AVS17 Breakout Session 21: Connected and Automated Vehicles in Traffic Signal Systems

Henry Liu, Larry Head, and Young-Jun Moon

July 12th, 2017

- The goal of this two-part breakout session is to explore opportunities for new approaches to control of signalized intersections (or more broadly controlled junctions) for CAV. This session explores the role of infrastructure and the vehicle in decision making and control decisions and how vehicles and the infrastructure can cooperate to safely and efficiently operate the intersection of roadways.

- Total 9 presentations (in 2 sessions) followed up a discussion.

Discussion Session

- Research questions:
  - Two dimensional diagram: connectivity and automation
    - How to improve intersection control from current practice by using CAV data?
    - How to consider different demand levels, multi-modal, infrastructure adaptation?
    - With fleet vehicles from shared mobility companies, how will that impact on the traffic control?
    - What we need to do to devices at the infrastructure (e.g. hardware change, firmware upgrade)?
    - How public agencies will be benefit from CAV technology?
  - Level of automation is also an another dimension

Intelligence level of traffic control

- How to define intelligence level of traffic control, similar to vehicle automation level defined by SAE
- For example:
  - Level 0: Fixed-time control (time of day)
  - Level 1: Existing adaptive control system (e.g. SCOOT)
  - Level 2: Detector free signal control (smarter coordinator at the intersection)
  - Level 3: ?
- Related to the connectivity and automation diagram, intersection intelligence level changes with levels of connectivity and automation

Performance measures

- Objective function of traffic control may be changed
  - From intersection delay for vehicle to personalized delay
  - New objectives
    - Sustainability
    - Energy
    - Risk minimization
  - Mixed objectives during the transition period

CAV Data

- CV: provide continuous data
- Trajectory data will replace conventional detection
  - Loop detectors disappear
  - Navigation data from Google, Tomtom
- Data from share mobility companies should be shared to the research community

Controllability and observability

- Controllability increase over time with change of automation levels
- Experience with Didi (related to observability)
  - Only 3% of vehicles are Didi vehicles
  - Without infrastructure detectors, only trajectory data, we can generate better signal timing plan
  - Signal retiming every week
  - Closed loop control instead of open loop control
- With different CAV PR, changes are not linear
  - People will be conservative when PR is low
  - A good practice from state-of-practice to the new paradigm

Capacity increase with CAV

- Theoretical analysis of capacity increase with the increase of automation level is missing
- Traditional traffic control: fixed capacity, just how to better allocate the capacity (remove inefficiency)
- Traffic control With CAV: increased capacity, allow more cars to move through
- Two issues:
  - Pedestrians are usually not considered when studying signal control with CAV
  - Increase capacity may increase demand which may result in more congestion

Other research topics

- Customer acceptance of CAV
- Impact of vehicle technologies to CAV
- Traffic control algorithms: centralized v.s. decentralized

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Managing Automated Vehicles at an Isolated Intersection with High Traffic Demand

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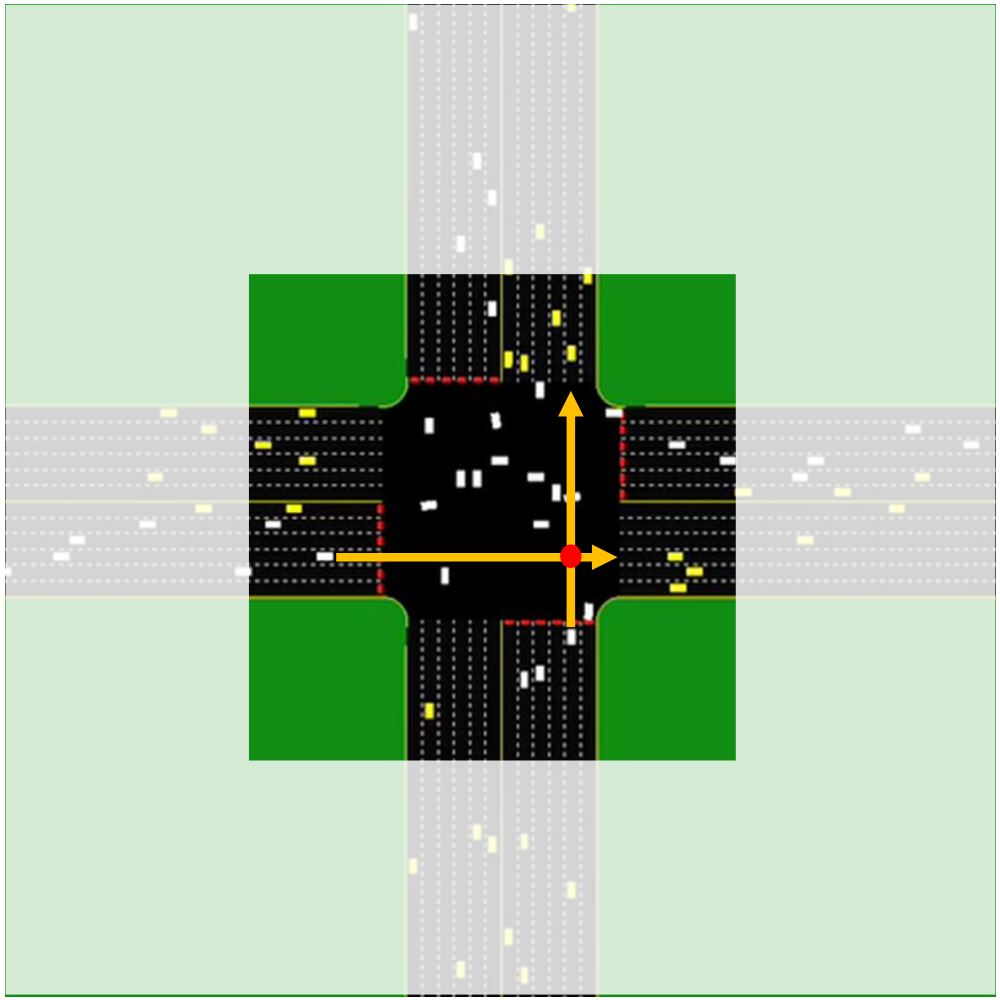
2017/7/18

OUTLINE

- **Background**
- **Problem description**
- **Theoretical analysis of reservation-based control**
- **Optimization-based control model for AVs**
- **Numerical examples**
- **Conclusions**

1. Background

- **Automated vehicles (AVs) & Signal-free control**
- **Reservation-based approach:** first-come-first-service (FCFS)



(https://www.youtube.com/watch?v=4pbAI40dK0A)

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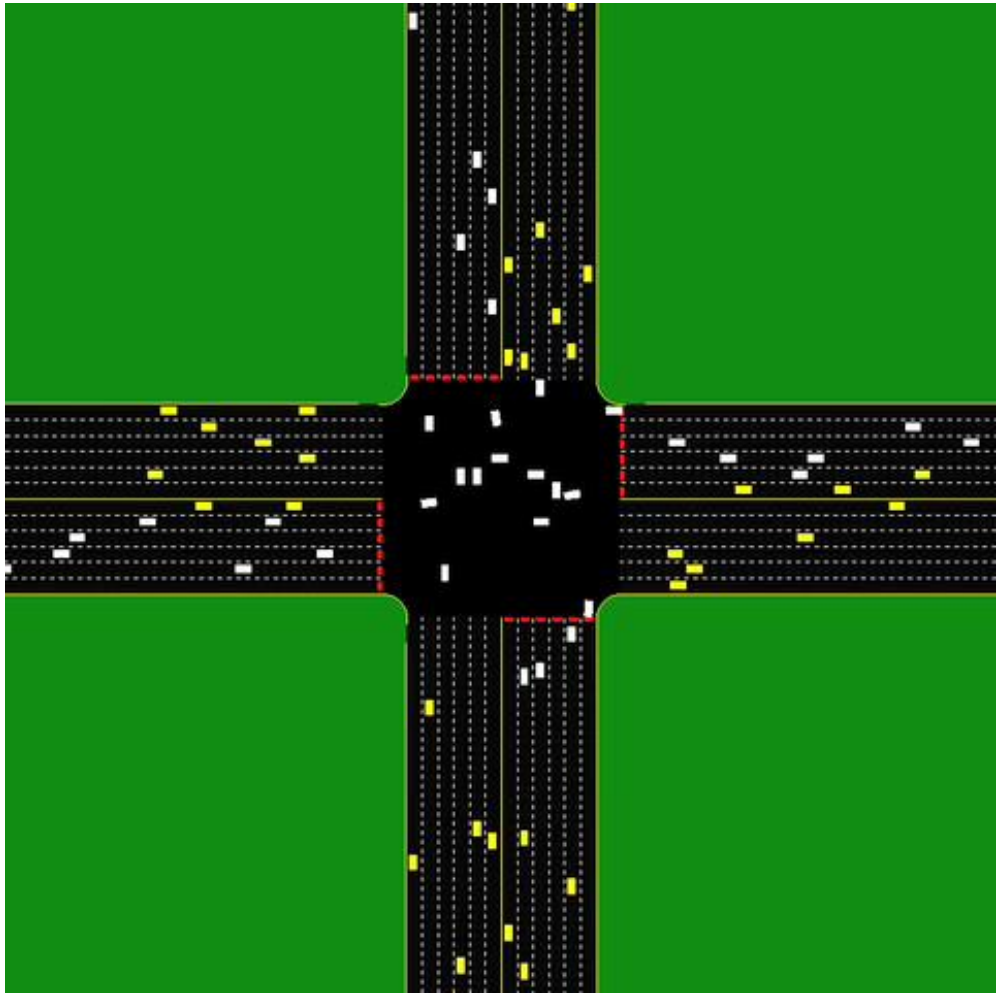

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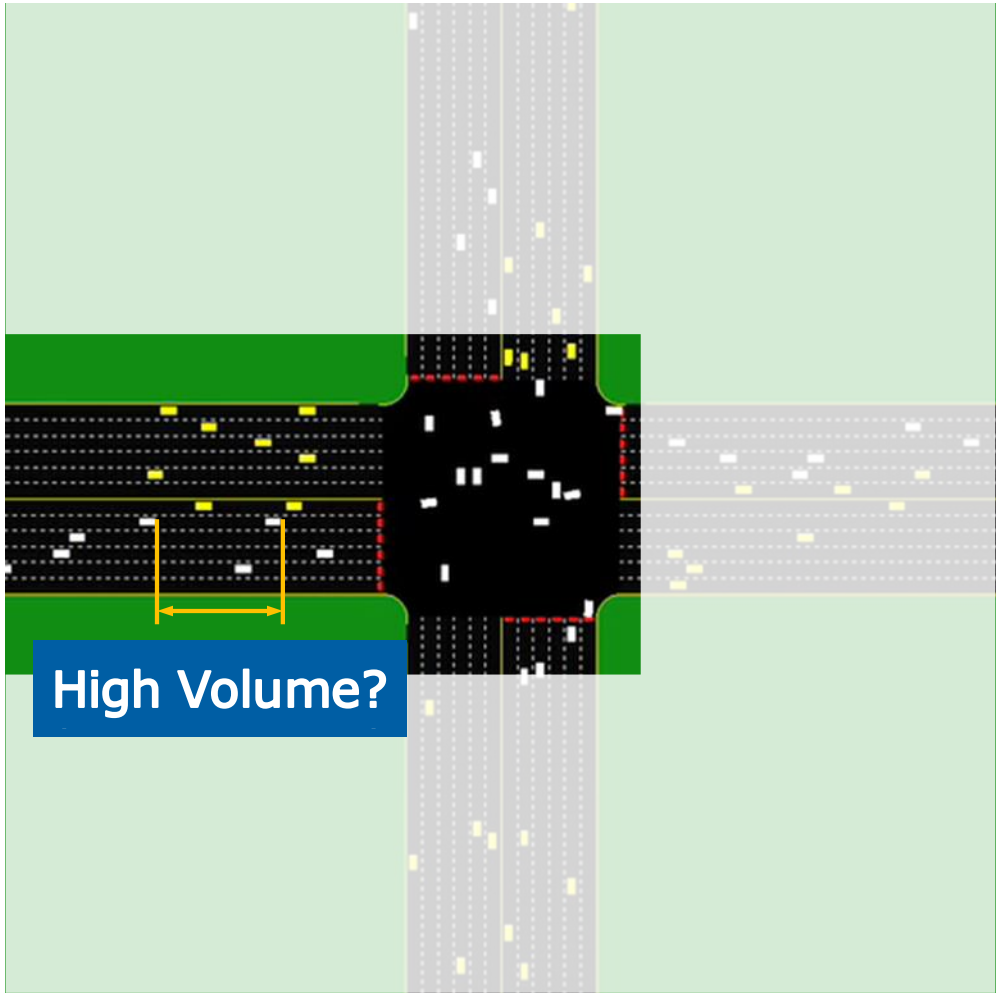
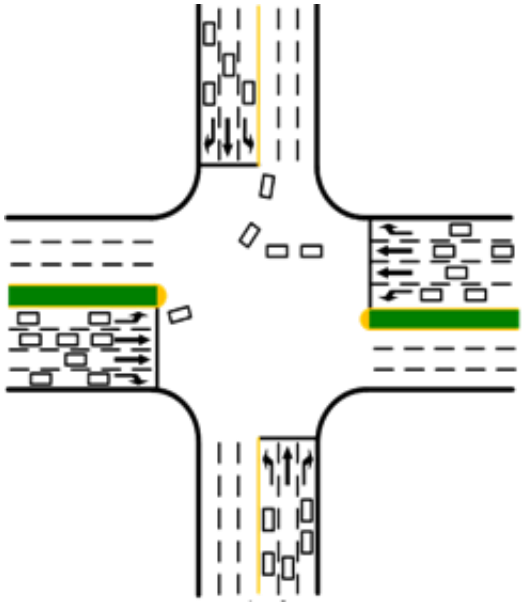


(https://www.youtube.com/watch?v=4pbAI40dK0A)

2. Problem description

- **Focus:** exploring the performance of **control approaches** for AVs at an isolated intersection at different **demand levels**.
- **Assumptions**
  - Vehicles can be controlled by a central controller once they enter the studied range at the intersection (e.g., 100 m from stop bars).
  - Each lane is dedicated to serve one specific traffic stream. Vehicles are already in their desired lanes when entering the studied range.
  - Vehicles follow certain car-following rule in each approach lane and have determined trajectories and speeds within the intersection area.



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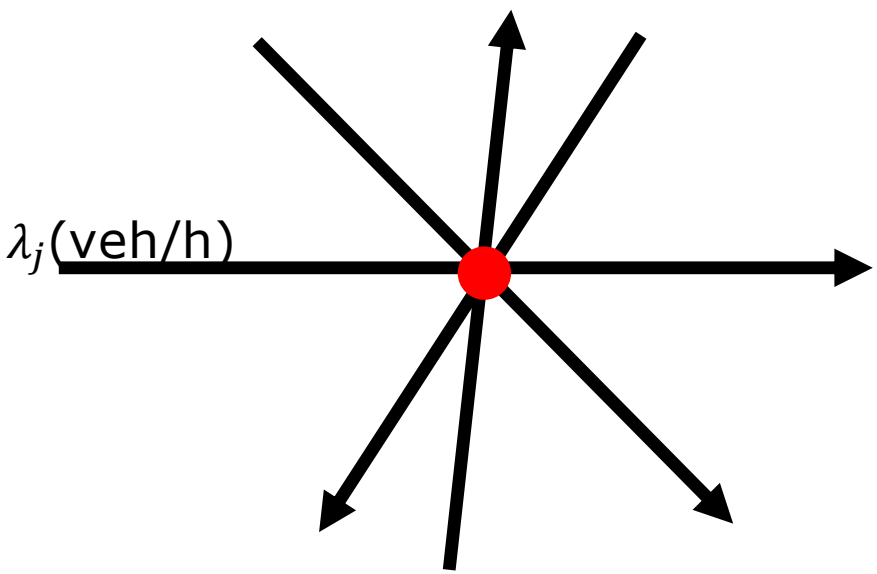
3. Theoretical analysis of reservation-based control

➢ **FCFS strategies** (Dresner and Stone, 2004, 2008)

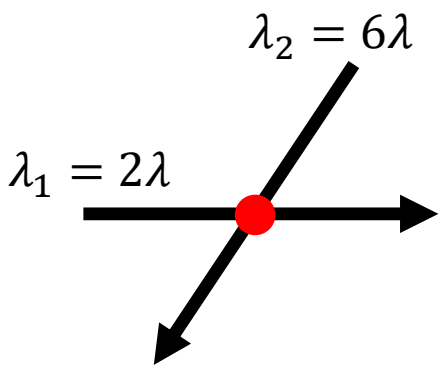
- All streams conflict with each other at one conflict point;
- Traffic arrivals of each stream follow the Poisson distribution independently;
- Vehicles are served based on FCFS strategy;
- Queueing theory: M/G/1 system.

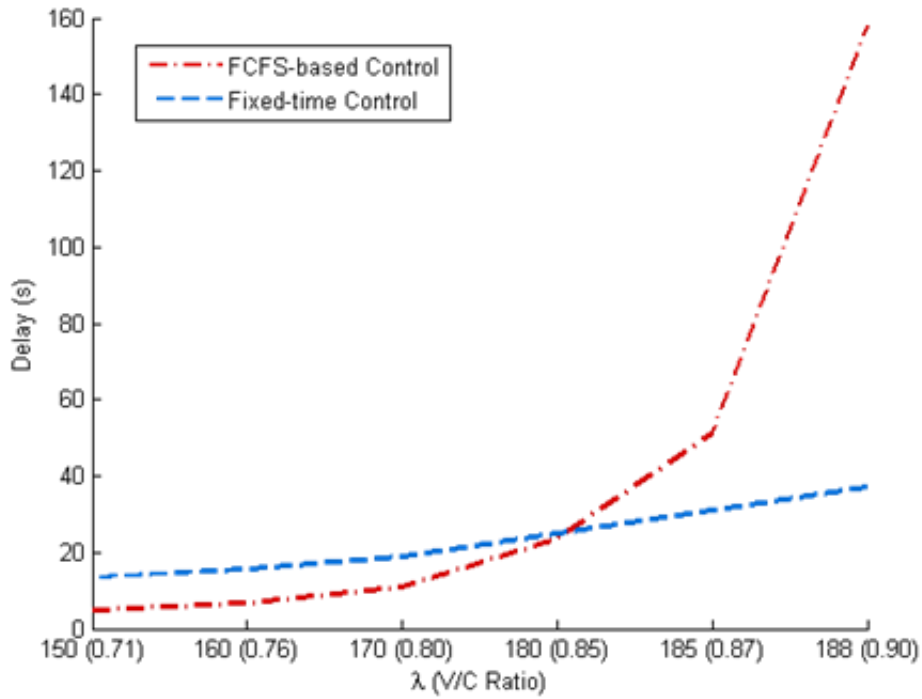


3. Theoretical analysis of reservation-based control

➢ FCFS strategies

- Delay
  - ✓ FCFS-based control
  - ✓ Fixed-time control (Webster, 1958)



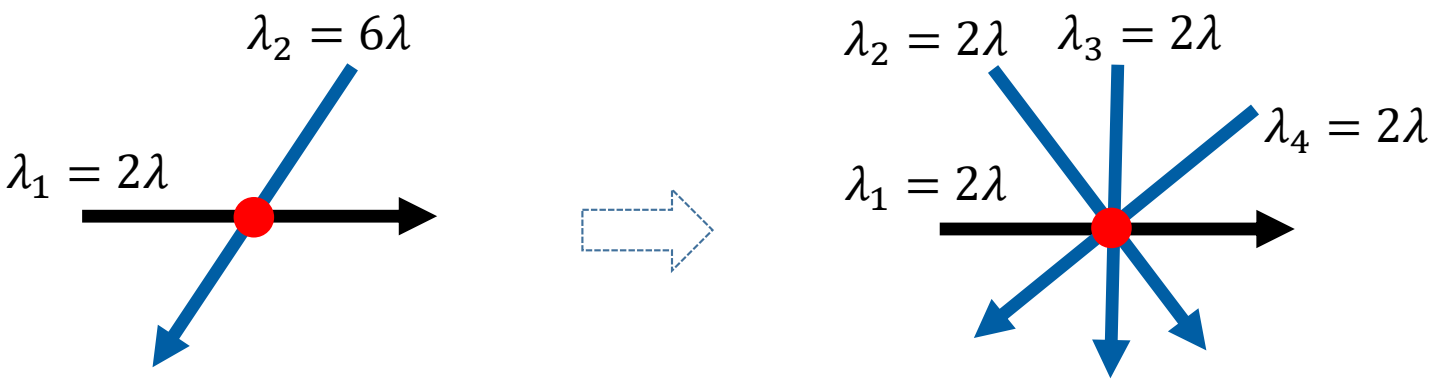


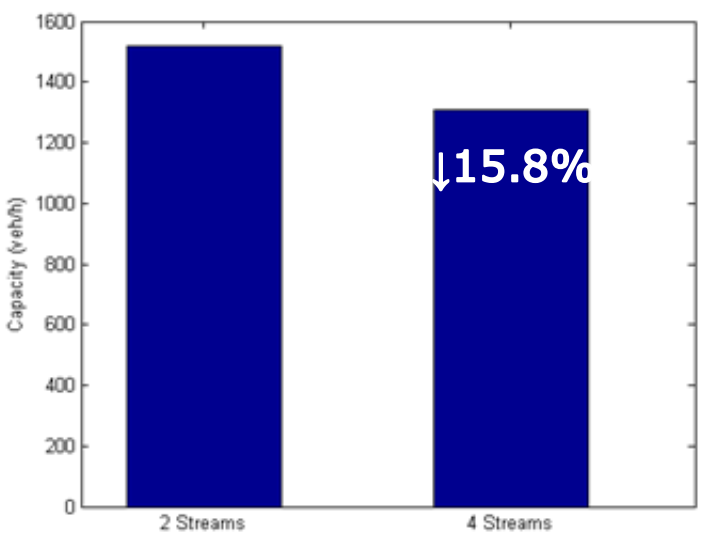
FCFS strategy outperforms fixed-time control at low demand levels but its delay increases more dramatically with increasing demand.

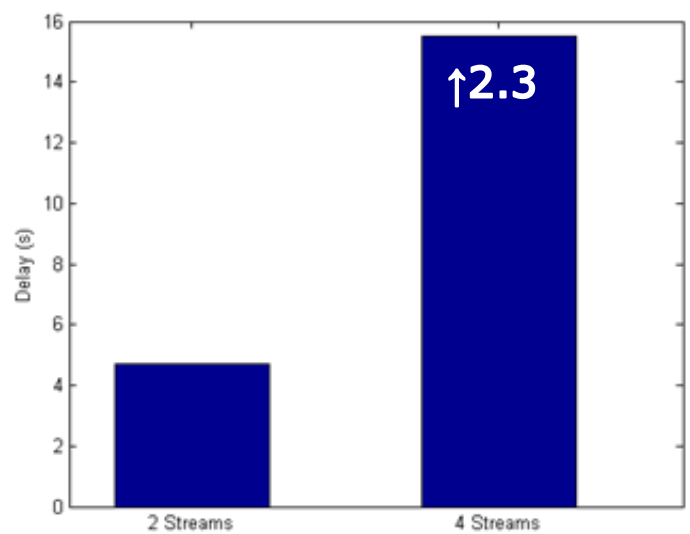
3. Theoretical analysis of reservation-based control

➢FCFS strategies

- Number of conflicting streams





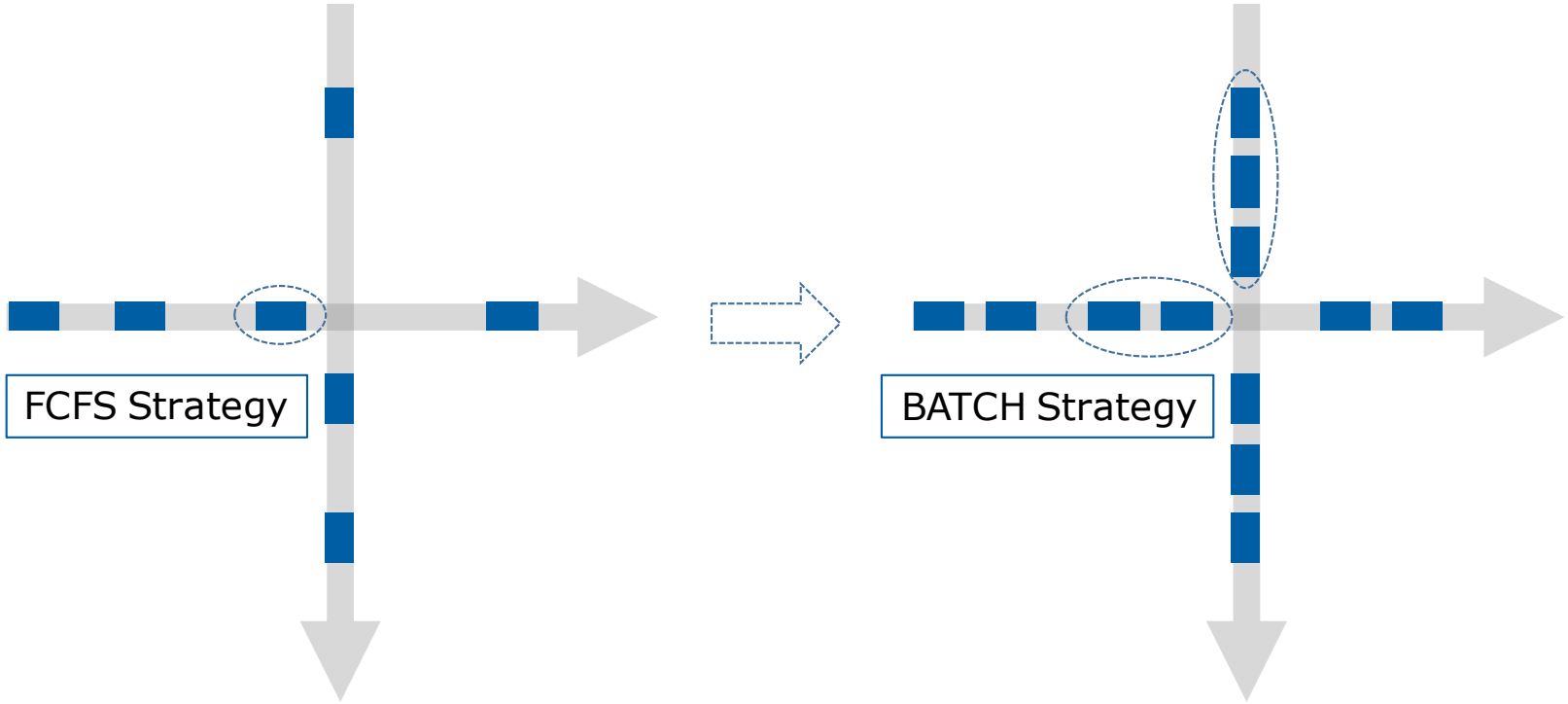


($\lambda = 150$ veh/h)

3. Theoretical analysis of reservation-based control

➢BATCH strategies

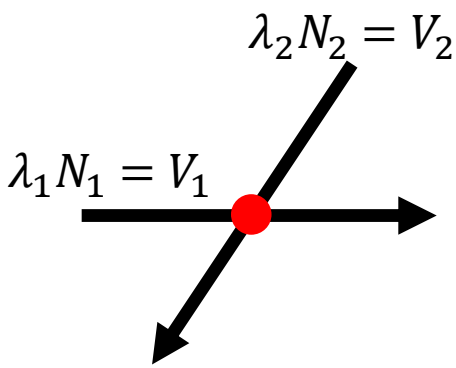
- FCFS principle holds based on a batch level;
- Batches are already formed before they enter the studied range;
- Batch arrivals conform to the Poisson distribution (batches/h);
- All batched streams conflict with each other at one point.

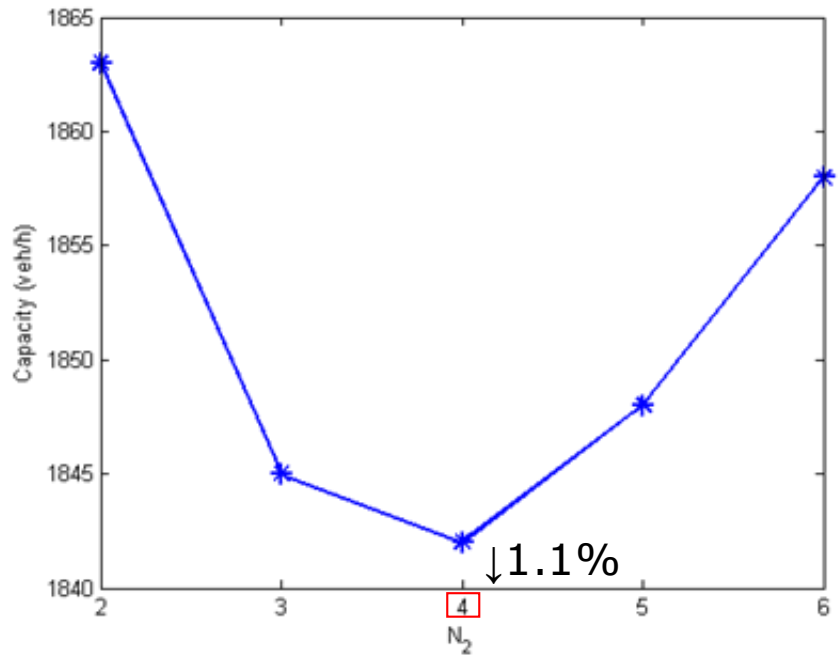


3. Theoretical analysis of reservation-based control

➢ BATCH strategies

- Batch sizes
  - ✓ Fixed demand $V_1 = 70$ veh/h and $V_2 = 400$ veh/h;
  - ✓ Batch arrival rates λ_1 and λ_2 (batches/h);
  - ✓ Batch size of stream 1 is $N_1 = 1$ veh/batch.





There exists a batch size threshold N_j^0 for each batched stream $j \in \mathbf{J}$, so that the capacity C_{BATCH} is monotonically increasing over the batch size N_j when $N_j \geq N_j^0$.

3. Theoretical analysis of reservation-based control

➢ BATCH strategies

- BATCH strategy and fixed-time control are equivalent in terms of intersection capacity if batch sizes and green splits are selected properly.
- How to form batches/platoons with varying traffic conditions?

