Traffic flow optimization at sags by controlling the acceleration of some vehicles

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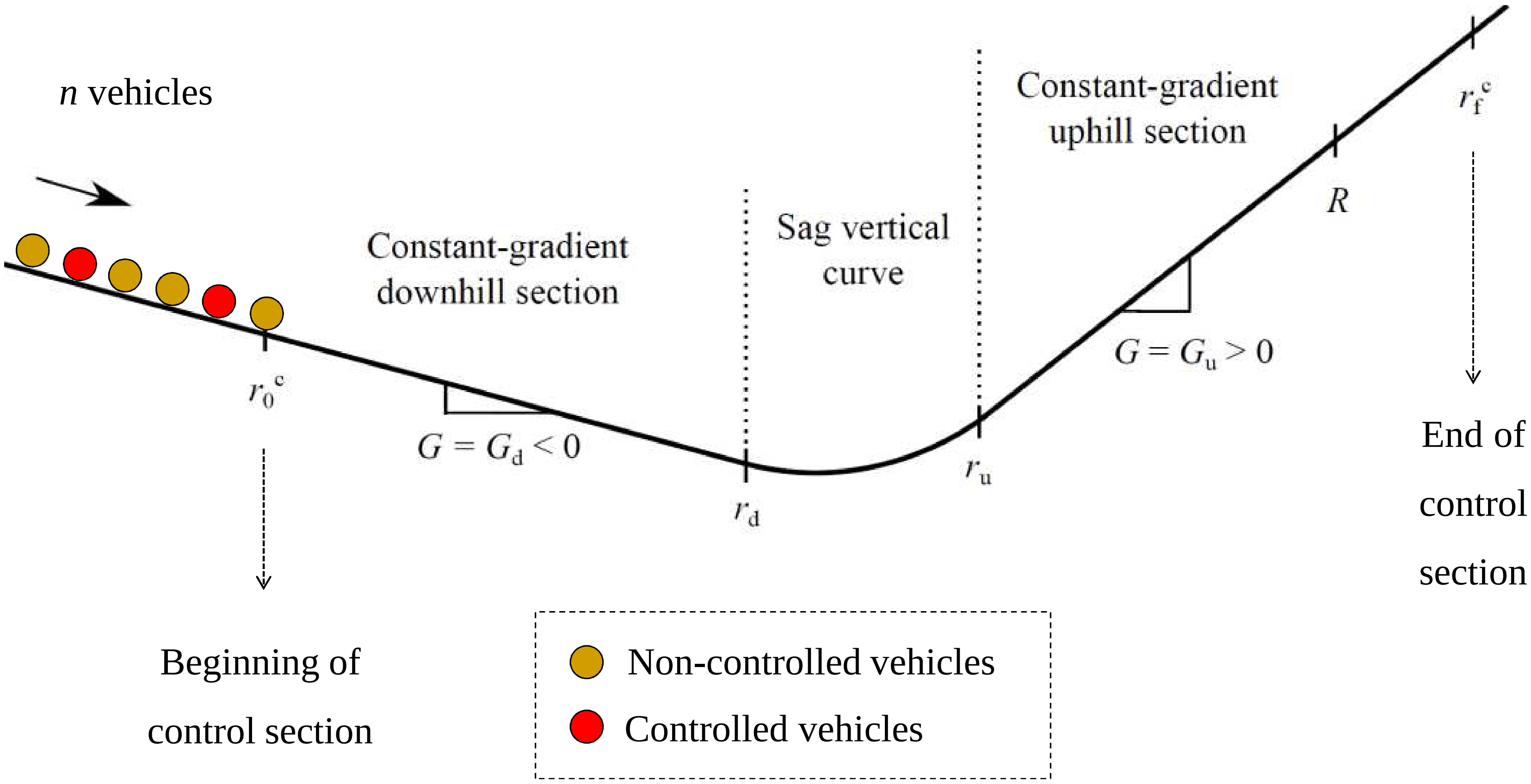
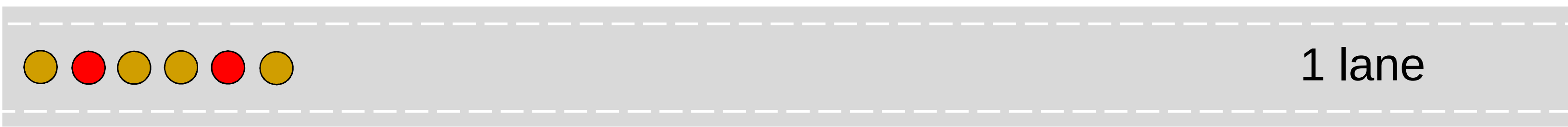
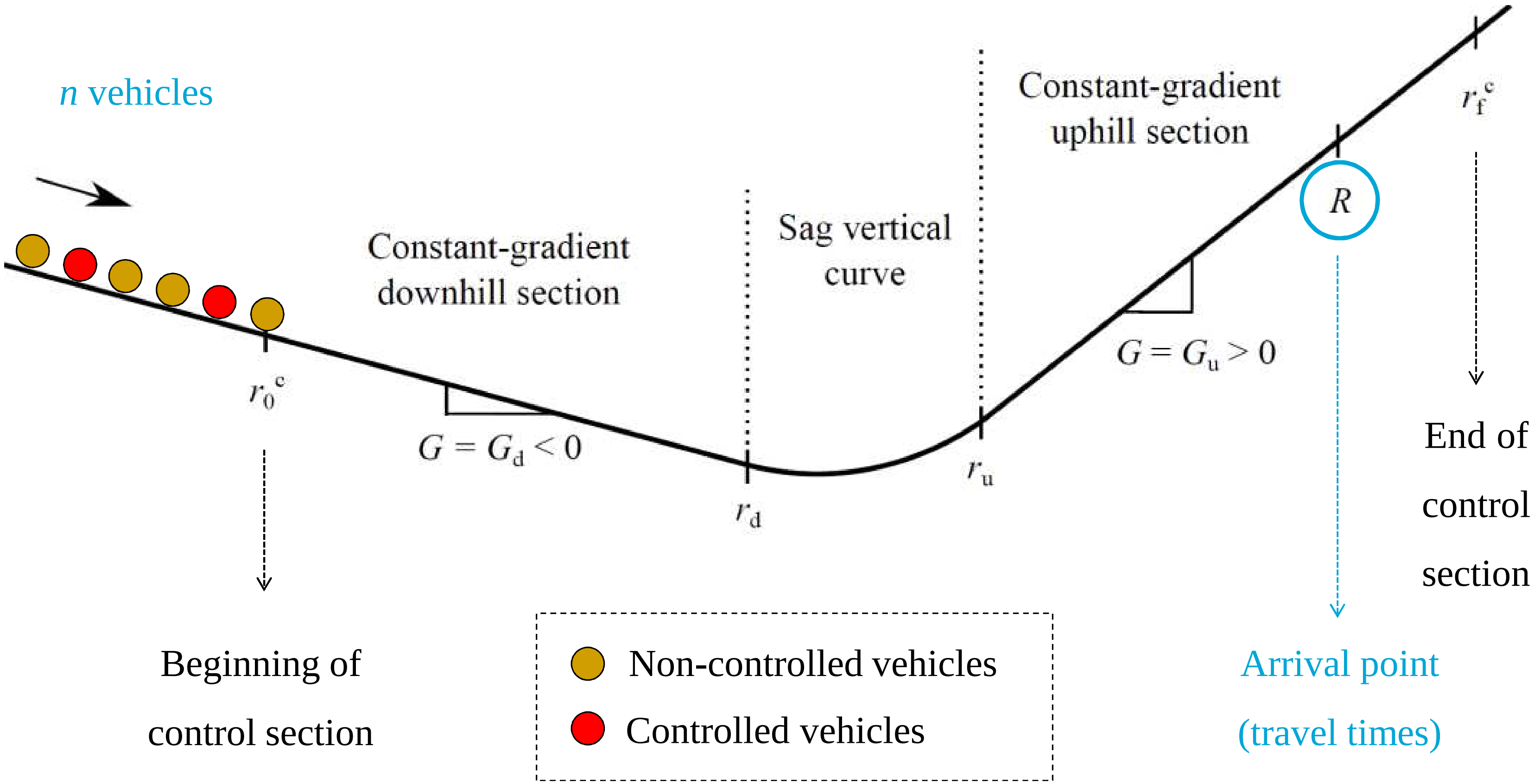
Characteristics of the freeway section and the traffic stream

