of the Saturation Flow

❑Worst arrangement (lowest saturation flow)



$$\bar{h}_k^{\text{worst}}(n) = \begin{cases} \dfrac{k \cdot h_{\text{av-nv}} + (k-1)h_{\text{nv-av}} + (n-2k)h_{\text{nv-nv}}}{n-1} & k/n < 0.5 \\ \dfrac{k \cdot h_{\text{av-nv}} + (k+1)h_{\text{nv-av}}}{n-1} & k/n = 0.5 \\ \dfrac{(n-k)h_{\text{av-nv}} + (n-k)h_{\text{nv-av}} + (2k-n-1)h_{\text{av-av}}}{n-1} & k/n > 0.5 \end{cases}$$

$$\mathrm{E}\left[\bar{h}^{worst}(k,n)\right] \approx \bar{h}_{\bar{k}}^{\text{worst}} |_{\bar{k}=\lfloor np \rfloor}$$

Approximate formula

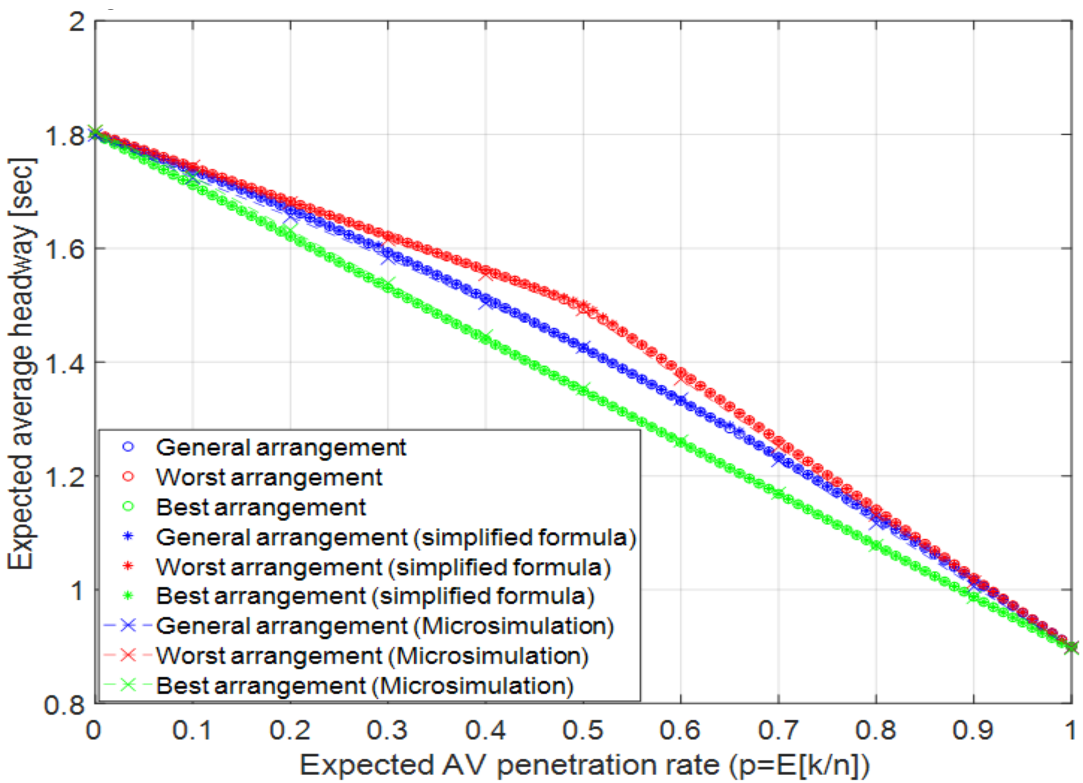
❑Best arrangement (highest saturation flow)

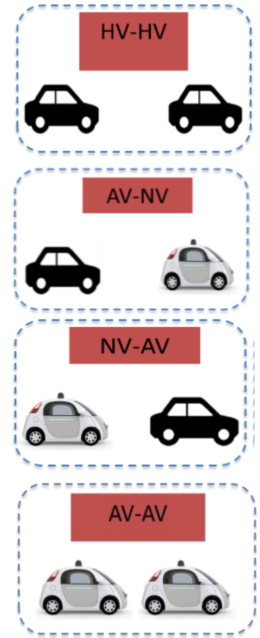
$$\bar{h}_k^{\text{best}}(n) = \begin{cases} \dfrac{(k-1)h_{\text{av-av}} + (n-k-1)h_{\text{nv-nv}} + h_{\text{nv-av}}}{n-1} & 0 < k < n \\ h_{\text{nv-nv}} & k = 0 \\ h_{\text{av-av}} & k = n \end{cases}$$

$$\mathrm{E}\left[\bar{h}^{best}(k,n)\right] = \bar{h}_{\bar{k}}^{\text{best}} |_{\bar{k}=\lfloor np \rfloor}$$

Approximate formula

Validation of the Headway Model



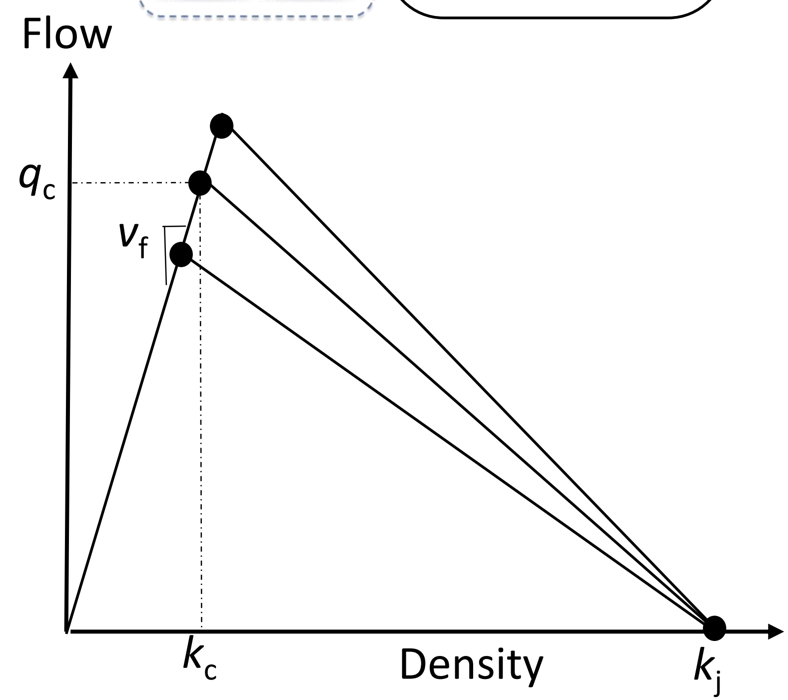


$h_{\mathrm{nv-nv}} = 1.8\ [sec]$

$h_{\mathrm{av-nv}} = 1.8\ [sec]$

$h_{\mathrm{nv-av}} = 1.2\ [sec]$

$h_{\mathrm{av-av}} = 0.9\ [sec]$



Delay Estimation

Dedicated lanes

Mixed-mixed lanes

Mixed-AV lanes

α_{av}

Proportion of AVs using the mixed lane

Mixed-HV lanes

α_{nv}

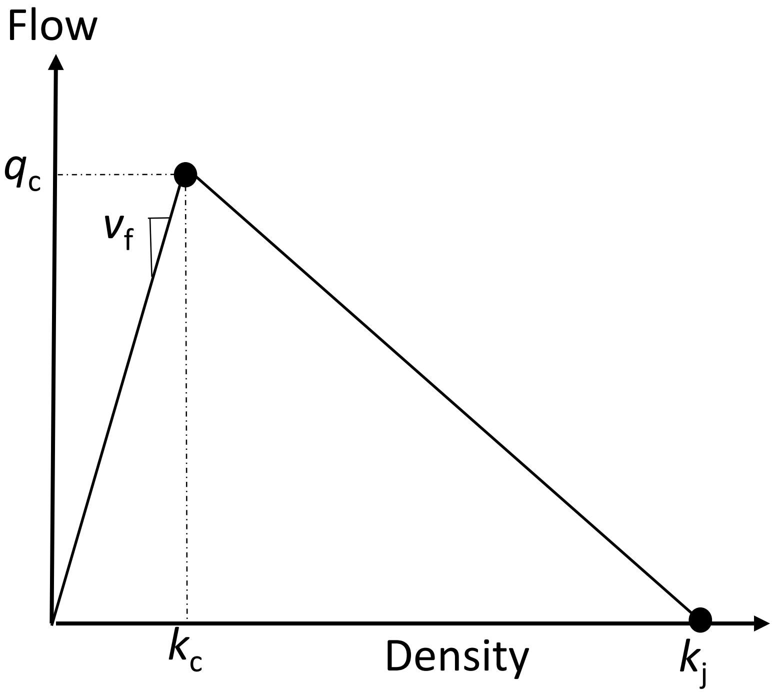
Proportion of HVs using the mixed lane

Delay Estimation

- Assumptions:
  - Well defined fundamental diagram
  - Constant arrival, and saturation flow and density in one cycle

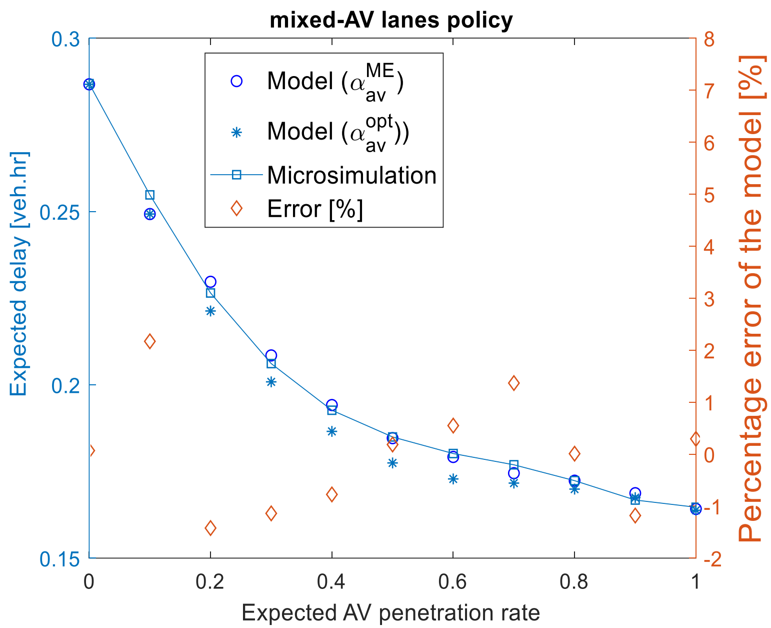
$$\mathrm{E}[D^{nv-av}(k,n_a)] = \sum_{k=0}^{n_a} D_k^{nv-av} P(X=k)$$