4. Optimization-based control model for AVs

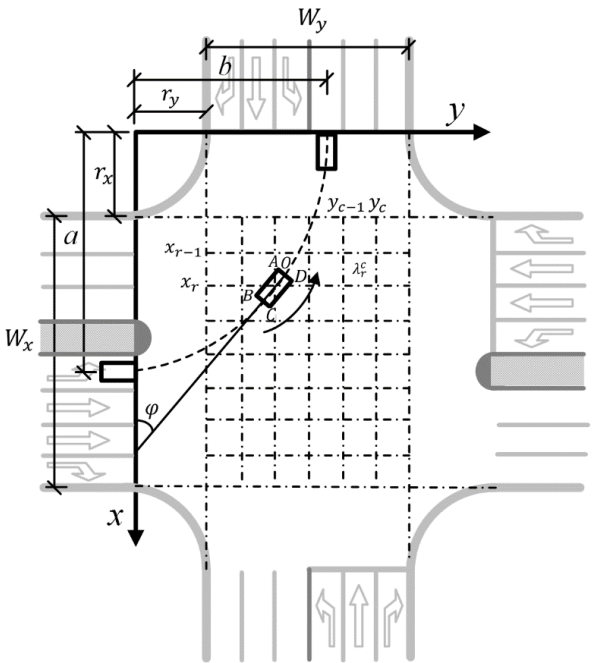
➢Optimization model

- Decision variables: departure time from stop bars
- Delay minimization

$$\min \sum_{i \in I} \sum_{\omega \in \Omega_i} t_d^{\omega}$$

  - ✓ Minimize vehicle departure time;
  - ✓ Encourage vehicles to be discharged as soon as possible;
  - ✓ Mixed-integer linear programming (MILP) model.

- Constraints
  - ✓ Car-following in approaches (Newell's model)
  - ✓ Collision avoidance within intersection areas.



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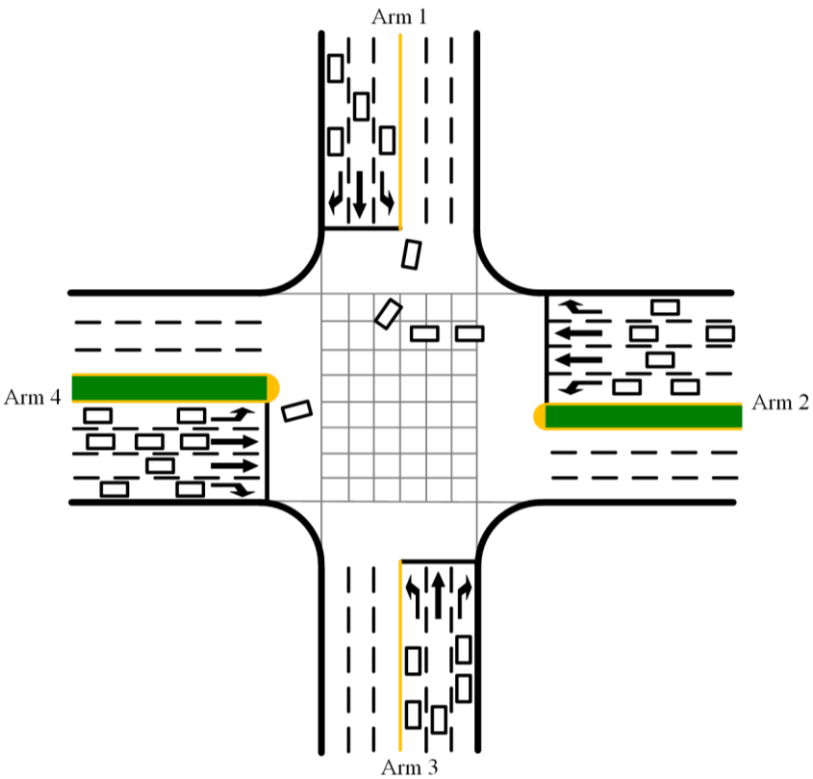
- **Numerical examples**
- Conclusions

5. Numerical examples

➢Simulation settings

- Four-arm intersection



- Control approaches
  - ✓ Optimization-based control
  - ✓ Reservation-based control
    - FCFS strategy (Dresner and Stone, 2004, 2008)
    - BATCH strategy (Tachet et al., 2016)
  - ✓ Actuated control
- Critical intersection V/C ratios
  - ✓ Approximated as the sum of the critical V/C ratio of each phase of actuated control with the maximum green durations
- Simulation duration
  - ✓ 1800 s

5. Numerical examples

➢Results and discussion

- Simulation results
  - ✓ Optimization-based control performs best;
  - ✓ A larger batch size is preferred;
  - ✓ Reservation-based control outperforms actuated control under low demand;
  - ✓ Actuated control is a good option at a high demand level.

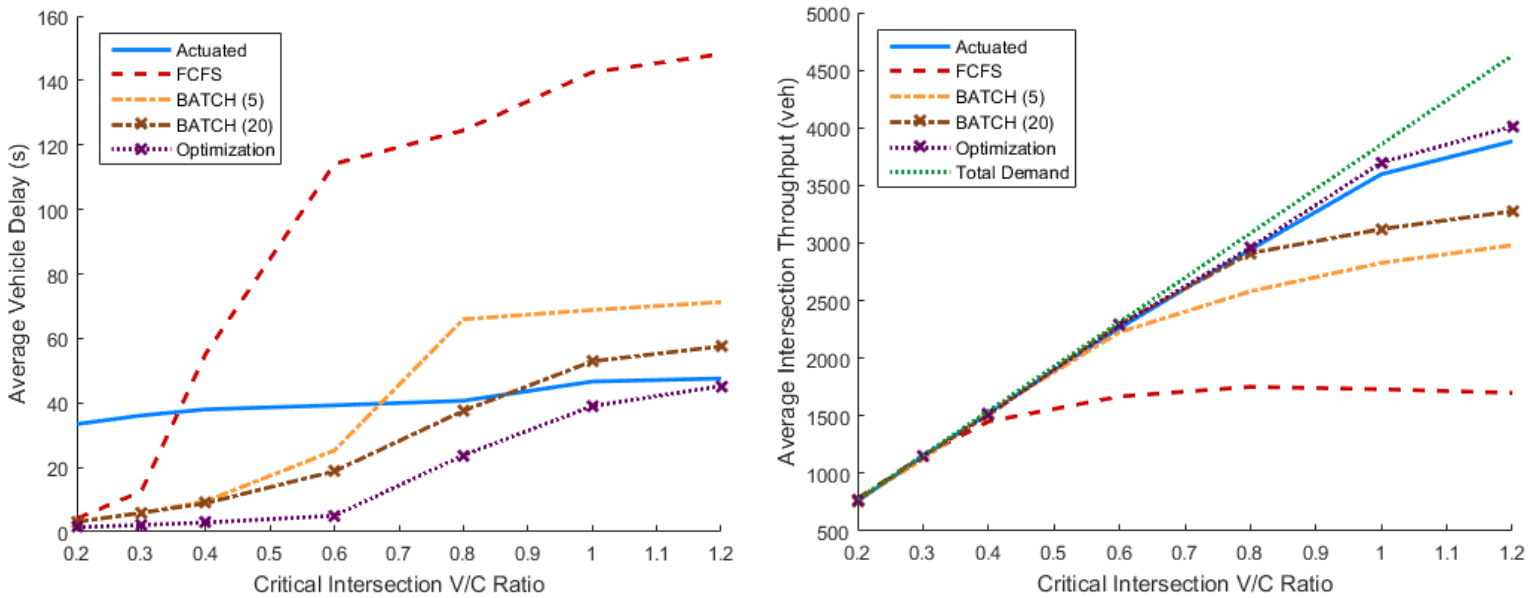


Fig. 4 Simulation results: (a) Average vehicle delays; and (b) Average intersection throughput

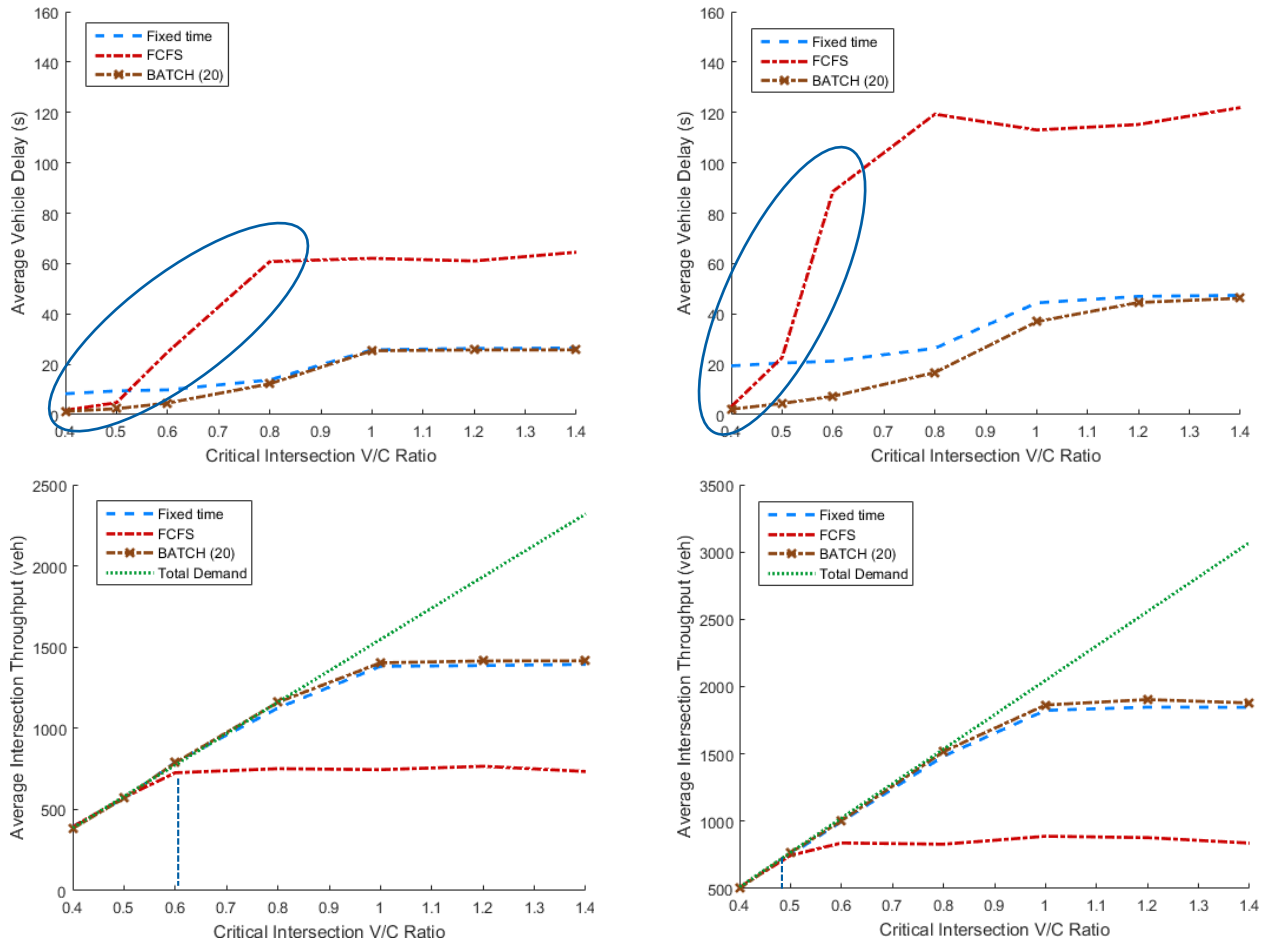
5. Numerical examples

➢Results and discussion

- Impacts of conflicting stream numbers on reservation-based control

Delay

Throughput



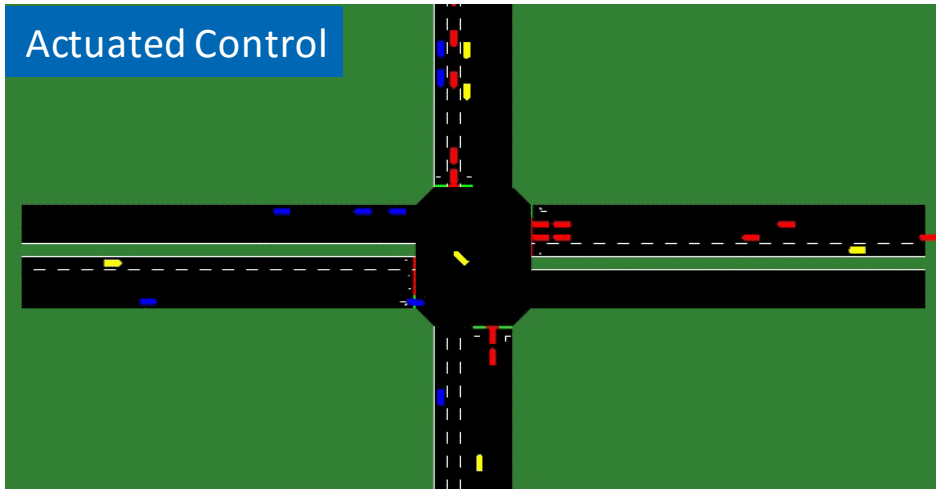
2 conflicting streams

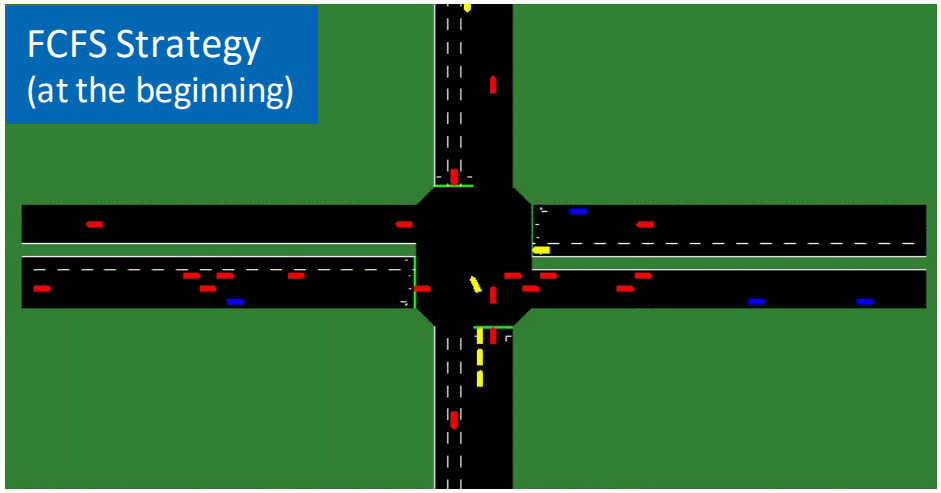
4 conflicting streams

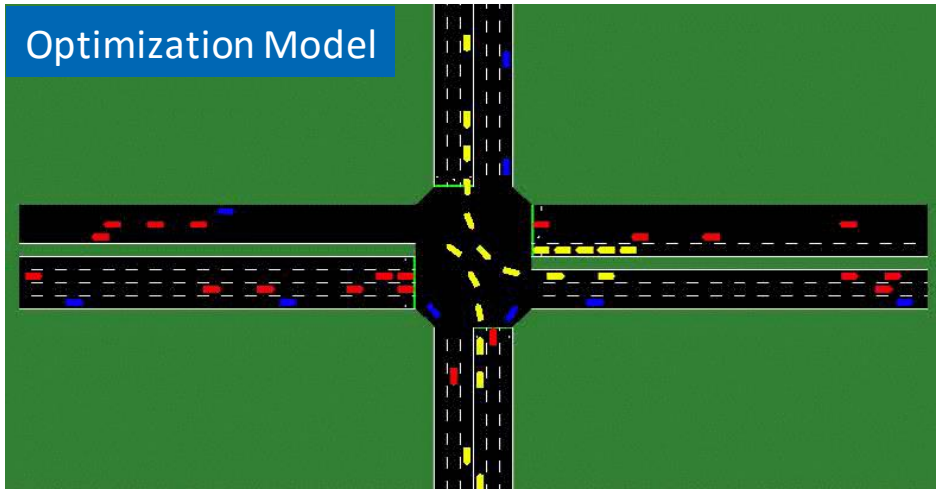
5. Numerical examples

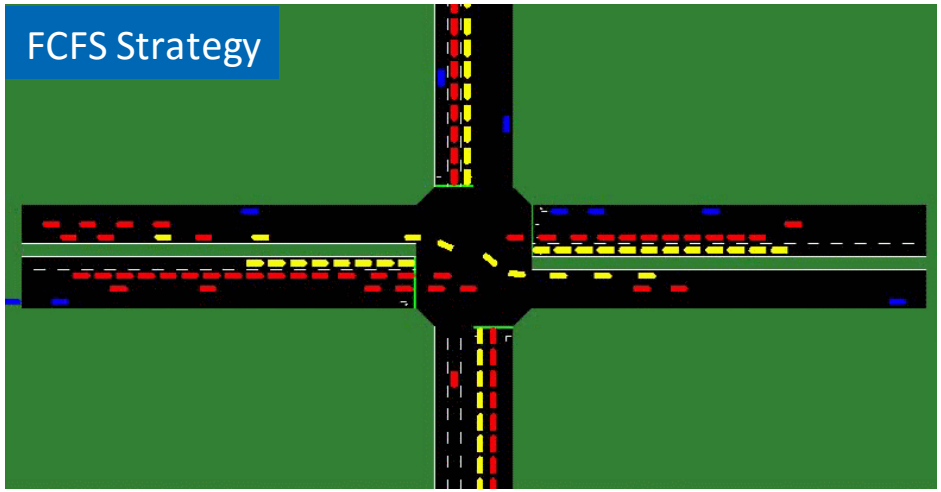
➢Simulation videos

- Intersection V/C ratio = 0.8









6. Conclusions

➢ Conclusions

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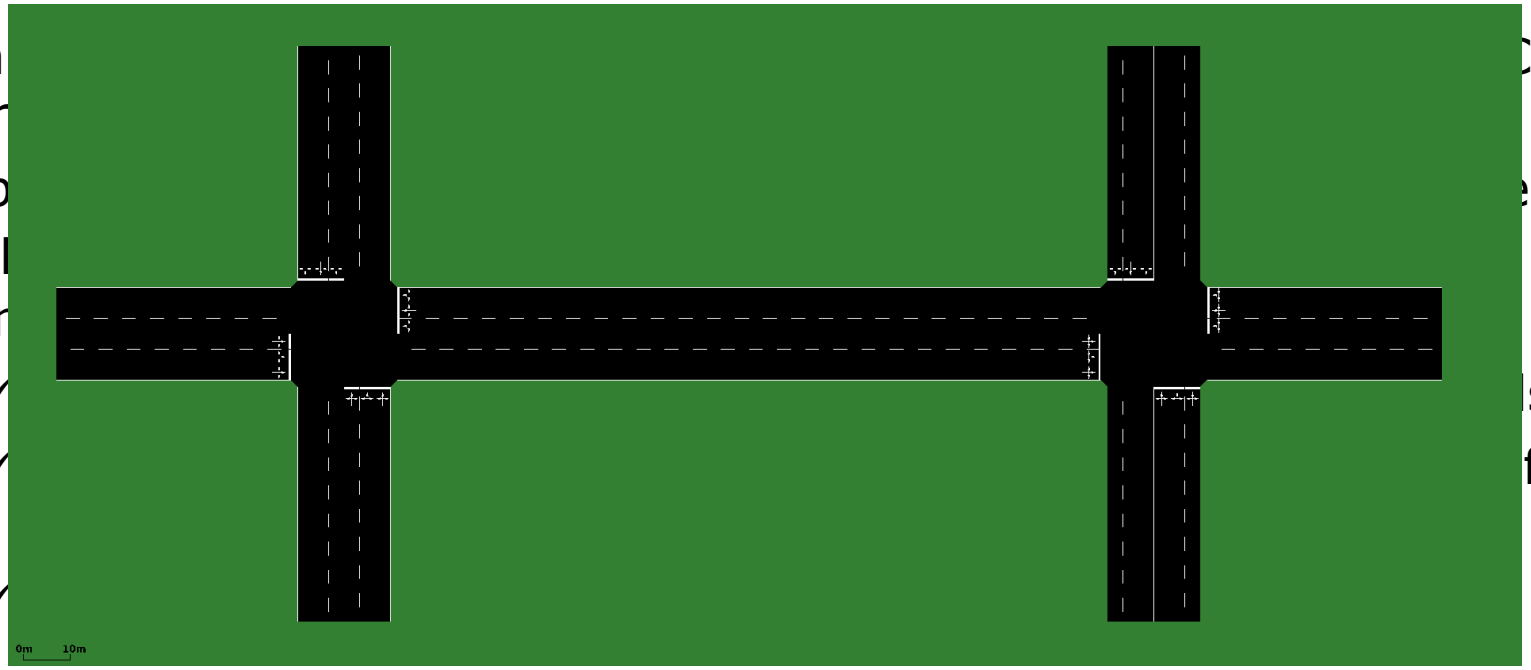

➢ Future work

- Efficient algorithms for the proposed MILP model
  - ✓ Quantum computers (IBM News room, 2016)
- Consideration of lane changing behaviors
- Coordination at corridor/network levels
- …

Thank You

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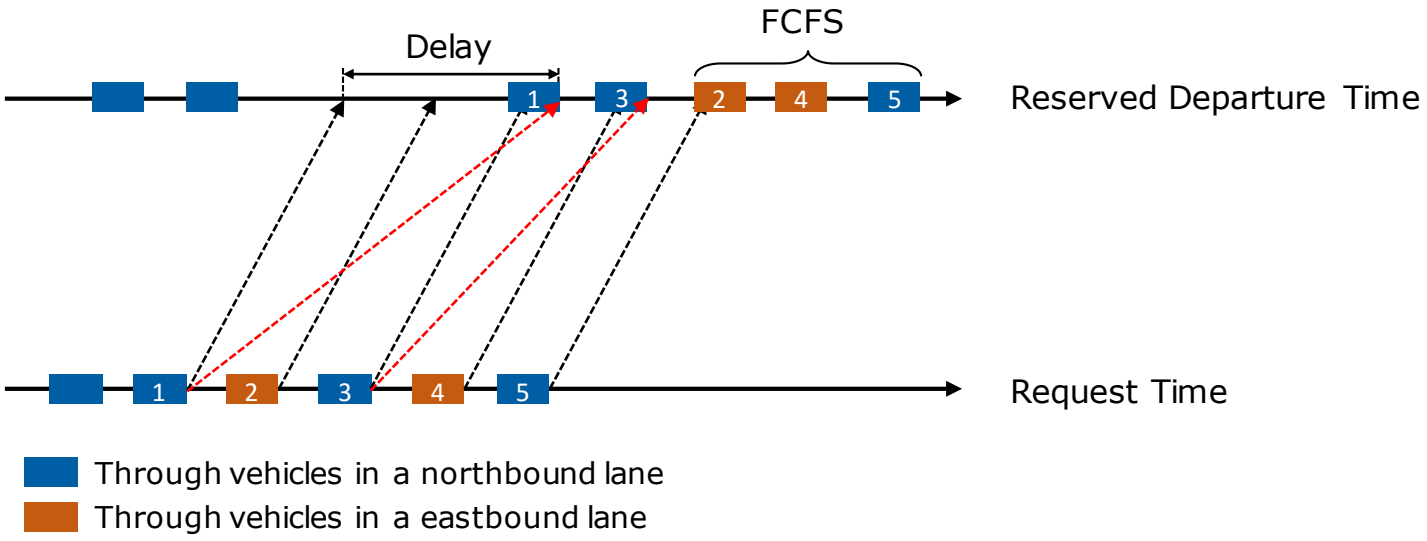
3. Theoretical analysis of reservation-based control

➢ Reservation-based control

- FCFS strategy (Dresner and Stone, 2004, 2008)
- BATCH strategy (Tachet et al., 2016)
  - ✓ Improved version of FCFS strategy
  - ✓ A maximum batch size is set to avoid a potentially boundless number of vehicles in one batch

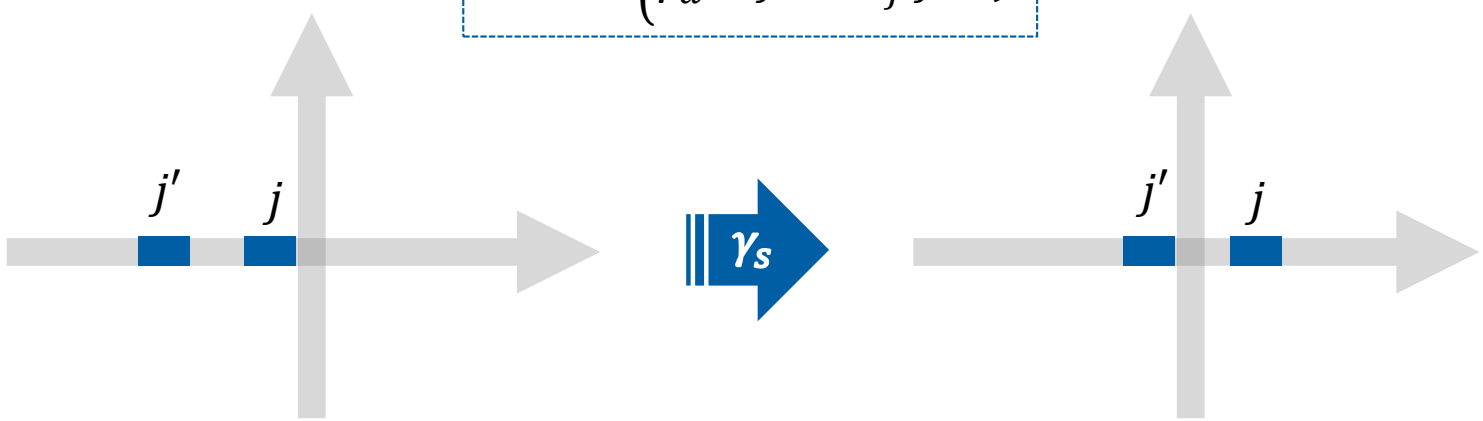


3. Theoretical analysis of reservation-based control

➢ FCFS strategies

- $\mathbf{J}$: set of traffic streams; each stream is $j \in \mathbf{J}$;
- $\mathbf{A}_j$: set of conflicting streams with stream j;
- λ_j: average arrival rate of stream j, veh/s;
- Vehicle arrivals of each stream conform to the Poisson distribution;
- All streams conflict with each other at one conflict point;
- $\pi_{j,j'}$: safety time gaps when a vehicle from stream j' follows a vehicle from stream j.

$$\pi_{j,j'} = \begin{cases} \gamma_s, \text{ if } j' = j, j \in \mathbf{J} \\ \gamma_d, \text{if } j' \in \mathbf{A}_j, j \in \mathbf{J} \end{cases}$$



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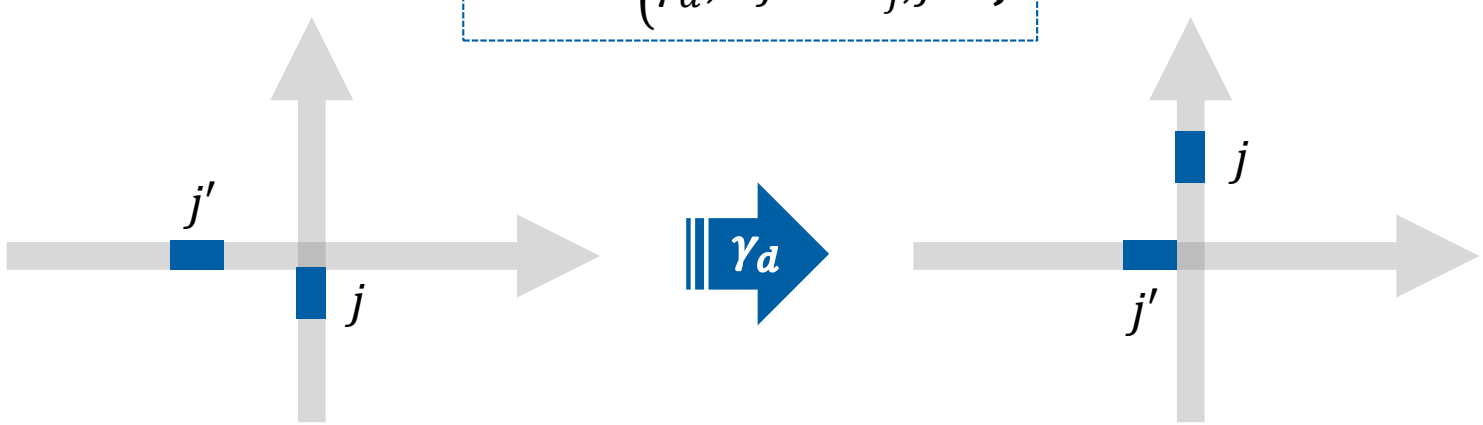


4. Optimal intersection control models

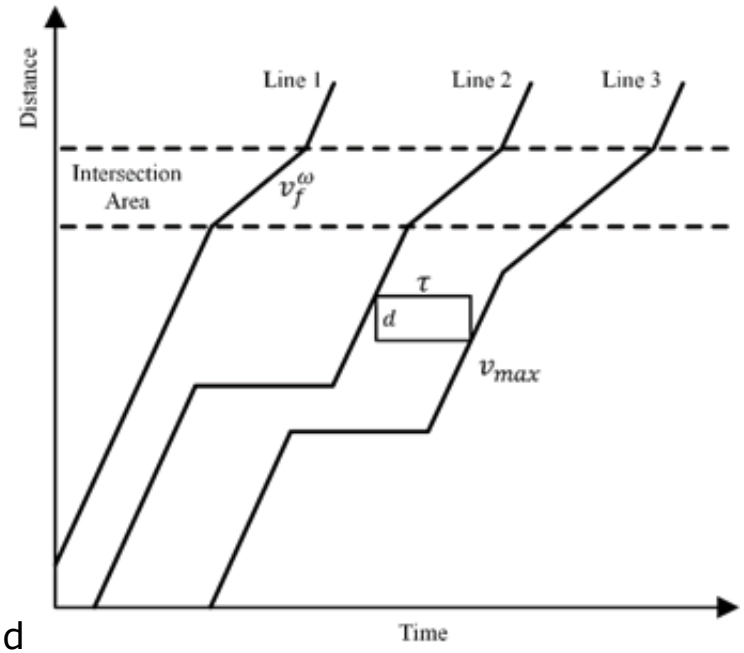
➢Constraints (1)

- Departure time from stop bars
  - ✓ Newell's car-following model

$$t_d^{\omega} \geq t_d^{\omega'} + \tau + \frac{d}{v_f^{\omega'}}, \forall \omega' \in \mathbf{\Omega}_{\omega}; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$

Departure time of following vehicles

Departure time of preceding vehicles



  - ✓ Speed limits

$$t_d^{\omega} \geq t_0 + \frac{x_0^{\omega}}{v_{max}}, \forall \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$

Distance between vehicle and stop bar

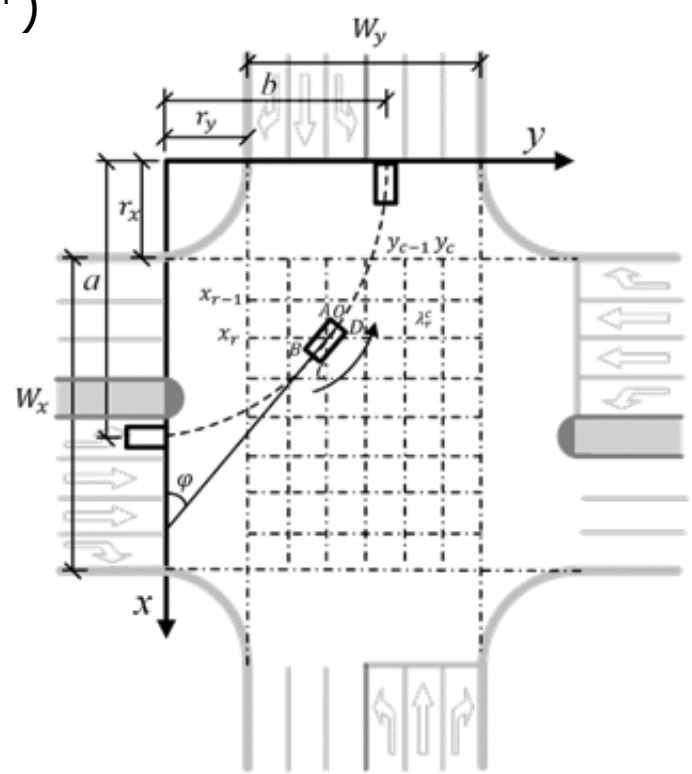
Maximum speed

Current time

4. Optimal intersection control models

➢Constraints (2)