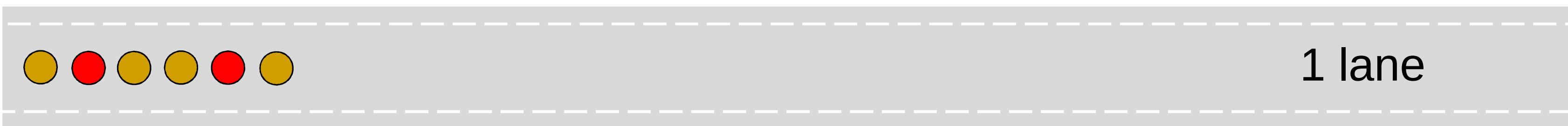




Optimization objective

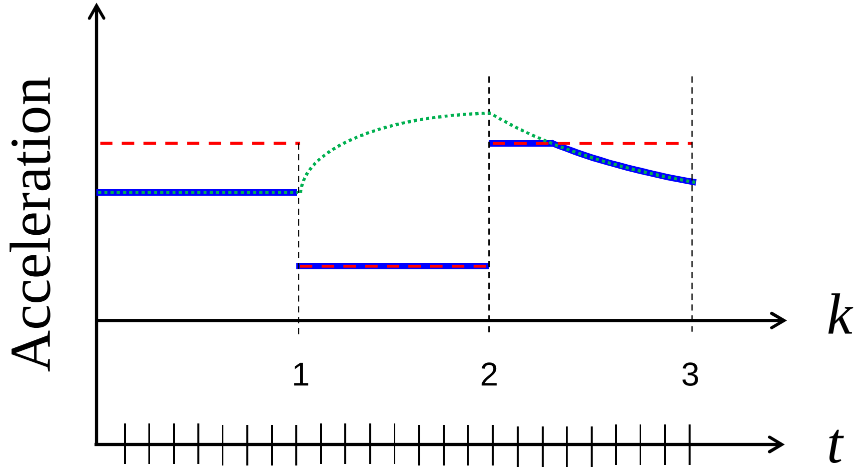
Minimize Total Travel Time of all vehicles (TTT)





Traffic state dynamics

- Vehicle positions ⇨ $r(t+1) = r(t) + v(t)\cdot T_s + \frac{a(t)}{2}\cdot T_s^2$
- Vehicle speeds ⇨ $v(t+1) = v(t) + a(t)\cdot T_s$
- Vehicle accelerations:
  - Non-controlled vehicles ⇨ CF model $\boxed{a(t) = a_{\mathrm{CF}}(t)}$
  - Controlled vehicles (inside cont. section) ⇨ $\boxed{a(t) = \min\,(\text{control input }(k), a_{\mathrm{CF}}(t))}$



t: simulation step index T_s: simulation step length k: control time step index

Optimal control problem

Find $\mathbf{u}^*(0), \mathbf{u}^*(1), \ldots, \mathbf{u}^*(\frac{T}{T_c})$ → Max. acceleration (of all controlled vehicles at all control time steps)

that minimize $J(\mathbf{x}(0), \mathbf{x}(1), \ldots, \mathbf{x}(\frac{T}{T_s}), \mathbf{u}(0), \mathbf{u}(1), \ldots, \mathbf{u}(\frac{T}{T_c}))$ → Total travel time

subject to:

$$\mathbf{x}(0) = \mathbf{x}_0$$ → Initial traffic state

$$\mathbf{u}(\kappa) \in \mathcal{U}, \text{ for } \kappa = 0, 1, 2, \ldots, \frac{T}{T_c}$$ → Admissible control region

$$\mathbf{x}(\tau + 1) = \mathbf{f}(\mathbf{x}(\tau), \mathbf{u}(\kappa)), \text{ for } \tau = 0, 1, 2, \ldots, \frac{T}{T_s}$$ → Traffic state dynamics

where κ is such that $\tau \cdot T_s \in [\kappa \cdot T_c, (\kappa + 1) \cdot T_c)$

- Characteristics:
  - Non-linear
  - Non-convex
- Solution method:
  - Sequential quadratic programming

Optimization experiments

Objectives:

To determine:

1. Optimal acceleration behavior of the controlled vehicles
2. Main effects on traffic flow
3. Reasons why total travel time decreases

In scenarios with:

- Nearly-saturated traffic conditions
- Low penetration rates (≤ 1%)

Experimental setup

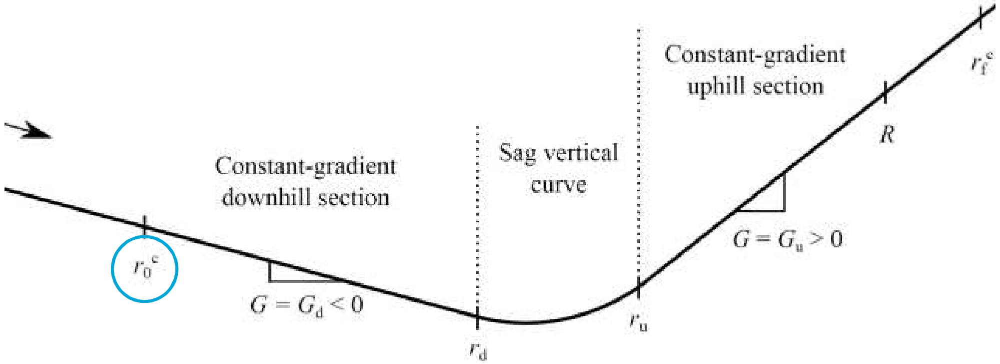
- Total number of vehicles: 300 → Same CF parameter values
- Controlled vehicles
  - Number: 0, 1, 2 or 3
  - Positions: 75, 150 and/or 225

Definition of scenarios

- Network parameters

Parameter	Value
G_d (%)	−0.5
G_u (%)	+2.5
r_d (m)	1000
r_u (m)	1600
R (m)	5000
r_0^c (m)	−2000
r_f^c (m)	7000

- Initial traffic state
  - Speed: Desired speed (120 km/h)
  - Position vehicle 1: r_0^c
  - Headway: Desired headway
- Simulation period = 800 s
- Time step length
  - Simulation step: 0.5 s
  - Control step: 8 s
- Admissible control set: [-0.5, 1.4] m/s^2