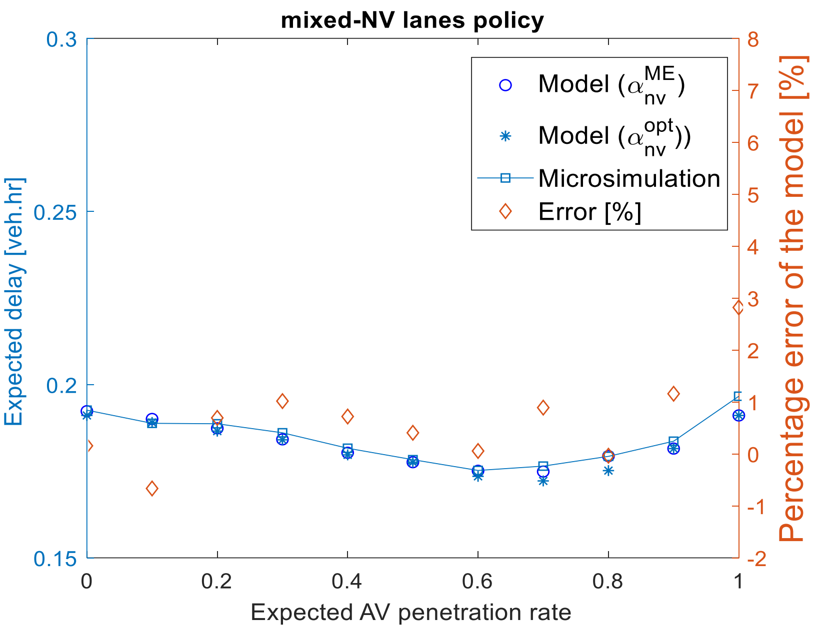
$$D_k^{nv-av} = \sum_{\zeta=\mathrm{nv,av}} \beta_k^{\zeta} \frac{Q_k^{a,\zeta} K^j}{K^j - K_k^{a,\zeta}} (R+L_\zeta)^2$$



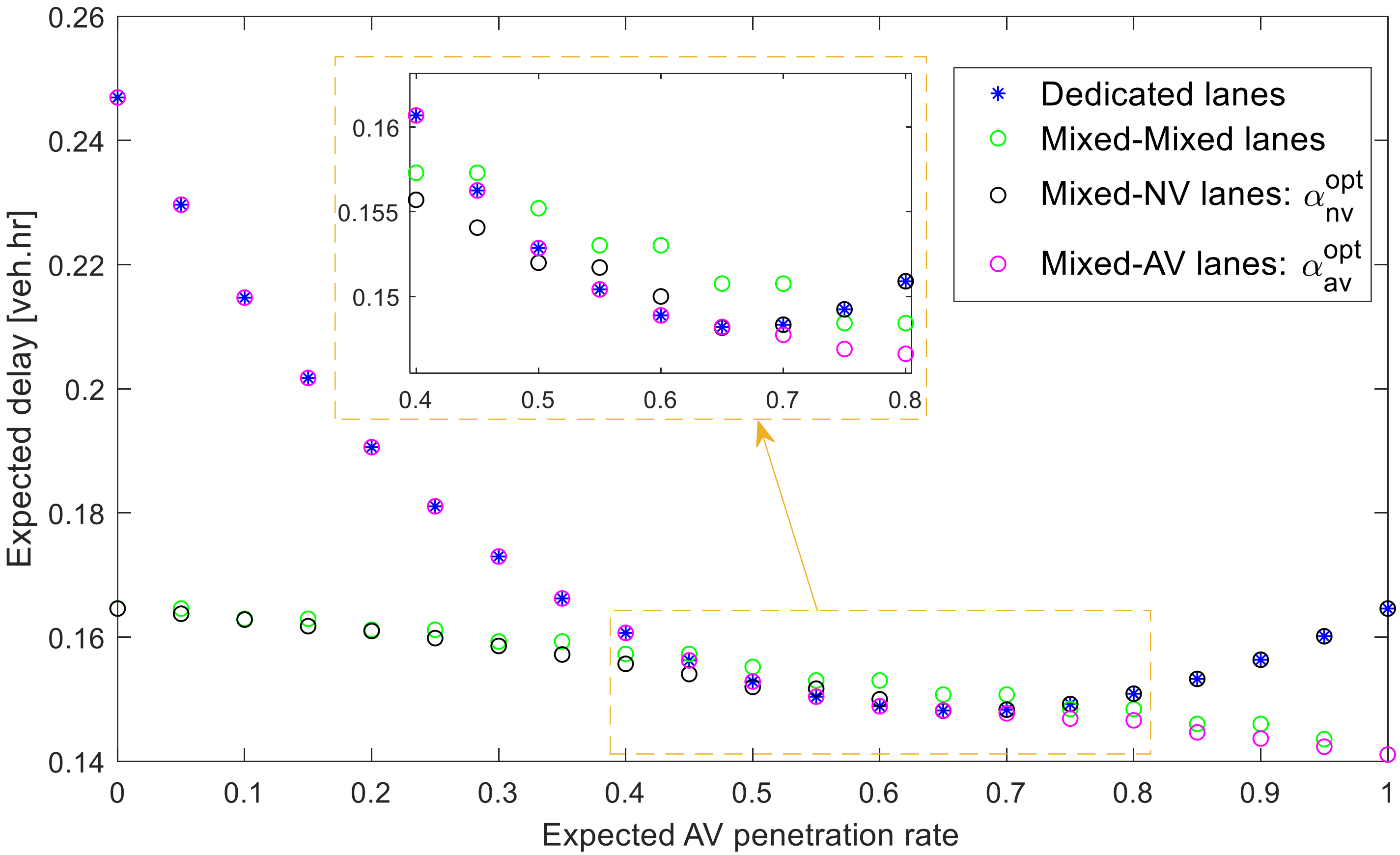
R. Mohajerpoor, M. Saberi, and M. Ramezani, *"Analytical derivation of the optimal traffic signal timing: minimizing delay variability and spillback probability for undersaturated intersections,"* Transportation Research Part B. vol. 119, pp. 45-68, 2019

Validation of the Delay Model





Optimal Lane Management Policy



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- Chapter Two: Control

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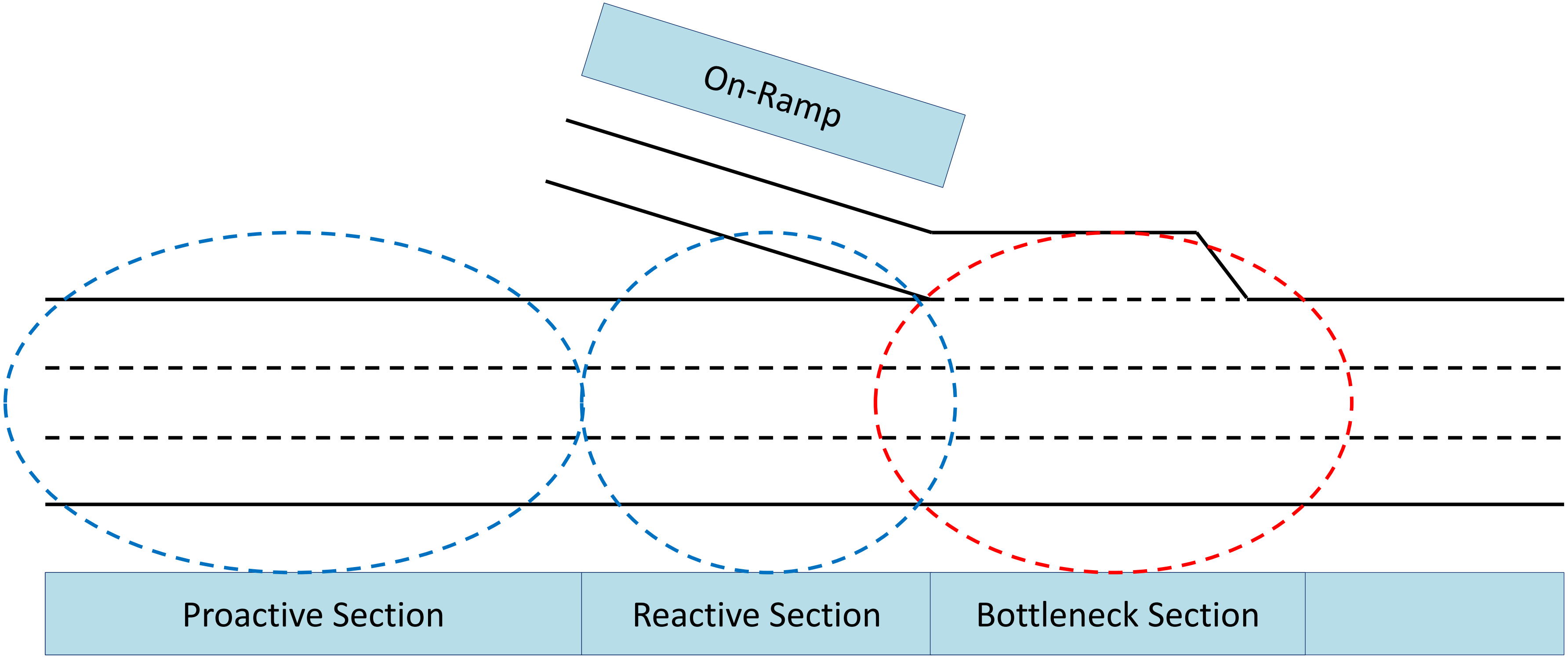
Highways

Highways


Google
self-driving car
OXFORD
CATAPULT
EPSRC
UBER
ADVANCED TECHNOLOGIES CENTER
M city
UNIVERSITY OF MICHIGAN

Road Network



Proactive control

deviations from the critical count in each lane; the number of lane changing manoeuvres

$$\min_{n_i^*(k)} J = \left[\underbrace{\sum_{i=1}^{I} \alpha_i (n_i^*(k) - n_i^{cr})^2}_{\text{deviations from the critical count in each lane}} + \beta \underbrace{\sum_{i=1}^{I} i(n_i^*(k) - n_i(k))}_{\text{the number of lane changing manoeuvres}} \right]$$

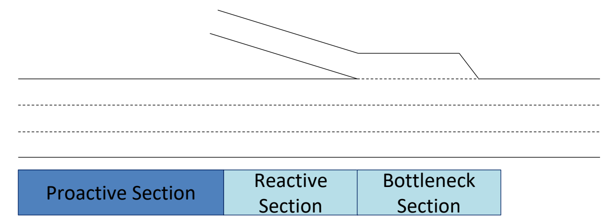
$$\text{s.t.} \sum_{i=1}^{I} n_i(k) = \sum_{i=1}^{I} n_i^*(k)$$