- Vehicle trajectories within a slot-based intersection
  - ✓ Desired speeds v_f^{ω} within the intersection: no acceleration, deceleration, or stops
  - ✓ Ellipse trajectories of turning vehicles
  - ✓ Travel time to enter and leave each tile from a stop bar (i.e., $\Delta t_{\lambda}^{\omega-}$ and $\Delta t_{\lambda}^{\omega+}$)



4. Optimal intersection control models

➢Constraints (2)

- Vehicle trajectories within a slot-based intersection
  - ✓ Vehicles in approach lanes

$$t_\lambda^{\omega-} = t_d^\omega + \Delta t_\lambda^{\omega-}, \forall \lambda \in \mathbf{\Lambda}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$ Entering time

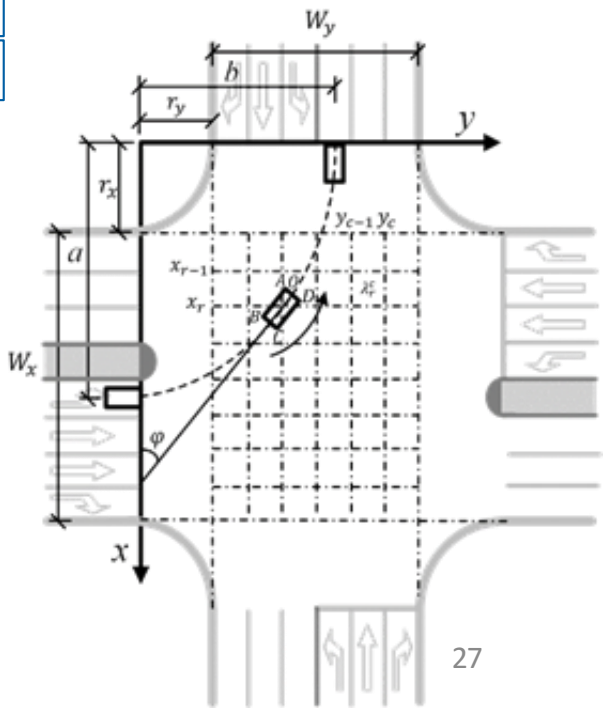
$$t_\lambda^{\omega+} = t_d^\omega + \Delta t_\lambda^{\omega+}, \forall \lambda \in \mathbf{\Lambda}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$ Leaving time

  - ✓ Vehicles within intersection areas

$$t_\lambda^{\omega-} = \tilde{t}_\lambda^{\omega-}, \forall \lambda \in \mathbf{\Lambda}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$ Entering time

$$t_\lambda^{\omega+} = \tilde{t}_\lambda^{\omega+}, \forall \lambda \in \mathbf{\Lambda}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$ Leaving time

$$[t_\lambda^{\omega-}, t_\lambda^{\omega+}]$$



4. Optimal intersection control models

➢Constraints (3)

- Avoidance of conflicts
  - ✓ Time gaps between vehicles that consecutively pass a same tile

    - If vehicle ω follows vehicle ω':

$$t_\lambda^{\omega'+} + \gamma \le t_\lambda^{\omega-} + M\left(1 - \delta_\lambda^{\omega',\omega}\right), \forall\lambda \in \mathbf{\Lambda}_\omega \cap \mathbf{\Lambda}_{\omega'}; \omega' \in \bar{\mathbf{\Omega}}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$

Leaving time Time gap Entering time

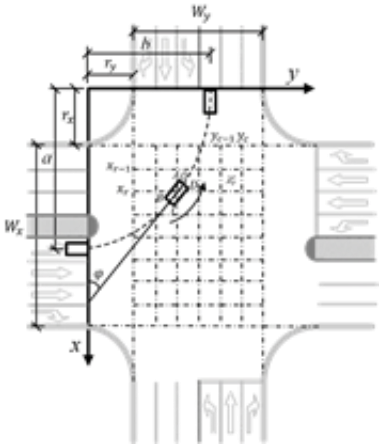
    - If vehicle ω' follows vehicle ω:

$$t_\lambda^{\omega+} + \gamma_d \le t_\lambda^{\omega'-} + M\left(1 - \delta_\lambda^{\omega,\omega'}\right), \forall\lambda \in \mathbf{\Lambda}_\omega \cap \mathbf{\Lambda}_{\omega'}; \omega' \in \bar{\mathbf{\Omega}}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$

    - Only one case exists:

$$\delta_\lambda^{\omega',\omega} + \delta_\lambda^{\omega,\omega'} = 1, \forall\lambda \in \mathbf{\Lambda}_\omega \cap \mathbf{\Lambda}_{\omega'}; \omega' \in \bar{\mathbf{\Omega}}_\omega; \omega \in \mathbf{\Omega}_i; i \in \mathbf{I}$$

1, if ω' enters λ before ω; 0, otherwise



Speed Coordination for Cooperative Vehicles at Intersections

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July 12, 2017

TUDelft

Outline

Motivation

- Many CAV applications on highway, e.g. CACC, platooning
- Challenging for such concepts at intersections:
  - more complex driving tasks: when and with which speed to cross, car-following, steering and pedal control
  - conflict avoidance with vehicles from different directions
  - safe interaction with non-motorized modes
  - no clear platoon leader at non-signalized intersection

Motivation[2]

Fundamental question for intersection control with CAV:

- will we still need traffic lights as actuators for traffic control
- can CAV interact safety and efficiently without traffic lights
- can CAV increase intersection capacity as they do in *uninterrupted* freeway traffic

A new perspective of intersection control with CAV

- Continuous v.s. binary control signal
  - Speed as traffic signal instead of traffic lights
- Anticipative v.s. reactive
  - Planning the speed trajectories of CAV instead of giving instantaneous right-of-way decisions
- Both centralized and distributed communication and control possible
  - Centralized (V2I/I2V): Intersection collects all information and makes centralized decisions for all CAV
  - Distributed (solely V2V): CAV talk *locally* and decide their speeds under a common goal

Design objective of optimal i-CACC

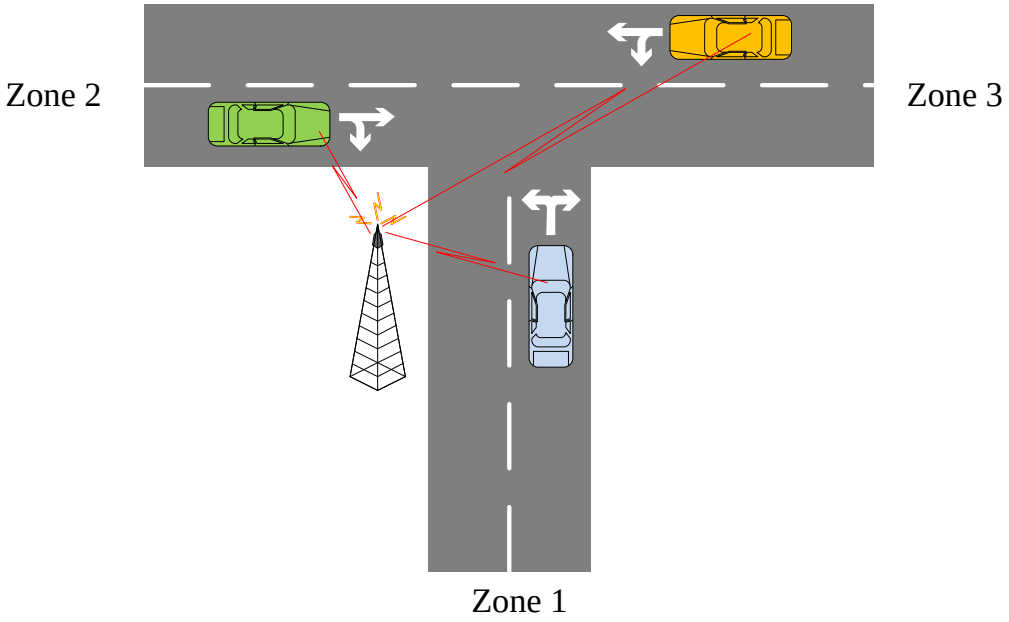
A flexible vehicle speed control strategy that:

- regulates the speeds of CAV
- functions as CACC (car-following control) at links and switches to intersection crossing at nodes
- maximizes utility/throughput of junction
- guarantees safety: avoiding conflicts
- ensures comfortable accelerations

Operational assumptions

1. A centralized (traffic) controller with DSRC
2. CAV send their O-D, x, v to traffic controller
3. Traffic controller predicts arrival times of all vehicles at the conflict zone and determines a *passing order* for conflicting vehicles
4. Optimal CAV accelerations trajectories in a *future horizon* computed by traffic controller
5. First sample of acceleration trajectories sent to CAV and used as commands by vehicle's lower-level control system
6. The process is repeated at regular time interval, e.g. Δt

Determine passing order



	1→2	1→3	2→1	2→3	3→1	3→2
1→2	N					
1→3	N	N				
2→1	N	N	N			
2→3	Y	Y	N	N		
3→1	Y	N	Y	Y	N	
3→2	Y	N	N	N	N	N

Determine passing order[2]

- Predicting arrival time based on current v and x

$$t_{\text{arrival},i} = \frac{\text{distance to conflict point}}{v_i(t_0)} \tag{1}$$

- Assign passing order order based on FIFO principle
- A safe time gap t_{min} is constrained between sequential conflicting vehicles

$$x_j - x_i > v_i t_{min} \tag{2}$$

with vehicle j the leader of vehicle i.

System dynamics

$$\frac{d}{dt}\mathbf{x}_i = \frac{d}{dt}\begin{pmatrix} x_i \\ v_i \\ a_i \end{pmatrix} = \begin{pmatrix} v_i \\ a_i \\ \frac{u_i - a_i}{\tau} \end{pmatrix} = \mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{3}$$

- u control input, *desired acceleration*
- τ is the actuator lag, i.e. retarded response due to driveline/brake dynamics: it takes some time τ for the lower-level vehicle system to reach the desired acceleration u

The optimal control problem

$$\min_{u_i(0:T)} \sum_i \int_0^T \beta_1 \underbrace{(v_i(t) - v_0)^2}_{\text{Efficiency}} + \beta_b \underbrace{u_i(t)^2}_{\text{Comfort}} + \beta_3 \underbrace{(x_j(t) - x_i(t) - v_i t_{min})^2}_{\text{Safe gap}} \tag{4}$$

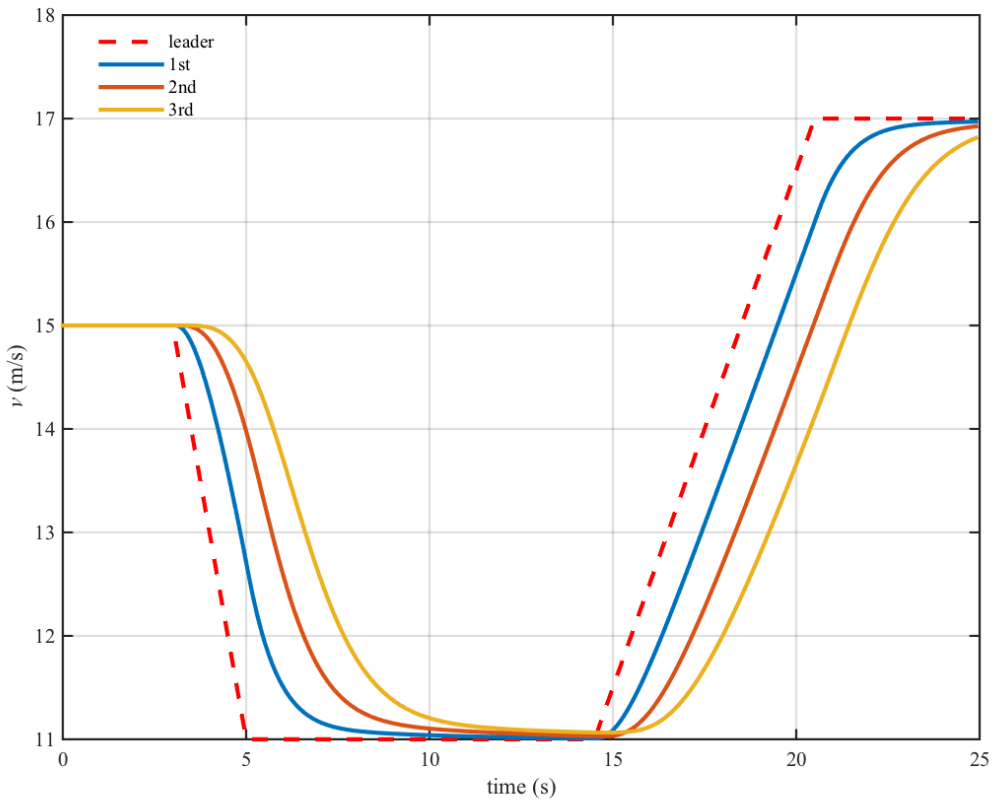
s.t.

$$\begin{aligned} x_j(t) - x_i(t) &\geq s_{\min} \\ 0 \leq v_i &\leq v_{\max} \\ u_{\min} \leq u_i &\leq u_{\max} \end{aligned} \tag{5}$$

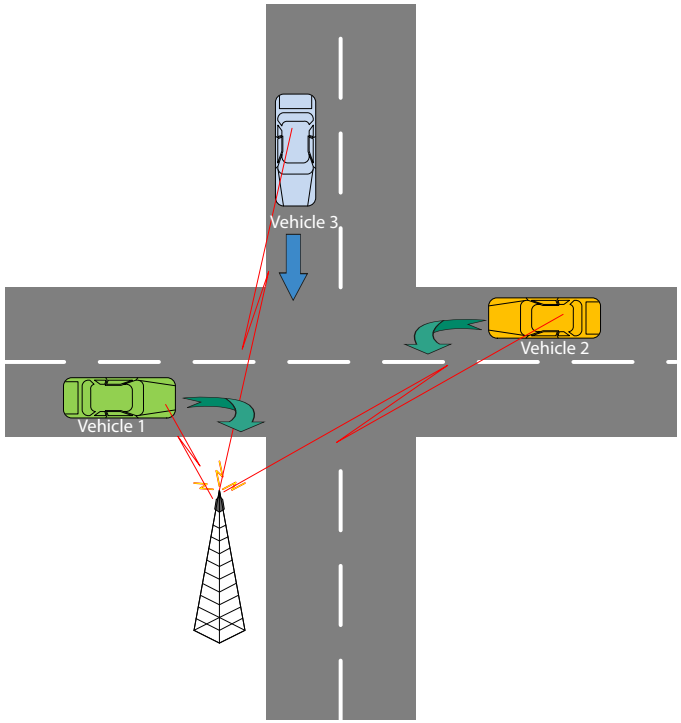
- T: prediction horizon
- v_0: free driving speed, e.g. the road speed limits
- β: weight coefficients
- Vehicle j is the *generalized* leader of vehicle i

Case 1: Car-following at link

Three vehicles following a leader with speed disturbance:



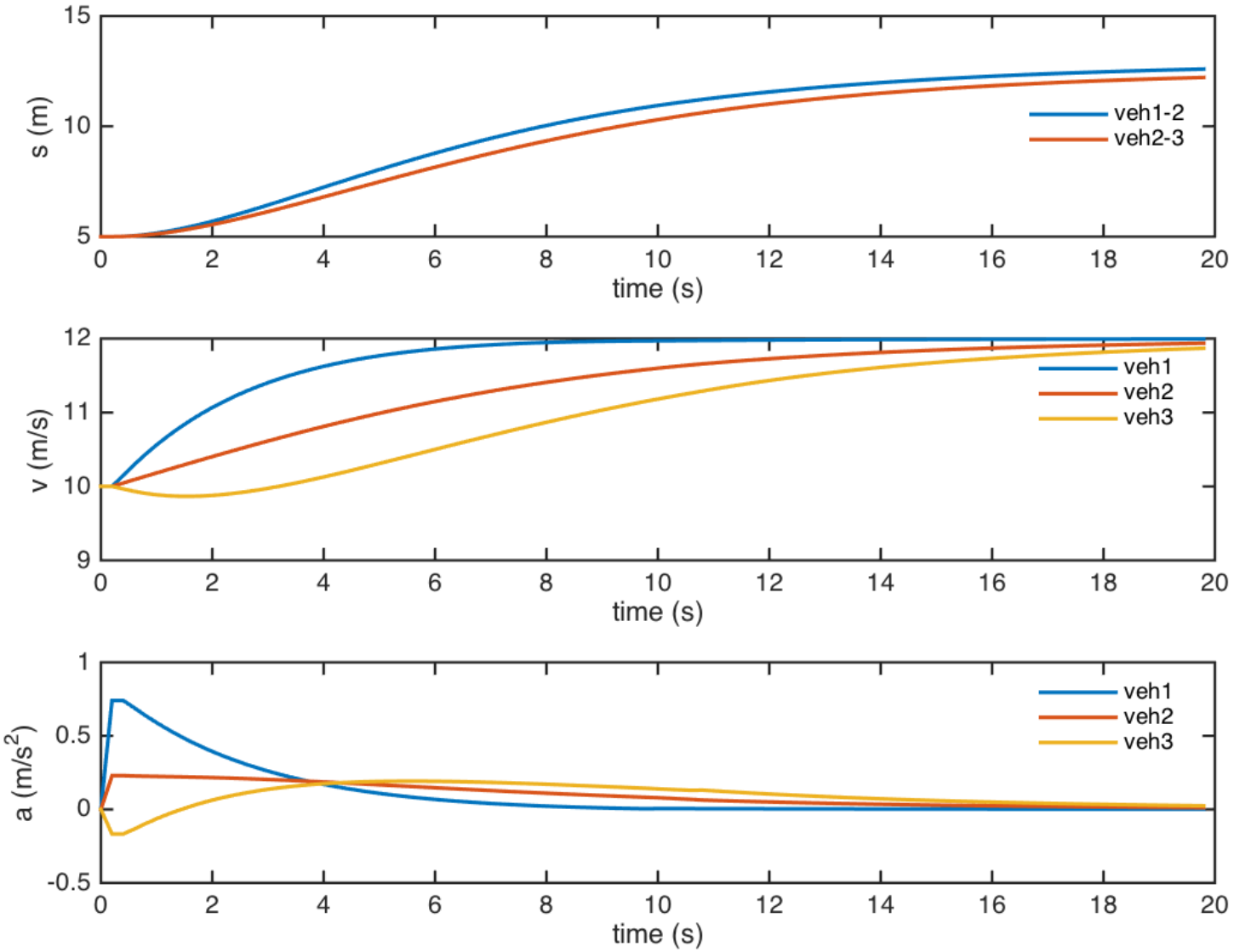
Case 2: Intersection crossing at node



- Initial distance to conflict point: [100, 105, 110]
- Initial speeds: [10, 10, 10] m/s
- Desired time gap: 1 s
- Speed limit: 12 m/s
- Acceleration range: [-4, 2] m/s^2
- Simulation period: 20 s

s

Case 2: Resulting trajectory



A simplified distributed algorithm (Lenin Mishra)

Heuristic-based algorithm:

- Distributed communication: only involving (local) V2V communication
- Defining the sequence of conflicting vehicles as *the heuristic*, i.e. decision-making protocol of cooperative vehicles
- Feedback algorithm: fast, not optimal
- Regulate the time gap between conflicting vehicles towards the minimum value
- May result in speed jumps and constraints violation

Implementation in VISSIM

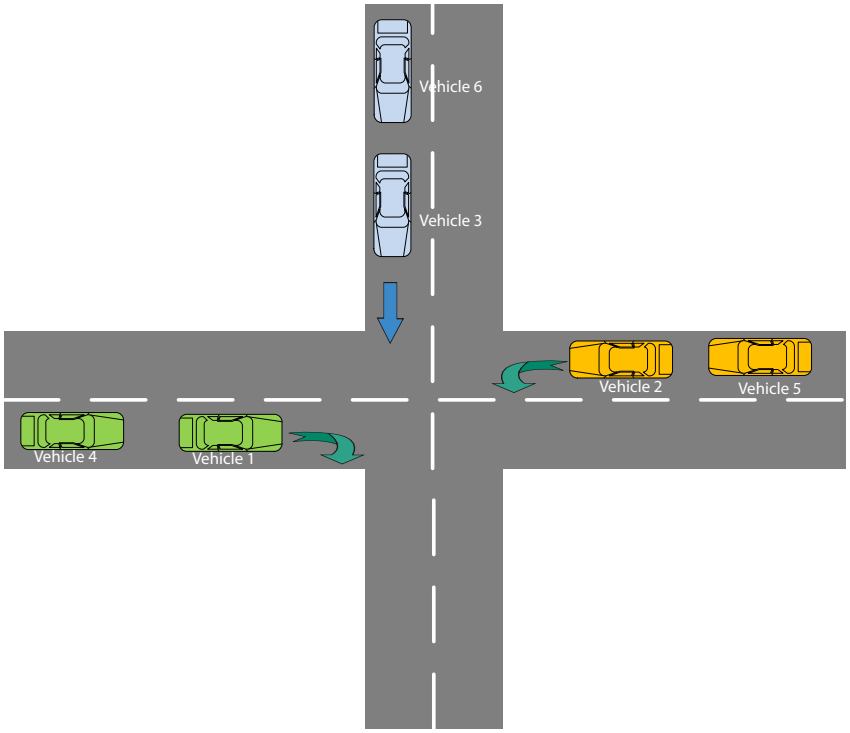
Summary

- Centralized MPC approach for vehicle speed coordination at intersections
- Works with transition from intersection crossing to car-following
- MPC algorithm verified with numerical example
- A distributed feedback algorithm proposed and tested in VISSIM

Thank you!

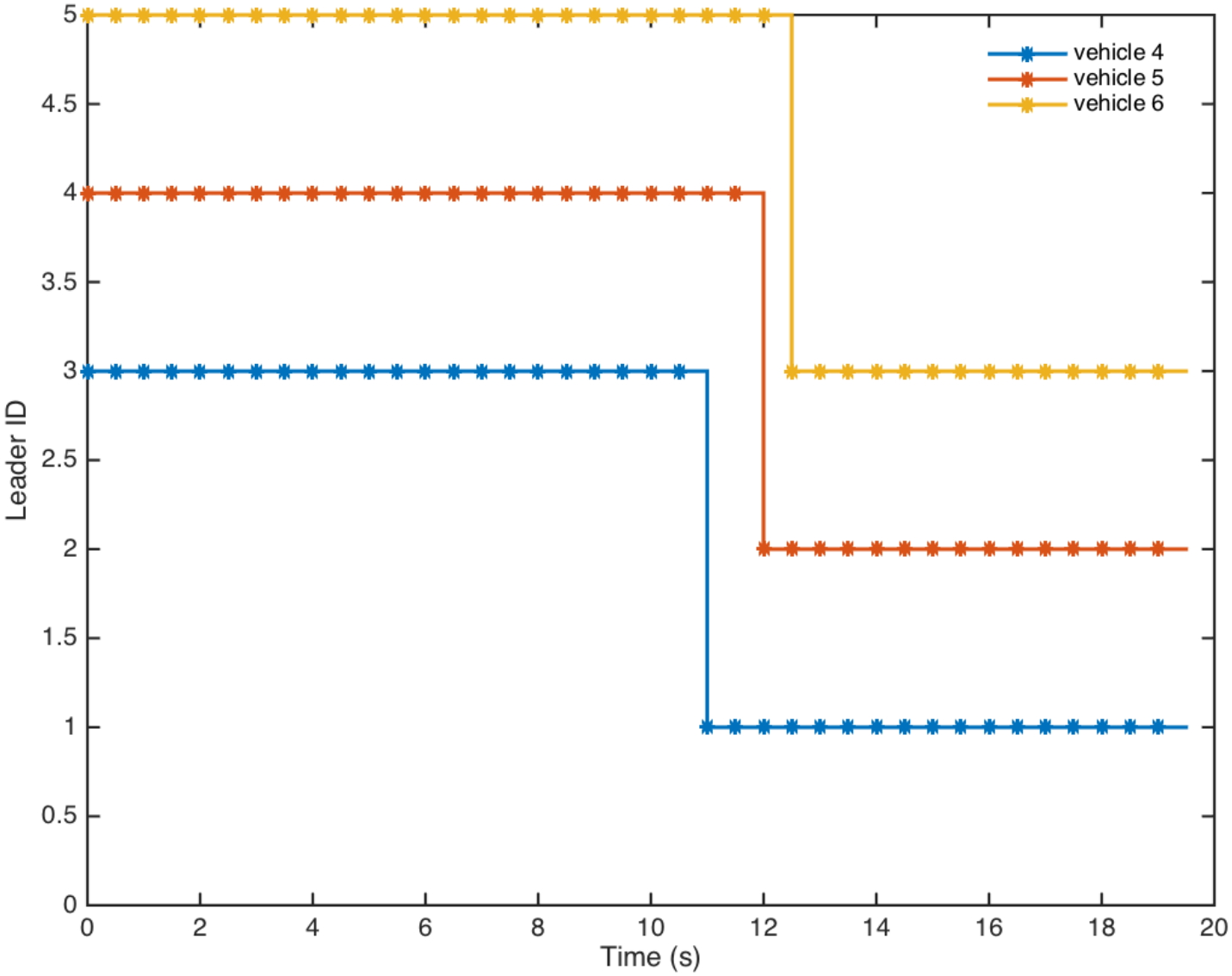
m.wang@tudelft.nl

Case 3: switching leader from crossing to following



- Initial distance to conflict point: [100, 105, 110, 115, 120, 125]
- Initial passing order: [1, 2, 3, 4, 5, 6]
- As vehicles pass the conflicting point, vehicles 4, 5, 6 should be able to switch leader from 3, 4, 5 to 1, 2 3 after passing conflict points respectively

Switching leader



Interacting with pedestrian

Assumptions

- Pedestrians make request at intersections at time t_k and at location x_0
- A fixed waiting time t_w before pedestrians are indicated to cross the road
- Pedestrian cross the intersection at normal walking speed, e.g. 1.4 m/s
- Vehicles pass the intersection after pedestrians complete the crossing

Adding constraints to the problem

Solution idea

- The CAVs conflicting with the pedestrian should yield sufficient (time) gap that allows the pedestrian crossing
- Identify the yielding vehicle i based on the predicted trajectory assuming no pedestrian and the crossing start time $t_k + t_w$
  - $\tilde{x}_i(t_k + t_w) < x_0$
- Add an additional constraint to the original problem:
  - $x_i(t_k + t_w + t_c + t_s) < x_0$

t_c: is the time needed for a pedestrian to cross the intersection.

t_s: some safety redundancy time after pedestrian crossing.

Traffic Signal Control with Connected & Automated Vehicles

Autonomous Vehicle Symposium 2017

Wan Li, Xuegang (Jeff) Ban

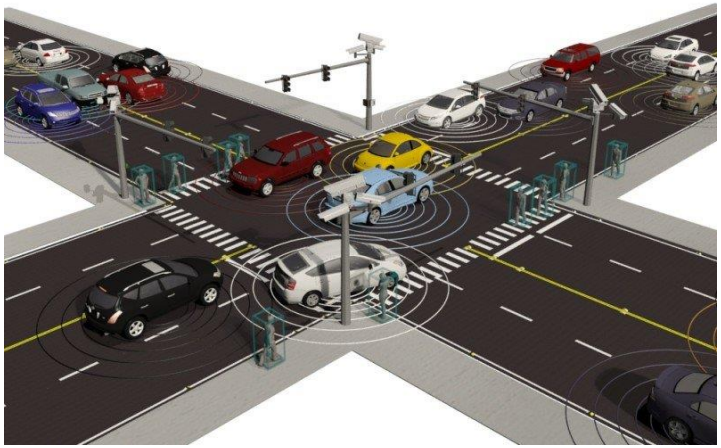
07/12/2017

intelligent Urban Transportation Systems
UNIVERSITY of WASHINGTON

Some Observations

New Technologies
(e.g., CAVs, ..)

Old Technologies (e.g., actuated control)



Light Traffic

Medium Traffic

Heavy Traffic

Objectives of Traffic Signal Control

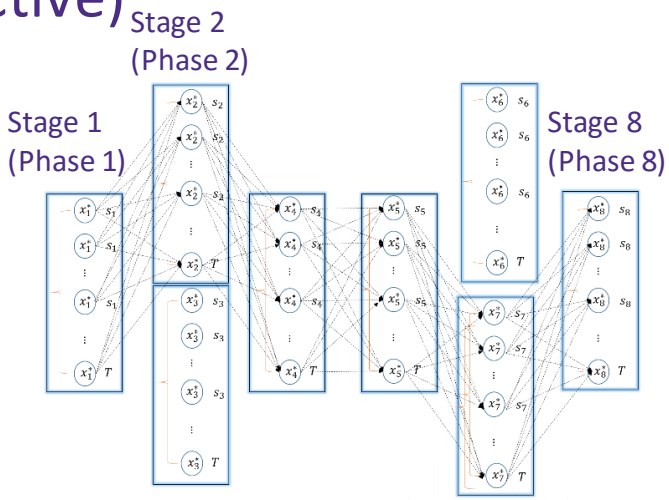
- Safety first & Mobility Second, with other objectives
- Many good design practices/principles to balance these objectives, e.g., ***dual ring diagram***
- Some existing CAV-based traffic signal design methods put mobility and/or other objectives over ***safety***.
- Traffic signals will still exist for foreseeable future; but may take a variety of forms

This Talk Is About …

- Traffic signal control under connected/automated vehicles (*CAVs*)
- Apply *dual ring diagram* design
- *Single* intersection: timing optimization
- *Multiple* intersections on a corridor: + offset optimization
- Currently assuming 100% CAV penetration, which can be relaxed (ongoing)
- Consideration of mobility and energy use of *individual* vehicles
- Overall methods: mixed integer nonlinear program (MINLP), with large dimension; reformulating as a DP after relaxation

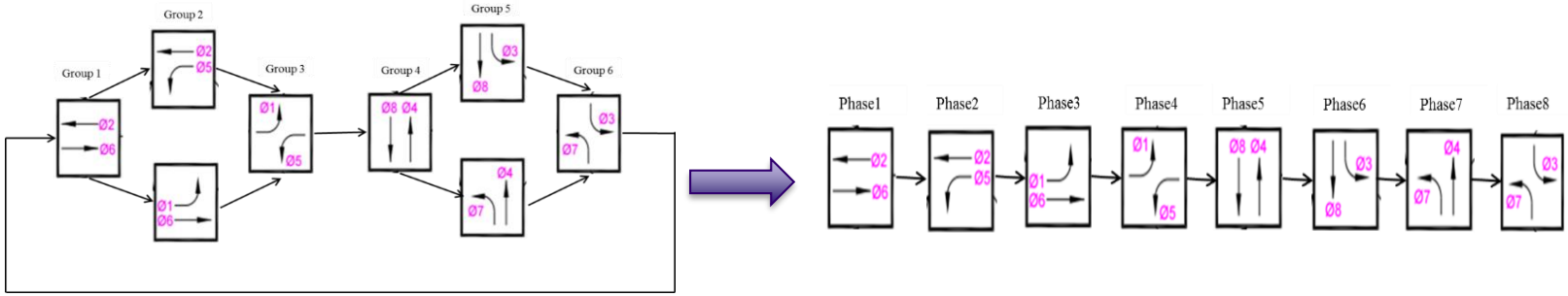
Dynamic Programming (DP) Formulation

- Well-known methods for signal control optimization (Sen and Head, 1997)
- Strictly speaking, signal optimization problem can NOT be formulated as a DP especially when individual vehicle mobility and energy use are considered.
- Vehicle mobility and energy use (objective) in a phase depend on not only the decision of the current phase but also the previous phases
- The objective is usually the total delay and/or energy use of all vehicles; approximation is possible (Sen and Head, 1997)



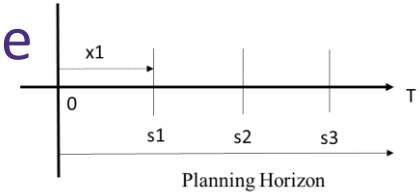
CV-Based Control for One Intersection

> Dual ring: 8 possible phases and their durations (could be 0)



> Can be formulated as a MINLP, with variables defined for each vehicle and each discrete-time instant (e.g., 1 sec).