Results

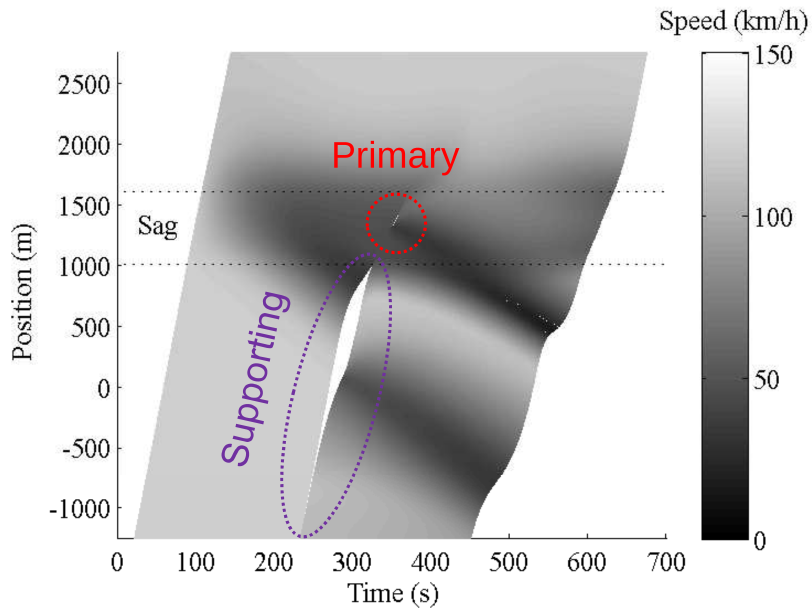
The optimal acceleration behavior of controlled vehicles is defined by two main strategies:

1. Primary strategy:
   DADA maneuver in the sag area

- Applied in all cases
- Maneuver with well defined general characteristics

2. Supporting strategy:
   DA maneuvers upstream of the sag

- Applied in some cases
- Maneuvers with case-specific characteristics



$M = \{150\}$

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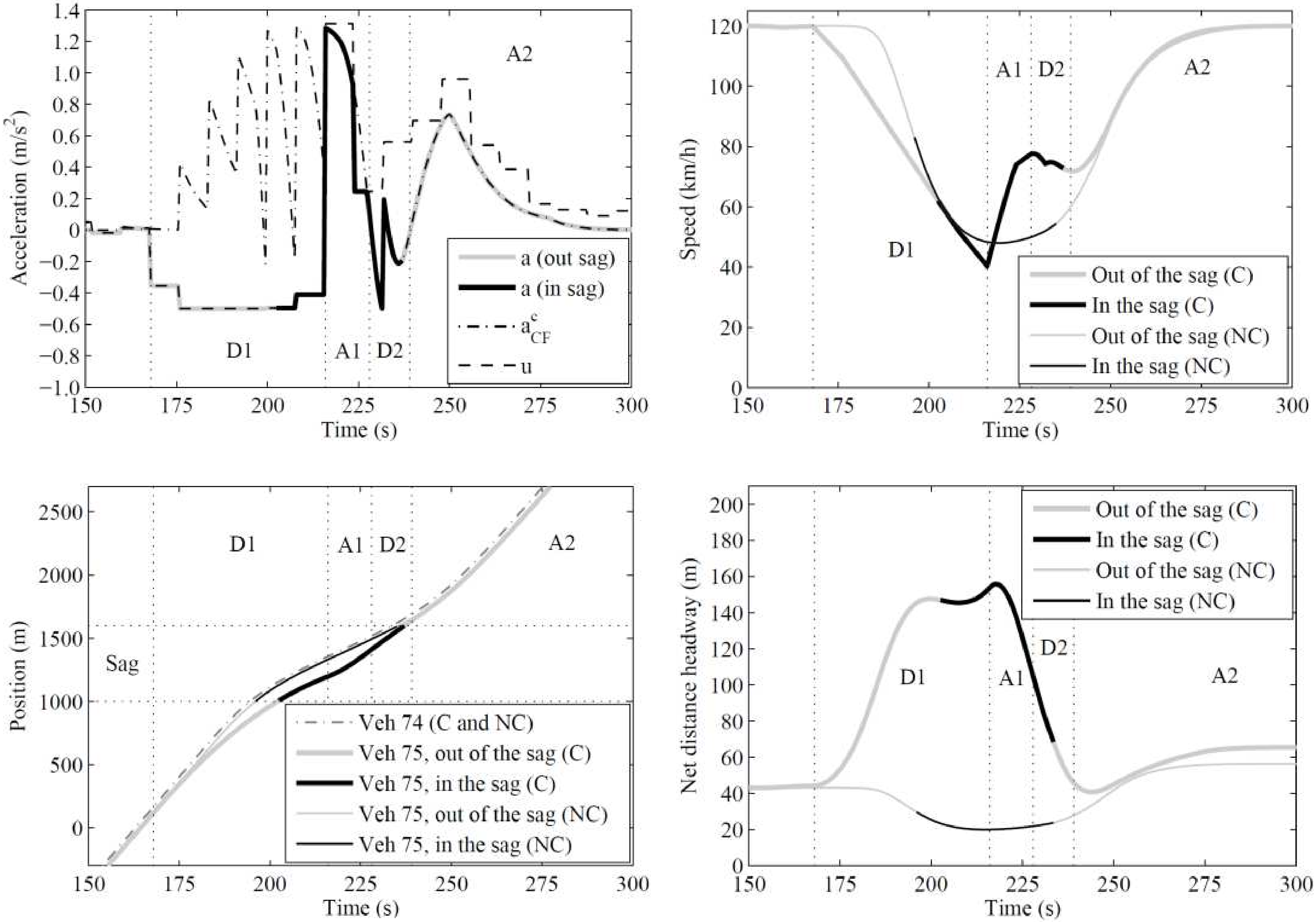
Primary strategy

- DADA maneuver in the sag area $M = \{75\}$



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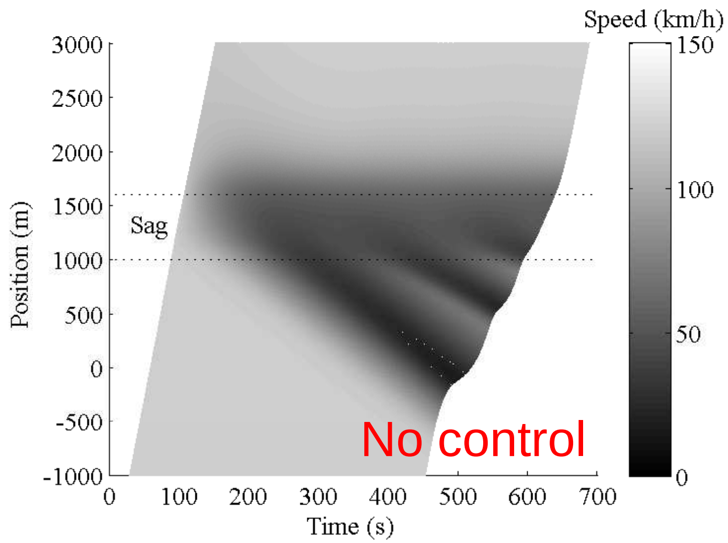
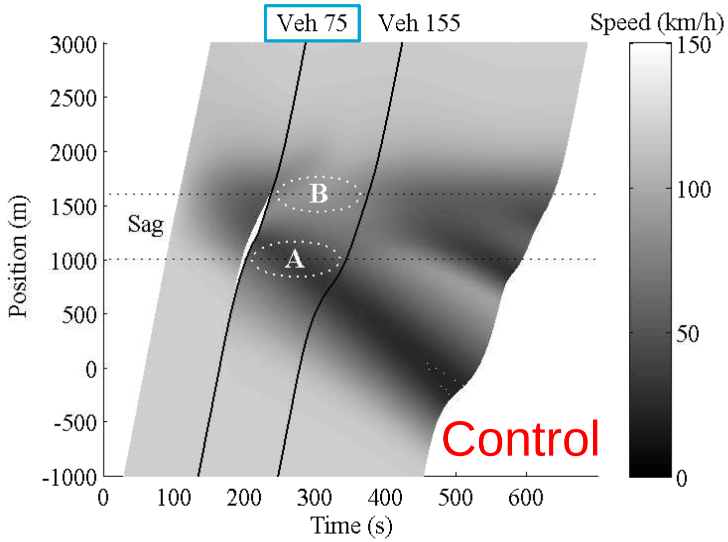
Primary strategy