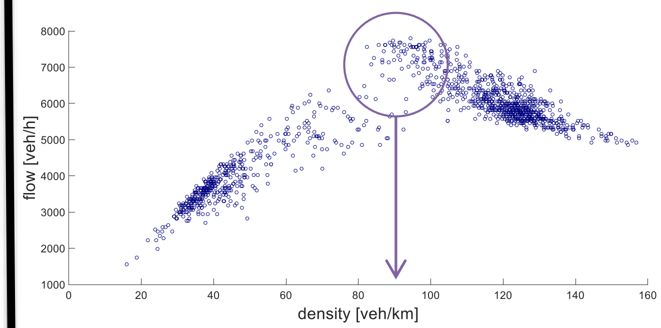
$$n_i^*(k), \ldots, n_I^*(k) \in \mathbb{N} = \{0, 1, 2, \ldots\}$$

Right-moving LC
$$\begin{cases} n_1(k) \geq n_i^*(k) \\ n_I(k) \leq n_I^*(k) \end{cases}$$

Left-most lane $n_i^{cr} = \gamma_i(\rho^{cr} - \rho^{r})L$

Other lanes $n_i^{cr} = \gamma_i \rho^{cr} L$



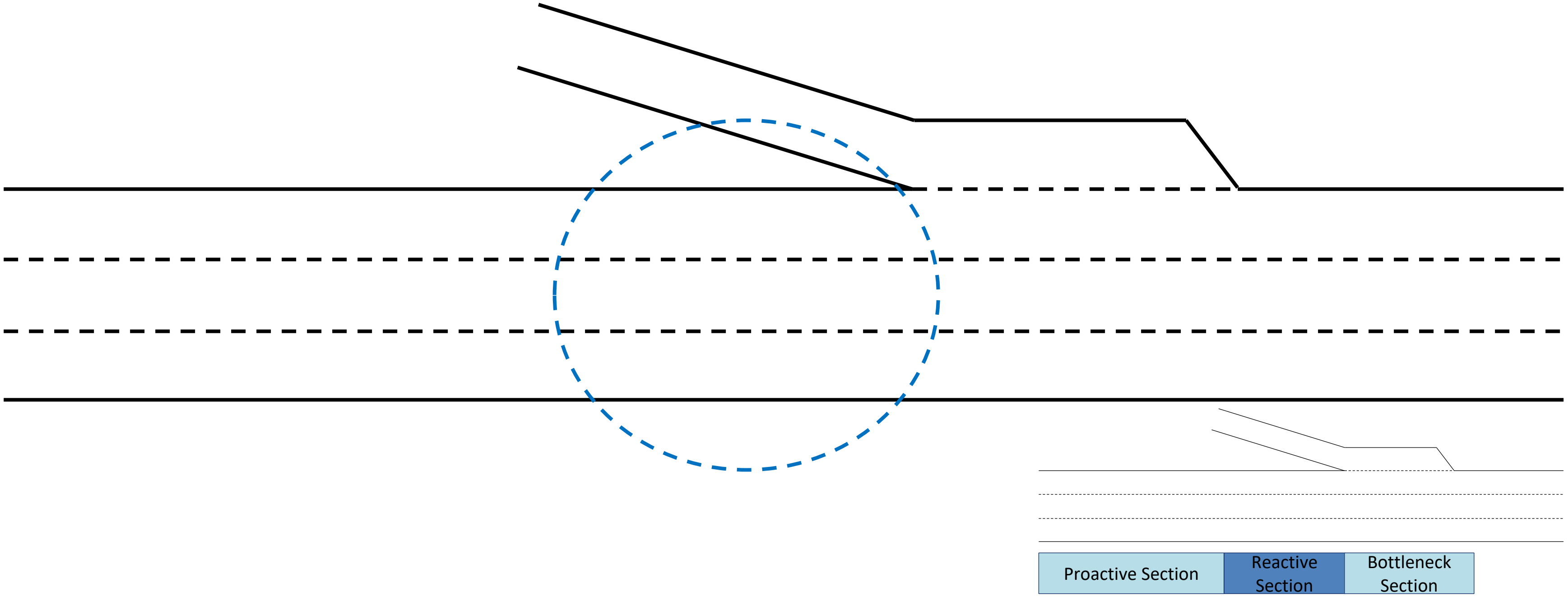


Solution space:

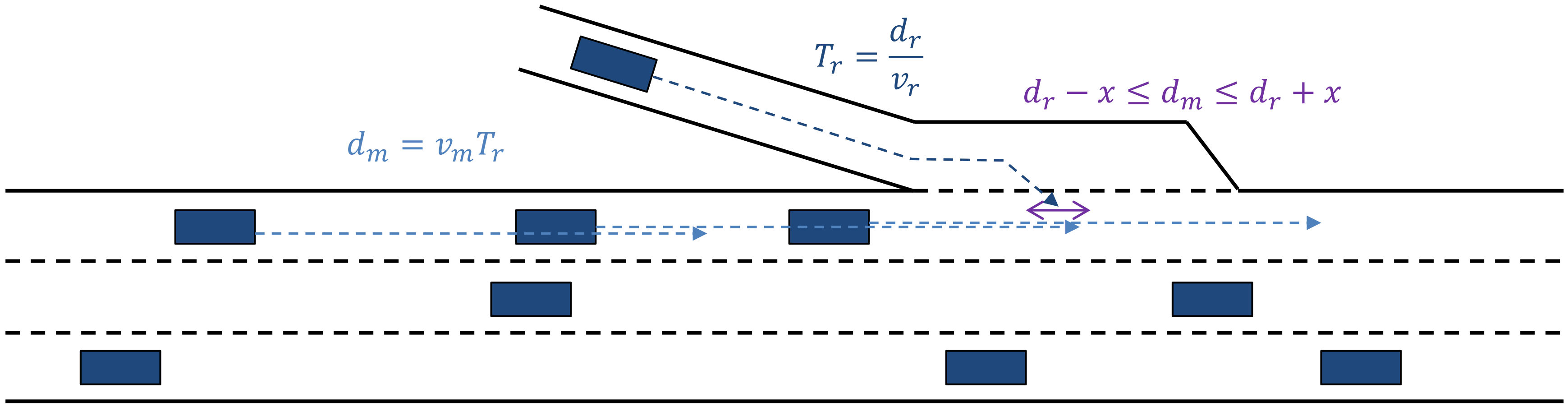
$$\prod_{i=1}^{I-1} (n_i + 1)$$

Reactive control

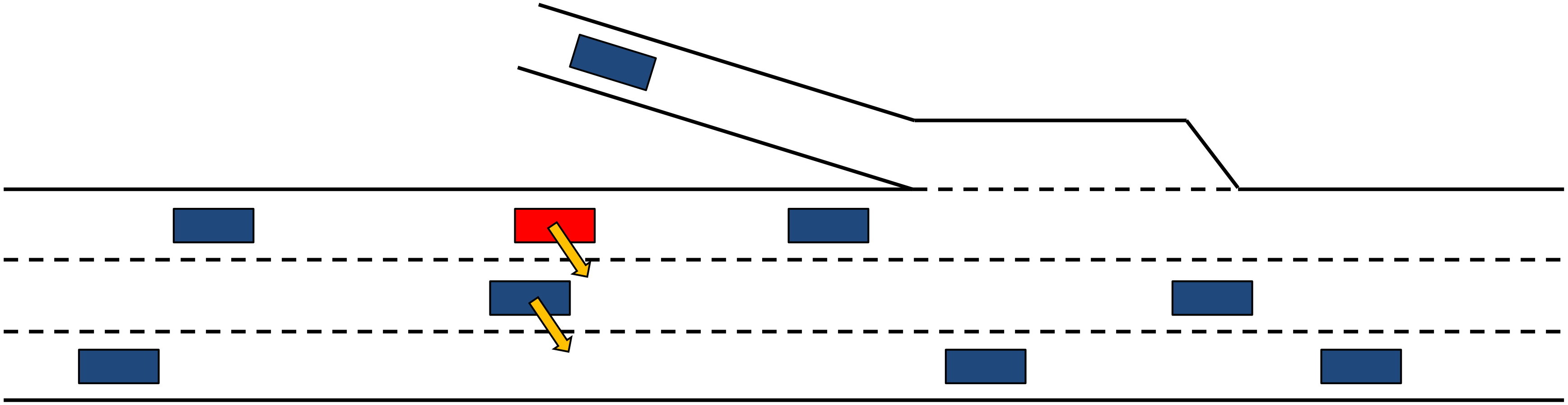
- Rule-based
- Collaborative



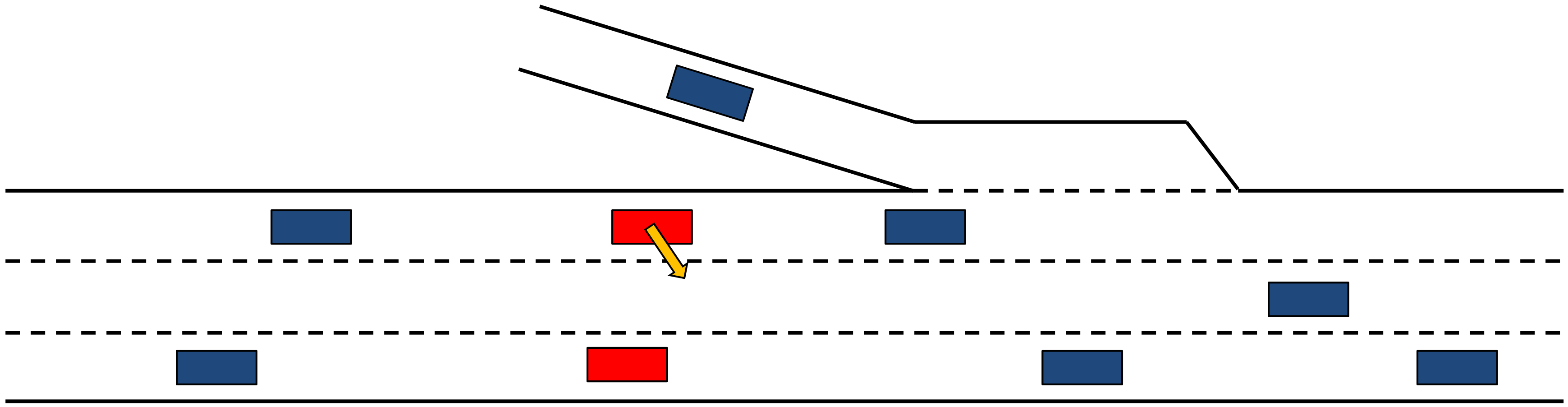
Reactive control



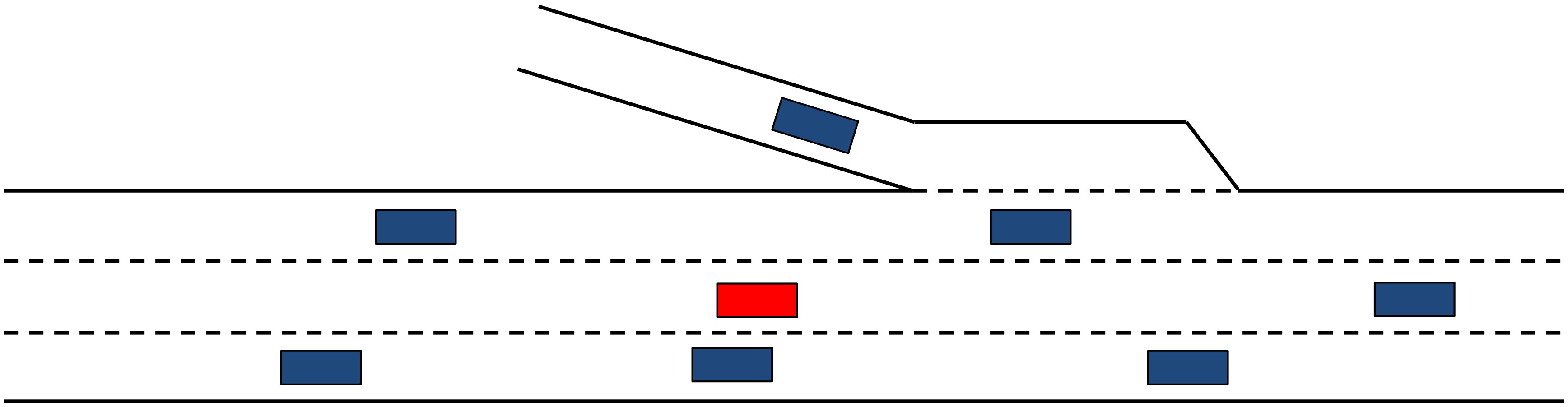
Reactive control



Reactive control



Reactive control



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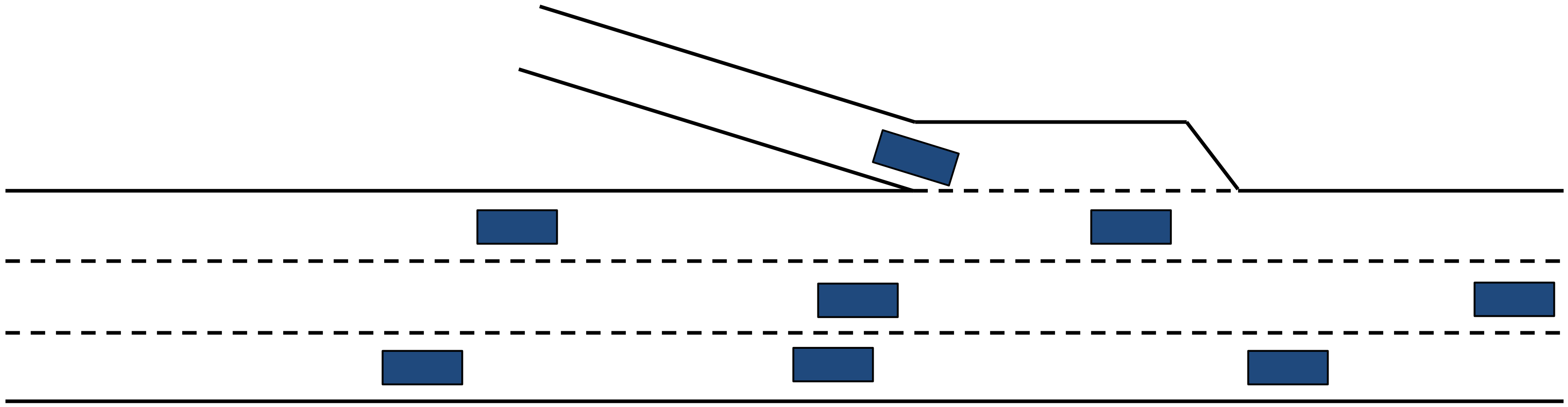

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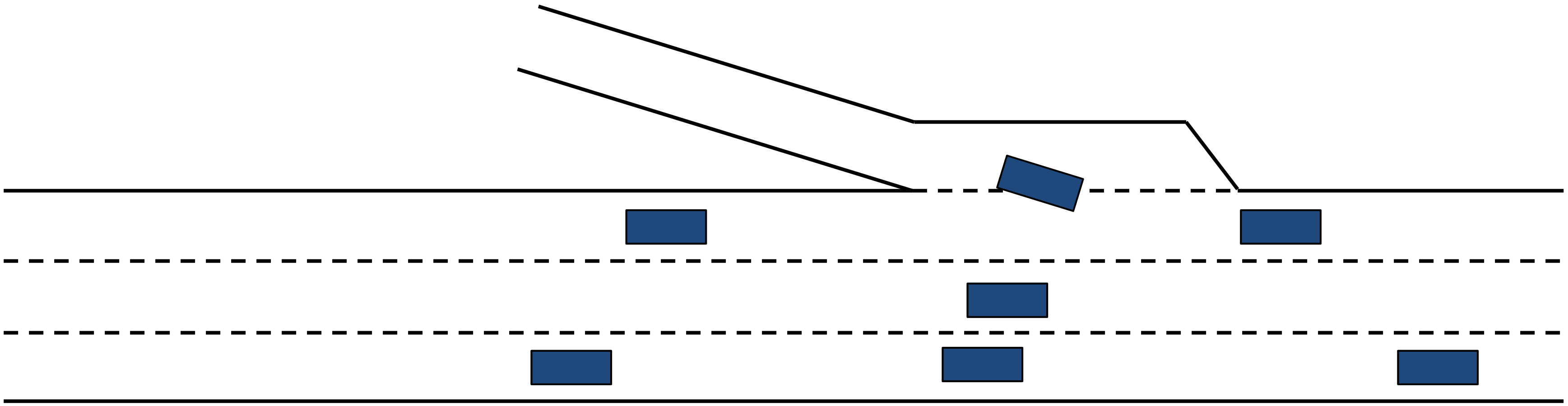


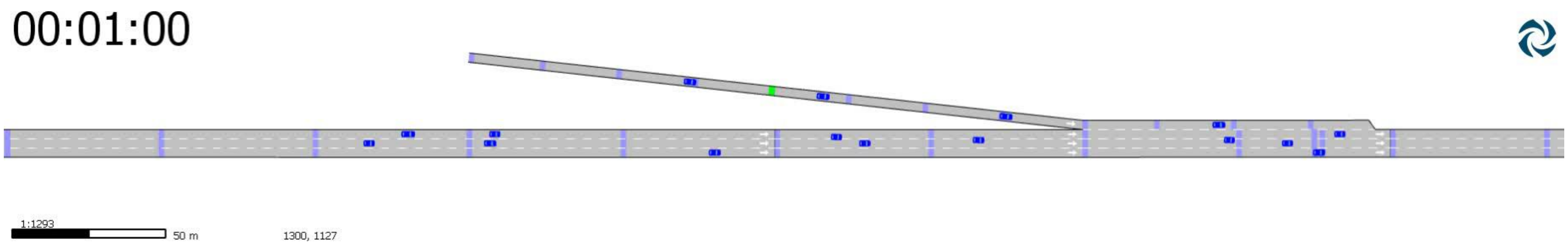
Reactive control

Algorithm 1 Reactive Control pseudo-code

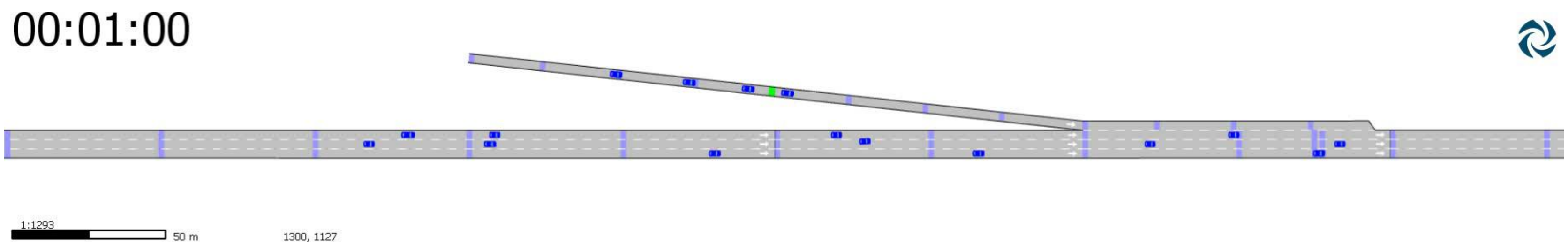
```
for Ramp vehicles do
  Determine time to merge (T_r = d_r/v_r)
  for AVs in left lane of Highway do
    Project future position, (d_m = v_m T_r)
    if Conflicting with merging (d_r − x ≤ d_m ≤ d_r + x) then
      Mark as conflicting AV
    end if
  end for
end for

for Each lane except right-most do
  if Vehicle is a conflicting AV then
    if (Lead gap > Minimum acceptable safe gap) & (Lag gap > Minimum acceptable
    safe gap) then
      Advise lane change
    else
      If adjacent vehicle on the target right lane preventing lane change is an AV, mark
      as conflicting AV
    end if
  end if
end for
```