> Approximated as a DP: the key is to approximate the objective of a stage (phase) as a function of the state and decision variables of the stage only



> Mobility (Feng et al., 2015); fuel consumption (Zhao et al., 2016; Li and Ban, 2016 & 2017)

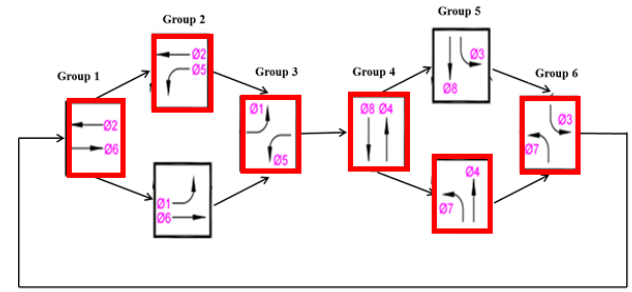
CV-Based Control for One Intersection

- **Fixed Cycle length (C)**: readily extended to signal coordination
- The fixed cycle length requirement will invalidate the DP formulation
- In Feng et al. (2015): formulating and solving a bilevel problem
- We propose a two-step method:
  - First step: end-stage cost to reduce the search space
  - Second step: branch-and-bound to find the optimal solution

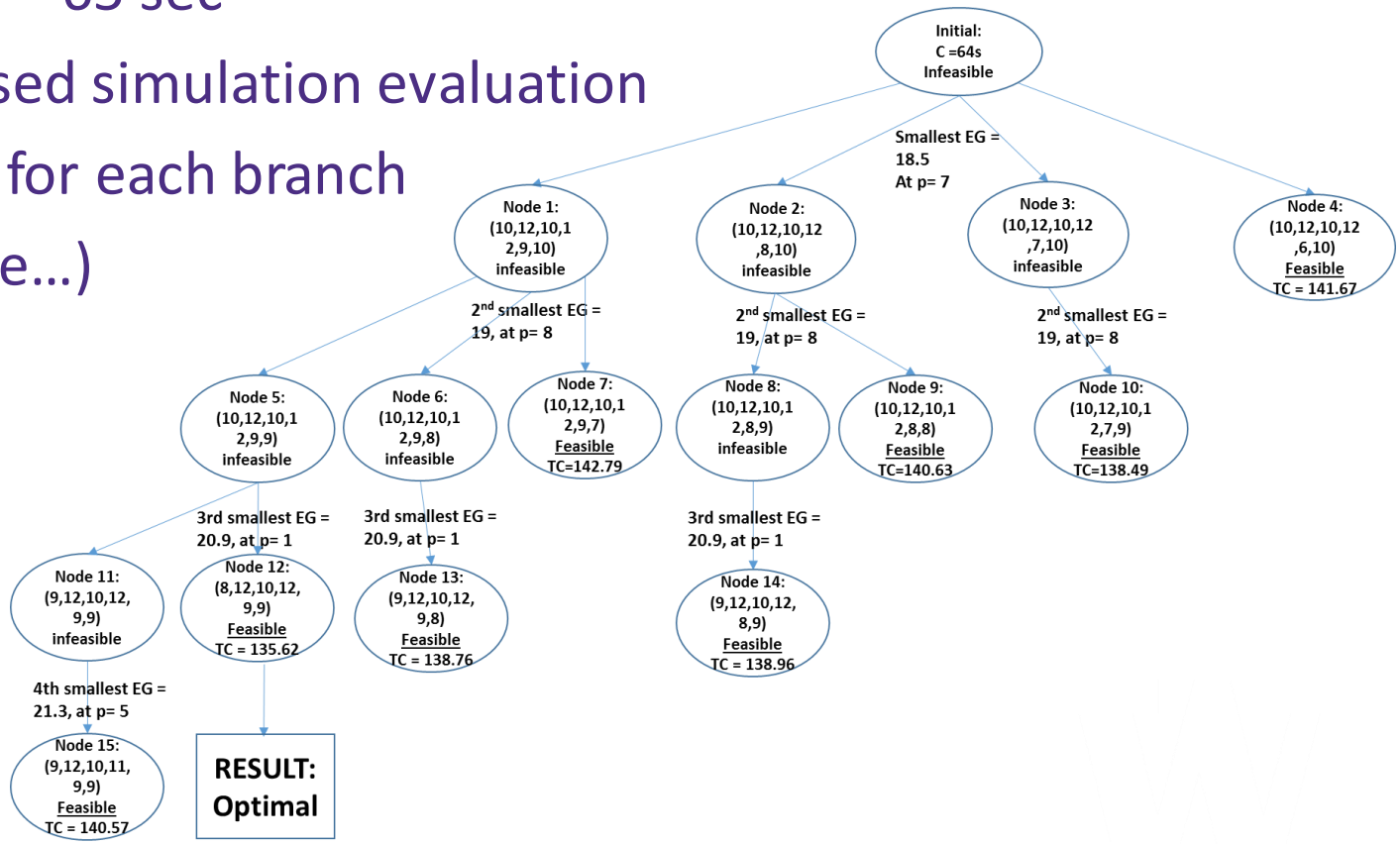
$$f_e = \begin{cases} 0, & if\ |C_e - C| < \sigma \\ w(C_e - C)^2, & otherwise \end{cases} \qquad C_e = \sum_{p=1}^{P} x_p$$

Example

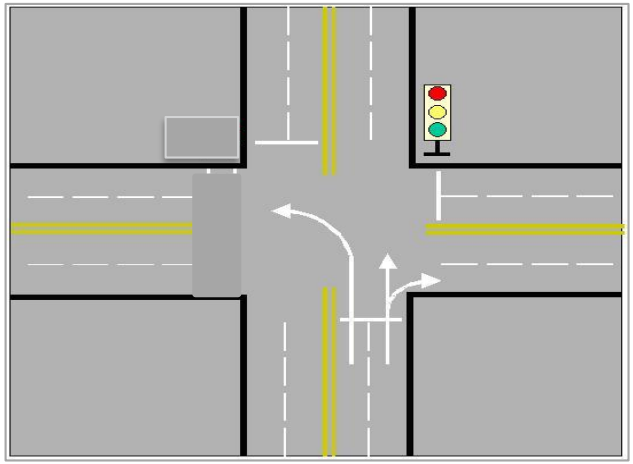
- Branch-and-Bound (C=60sec, σ=5)
- The first step produces a solution with C: 55 – 65 sec
- A IDM-based simulation evaluation is needed for each branch (takes time…)



x_p	10	12	10	12	10	10	64s > C = 60s
EG	20.9	27.4	22.3	21.3	18.50	19	TC = 129.4



Numerical Examples



- A single intersection
- Demand: VISSIM
  - Case I: 250 vph; Sedan
  - Case II: 500vph; Sedan
  - Case III: 800vph; Sedan.
  - Case IV: 250 vph; NS: EVs; WE: Bus
  - Case V: 500vph; NS: EVs; WE: Bus
  - Case VI: 800vph; NS: EVs; WE: Bus
- Total time span: 10 cycles
  - First 8 cycles: with demand
  - Last 2 cycles: without demand (cool down)

Numerical Examples

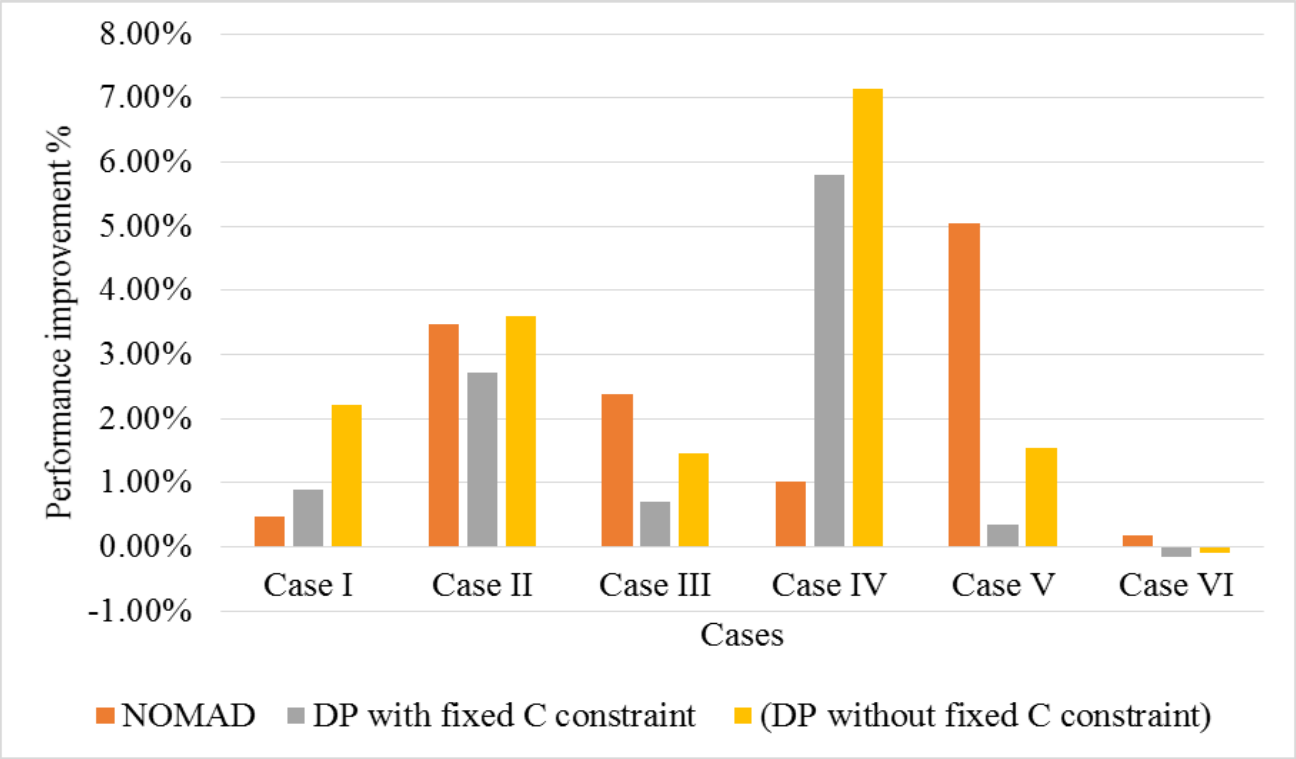
- 1. Cycle Length Optimization
  - Low demand (250 vph) : 60s
  - Medium demand (500 vph): 65s
  - High demand (800 vph): 120s
- 2. Compare optimal timing plans from different models
  - SYNCHRO (Actuated)
  - NOMAD (a *black-box* optimization method in Matlab)
  - DP
- 3. Implement optimal results from ALL models in IDM and compare the objectives

Numerical Examples

Model	Case I	Case II	Case III
	250 vph, sedan	500 vph, sedan	800 vph, sedan
1. SYNCHRO	143.55	359.53	953.8
2. NOMAD	142.87	347.03	931.19
3. DP with fixed C constraint (DP without fixed C constraint)	142.27 (140.37)	349.75 (346.58)	947.19 (939.87)

Model	Case IV	Case V	Case VI
	250 vph; NS: EVs; WE: Bus	500 vph; NS: EVs; WE: Bus	800 vph; NS: EVs; WE: Bus
1. SYNCHRO	228.14	581.6	1423.27
2. NOMAD	225.81	552.21	1420.82
3. DP with fixed C constraint (DP without fixed C constraint)	214.89 (211.85)	579.64 (572.59)	1425.58 (1424.66)

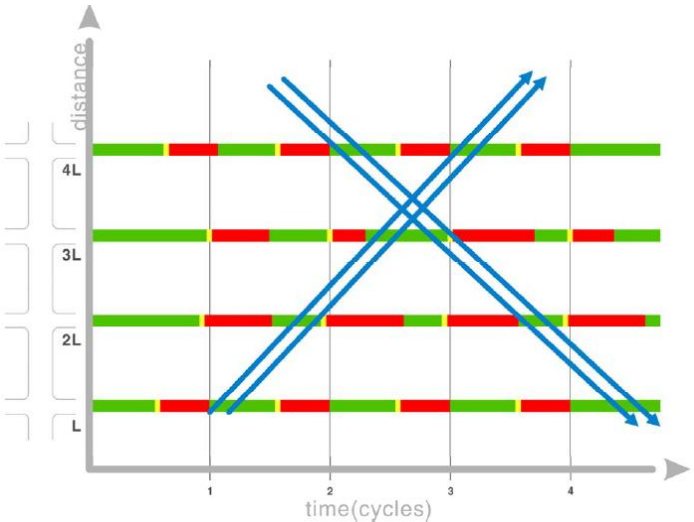
Numerical Examples



- DP method is always superior to SYNCHRO for all cases except case VI.
- DP performs better than NOMAD under low traffic demands (case I and IV)
- When the demand is medium or high, the performance improvement of DP to SYNCHRO is getting decreased from 7.14% to -0.16%.
- When the demand is high, the performances of the three methods are similar

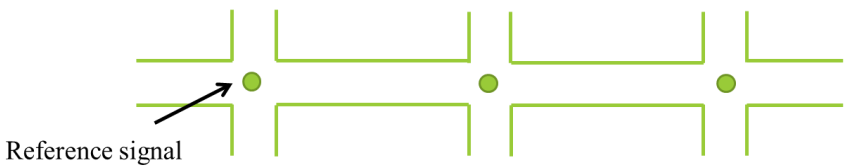
CV-Based Control for Multiple Intersections

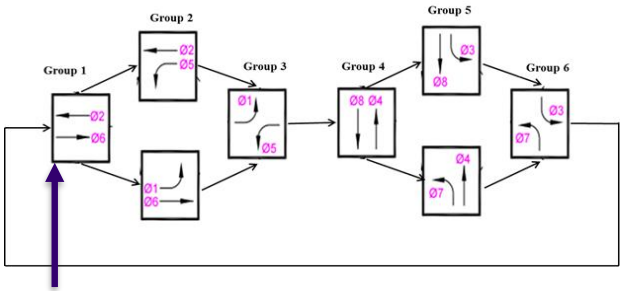
- **Coordination**
  - synchronize multiple intersections to enhance the operation of one or more directional movements in a system
  - **When to use coordination?**
    - √： **arriving** traffic formed by the release of vehicles from the upstream intersection
    - ×： **random** vehicle arrivals & unrelated to the upstream intersection operation



CV-Based Control for Multiple Intersections

- **Two - level optimization**
  - Intersection level: optimal phase split
  - Corridor level: optimal offset
- Guarantee fixed cycle length
- Offset reference point: start of phase group 1
- Need measurement of offset





Offset reference point

Corridor Level

- **Offset optimization – NOMAD**
  - Available information
    - Fixed cycle length – intersection level
    - Optimal phase timing for each intersection – intersection level
    - Vehicle trajectories – IDM
  - Objective: produce optimal offsets by minimizing delay
    - Vehicle traveling along the coordinated movement (main street).
    - Establish the connection between offsets and delay
- **Ongoing**

Summary of Findings (so far)

- Signal timing optimization models under the CV environment.
- Three methods:
  - SYNCHRO (Actuated)
  - NOMAD
  - DP: via an approximation method & a two-step method to solve the fixed cycle-length issue.
- DP can generate better performance than NOMAD under low traffic demands
- Different methods perform more similarly under high traffic demand

Current / Future Work

- CV-based optimization/coordination of traffic signals
- Varying penetration rates of CVs: approximating the trajectories of unequipped vehicles.
- Coupled vehicle and traffic signal (CVTS) control
  - *Traffic signal control*: optimizing timing plan and offets
  - *Vehicle control*: optimizing vehicle speeds/trajectories
  - Single intersection
  - Optimization/coordination of multiple intersections along a corridor

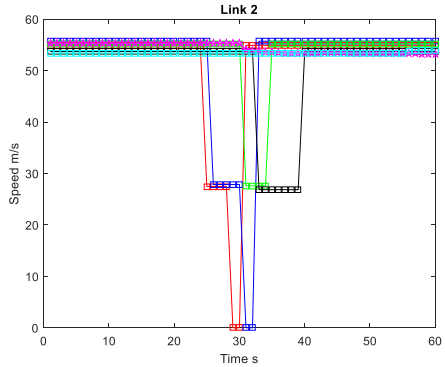
Thank You!

Contact: banx@uw.edu

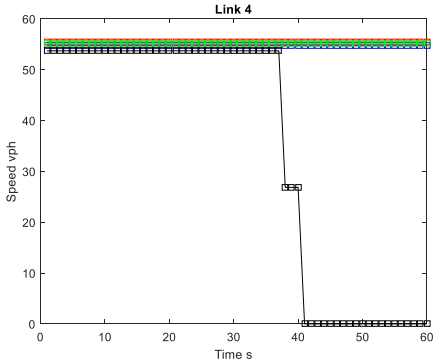
Backup Slides

Numerical Examples

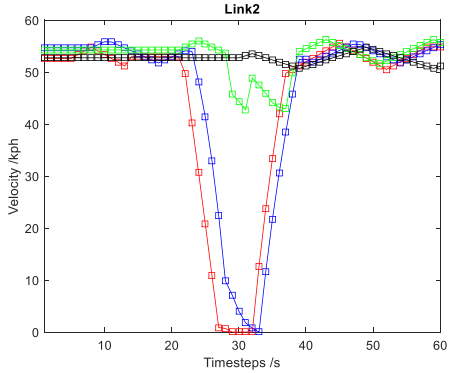
> Speed Approximation in DP



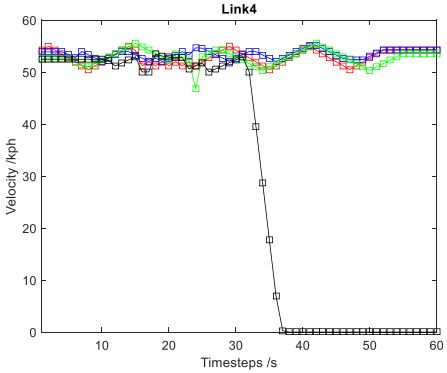
(a) **Approximated** Speed –N→W



(b) **Approximated** Speed – W→N



(c) **VISSIM** Speed – N→W



(d) **VISSIM** Speed – W→N

CV-Based Control for Multiple Intersections

> Corridor level – NOMAD

- Identify local time for intersection j , e.g., W→E direction:

$$t_j' = mod(t - O_j, cycle), \quad 0 \le t_j' \le \text{cycle}$$

mod : modulo operation.

- Identify the serving phase $\bar{k}$ by comparing t' with the optimal phase split generated from DP
- Identify the current signal status of intersection *j* at time *t*:

$$S_{j,\bar{k}}(t) = \begin{cases} 0, & if \sum_{k=1}^{k=\bar{k}-1} g_j^i \le t_j' \le \sum_{k=1}^{k=\bar{k}} g_j^i \\ 1, & otherwise \end{cases}$$

g_j^i: phase split of intersection *j* at cycle *i*, generated from DP

- Update the vehicle trajectories based on $S_{j,\bar{k}}(t)$ and IDM
- Update the delay and fuel consumption.

Numerical Results

- Consider 5 intersections, 10 cycles.
- 500 vph, all sedan
- DP: optimal phase splits; NOMAD: offset

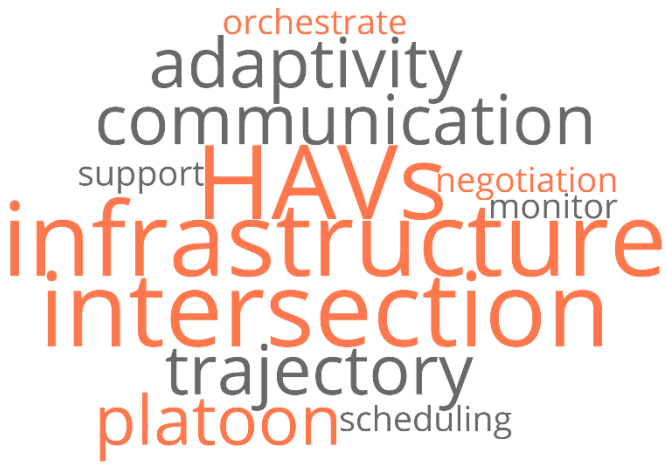
Intersection	Phase	Cycles										Offset	Cost Function
		1	2	3	4	5	6	7	8	9	10		
1	1	20	18	19	17	20	17	20	16	15	17	0	1747.49
	2	0	0	8	6	7	0	7	9	9	0		
	3	8	4	0	0	0	6	0	0	0	7		
	4	5	10	5	8	8	9	8	10	8	8		
	5	17	18	16	16	17	16	13	17	17	18		
	6	0	7	0	9	5	8	7	0	0	7		
	7	8	0	9	0	0	0	0	6	8	0		
	8	7	8	8	9	8	9	10	7	8	8		
2	1	17	18	19	17	16	14	17	21	17	15	22	
	2	0	9	0	0	0	9	7	0	8	9		
	3	6	0	5	6	8	0	0	6	0	0		
	4	9	9	9	9	9	10	8	5	9	10		
	5	16	17	15	16	16	19	17	18	16	14		
	6	8	0	9	8	6	6	8	8	0	7		
	7	0	5	0	0	0	0	0	0	7	0		
	8	9	7	8	9	10	7	8	7	8	10		
3	1	14	16	18	15	20	17	19	19	16	16	47	
	2	9	0	7	0	8	8	0	7	0	0		
	3	0	7	0	10	0	0	7	0	7	8		
	4	8	10	11	8	8	9	8	7	9	10		
	5	19	13	15	17	14	19	15	17	16	15s		
	6	7	9	5	5	6	0	9	8	8	0		
	7	0	0	0	0	0	5	0	0	0	7		
	8	8	10	9s	10	9	7	7	7	9	9		
…													

If all offsets =0, cost =**1786.14**. Reduce 2.2%.

CVTS for Single Intersection

- Xu, B., Ban, X., Bian, Y., Wang, J., Li, K., 2017. *V2I Based Cooperation between Traffic Signal and Approaching Automated Vehicles*. In *Proceedings of the 28th IEEE Intelligent Vehicles Symposium*, June 11-14th, 2017, Redondo Beach, California.
- The paper was selected for the **Best Paper Award** (2nd Prize) by the *IEEE Intelligent Vehicles Symposium*, 2017, which was selected from over 300 papers accepted by the Symposium
- Traffic signal control: Macro-level control for minimizing the delays of all vehicles
- Vehicle control: Micro-level control for minimizing the fuel consumption of each individual vehicle, given the travel time of the vehicle

Managing automated vehicles at signalized intersections



Dr. Jaap Vreeswijk
MAP traffic management, the Netherlands

Automated Vehicle Symposium 2017, 12 July 2017, San Francisco
Breakout 21: Connected and Automated Vehicles in Traffic Signal Systems

MAVEN is funded by the EC Horizon 2020 Research and Innovation Framework Programme, under Grant Agreement No. 690727

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Safe and connected automation

H2020 call MG3.6a - 2015

Specific challenge: Automated and progressively autonomous driving applications in road transport, actively interacting with their intelligent environment could provide an answer to the EU objective of reconciling growing mobility needs with more efficient transport operations, lower environmental impacts and increased road safety.

…

Automation in road transport should make best use of the evolution of Cooperative ITS and the benefits made available by satellite navigation systems, such as the increased accuracy and robustness.

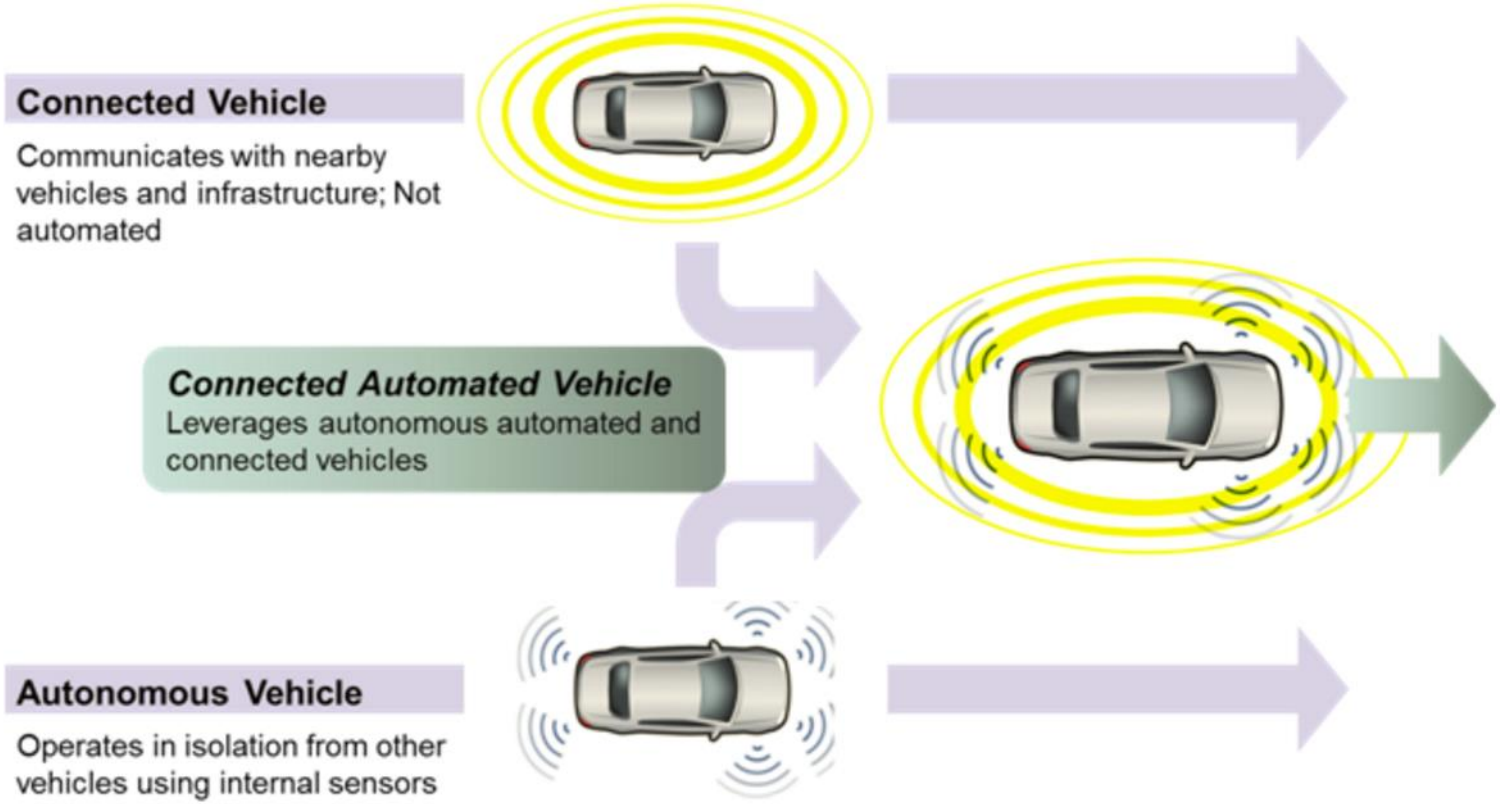
…

Novel transport, service and mobility concepts in real-life situations enabled by automated driving and connectivity. These services and concepts could benefit from cloud computing and data management and data aggregation techniques for road transport big data.

MAVEN is funded by the EC Horizon 2020 Research and Innovation Framework Programme, under Grant Agreement No. 690727

European Commission

Connected automation



ource: Thinkstock/USDOT

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An intelligent environment *with infrastructure*

- **Communication a precondition for highly automated driving**
- **'Public' traffic management and control remains necessary**
  - ✓ Safeguard societal interests
  - ✓ Setting constraints and rules
  - ✓ Intervene in case of oversaturated conditions

- **Offers new possibilities for optimisation in traffic management and control**
- **Three operational perspectives:**
  - ✓ Each vehicle individually (autonomous)
  - ✓ Vehicles part of a group process (e.g. platoon)
  - ✓ Vehicles part of a system process (e.g. intersection control)

MAVEN is funded by the EC Horizon 2020 Research and Innovation Framework Programme, under Grant Agreement No. 690727

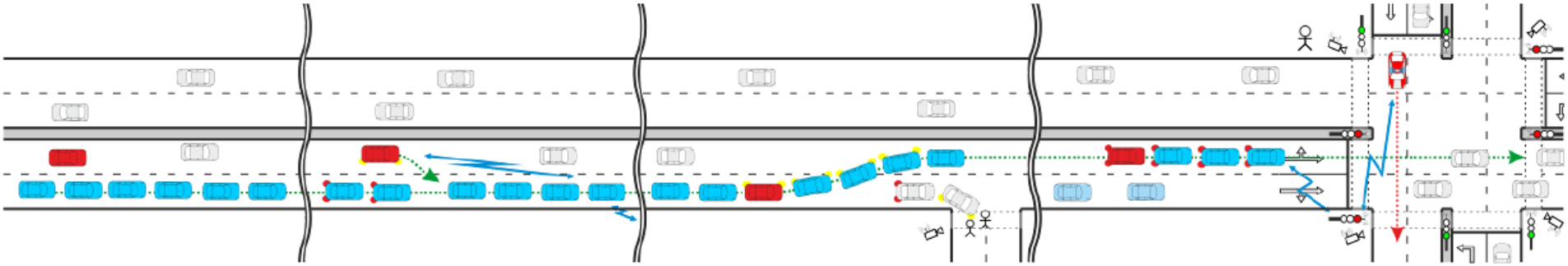
Project overview

- **Project title:**
  - ✓ Managing Automated Vehicles Enhances Network
- **Project period:**
  - ✓ 01-09-2016 ~ 31-08-2019
- **Funded by EC Horizon2020**
  - ✓ Budget: € 3.149.661,-
- **Consortium**
  - ✓ Nine partners from five countries: DE, NL, CZ, BE, UK

MAVEN is funded by the EC Horizon 2020 Research and Innovation Framework Programme, under Grant Agreement No. 690727

MAVEN project summary

- MAVEN will develop **management regimes** for highly automated driving in **urban areas**.
- Road infrastructure will be able to **monitor, support and orchestrate** vehicle and VRU movements to guide vehicles at **signalized intersections** and corridors in urban areas.
- Beyond the state-of-the-art of ADAS and C-ITS services like GLOSA, by adding cooperative **platoon organization** and signal plan negotiation to **adaptive traffic light control**.
- Develop suitable enables technologies, e.g. **communication protocols**, and test and validate via simulation and real-world prototype (ITS-G5 based).