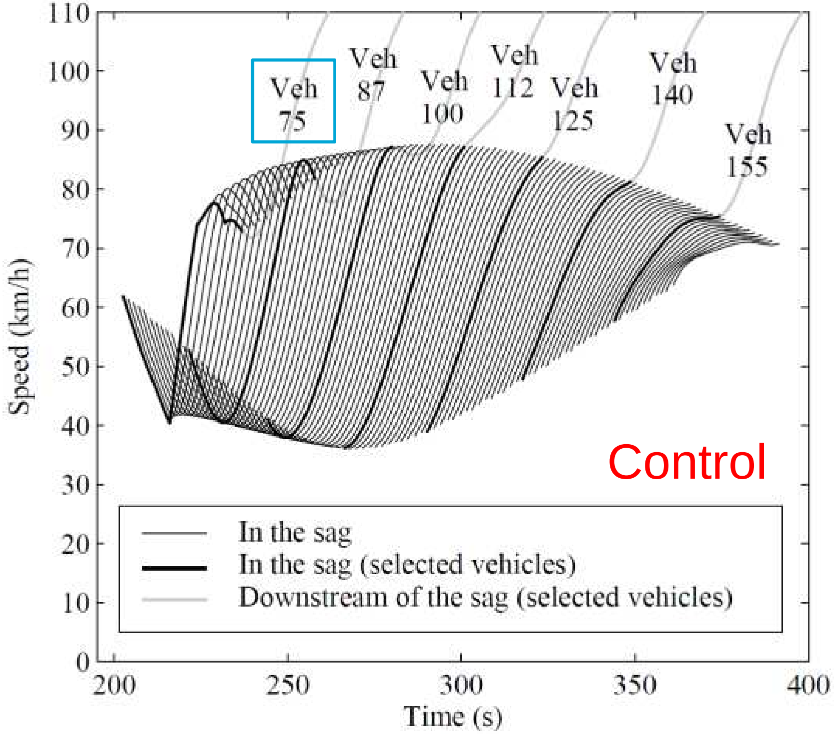
ΔAVD = -2.9 s

M = {75}

- Effects on traffic flow

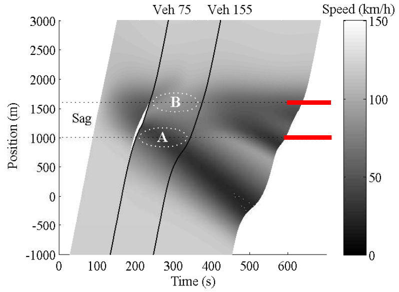






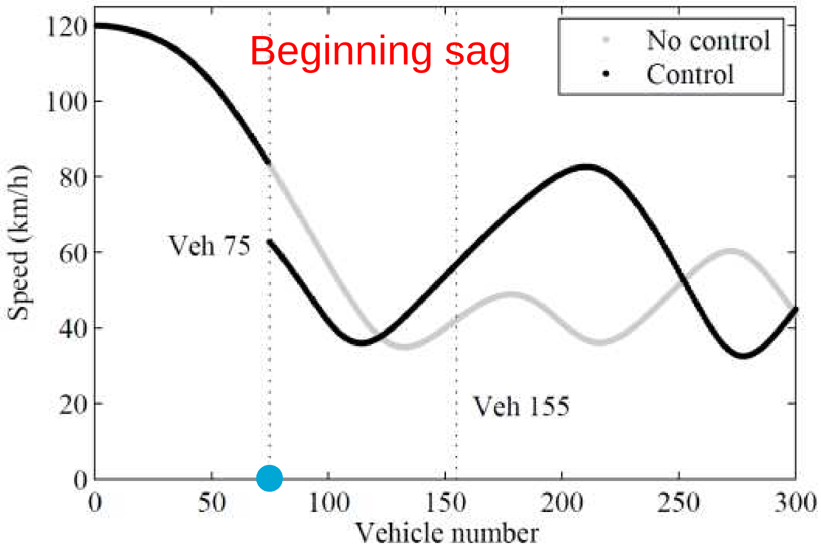
Primary strategy

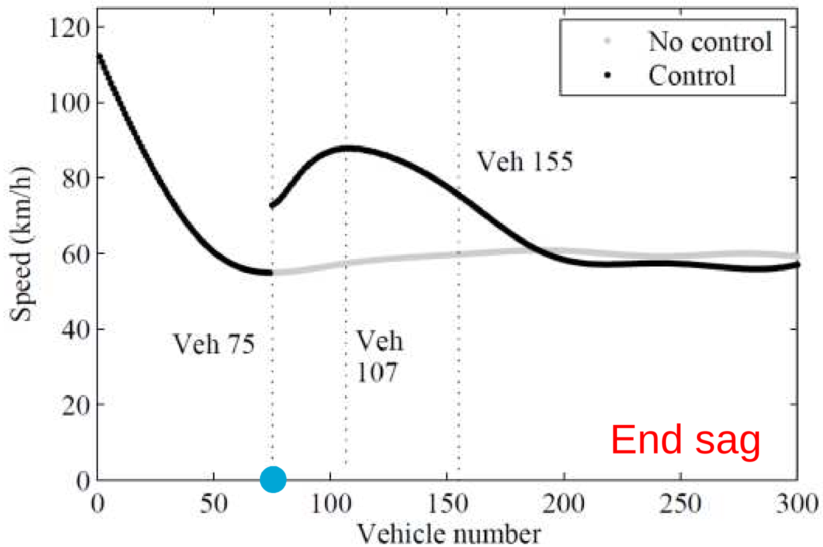
- Effects on traffic flow

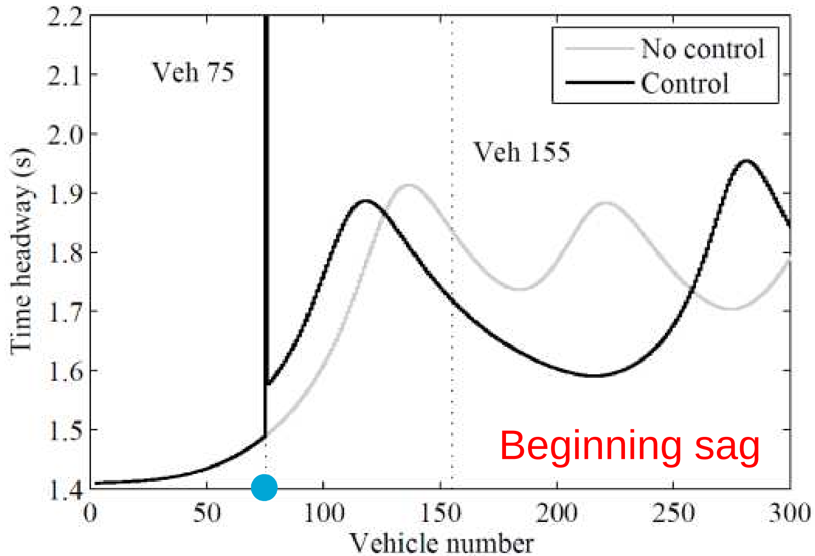


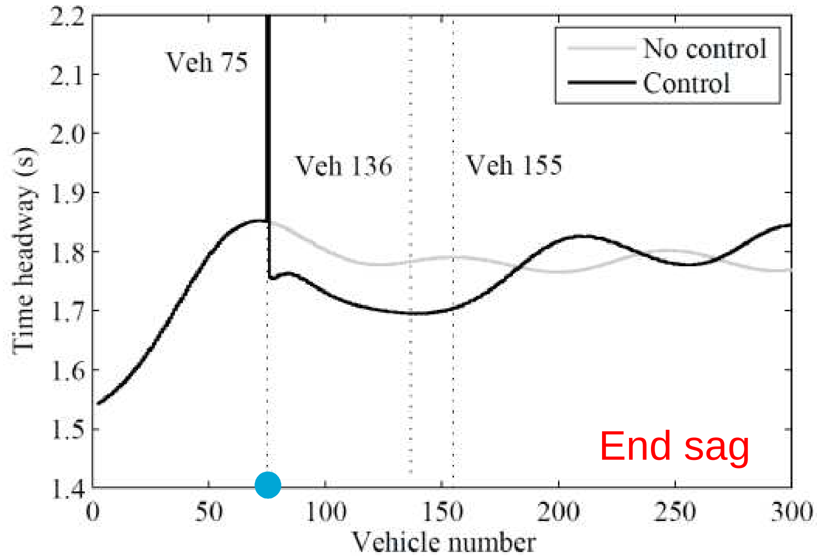