Simulation

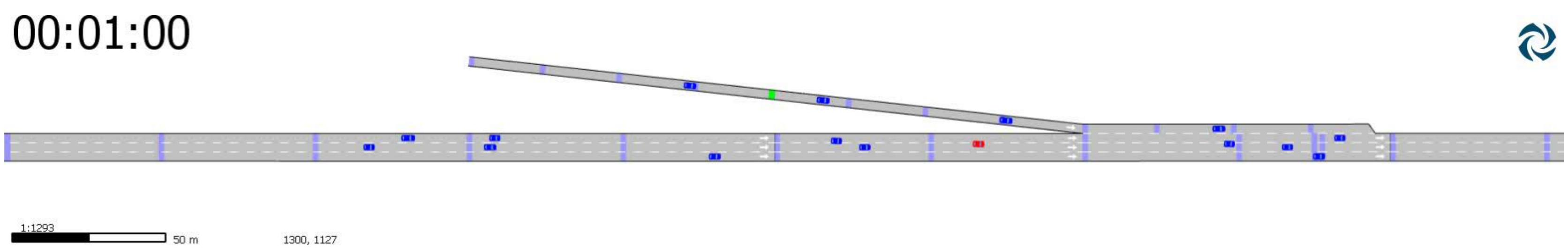
No Control



ALINEA



Lane Change Control

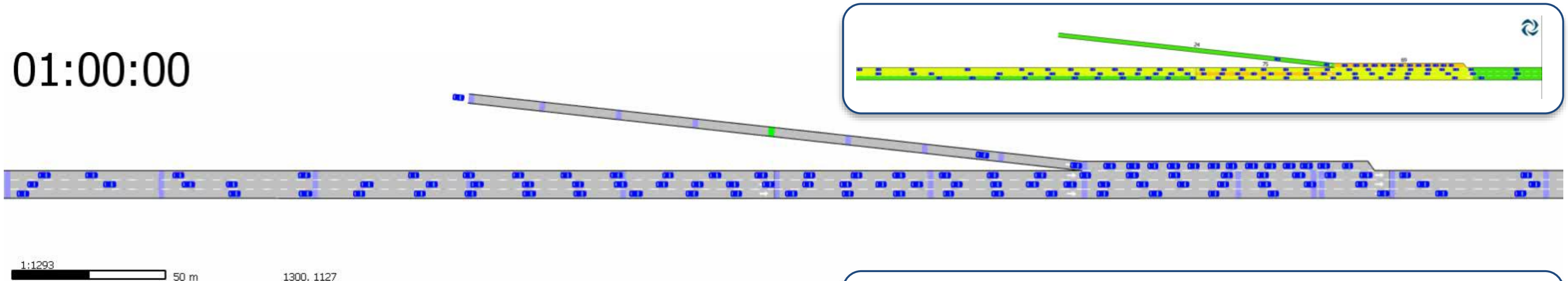


Ramp flow: 500 veh/h

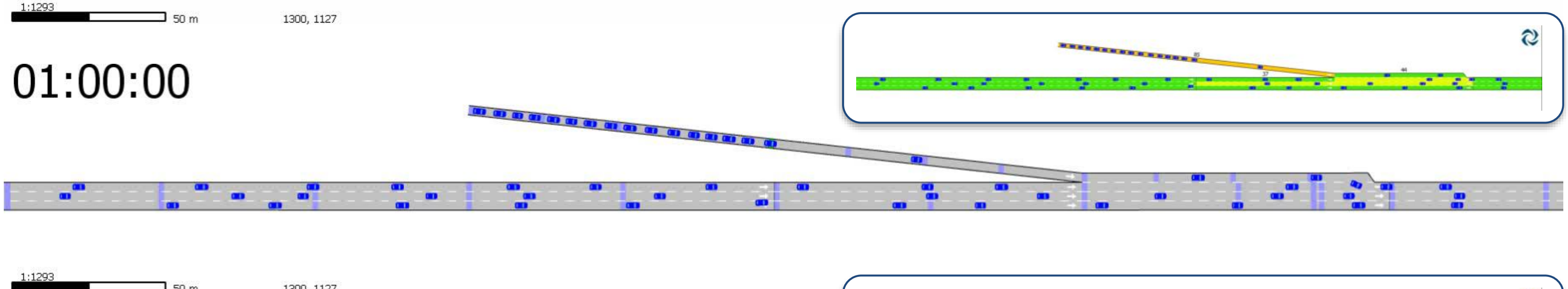
Mainline flow: 3000 veh/h

Simulation

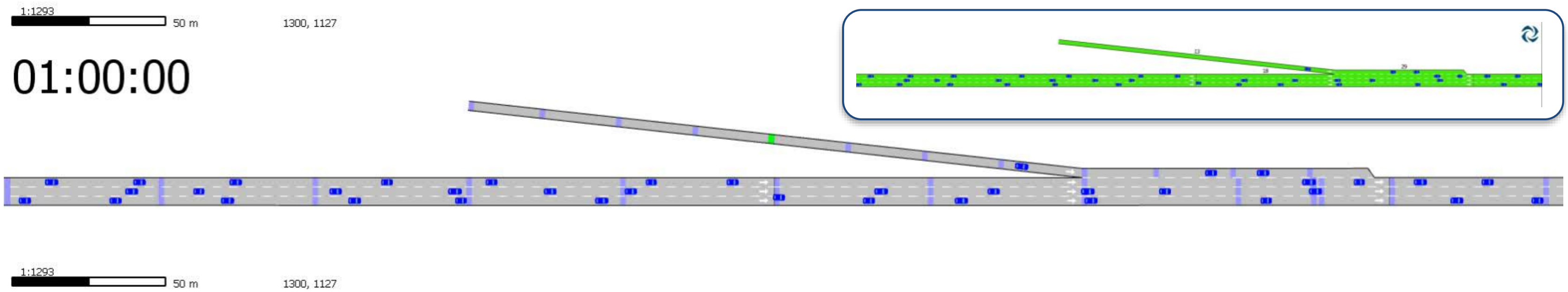
No Control



ALINEA