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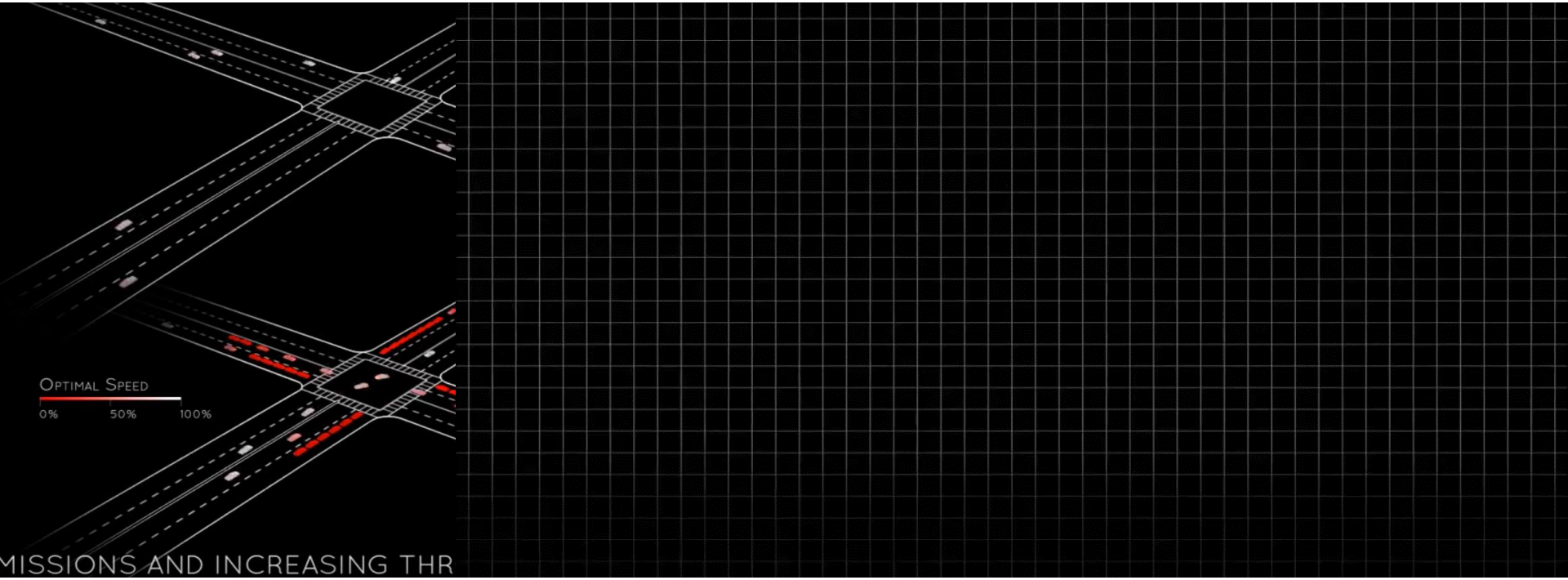
Virtual traffic light controller



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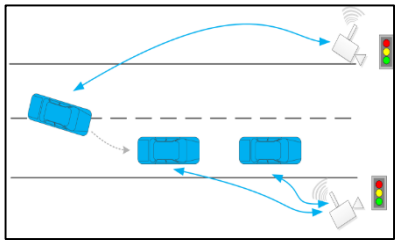
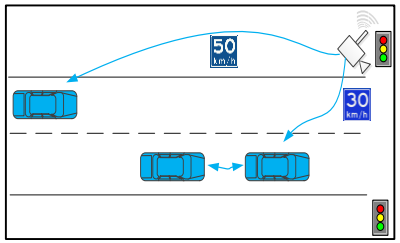
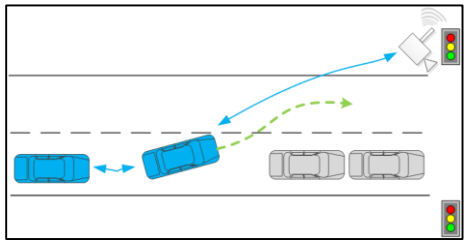
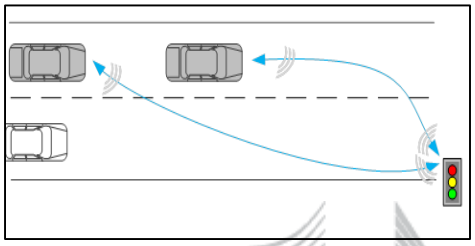
Infra-initiated and/or infra-assisted

- **Platoon management (group process)**
  - ✓ Forming, joining, progression, leaving, breaking a platoon
- **Infrastructure-to-vehicle interactions (system process)**
  - ✓ Negotiation (signal timing vs. arrival pattern), speed advisory, lane advisory
- **Traffic control optimization (and scheduling)**
  - ✓ Signal optimization, priority management, queue estimation, green wave
- **Conventional traffic and vulnerable road users**
  - ✓ Detection of non-cooperative vehicles, VRUs, emergency situations









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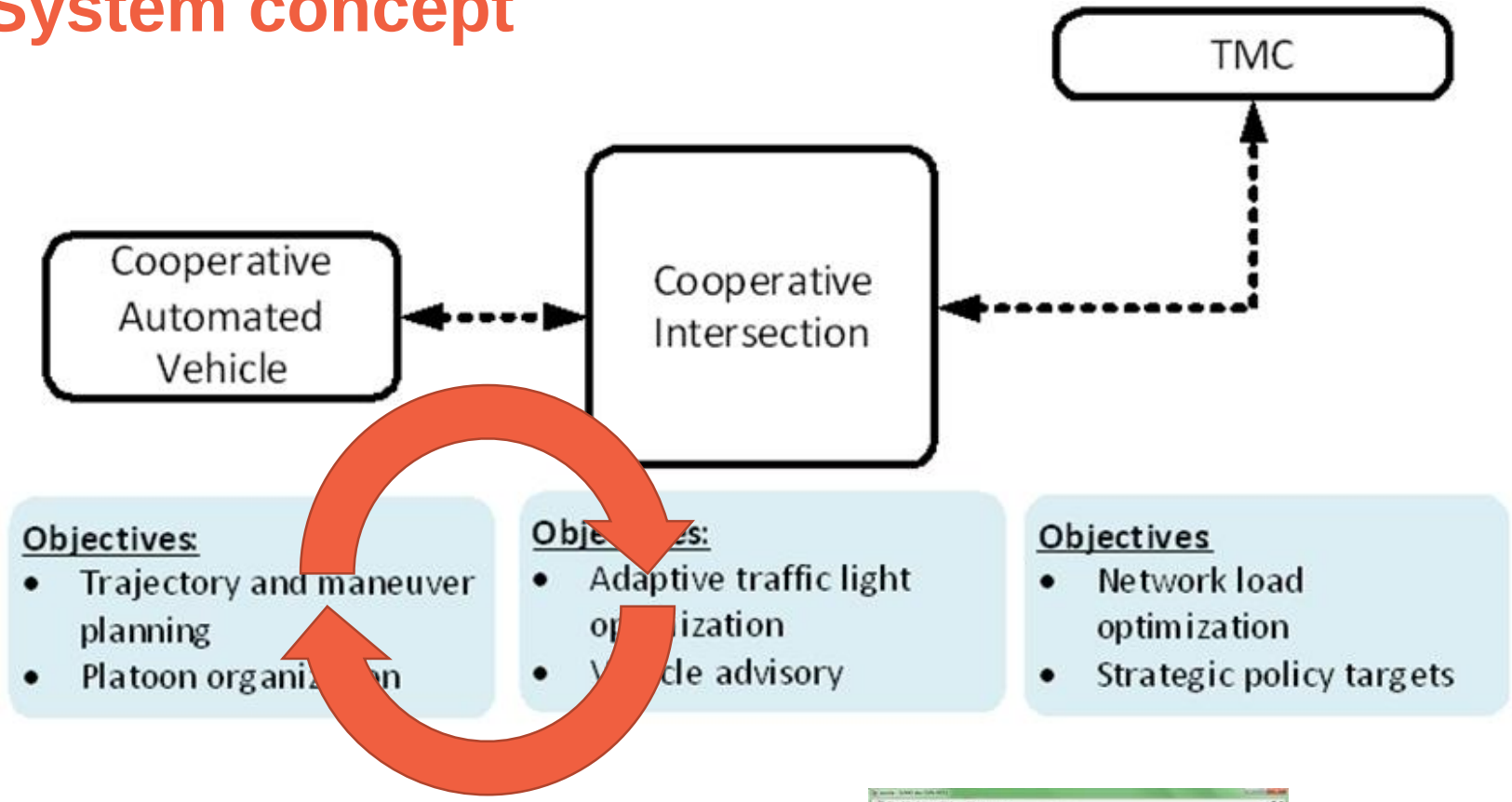
System concept



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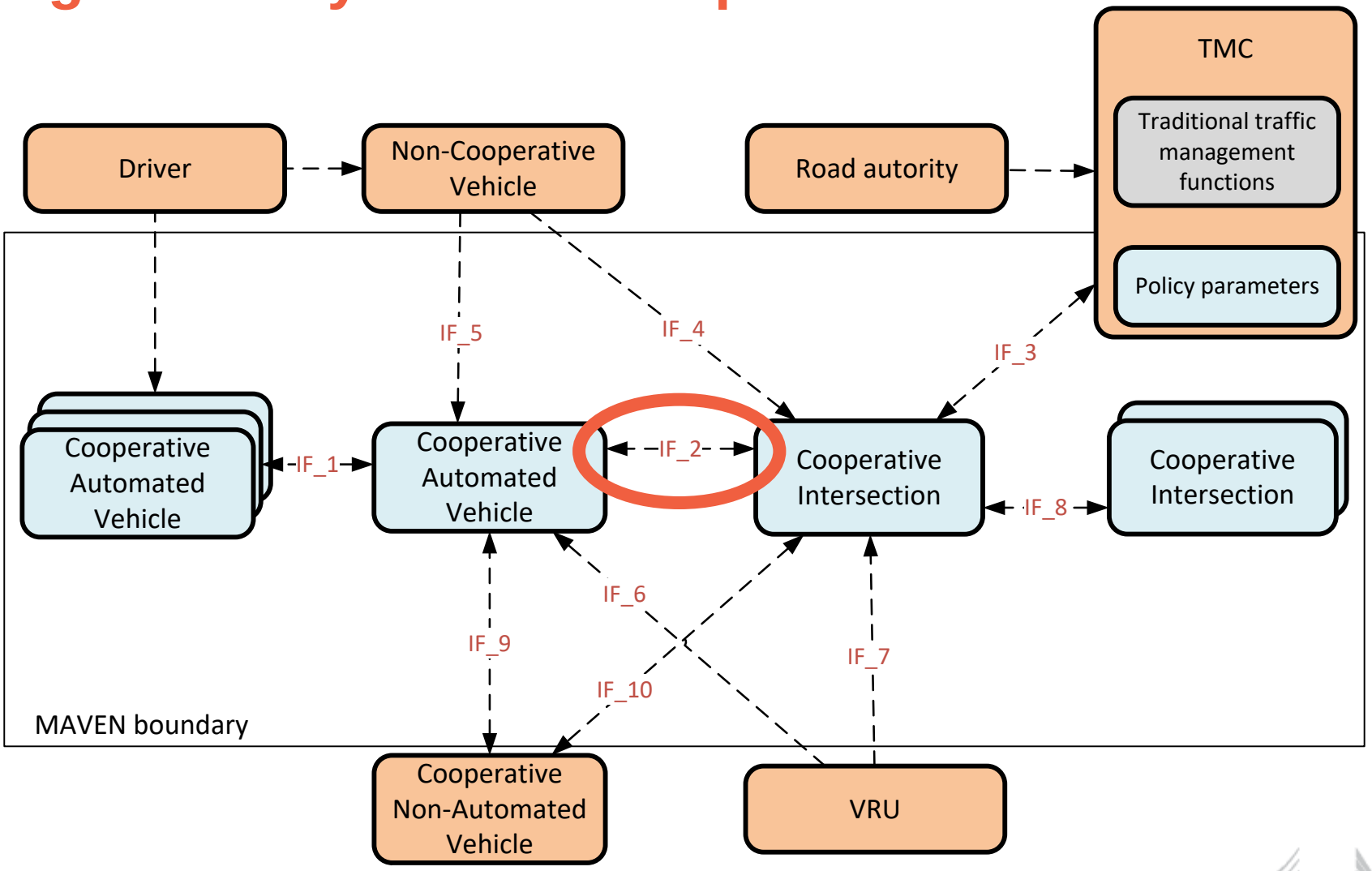
High-level system decomposition



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Necessary V2X extensions

- **V2I – e.g. Cooperative Awareness Message (CAM)**
  - ✓ Planned manoeuvre (intention);
  - ✓ Desired speed range;
  - ✓ Platoon properties (size, length, roles, speed, headway, composition, etc.);
  - ✓ Acknowledgments of intentions and compliance (negotiation).

- **I2V – e.g. Signal Phase and Timing Message (SPAT) or new message (?)**
  - ✓ Differentiated speed advisory;
  - ✓ Lane advisory;
  - ✓ Appropriate headway;
  - ✓ Maximum platoon length or prohibition;
  - ✓ Feasible level of automated driving.

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Transferability to Truck Platooning

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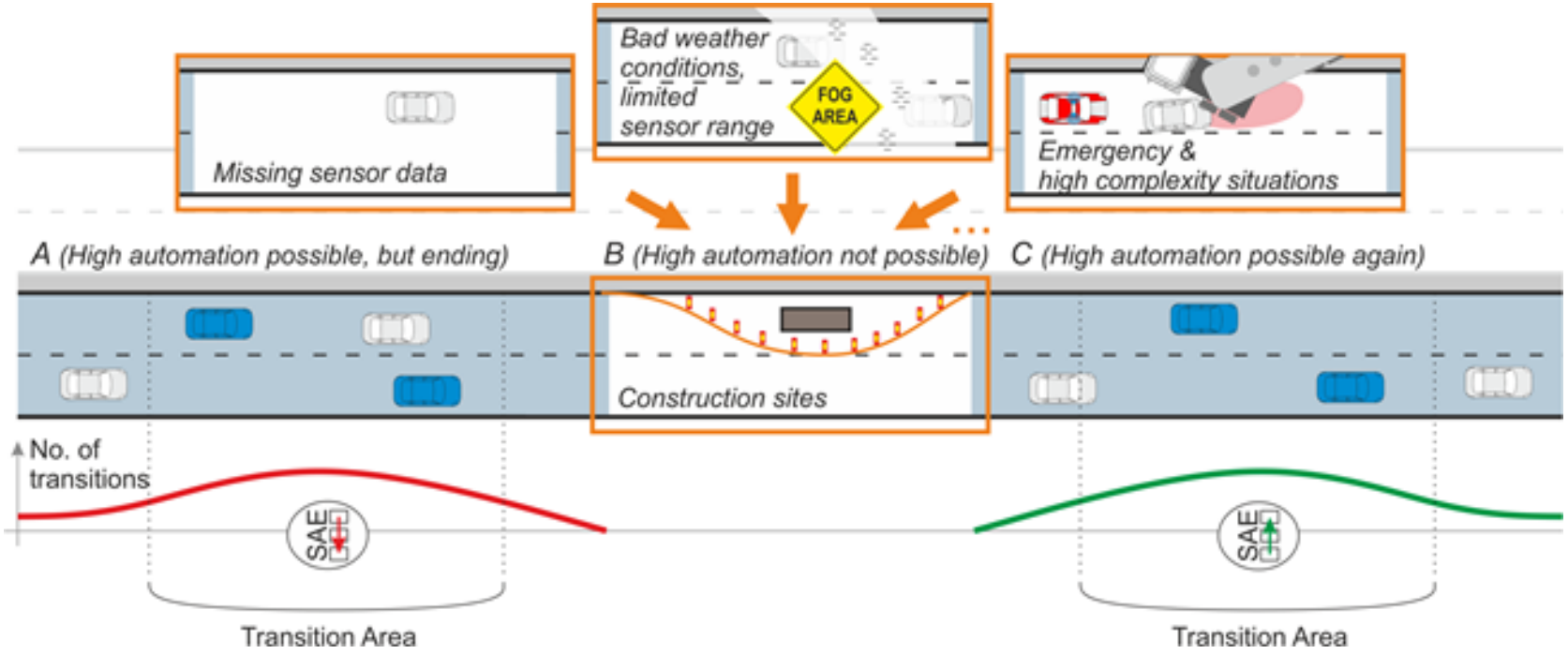
Transferability to transition areas



TransAID project (H2020)

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To conclude

- Infra-assistance for highly automated driving
  - ✓ Managing Automated Vehicles Enhances Network (MAVEN)
  - ✓ Transition Areas for Infrastructure-Assisted Driving (TransAID)
  - ✓ Truck Platooning (Real-Life Cases Program)

- A necessity but also a new dimension of Traffic Management and Control
  - ✓ Explicit intervention (control)
  - ✓ Implicit response (inform)

- Many ideas and concepts, equal amount of questions: explorative research!

- Great interest (local) road authorities in guidelines and broader city mobility context

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mobile.TUM.2017 4-5 July 2017 Munich, Germany

MAVEN

Managing Automated Vehicles Enhance Network

HORIZON 2020

The 3-year EU-funded MAVEN project aims to develop solutions for managing level-4 HAVs at (urban) signalized intersections. It will develop algorithms for infrastructure-initiated guidance of HAVs using negotiation protocols between vehicles and the infrastructure. Iteratively, HAVs receive advice and/or commands from the road infrastructure to adjust their trajectory and maneuvering policies, while the infrastructure dynamically adapts the traffic light timing of single or multiple signalized intersections based on the anticipated vehicle arrival pattern. The MAVEN project will build a system prototype that will be used both for field tests and modelling.

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orchestrate adaptivity communication support HAVs negotiation monitor infrastructure intersection trajectory platoon scheduling

USE CASES

- I2V interactions
  - Negotiation (signal timing vs. arrival pattern)
  - Speed change advisory
  - Lane change advisory
- Platoon management
  - Forming
  - Joining
  - Progression
  - Leaving
  - Breaking a platoon
- Traffic controllers optimization
  - Signal optimization
  - Priority management
  - Queue estimation
  - Green wave
- Conventional traffic and VRUs
  - Detection of non-cooperative vehicles
  - VRUs
  - Emergency situations

PROJECT CONSORTIUM

DLR, dynniq energising mobility, HYUNDAI MOTOR GROUP, MAP TRAFFIC MANAGEMENT, TomTom, CTU, POLIS, ROYAL Borough of GREENWICH, Gemeente Helmond

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MAP TRAFFIC MANAGEMENT
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AVS Symposium

The Capacity and Delay Implications of CAV at Signalized Intersections and How They Can be Accounted For in the Highway Capacity Manual Approach

Erik Ruehr, Alexander Skabardonis

San Francisco, July 12, 2017

Problem Statement

- **Signalized Intersection Capacity and Operational Performance**
  Control settings/strategy
  Vehicle characteristics
  Communications

- **Highway Capacity Manual Procedures**
  Use of "adjustment factors"
  Example: Critical Intersection control strategy improves intersection capacity by 7%
  Based on field data

- **CAVs**
  Opportunities (examples)
  Impact of penetration rates
  Luck of field data

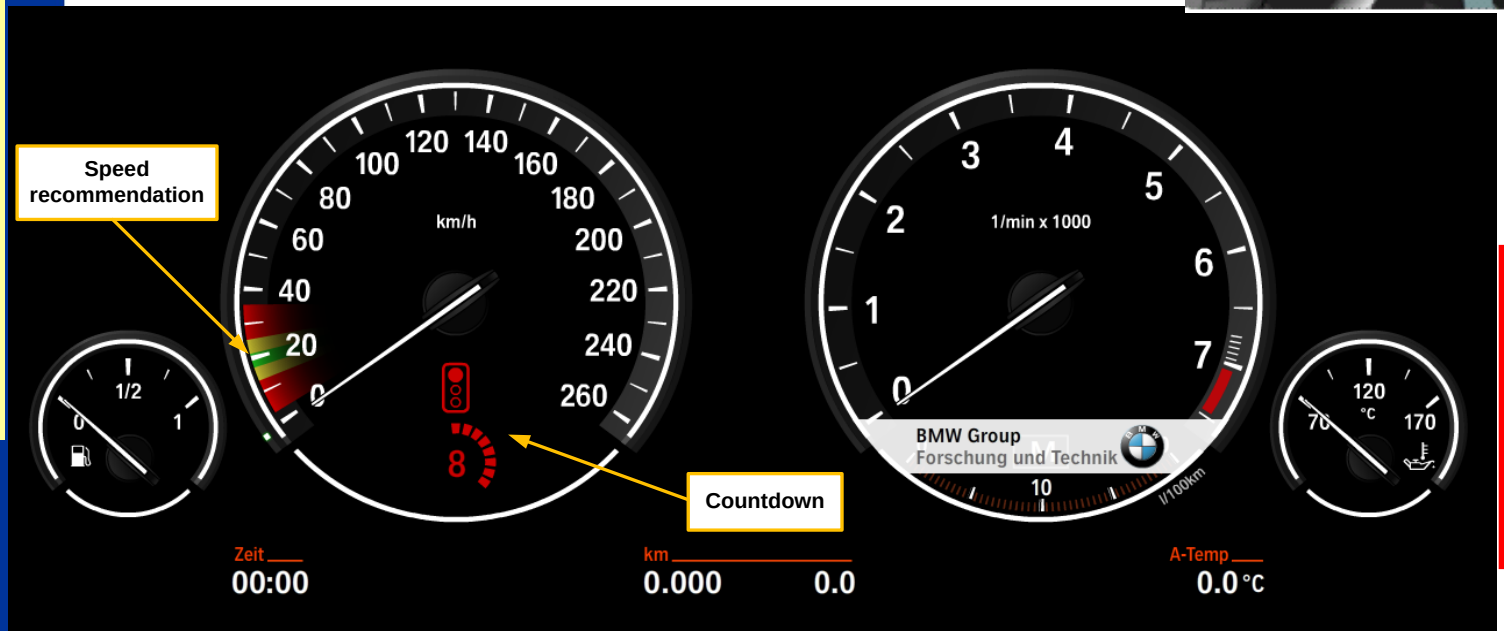
CV & Traffic Signals: Eco-Driving

Messages

"Here I am"

Signal Phase & Timing (SPaT)

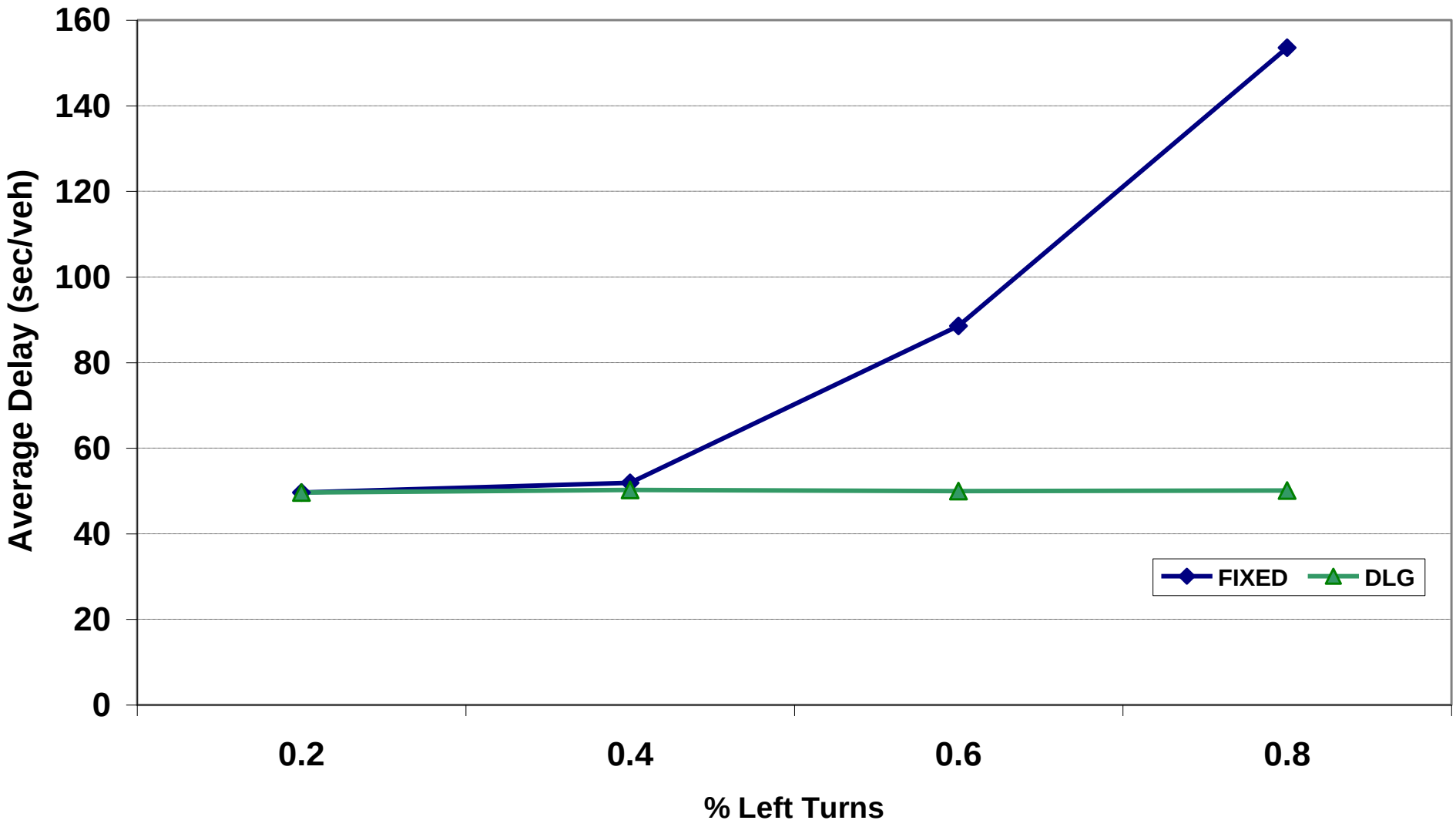
Application: Dynamic Speed Advisory (source: UC & BMW)



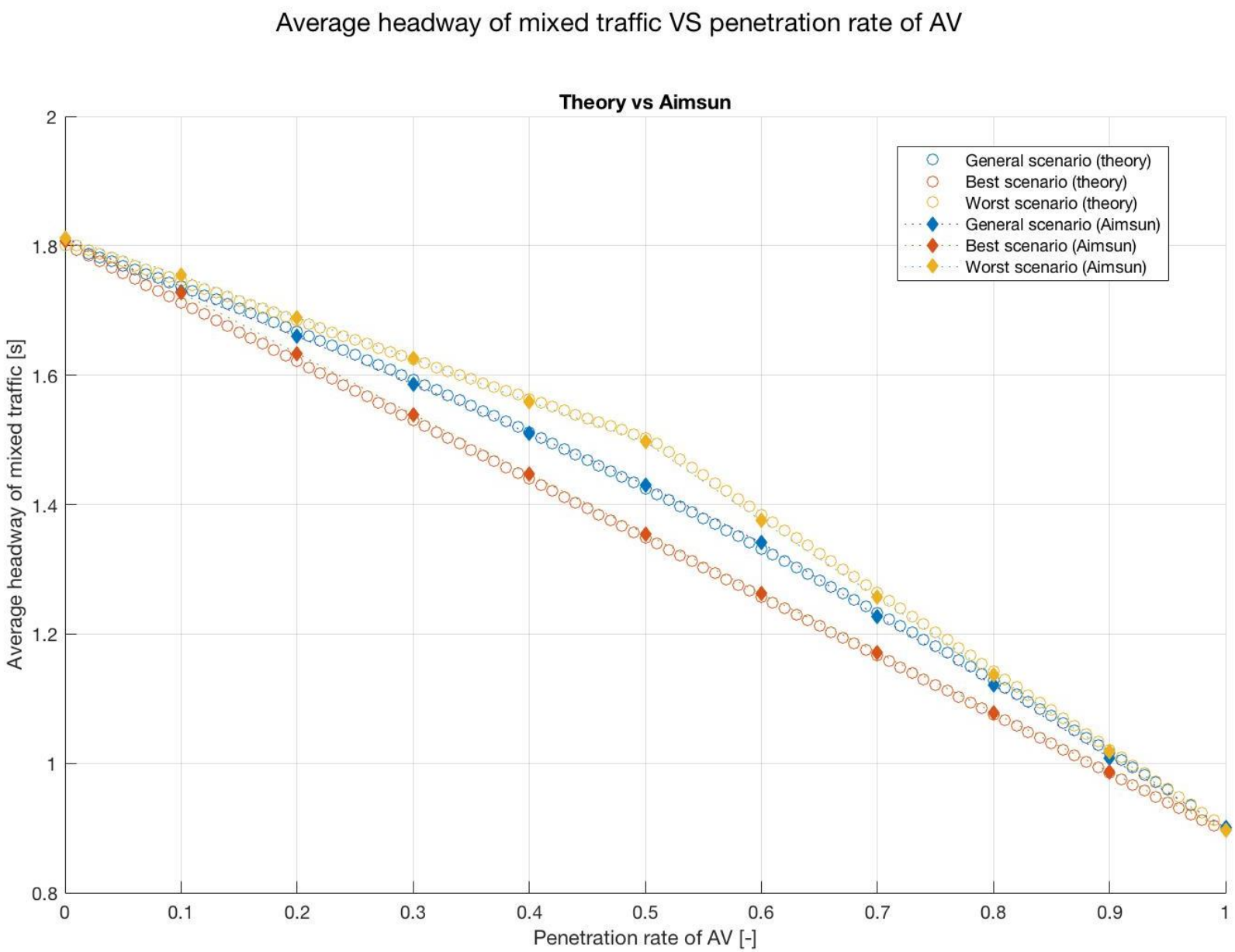
14% Reduction in Fuel Use

Delay Savings

CAV & Traffic Signals: Dynamic Lane Grouping



CAVS & Traffic Signals: Saturation Headway



HCM Intersection Capacity Analysis Methodology

- **Observe Operations to Determine Appropriate Parameters**
- **Data Collection**
- **Data Analysis to Determine Sensitivity of Input Parameters**
- **Develop Model**
  Analysis supplemented by Simulation
- **Calibrate Model based on Observed Data**
- **Validate Model**

- **HCM procedures**
  Planning (*simple*) and Operations (*complicated)*

Intersection Capacity factors Affecting CAVs

- **Saturation Flow Rate**
- **Lost Time**
- **Signal Settings**
  green time, cycle length
- **Proportion of Vehicles Arriving on Green**
- **Approach Speed**

Opportunities

- **Provide advance information on signal operations to CAVs**
- ***SPaT***
- ***Dynamic lane allocation***

- **Reduce lost time**

- **Increase saturation flow rate**

- **Increase vehicle arrivals on green**

Challenges

- **Effect of advance information on CAVs is unknown until tested**

- **Operational Characteristics of CAVs not yet determined**

- **Impacts on intersection capacity and performance depend on CAVs penetration rate (*will change over time*)**

- **Intersection capacity may decrease for *autonomous* vehicles because of security concerns**

同济大学交通运输工程学院
COLLEGE OF TRANSPORTATION ENGINEERING
TONGJI UNIVERSITY

AUTOMATED VEHICLES SYMPOSIUM 2017
USERS. VEHICLES. INFRASTRUCTURE.