ΔAVD = -2.9 s

M = {75}





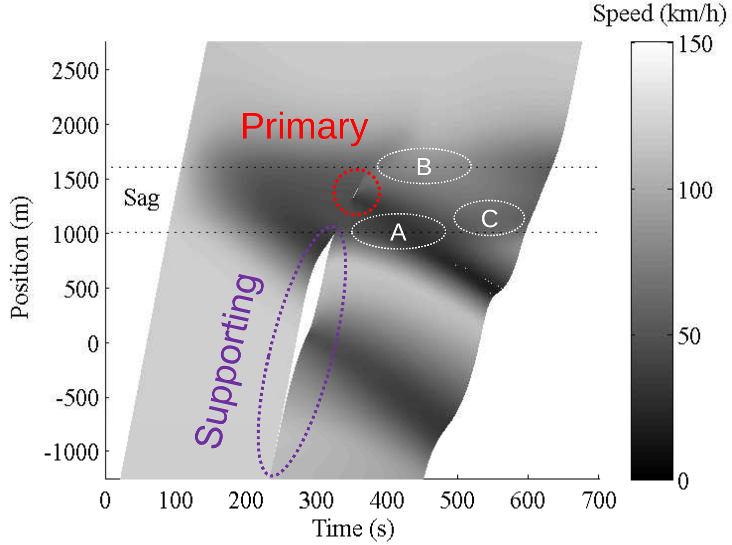




Supporting strategy

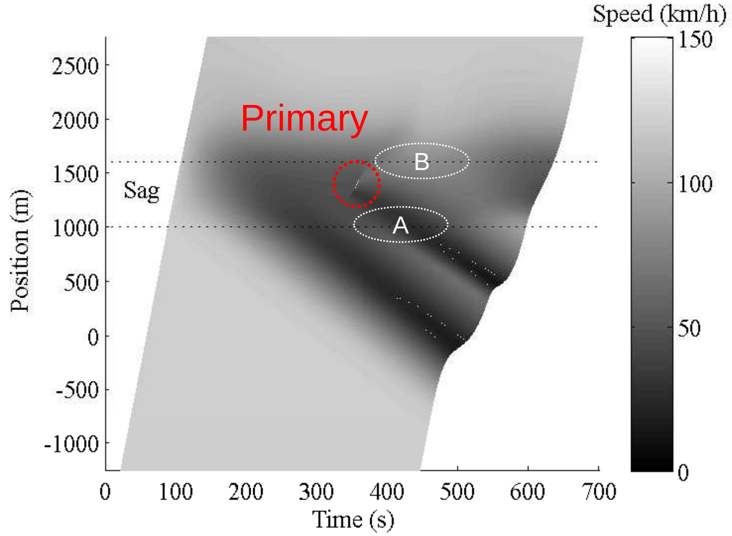
- Effects on traffic flow

M = {150}



Primary strategy + **Supporting** strategy

ΔAVD = -2.4 s

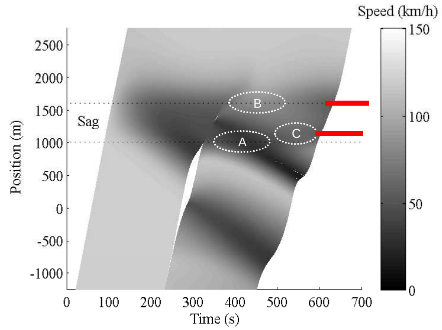


Primary strategy (supporting strategy excluded)