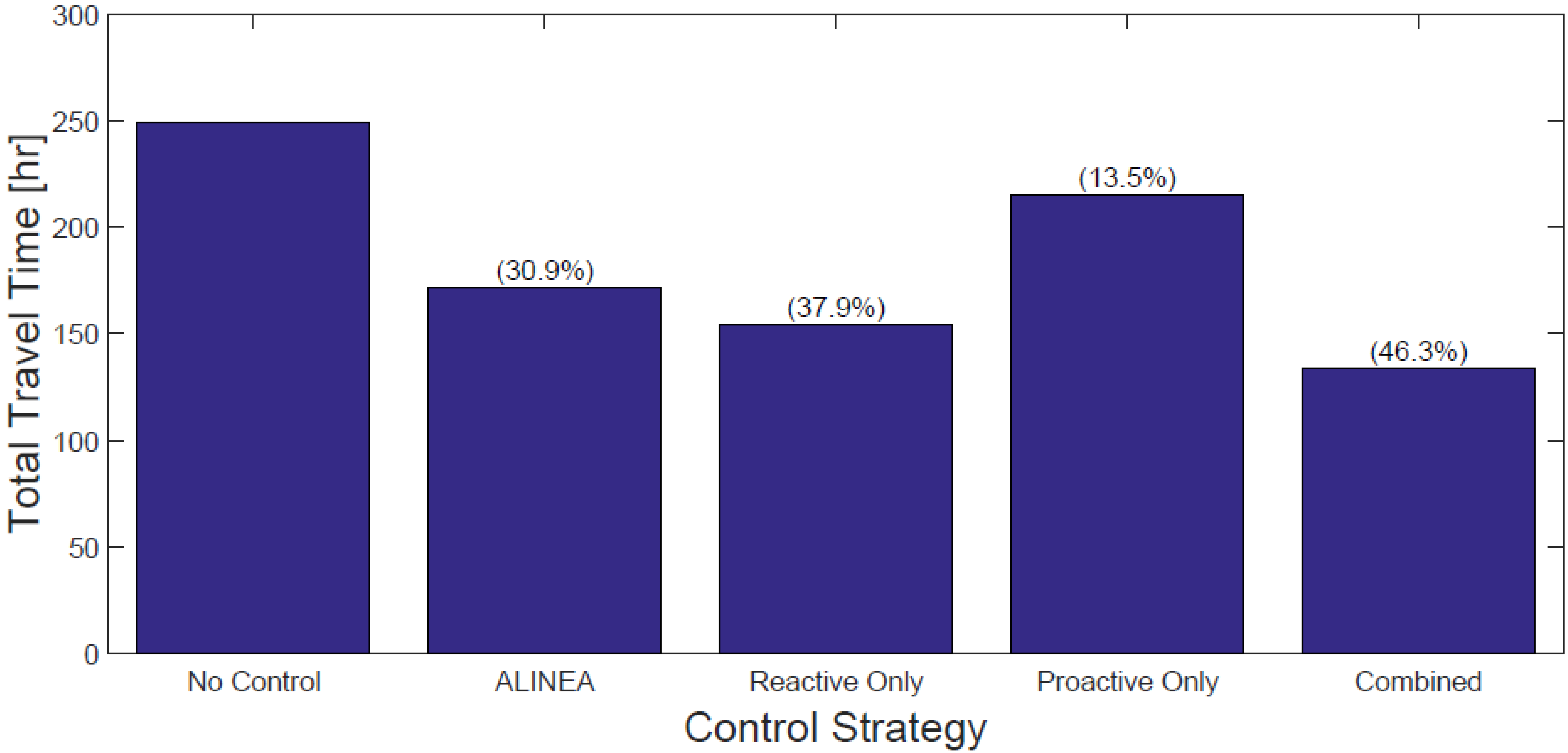


Lane Change Control

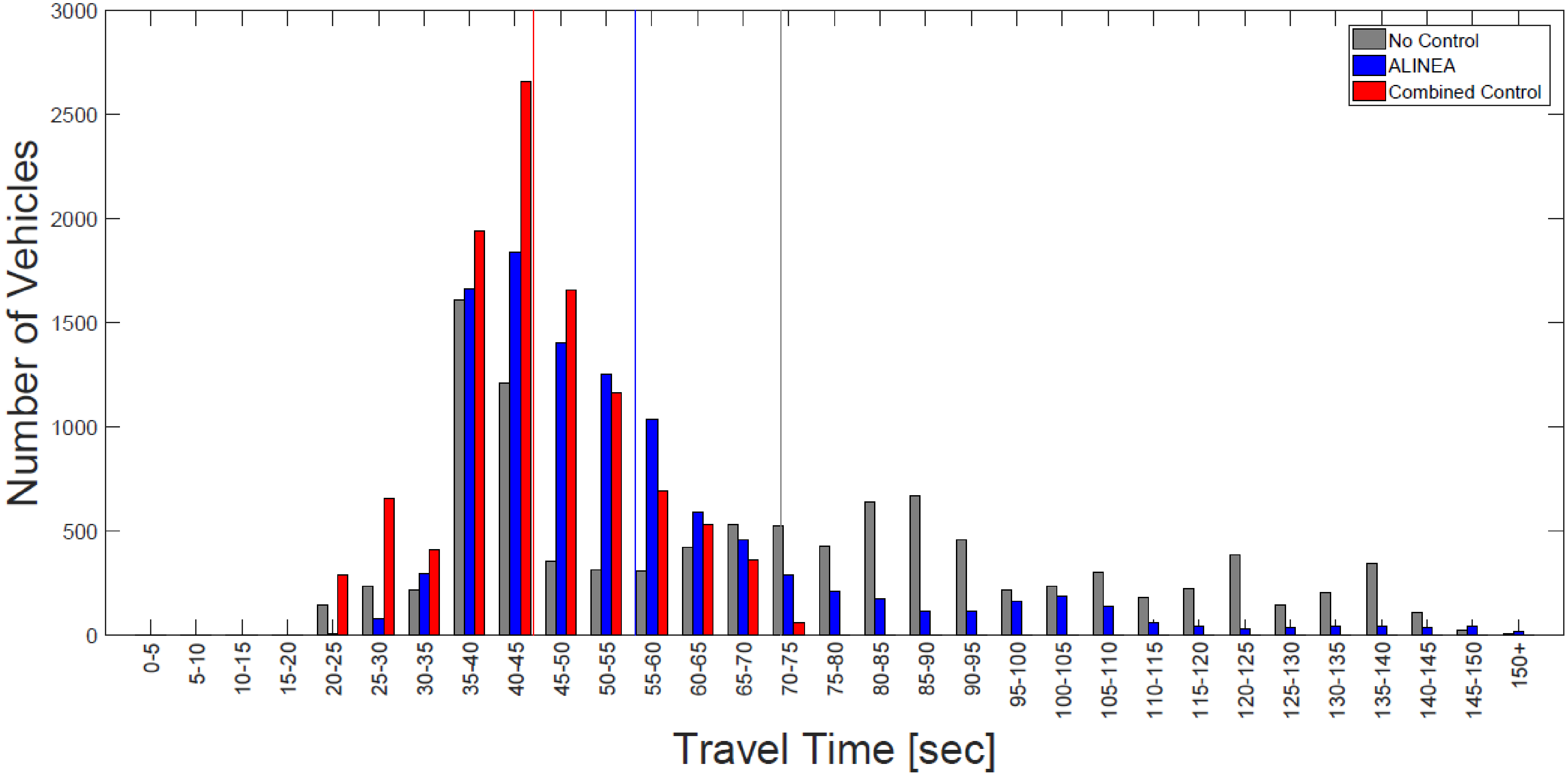


Ramp flow: 1000 veh/h **Mainline flow**: 6000 veh/h

Results – Total Travel Time

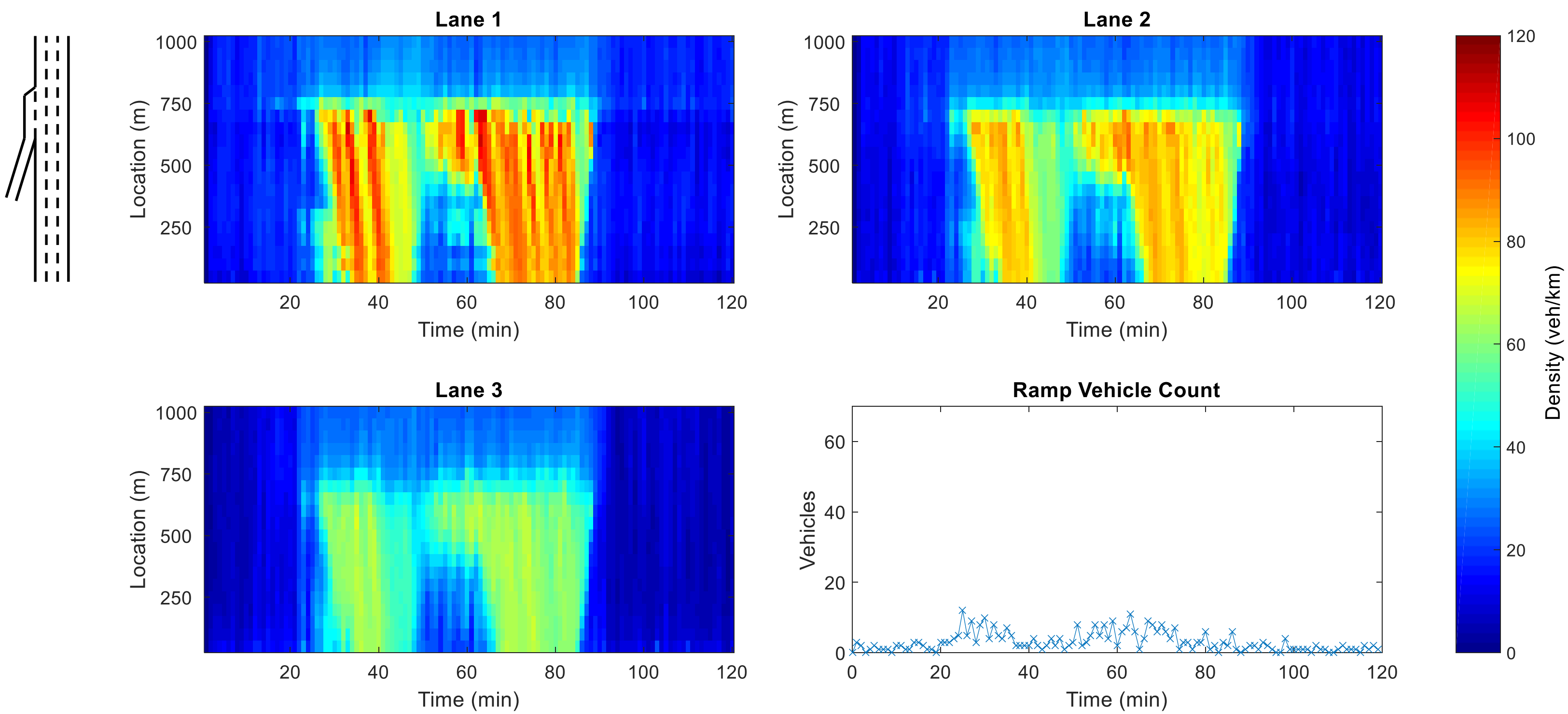


Results – Travel Time Distribution



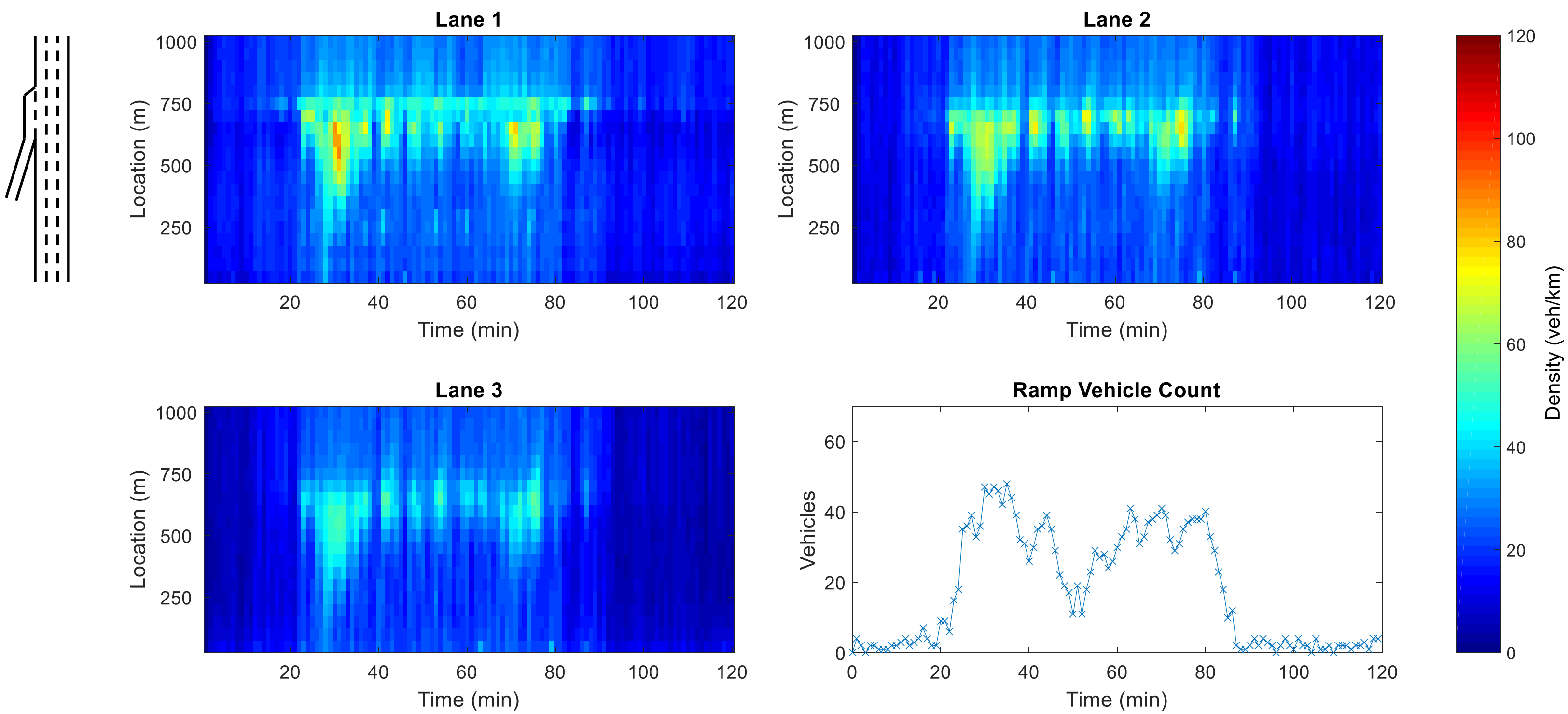