OPTIMIZATION OF SPATIAL–TEMPORAL RESOURCES FOR ISOLATED INTERSECTION IN CAV ENVIRONMENT

Wanjing Ma 馬万经 Huizhao Tu

College of Transportation Engineering
Tongji University

Outline

1. **Motivation**
2. **Control Framework**
3. **Models**
4. **Examples and discussion**
5. **Conclusion**

1. Motivation

Four categories of intersection control methodology

1. Stage-based approach (Webster, 1958)
2. Group-based approach (Heydecker, 1987)
3. Lane-based approach (Wong, 2003)

4. Automated vehicle-based approach :

- Automated Intersection Management (AIM) (Dresneer and Stone, 2004)
- Cooperative Vehicle Intersection Control (CVIV) (Rakha et al., 2011)

1. Motivation

Purpose

The objective of this research is to propose a control method that **can minimize the total delay** in an automated and connected vehicle environment **without explicitly using lane marking and traffic light.**

2. Control Framework

Assumptions

(1)Our research uses the automated vehicle technology as implement measure.

(2)The traffic flow theory of our control is Triangular Fundamental Diagram.

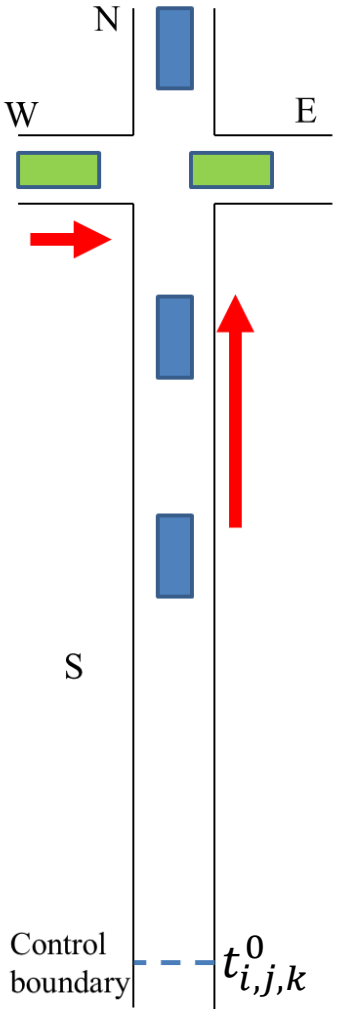
(3)The demand of traffic flow approaching the intersection is lower than the capacity of road segment upstream the intersection.

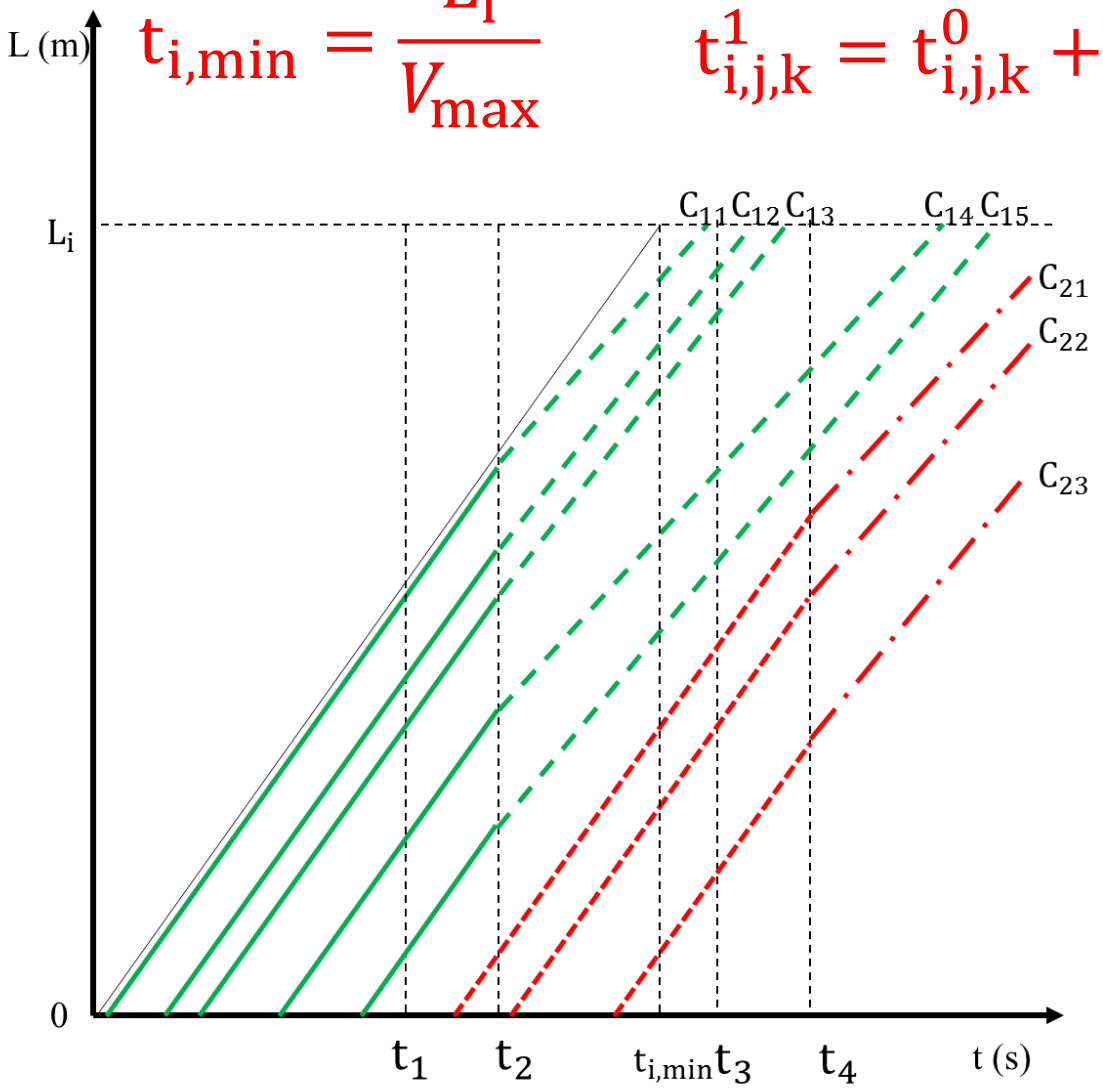
(4)There is no overtaking in the same turn movement before the vehicles depart the intersection.

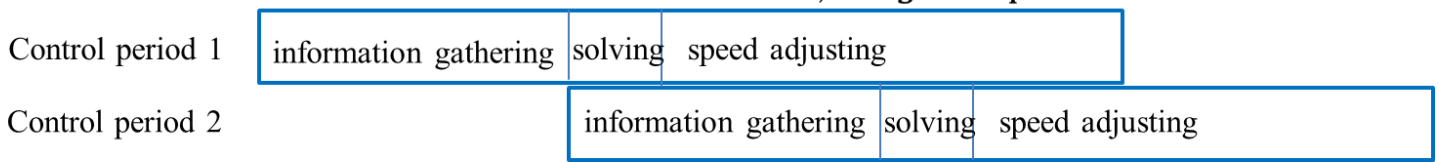
2. Control Framework

$$t_{i,min} = \frac{L_i}{V_{max}}$$

$$t^1_{i,j,k} = t^0_{i,j,k} + t_{i,min} + d_{i,j,k}$$

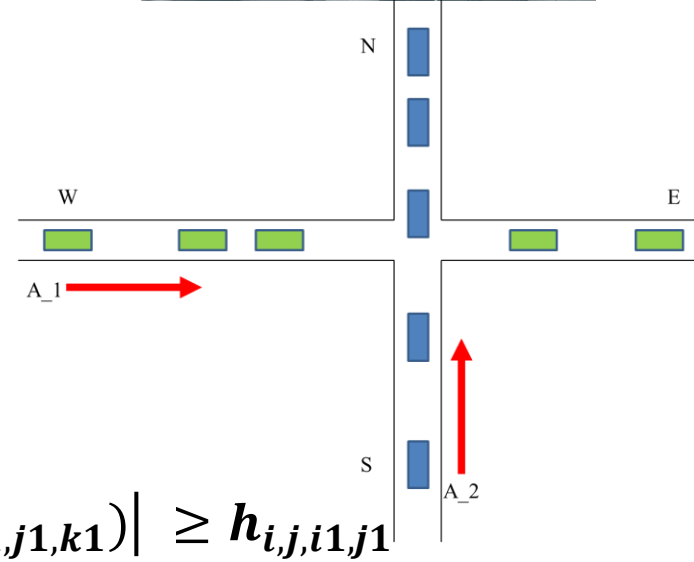






3. Models

3.1 Parallel model



$$\min f = \sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K_{i,j}} \mu_{i,j,k} \cdot d_{i,j,k}$$

Subject to:

(1) $d_{i,j,k} \geq 0$

(2) $\boldsymbol{(t^0_{i,j,k+1} + d_{i,j,k+1}) - (t^0_{i,j,k} + d_{i,j,k}) \geq h_{i,j,i,j}}$

(3) $t^0_{i,j,1} + t_{i,min} + d_{i,j,1} - t^1_{i,j,0} \geq h_{i,j,i,j}$

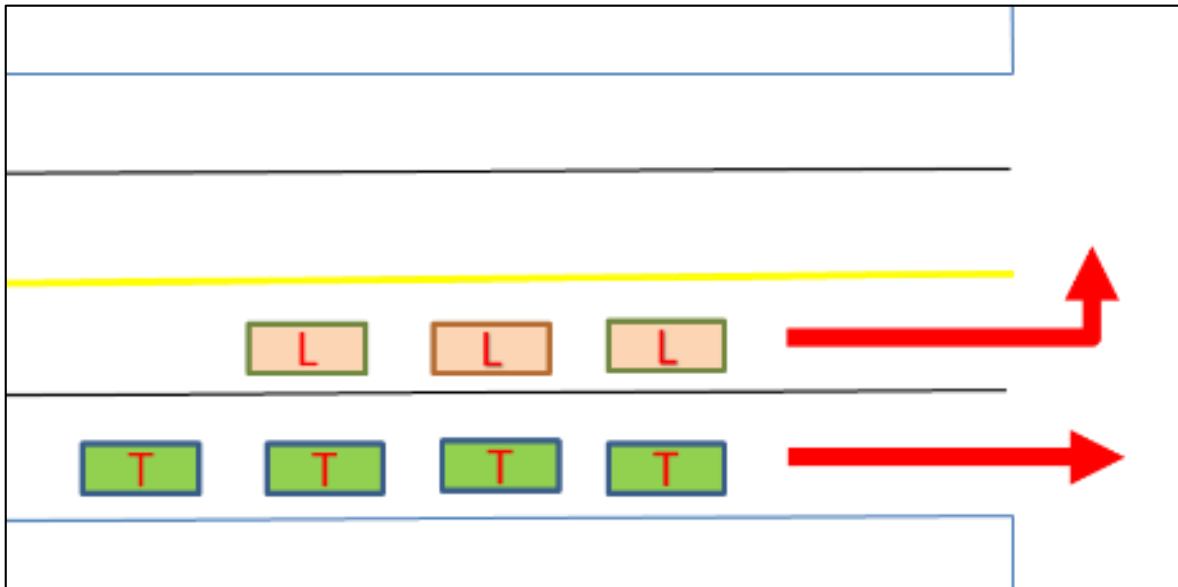
(4) $\boldsymbol{\left|(t^0_{i,j,k} + t_{i,min} + d_{i,j,k}) - (t^0_{i1,j1,k1} + t_{i1,min} + d_{i1,j1,k1})\right| \geq h_{i,j,i1,j1}}$

(5) $\left|(t^0_{i,j,0} + t_{i,min} + d_{i,j,0}) - t^1_{i1,j1,0}\right| \geq h_{i,j,i1,j1}$

(6) $arm_i = \sum_{j=1}^{N_i} arm_{i,j}$

(7) $arm_{i,j} \geq 1$

(8) $\boldsymbol{h_{i,j,i,j} = \frac{h^{one\ lane}_{i,j,i,j}}{arm_{i,j}}}$



3. Models

3.2 Serial model

$$\min f = \sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K_{i,j}} \mu_{i,j,k} \cdot d_{i,j,k}$$

Subject to:

$$d_{i,j,k} \geq 0$$

$$(t^0_{i,j,k+1} + d_{i,j,k+1}) - (t^0_{i,j,k} + d_{i,j,k}) \geq h_{i,j,i,j}$$

$$t^0_{i,j,1} + t_{i,min} + d_{i,j,1} - t^1_{i,j,0} \geq h_{i,j,i,j}$$

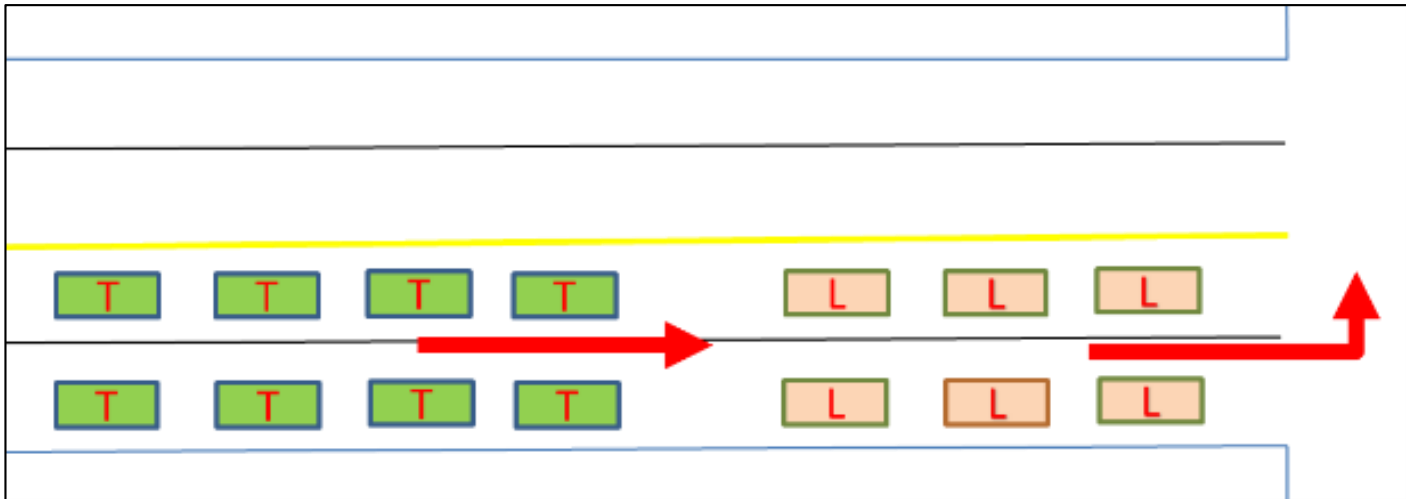
$$\left|(t^0_{i,j,k} + t_{i,min} + d_{i,j,k}) - (t^0_{i1,j1,k1} + t_{i1,min} + d_{i1,j1,k1})\right| \geq h_{i,j,i1,j1}$$

$$\left|(t^0_{i,j,0} + t_{i,min} + d_{i,j,0}) - t^1_{i1,j1,0}\right| \geq h_{i,j,i1,j1}$$

$$\boldsymbol{arm_{i,j} = arm_i}$$

$$\boldsymbol{h_{i,j,i,j} = \frac{h^{one\ lane}_{i,j,i,j}}{arm_i}}$$

$$\boldsymbol{h_{i,j,i,j1} = h^{min}_{i,j,i,j1}}$$



3. Models

3.3 Extended model

$$\min f = \sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K_{i,j}} \mu_{i,j,k} \cdot d_{i,j,k}$$

Subject to:

$$d_{i,j,k} \geq 0$$

$$(t^0_{i,j,k+1} + d_{i,j,k+1}) - (t^0_{i,j,k} + d_{i,j,k}) \geq h_{i,j,i,j}$$

$$t^0_{i,j,1} + t_{i,\min} + d_{i,j,1} - t^1_{i,j,0} \geq h_{i,j,i,j}$$

$$\left|(t^0_{i,j,k} + t_{i,\min} + d_{i,j,k}) - (t^0_{i1,j1,k1} + t_{i1,\min} + d_{i1,j1,k1})\right| \geq h_{i,j,i1,j1}$$

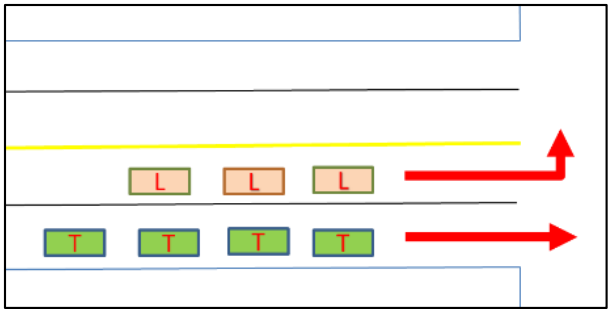
$$\left|(t^0_{i,j,0} + t_{i,\min} + d_{i,j,0}) - t^1_{i1,j1,0}\right| \geq h_{i,j,i1,j1}$$

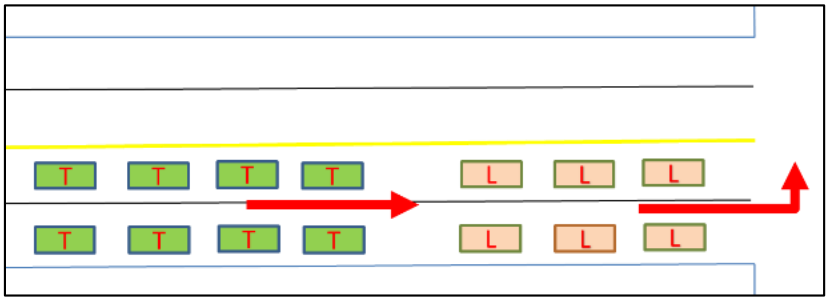
$$\boldsymbol{arm_i = arm_i \times (1-\theta) + \theta \times \sum_{j=1}^{N_i} arm_{i,j}}$$

$$\boldsymbol{arm_{i,j} \geq \theta}$$

$$\boldsymbol{h_{i,j,i,j} = \frac{h^{one\ lane}_{i,j,i,j}}{arm_{i,j} \times \theta + arm_i \times (1-\theta)}}$$

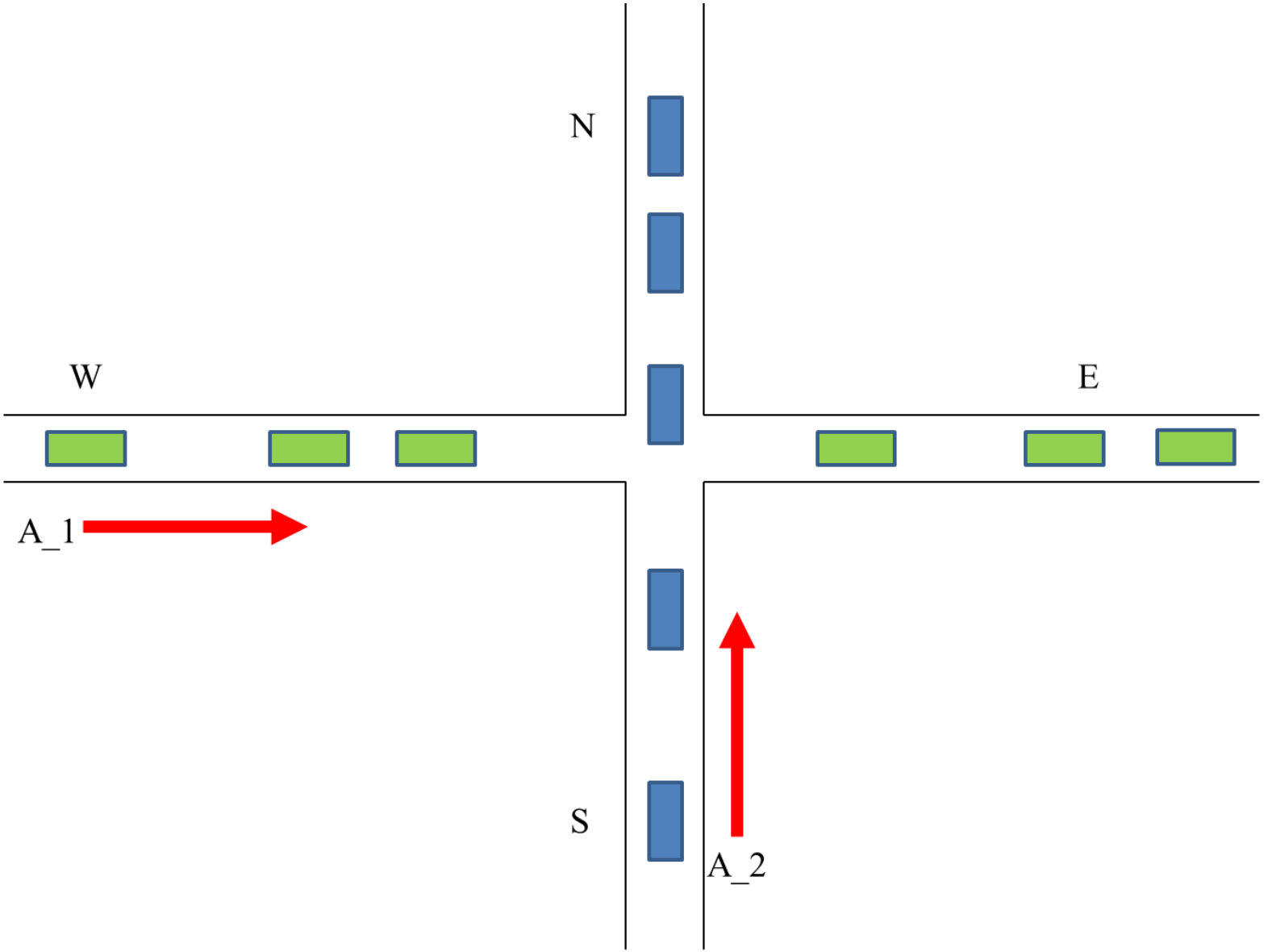
$$\boldsymbol{h_{i,j,i,j1} = h^{min}_{i,j,i,j1} \times (1-\theta)}$$





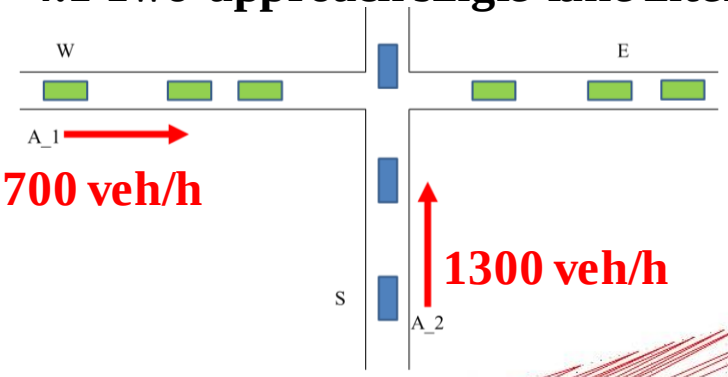
4. Examples and discussion

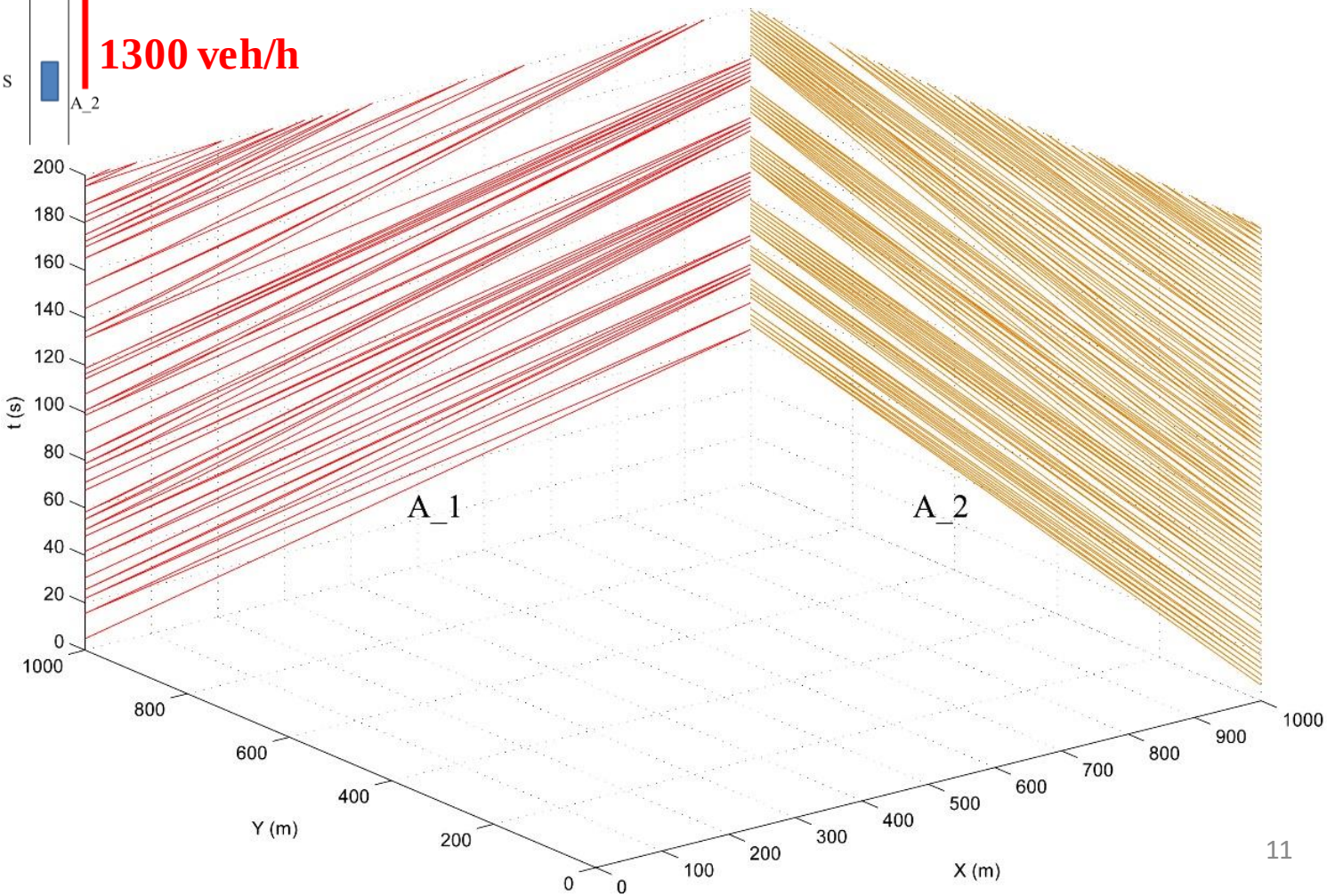
4.1 Two-approach single-lane intersection



4. Examples and discussion

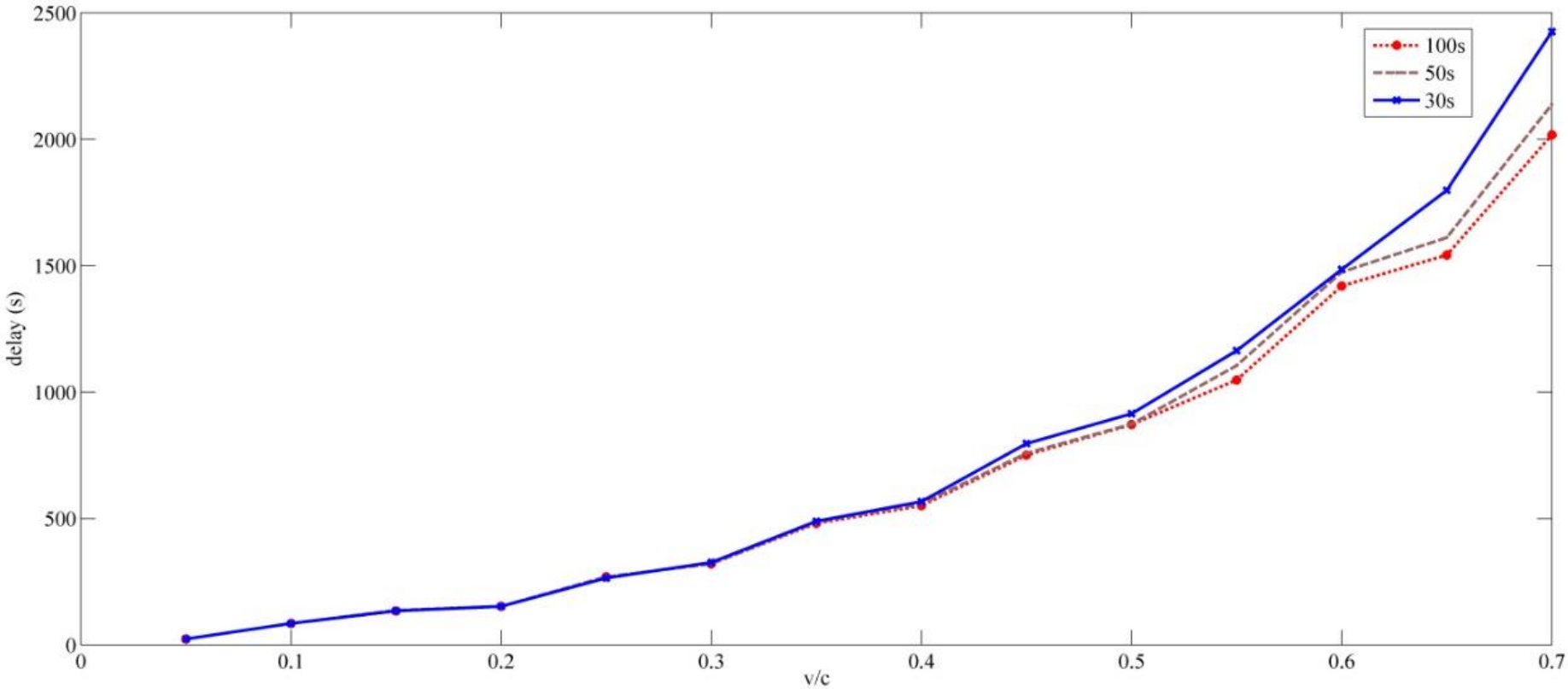
4.1 Two-approach single-lane intersection