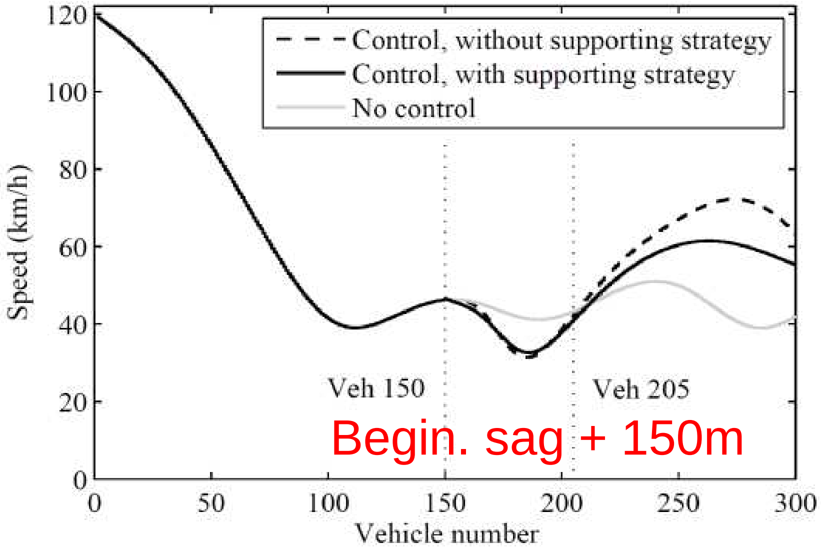
ΔAVD = -2.1 s

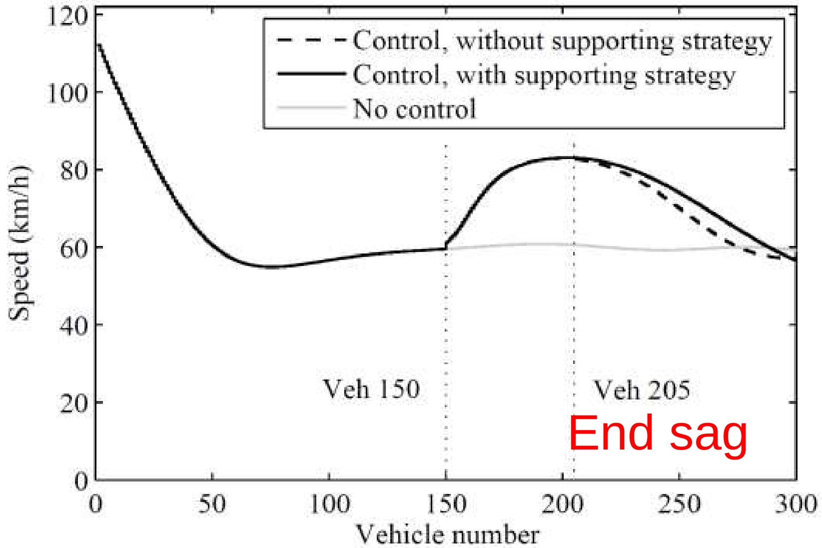
Supporting strategy

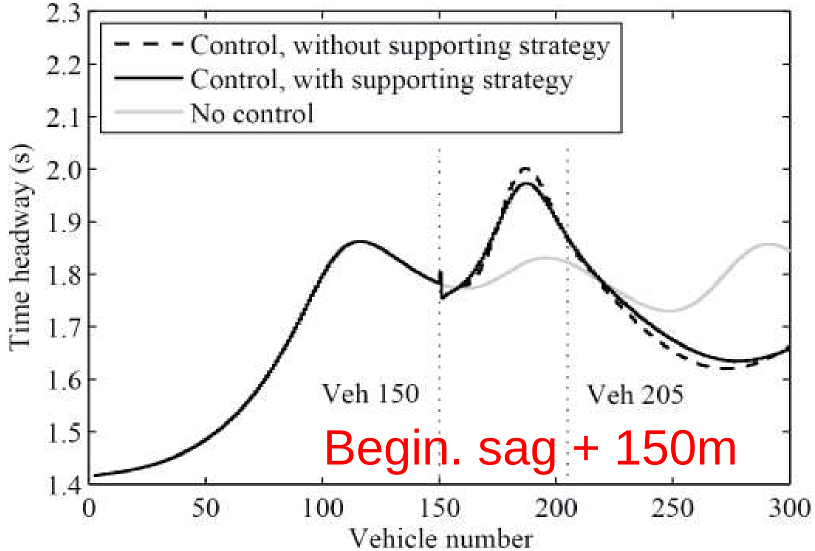
- Effects on traffic flow

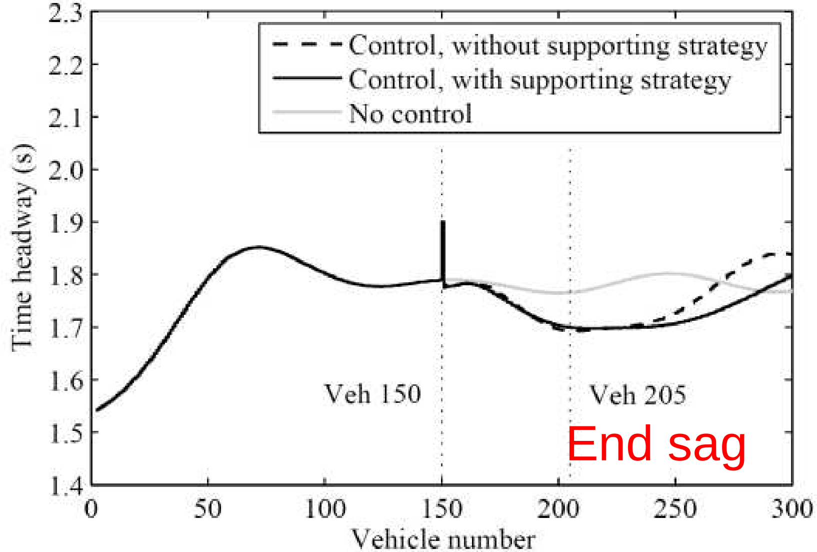


$M = \{150\}$



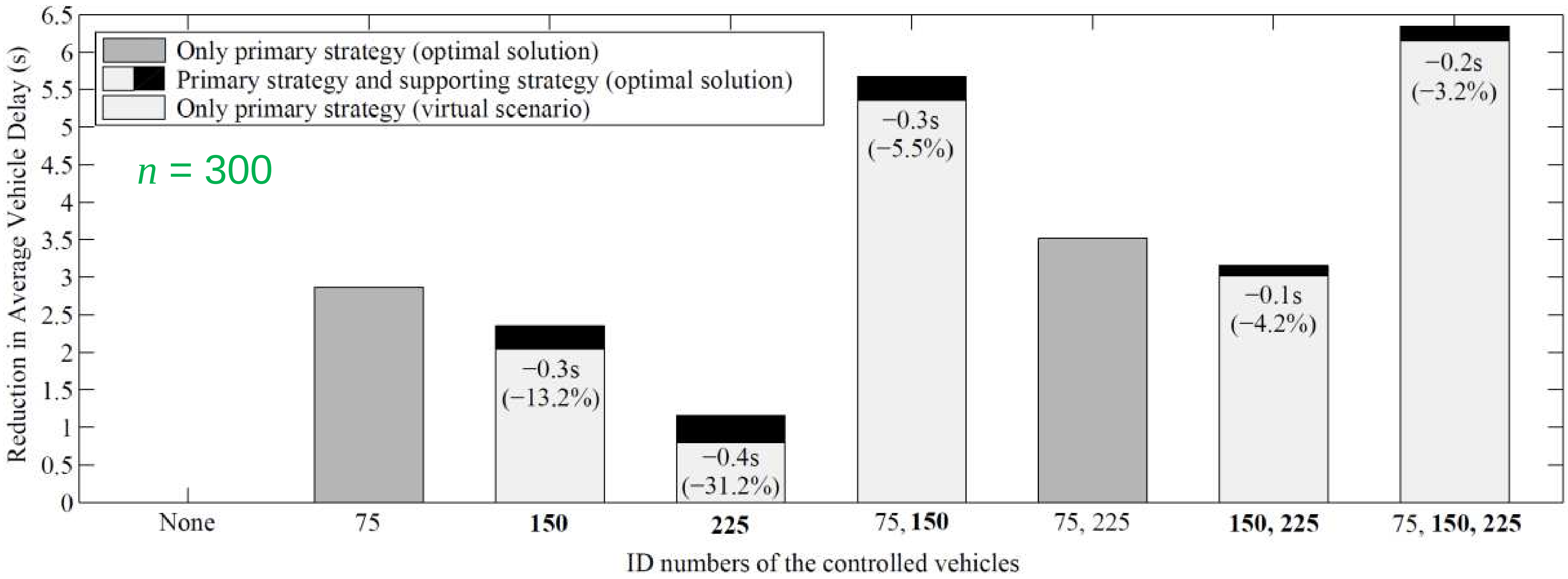






Results

- Reduction in AVD in comparison with no control: 1.2 - 6.3 s
- The primary strategy is the one that contributes the most to reduce AVD
- More controlled vehicles and closer to 1st vehicle → Greater reduction in AVD [assuming low penetration rates]



Conclusions

- Our optimization method is effective (and transferable)

- The optimal acceleration behavior of controlled vehicles primarily involves performing a DADA maneuver in the sag
  - Main effects on traffic:
    - Temporary limitation of inflow to the sag
    - Temporary increase in traffic speed and flow at the bottleneck
  - Significant reduction in AVD, at low penetration rates (up to 6s with 1% controlled vehicles)

- Further research:
  - Development of traffic control measures based on this principle
  - Traffic flow optimization in scenarios with:
    - Multi-lane freeway section
    - Higher penetration rates of controlled vehicles

Questions?