Results

No Control



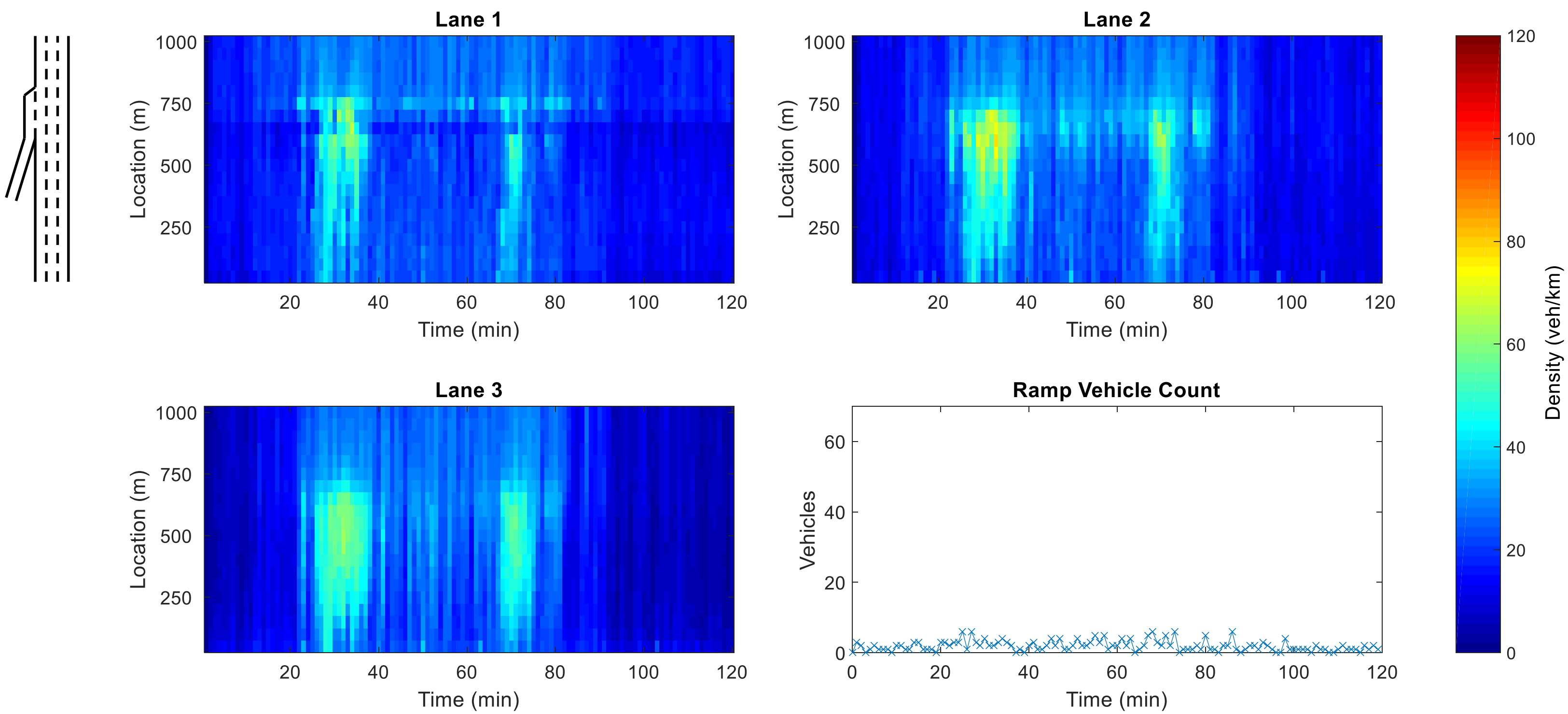
Results

ALINEA

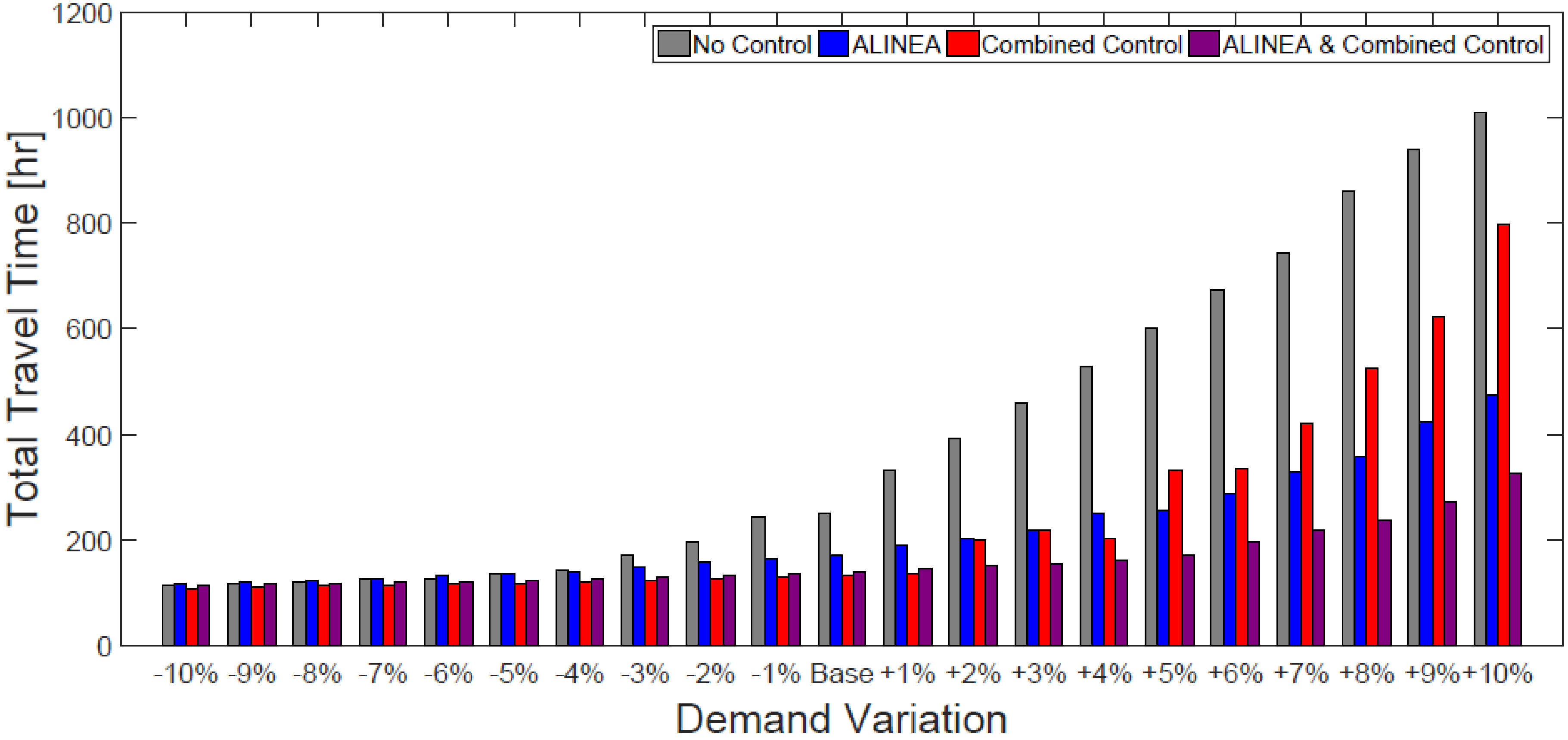


Results

Lane Change Control

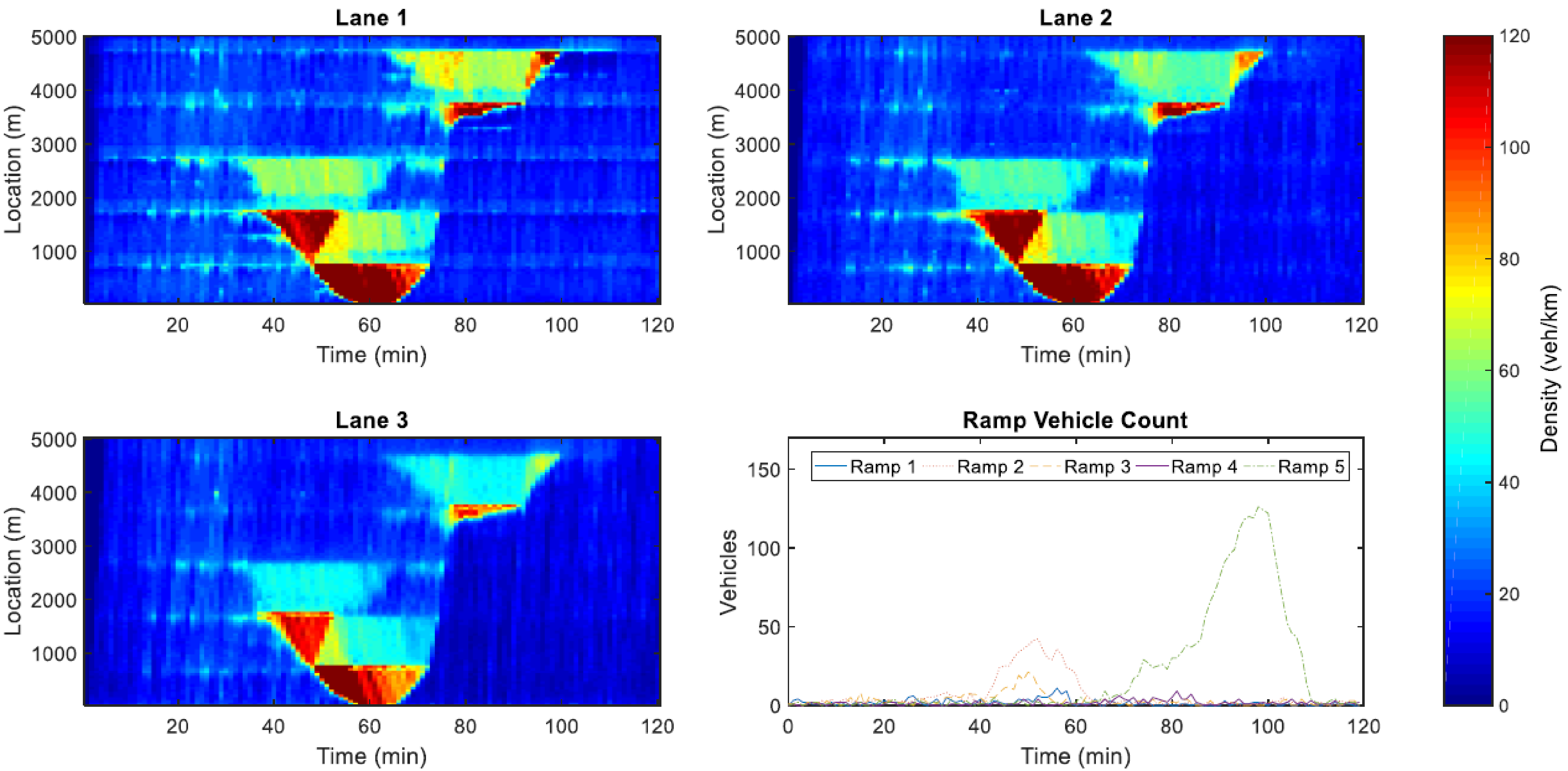


Results – Demand Variation



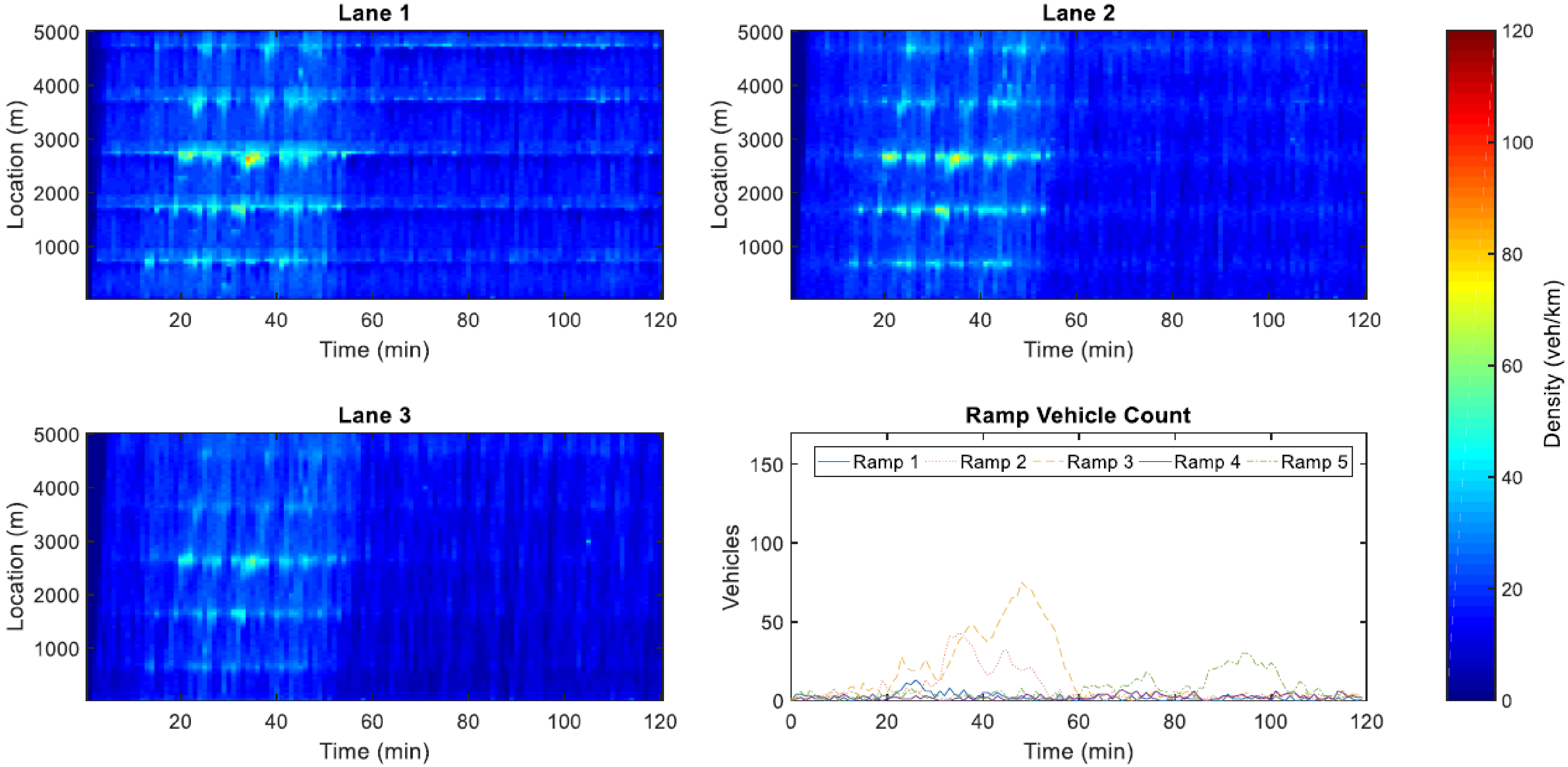
Results – Multiple Ramps