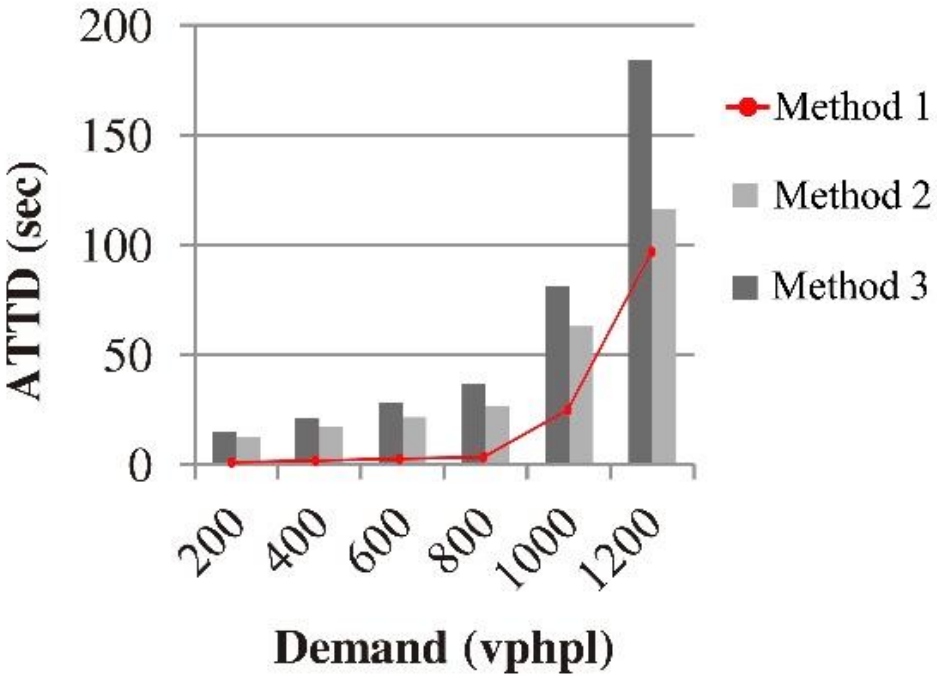
4. Examples and discussion

4.2 The influence of information collection interval on efficiency

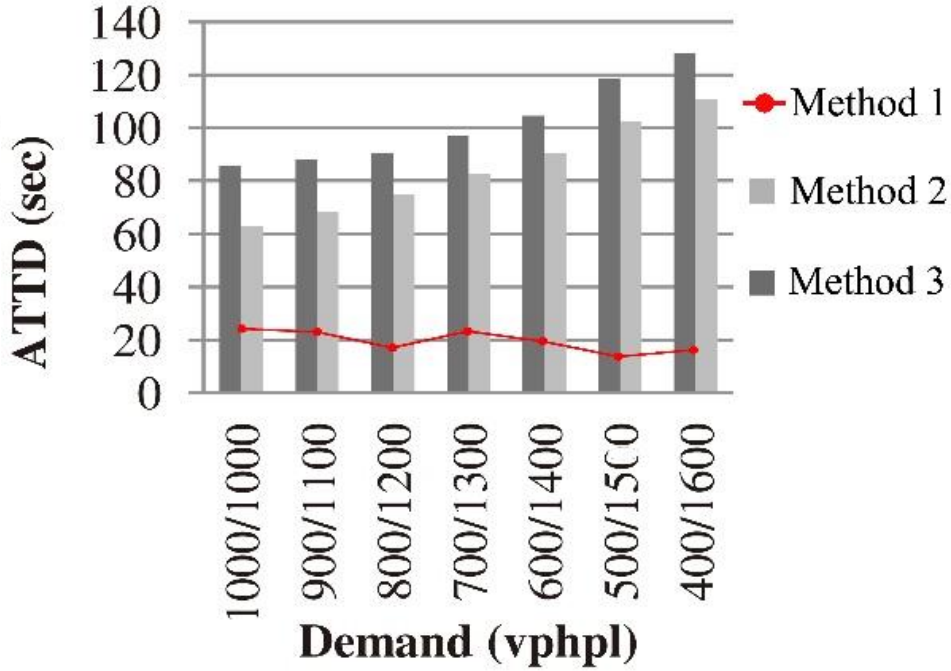


4. Examples and discussion

4.3 The analysis of control efficiency



(a) Comparison of ATTD (Balanced Demand)

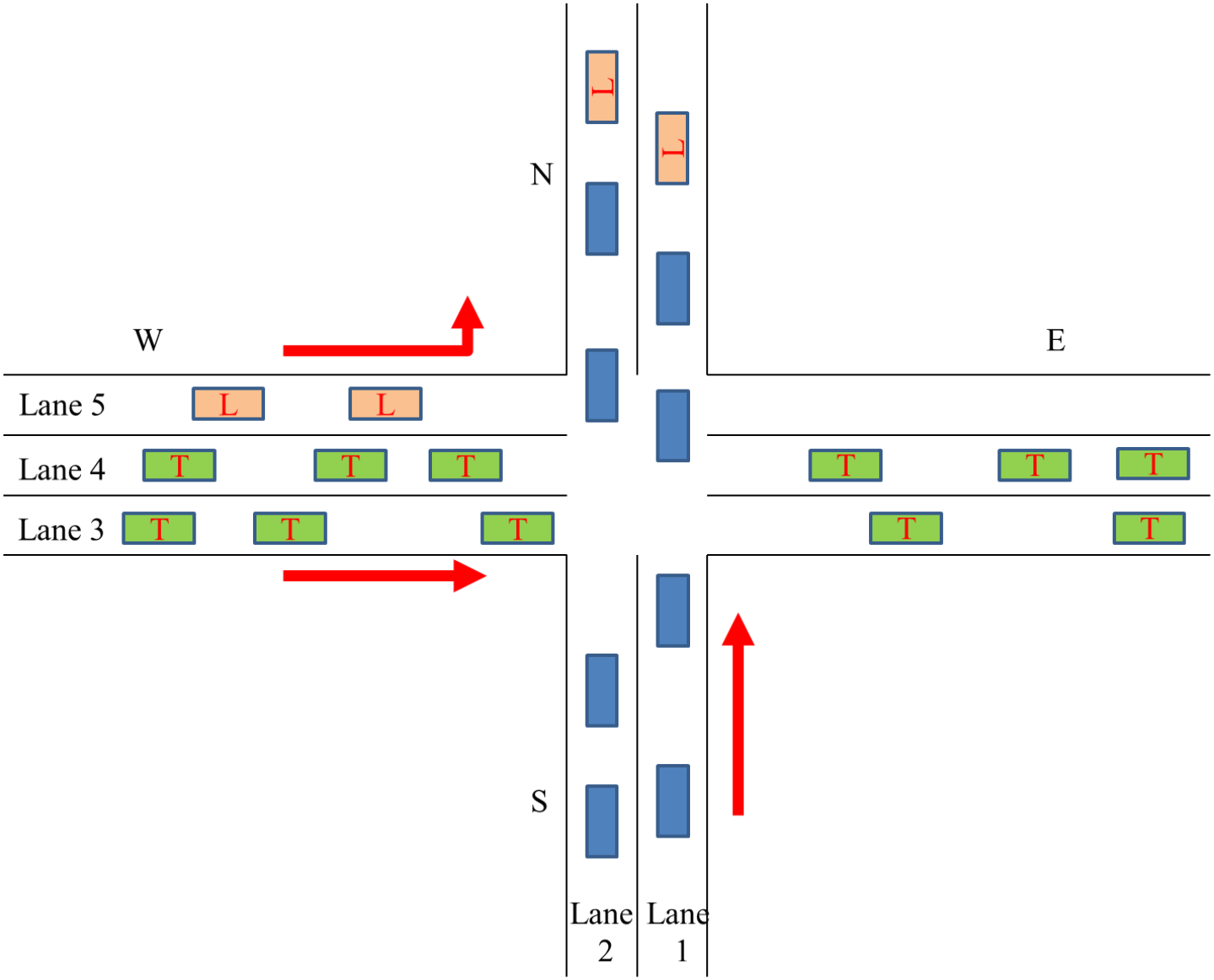


(b) Comparison of ATTD (Unbalanced Demand)

Comparison of the proposed **model (Method 1)**, **the Zhoufei Li's signal control (Method 2)**, and **the actuated signal control (Method 3)** of various demand levels

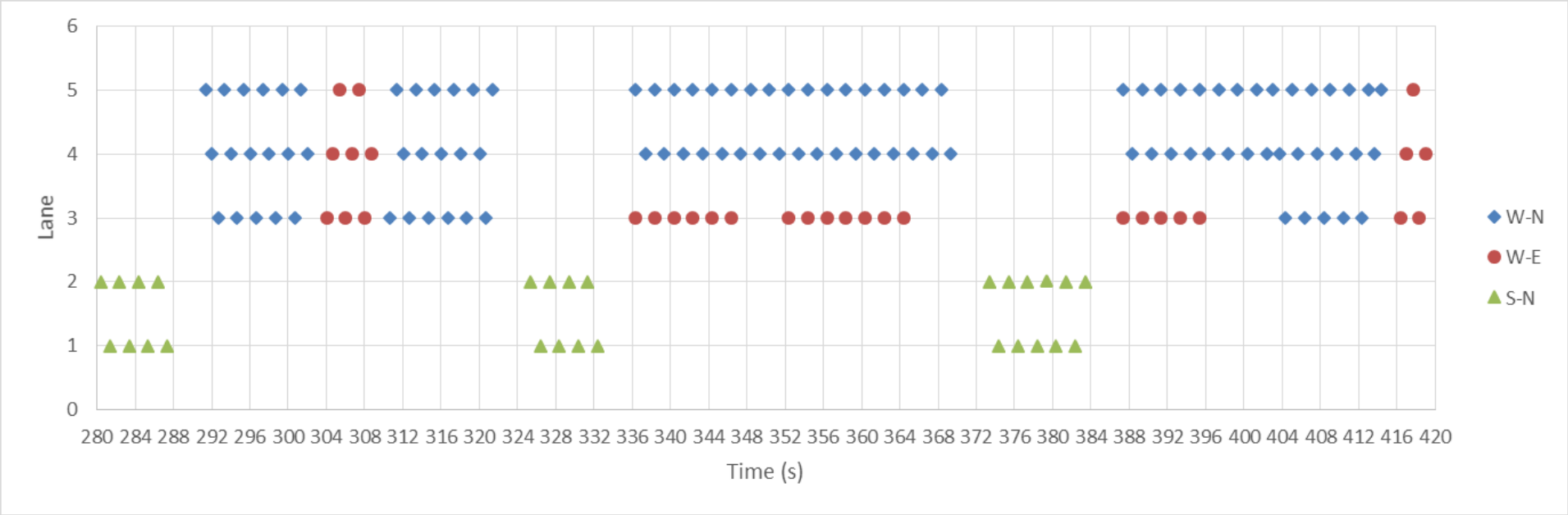
4. Examples and discussion

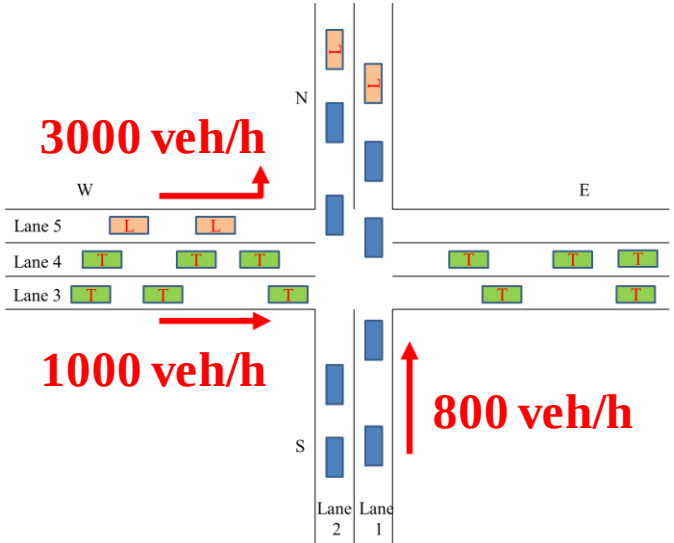
4.4 The efficiency of extended model



4. Examples and discussion

4.4 The efficiency of extended model

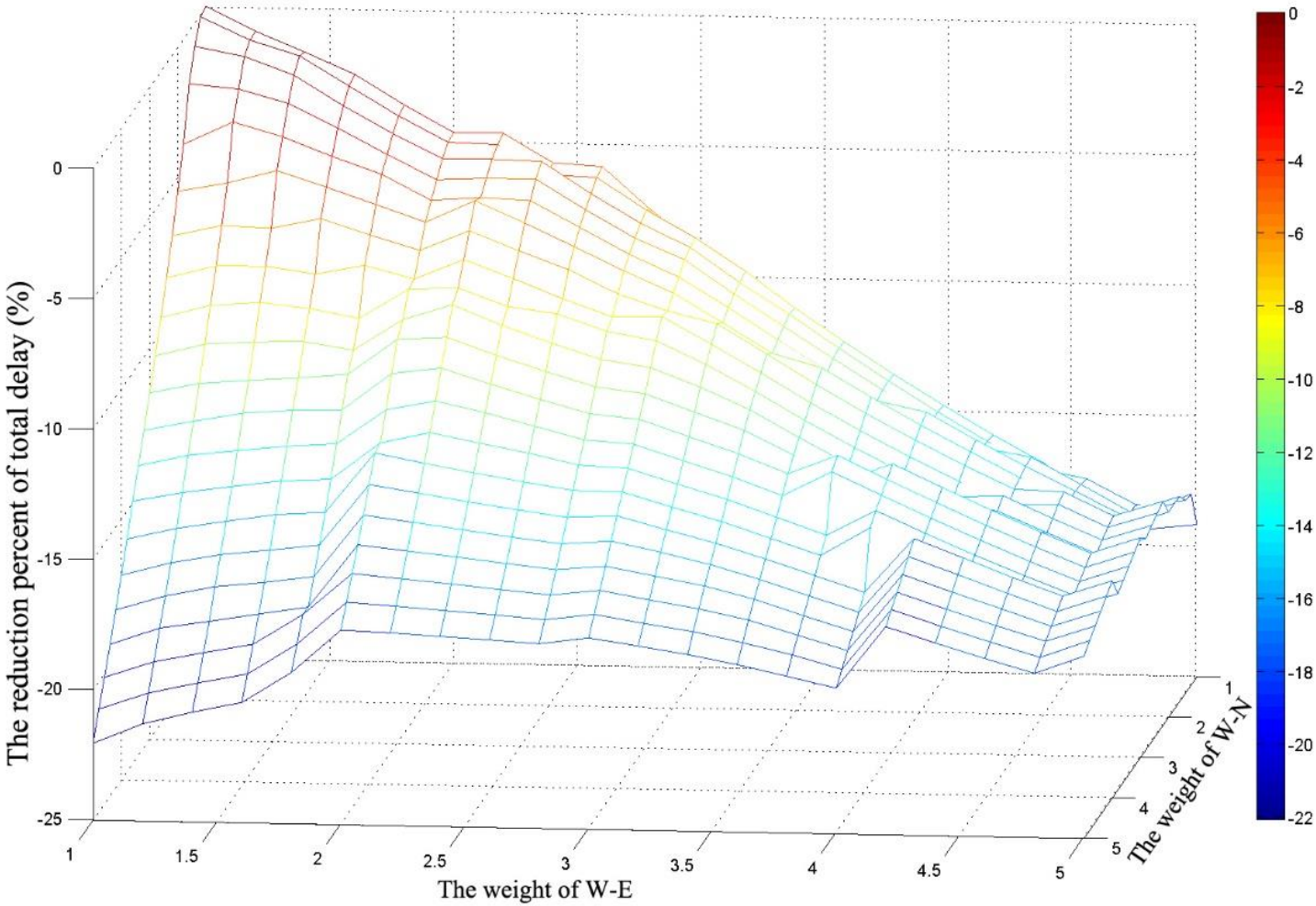




4. Examples and discussion

4.4 The efficiency of extended model

$$\min f = \sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K_{i,j}} \mu_{i,j,k} \cdot d_{i,j,k}$$



5. Conclusion

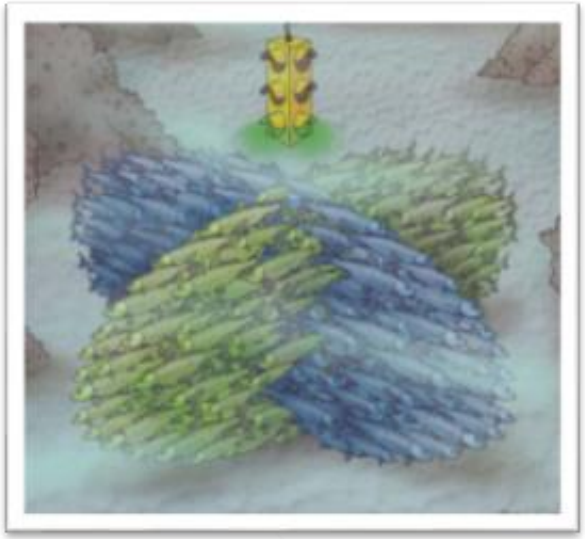
1. This paper proposed an automated vehicle-based intersection control method to minimize total delay in operation phase.
2. The basic models are BMILP and BMIP, which are solvable by standard branch-and-bound routine. And the extended model is also solvable by enumeration algorithm.

Advantages shown by numerical experiments:

1. The proposed serial model with information collection interval of 20s is still prior to Li's and actuated control.
2. Besides minimizing total delay under safety, the variation of speed is also reduced, which improves driving comfort.
3. Longer information collection interval produces higher control efficiency.
4. The extended model, which integrates two basic models, is the most efficient.

同濟大學
TONGJI UNIVERSITY

With a good model comes discovery,
with discovery comes understanding,
with understanding comes control!



Thank you

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Connected and Automated Driving at an Signalized Intersection – Two Examples of Vehicle-Signal Cooperation

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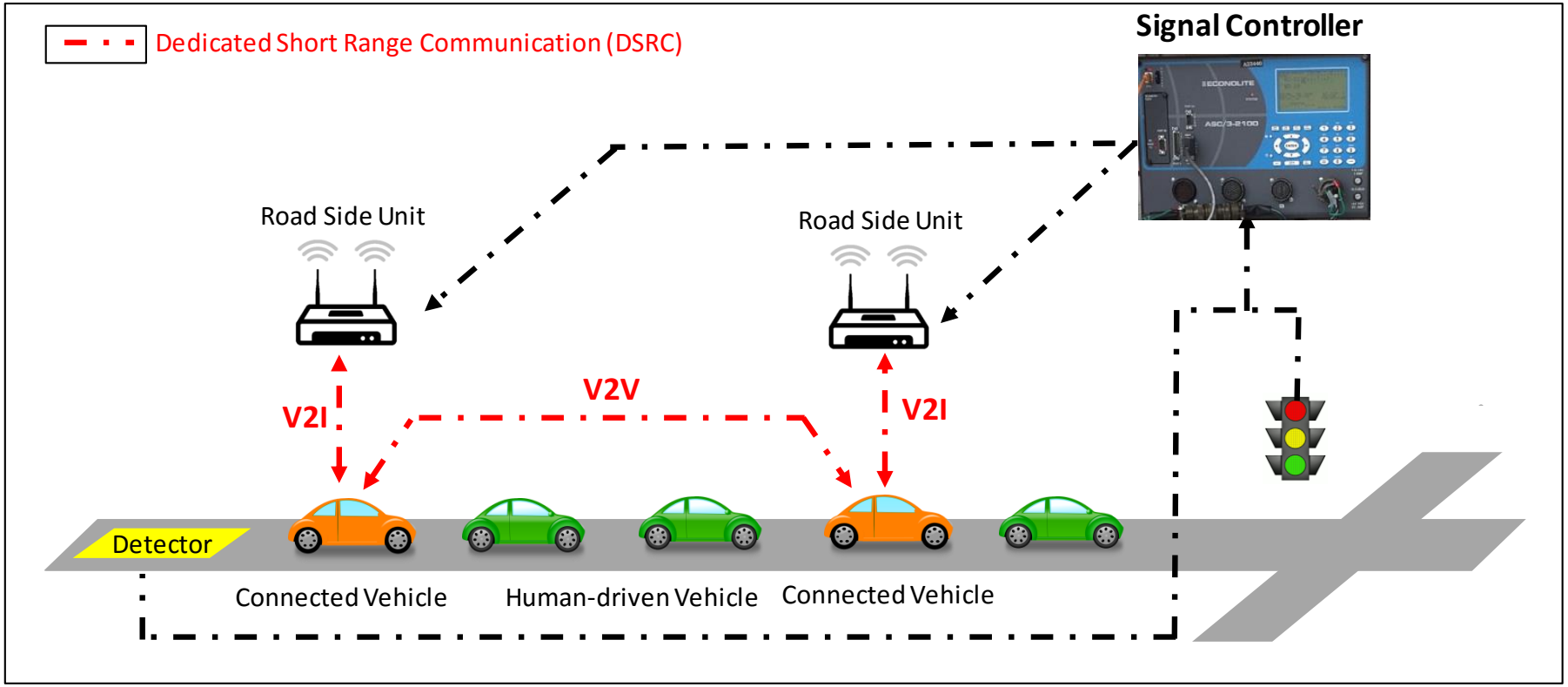
U.S. Department of Transportation
FEDERAL HIGHWAY ADMINISTRATION

Content

Stage 1: Vehicle Automation Only

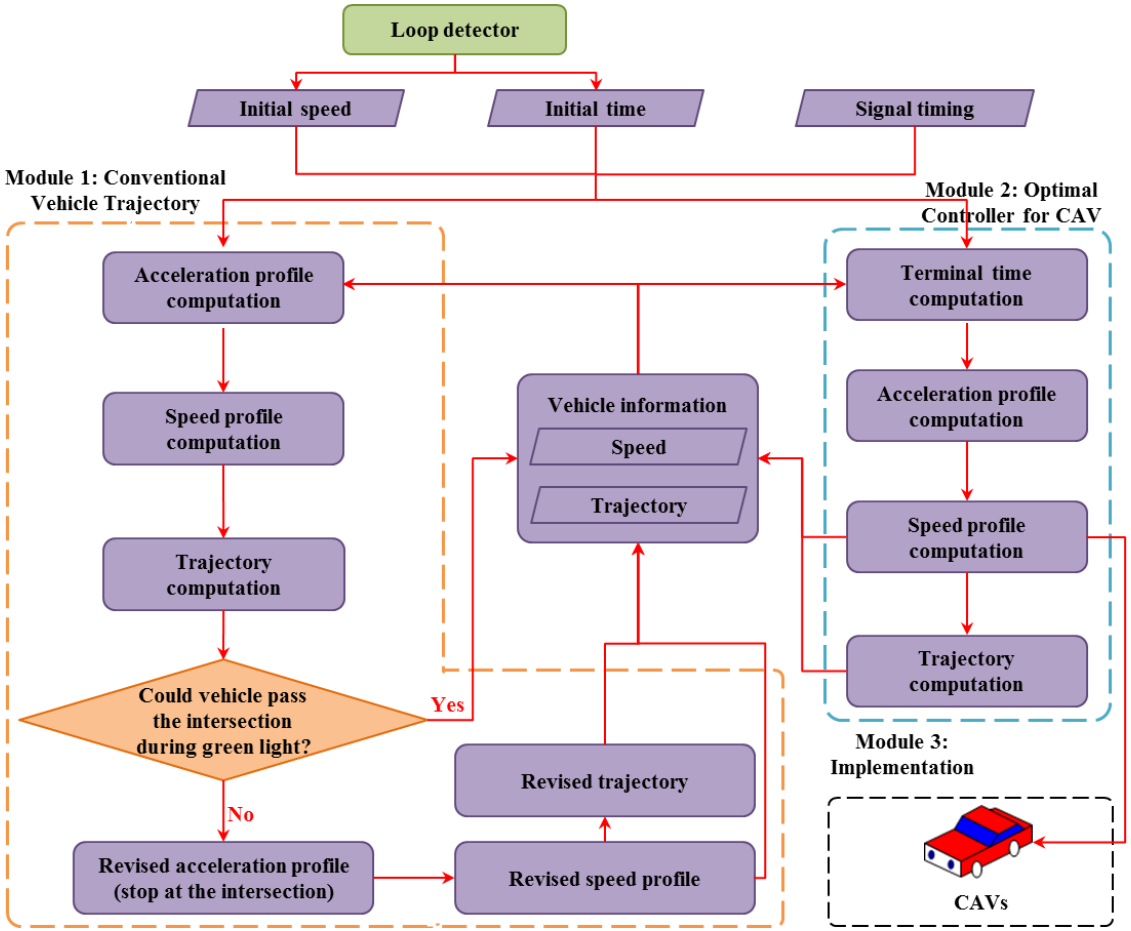
Stage 2: Vehicle-Signal Cooperation

Stage 1 Vehicle Automation Only



- Pure effort from Connected Automated Vehicles (CAV)
- Signal control provides only SPaT information
- Partial CAV traffic

Control Structure

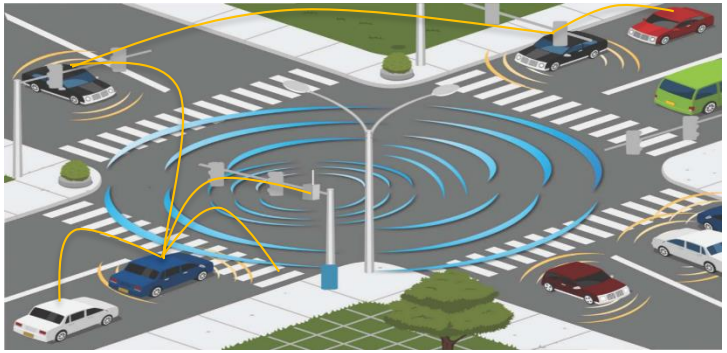


Features

CAV + Human
Mix Traffic

Mobility Before
Ecology

Real-Time
Implementation



Isolated Intersection
with One Lane

Highlights

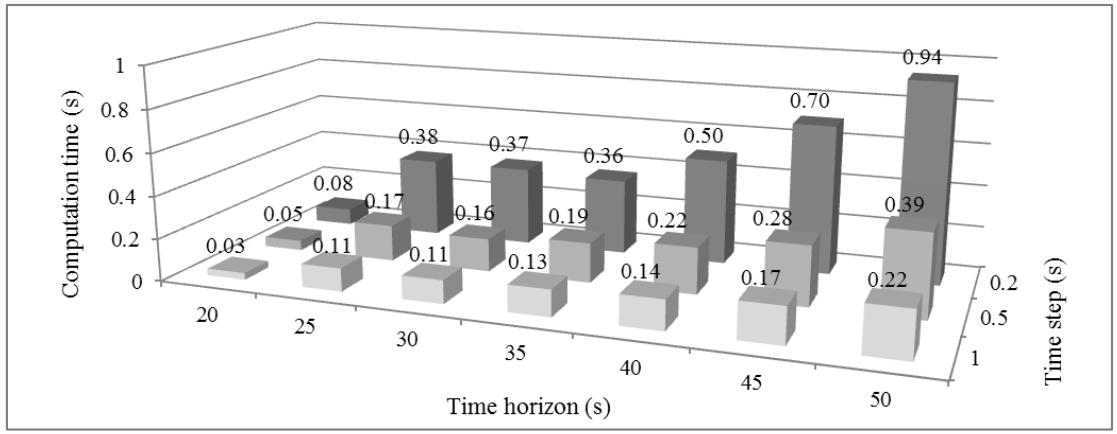
Eco-driving with mobility priority

- Optimize mobility (throughput) before optimize ecology
- Enforce the CAV's headway and speed at the stop line

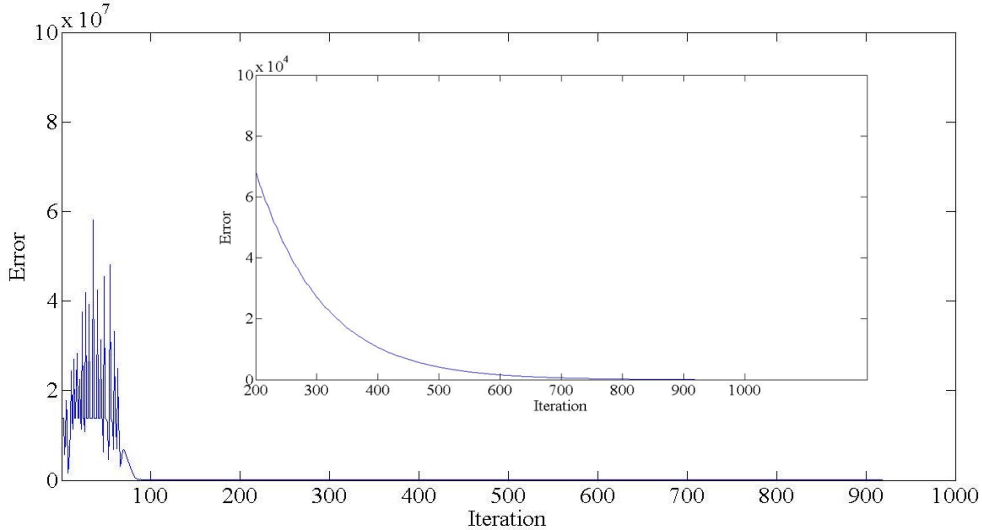
"Control" non-CAVs

- Optimize the entire traffic flow (both CAVs and conventional non-connected vehicles) by optimizing speed profiles of the CAVs.
- Uninformed vehicles have their travel pattern (car-following model). They can be a part of a controlled system, even though they cannot be controlled directly.