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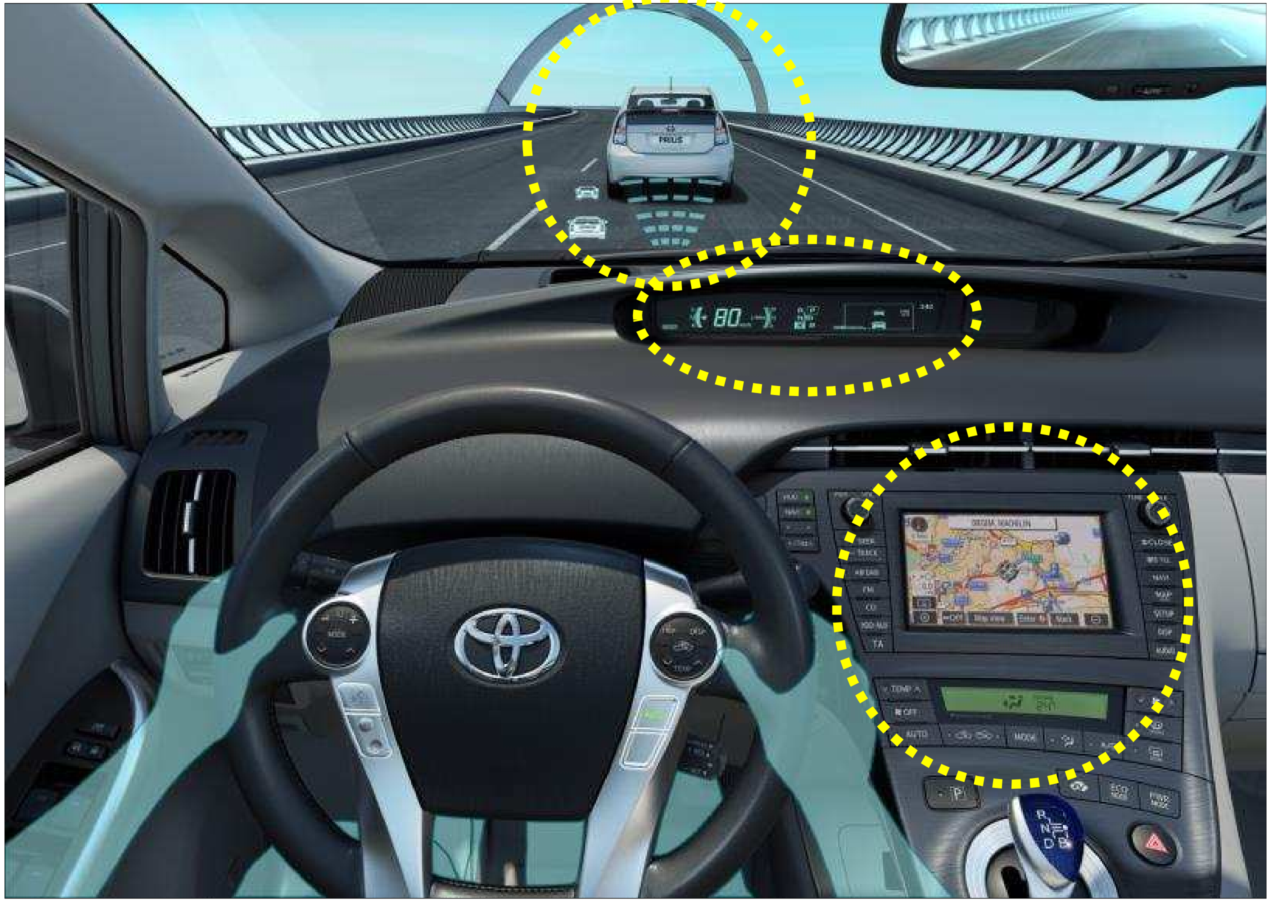
In-car systems

- Cooperative ACC systems
- In-vehicle advisory systems
- Others

Influence on longitudinal vehicle acceleration



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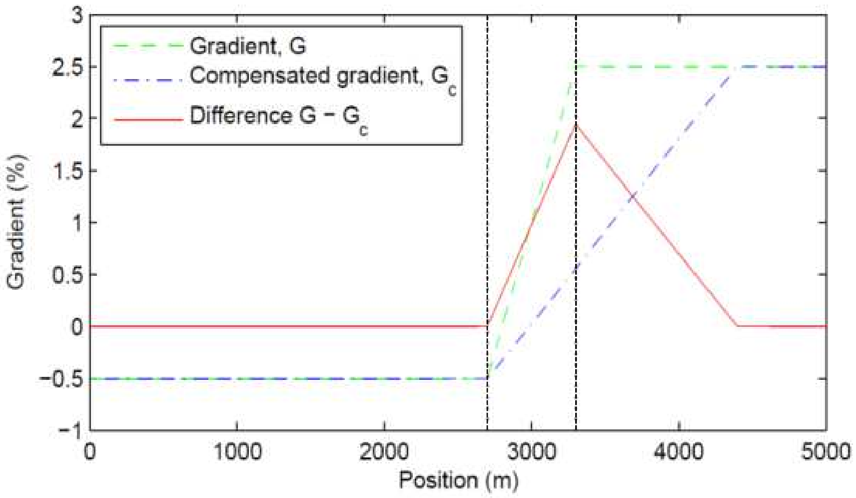
Car-following model

$$a_{\mathrm{CF},i}(\tau) = \alpha_i \cdot \min\left[1 - \left(\frac{v_i(\tau)}{v_{\mathrm{des},i}}\right)^4, 1 - \left(\frac{\boxed{s_{\mathrm{des},i}(v_i(\tau), \Delta v_i(\tau))}}{s_i(\tau)}\right)^2\right] -$$

$$-\theta_i \cdot \left(G(r_i(\tau)) - \boxed{G_{\mathrm{com},i}(\tau)}\right)$$

$$\boxed{s_{\mathrm{des},i}(v_i(\tau), \Delta v_i(\tau))} = s_{\mathrm{s},i} + v_i(\tau) \cdot H_i + \frac{v_i(\tau) \cdot \Delta v_i(\tau)}{2 \cdot \sqrt{\alpha_i \beta_i}}$$

$$\boxed{G_{\mathrm{com},i}(\tau+1)} = \begin{cases} G(r_i(\tau+1)) & \text{if } G(r_i(\tau+1)) \leq G_{\mathrm{com},i}(\tau) + \lambda_i \cdot T_{\mathrm{s}} \\ G_{\mathrm{com},i}(\tau) + \lambda_i \cdot T_{\mathrm{s}} & \text{if } G(r_i(\tau+1)) > G_{\mathrm{com},i}(\tau) + \lambda_i \cdot T_{\mathrm{s}} \end{cases}$$