No Control



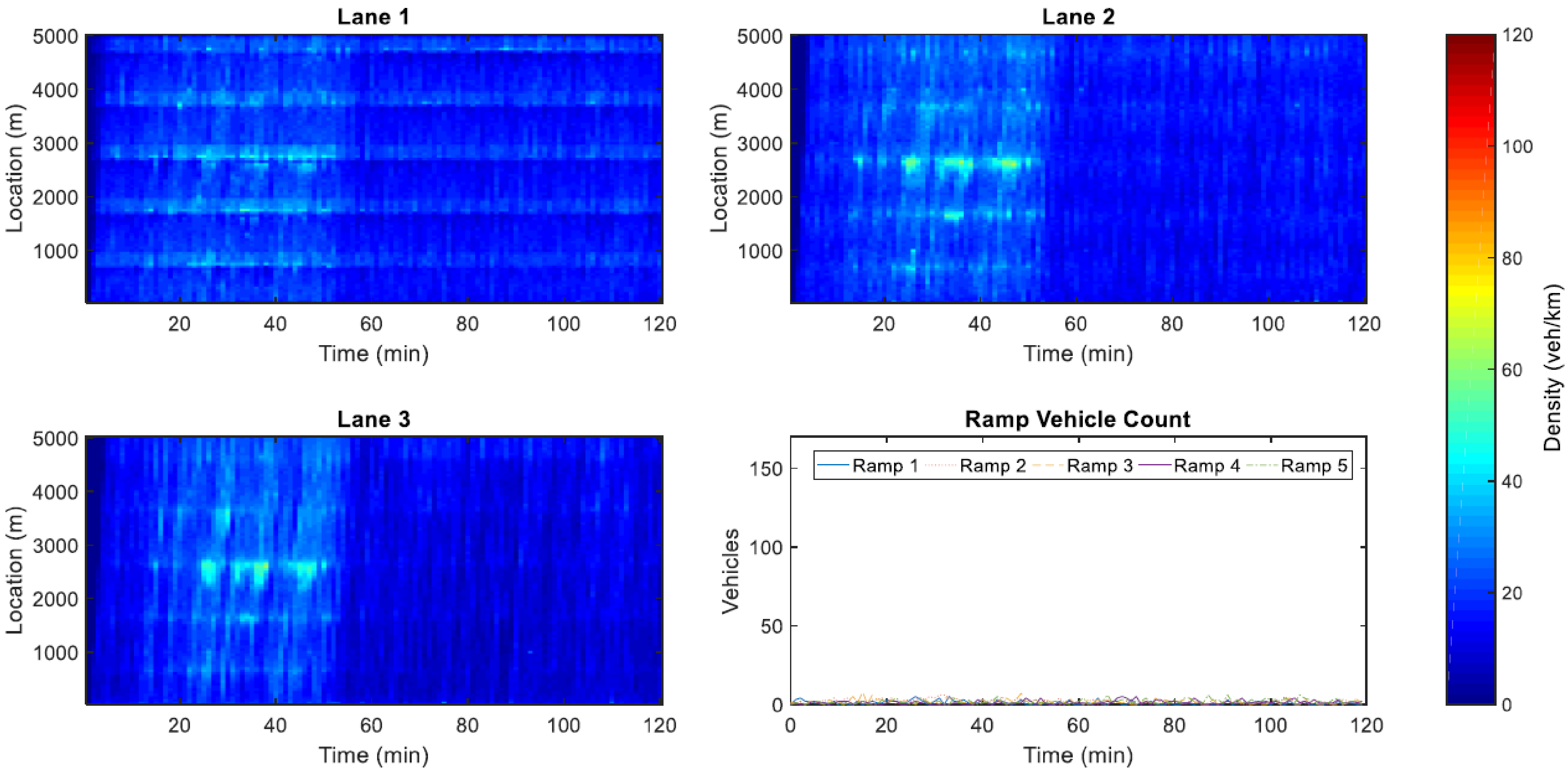
Results – Multiple Ramps

ALINEA

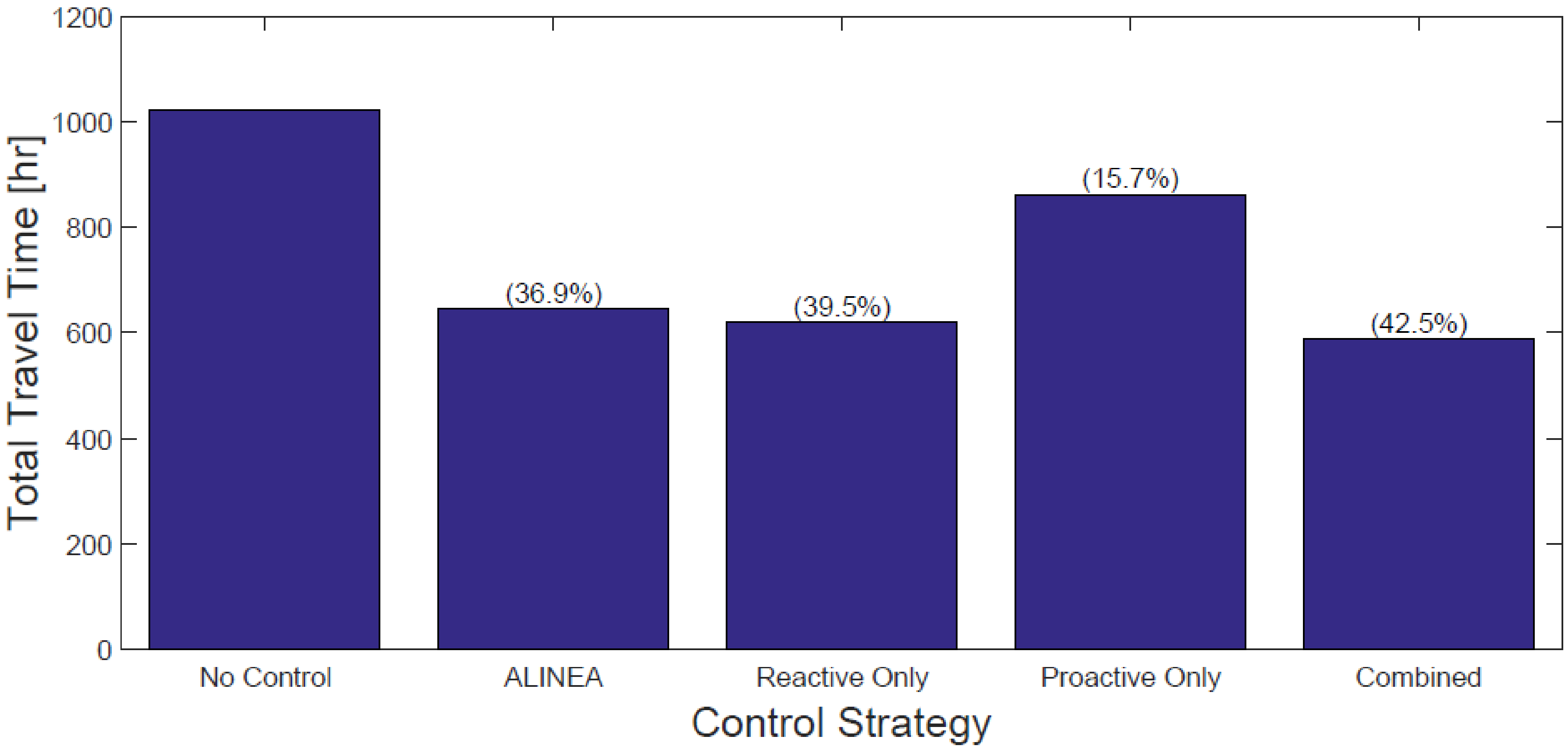


Results – Multiple Ramps

Lane Change Control



Results – Multiple Ramps



Discussion

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Results – AV Penetration Rate