Computing Speed

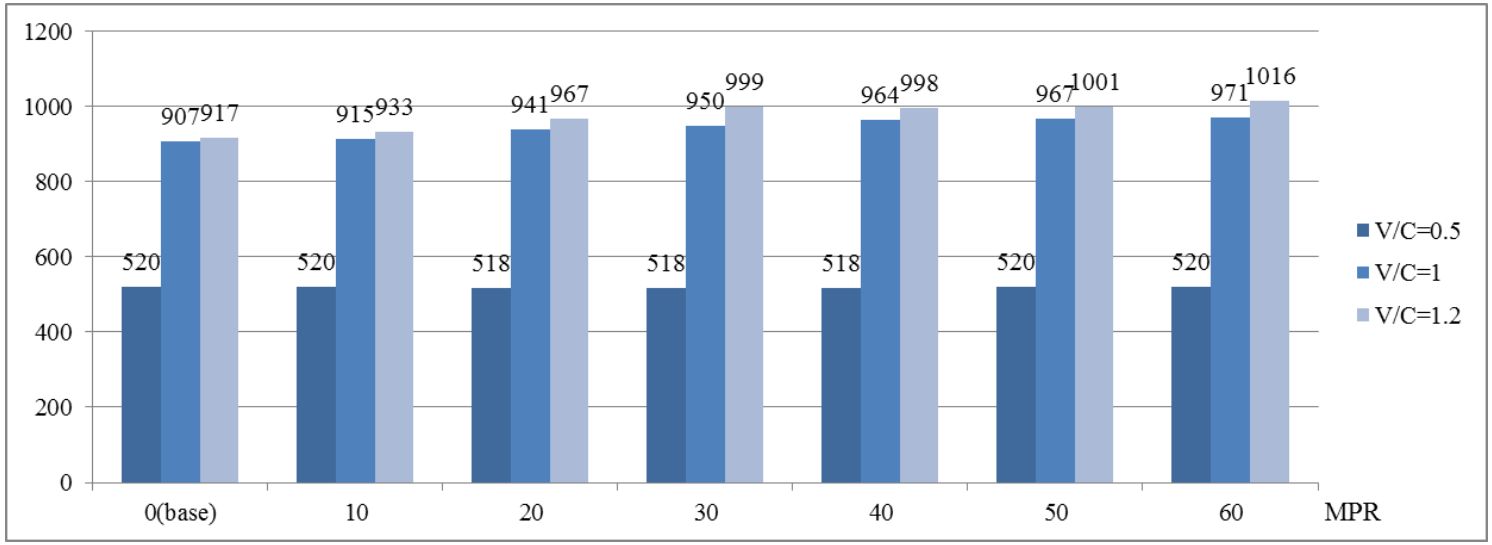


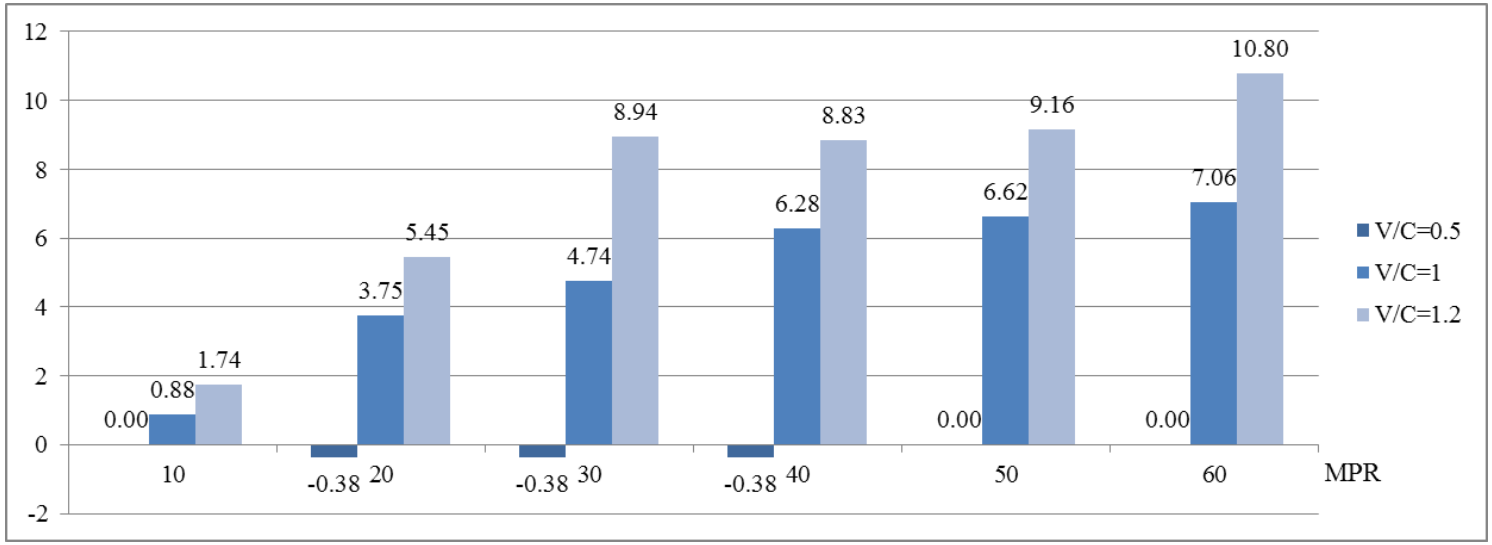
(a) Optimal controller computation time



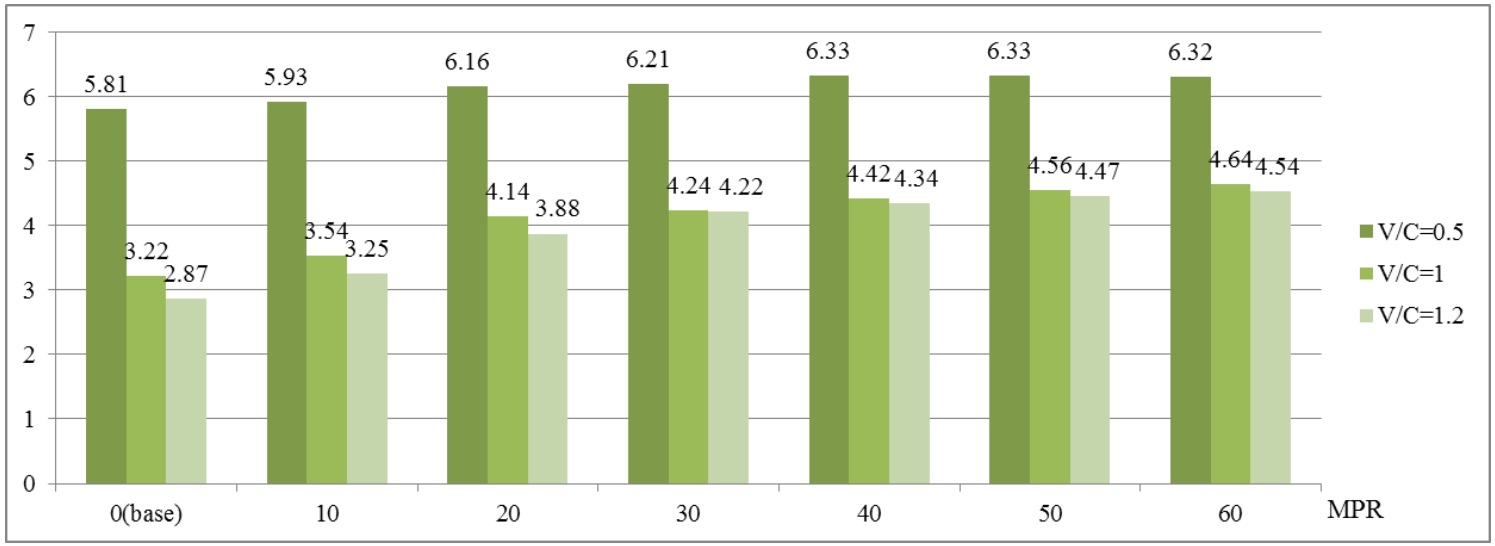
(b) Convergence curve of iterative PMP

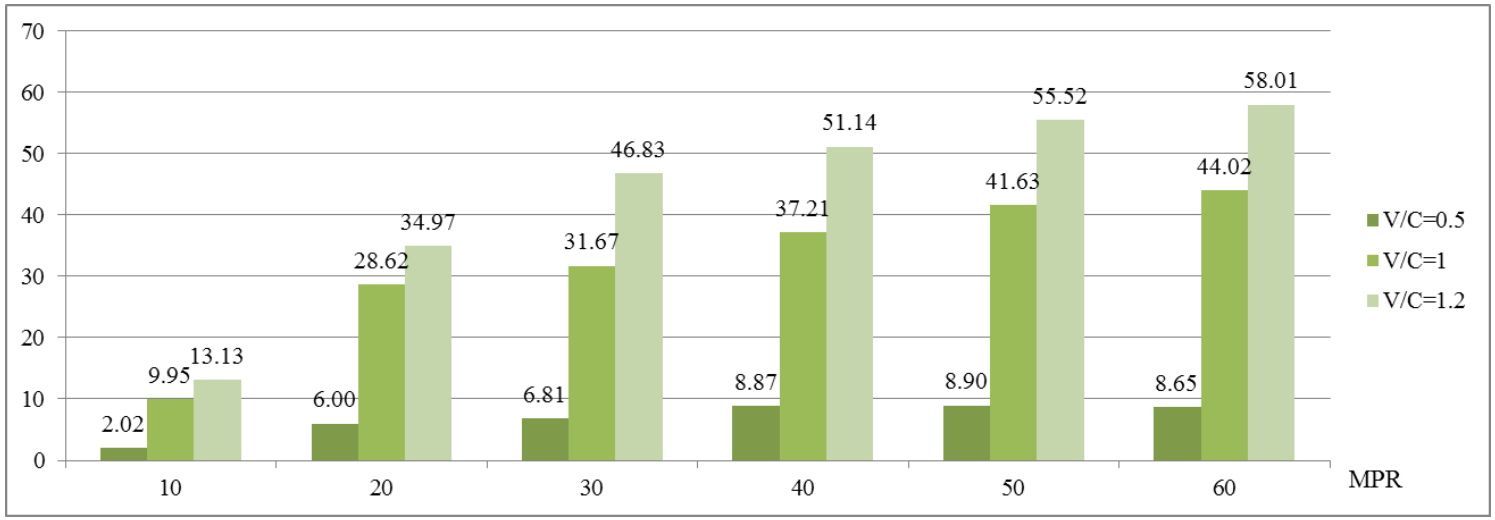
Results: Throughput



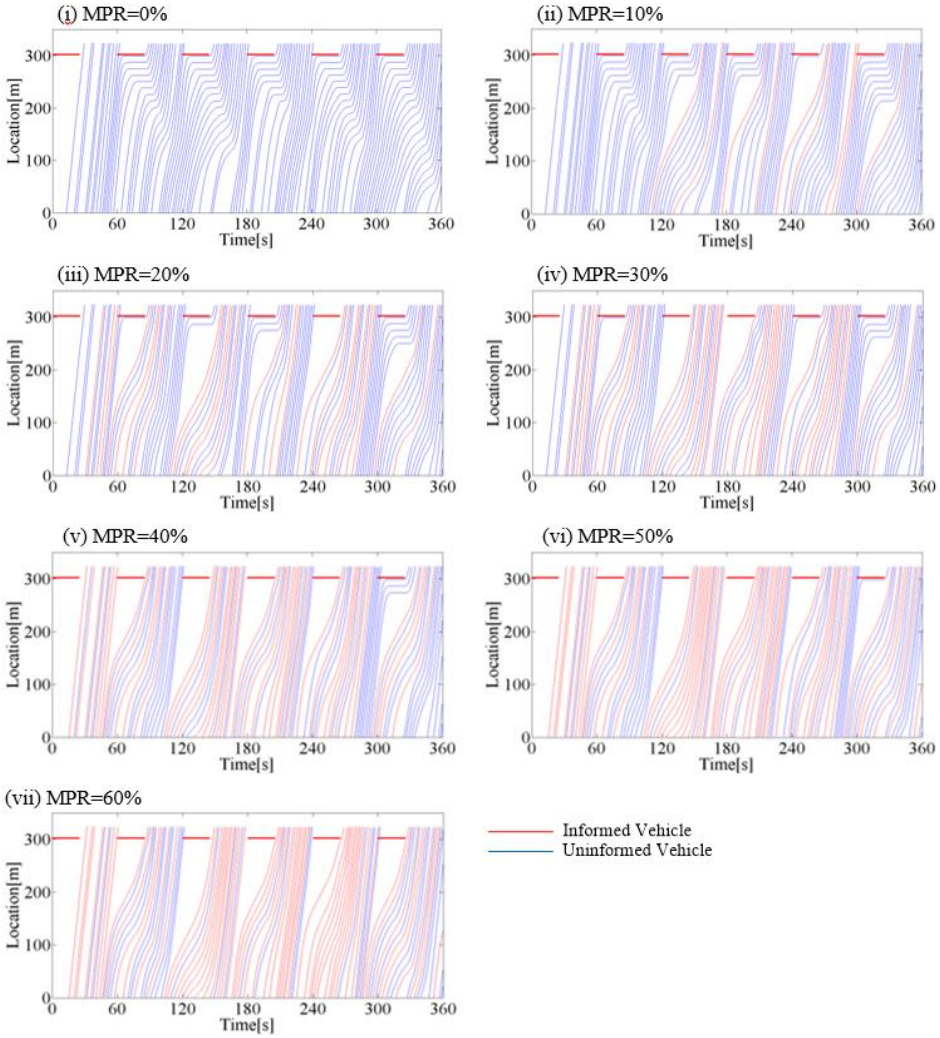


Results: Energy





Results: Trajectory



- MPR of CAVs increases, fewer conventional vehicles need to queue and waiting for green phase.
- Shock waves caused by signal control are smoothed out. It explains the throughput benefit.
- MPR <= 30% shows the most benefits.

Signal-Vehicle Cooperation

- **Goal:**

  Delay ↓ Throughput ↑ Fuel efficiency ↑

- **Scope:**

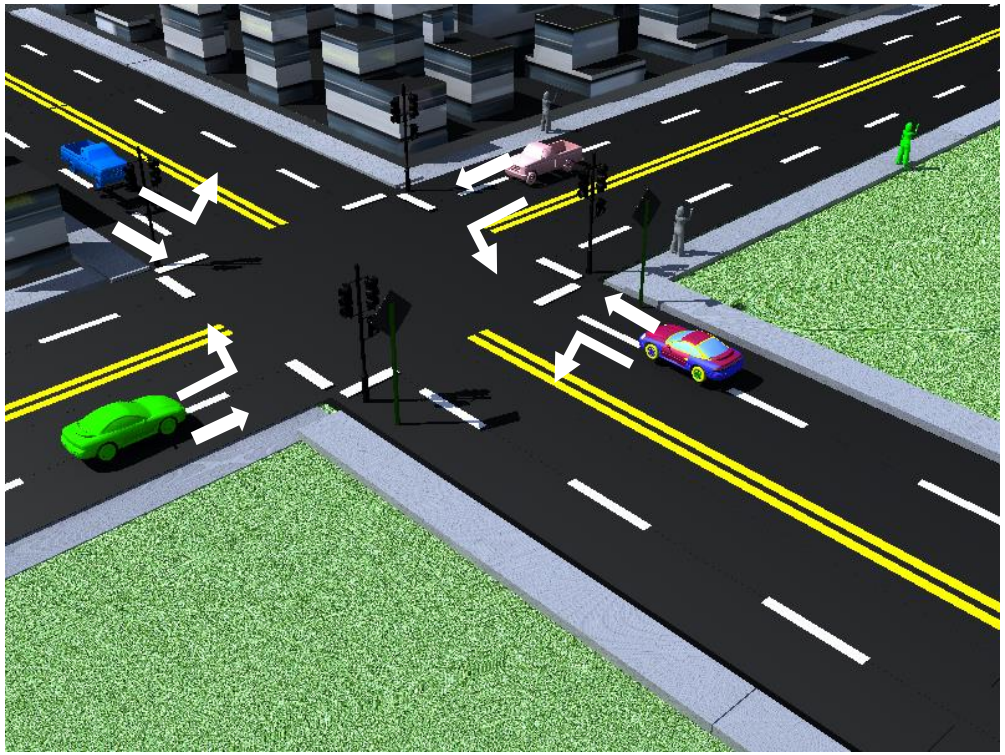
  Isolated Intersection

  Eight Movements

  100% CAV traffic

  Actuated Signal Control

  Dual-Ring Barrier control



- **Decision Variables:**

  Signal Schedule

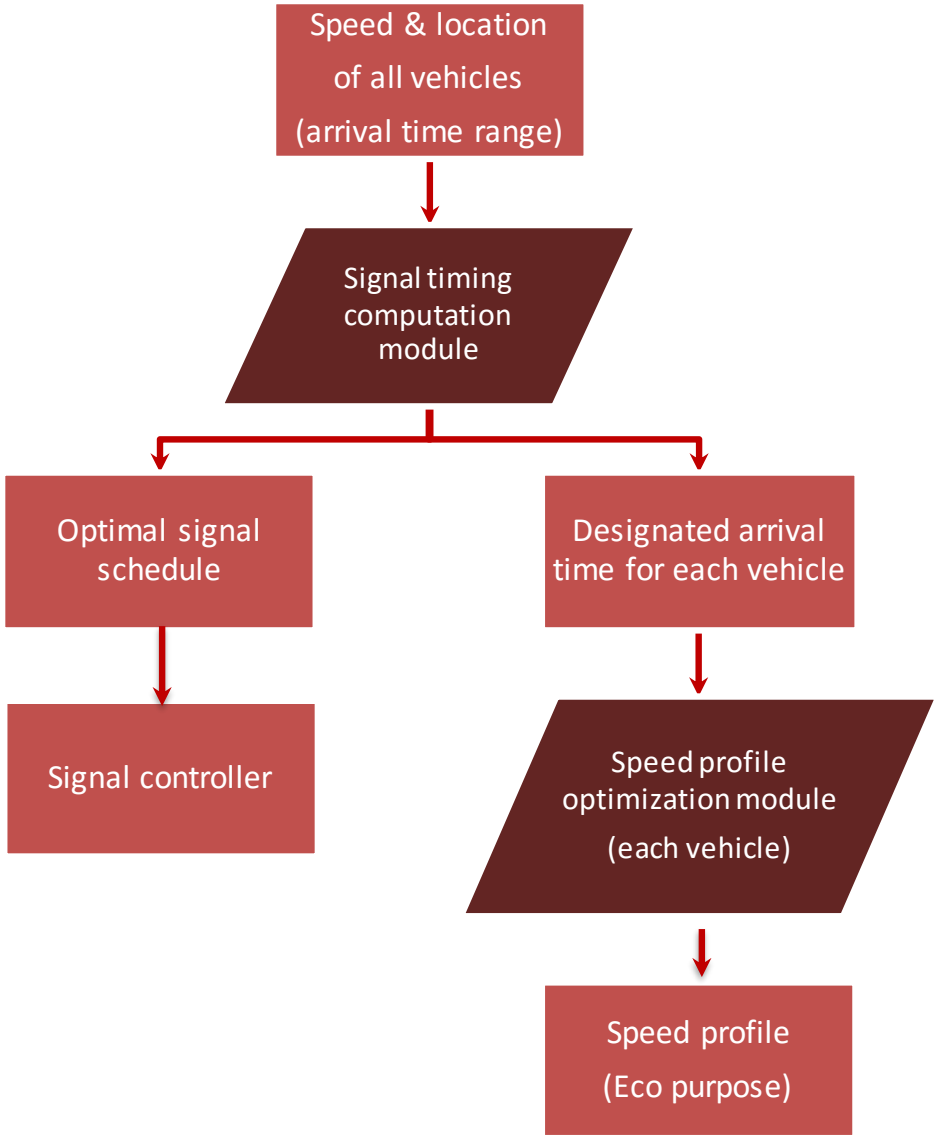
  Vehicle Speed

Structure

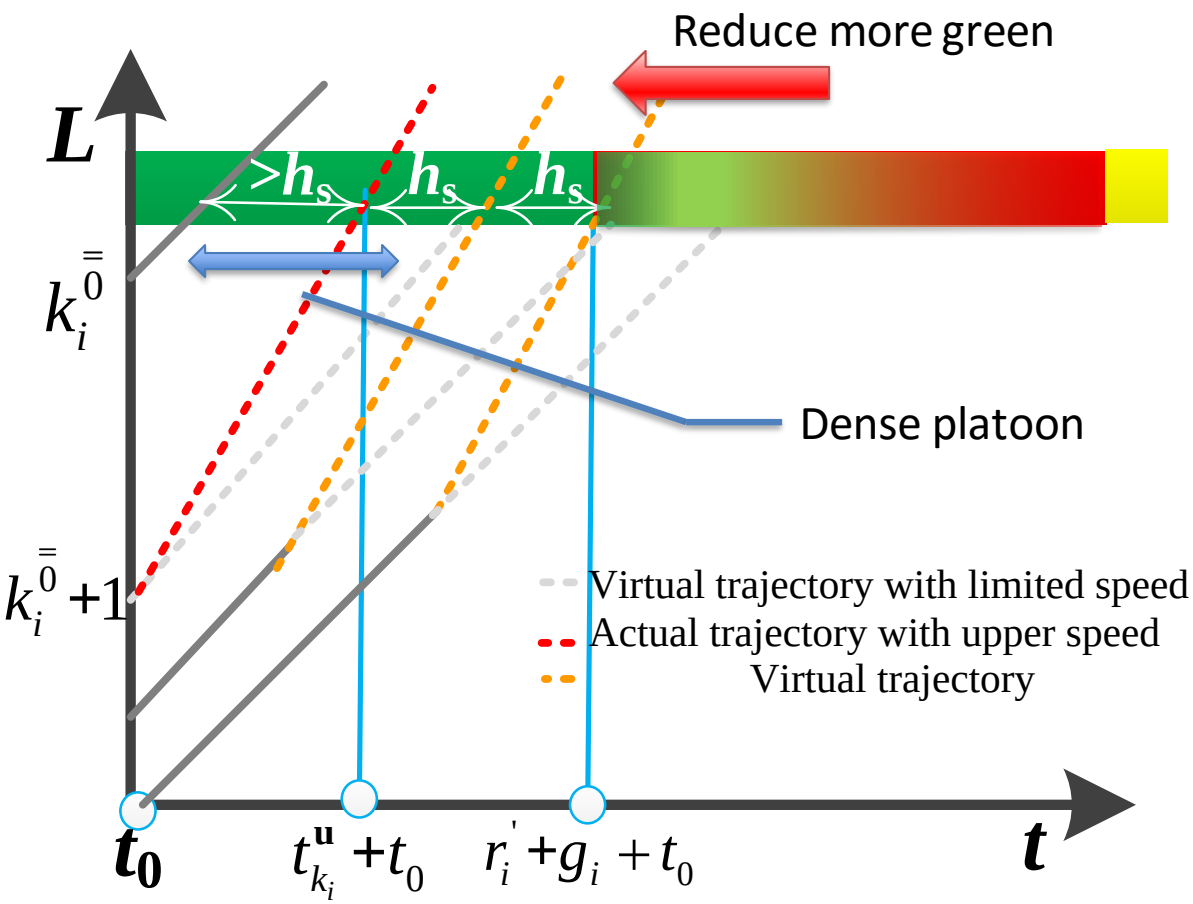
- **Signal Control**
  - Modified Multi-Modal Intelligent Traffic Signal System (MMITSS)
  - Potential to upgrade to heterogeneous traffic
  - Potential to upgrade to partial CAV traffic
  - Potential for signal priority

- **Vehicle Control**
  - Previously developed optimal controller
  - Decentralized controller

Logic


Speed & location
of all vehicles
(arrival time range)
Signal timing
computation
module
Optimal signal
schedule
Designated arrival
time for each vehicle
Signal controller
Speed profile
optimization module
(each vehicle)
Speed profile
(Eco purpose)

Logic


Reduce more green
L
>h_s
h_s
h_s
k_i^0
Dense platoon
k_i^0 +1
Virtual trajectory with limited speed
Actual trajectory with upper speed
Virtual trajectory
t_0
t_{k_i}^u +t_0
r_i' +g_i +t_0
t

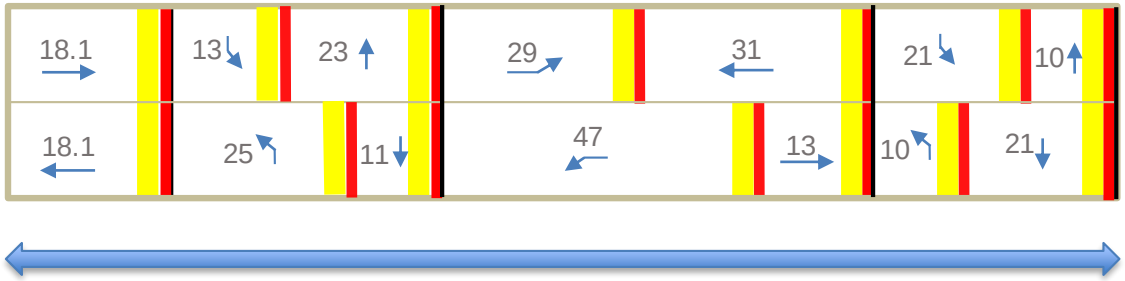
Case Study Setup

- Vehicle Input Snapshot from a VISSIM simulation
  - Isolated four-leg eight-phase intersection
  - v/c = 1
  - 1000m length on each direction
  - Actuated Signal Control
  - Snap shot taken after 600 sec simulation

- Vehicle Control Radius = 300 m

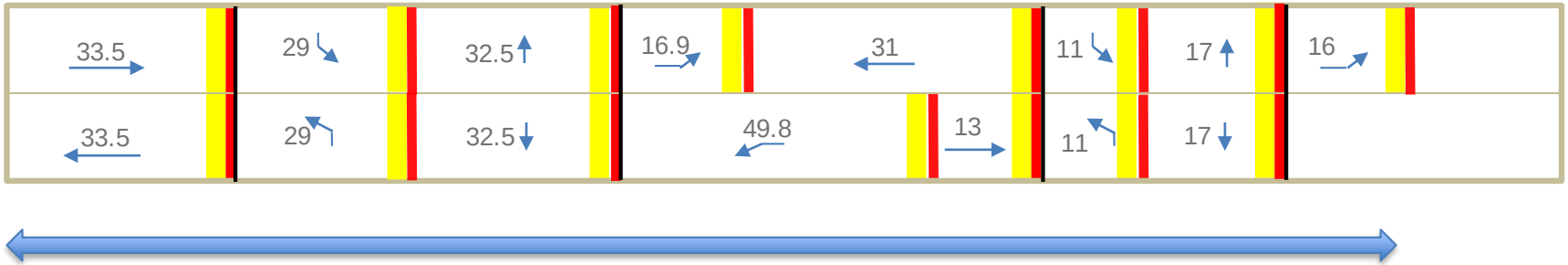
Result: Signal Schedule

- **Optimal Signal Timing Schedule**



145 Seconds

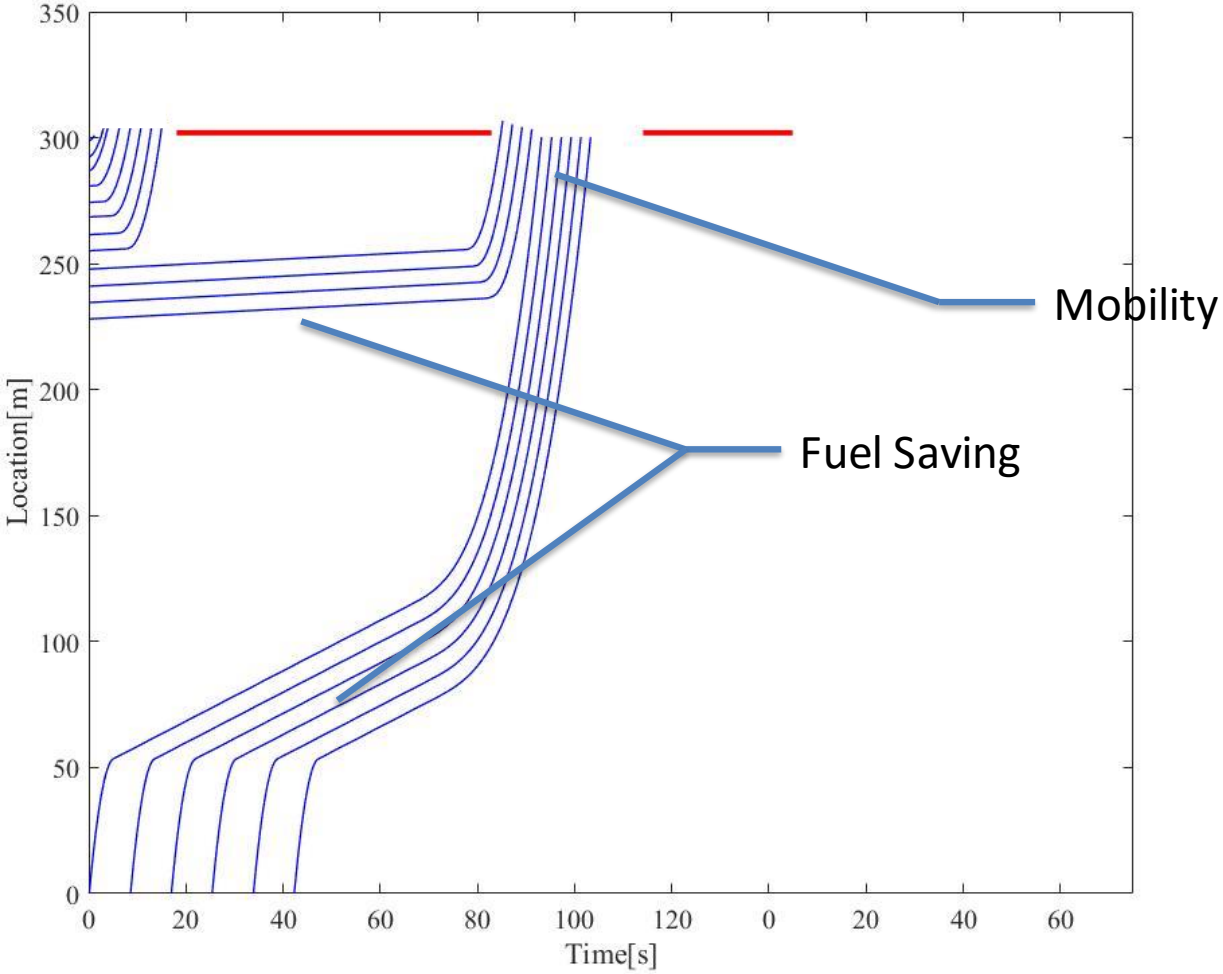
- **Actuated Signal Control Timing**



202 Seconds

Result: Sample Trajectory

Optimal Time-Space Trajectory For Phase 2

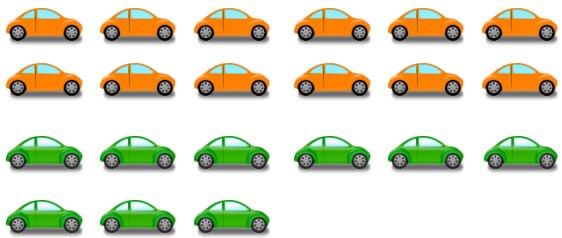


Result: Delay Reduction

Case 1:
Full Cycle v.s. Full Cycle
145 sec v.s. 202 sec

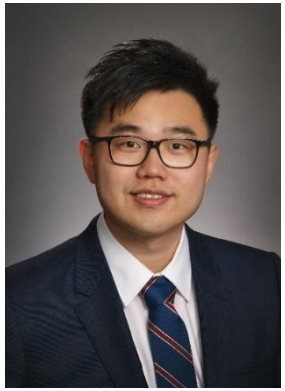
Delay Reduction: **27.8%**

Case 2:
Full Cycle v.s. Partial Cycle
145 sec v.s. 145 sec



Delay Reduction: **15.2%**

Contact



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