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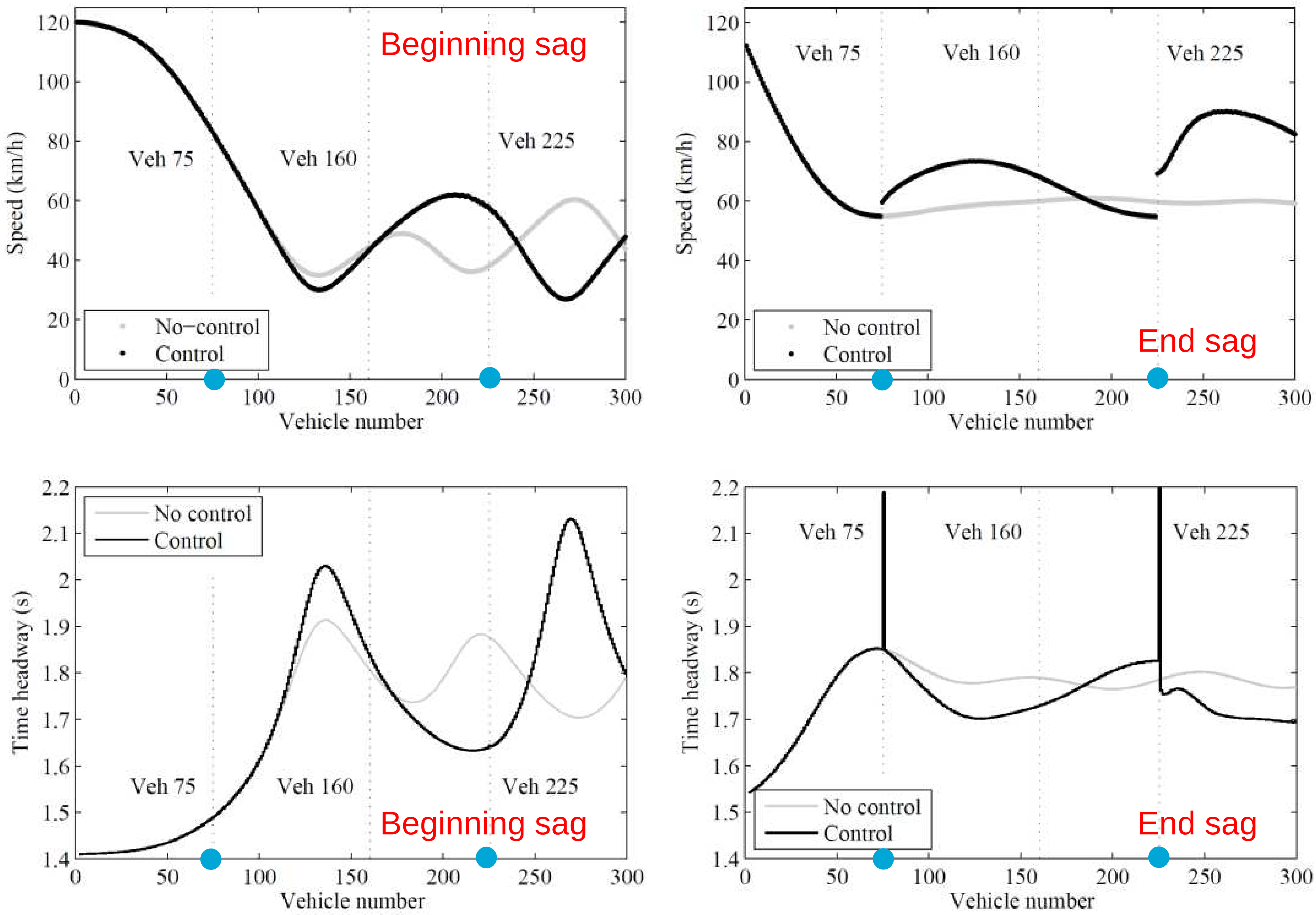
Primary strategy

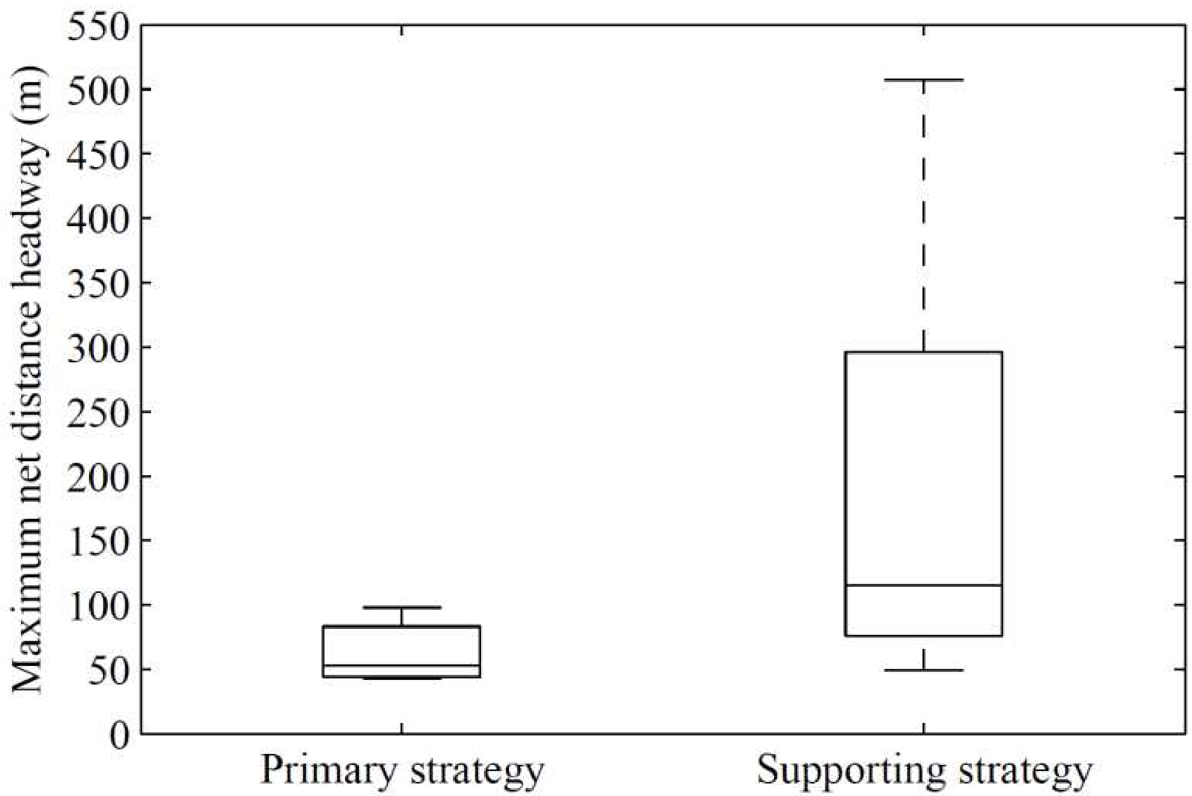
ΔATT = -3.5 s

- Effects on traffic flow (2 controlled vehicles) M = {75,225}



Maximum distance headways

- **Primary strategy**: narrow range, not too long
- **Supporting strategy**: wide range, longer



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