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T3e Webinar

Smart Sensors and Infrasructures for Transportation
July 29, 2021

Adaptive and Multi-Path Progression Signal Control Under Connected Vehicle Environment

Qinzheng Wang

Department of Civil & Environmental Engineering

University of Utah

07/29/2021

OUTLINE

1 • **Background**

2 • **Sensor-based Traffic Signal Control**

3 • **Numerical Examples**

4 • **Conclusions**

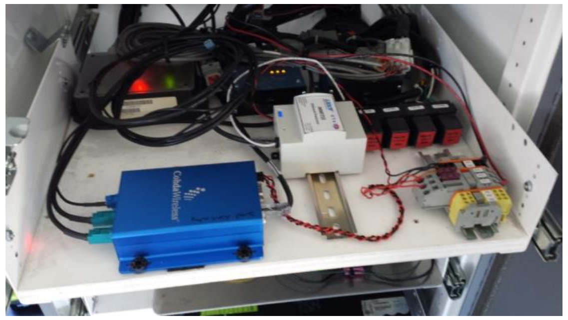
Background

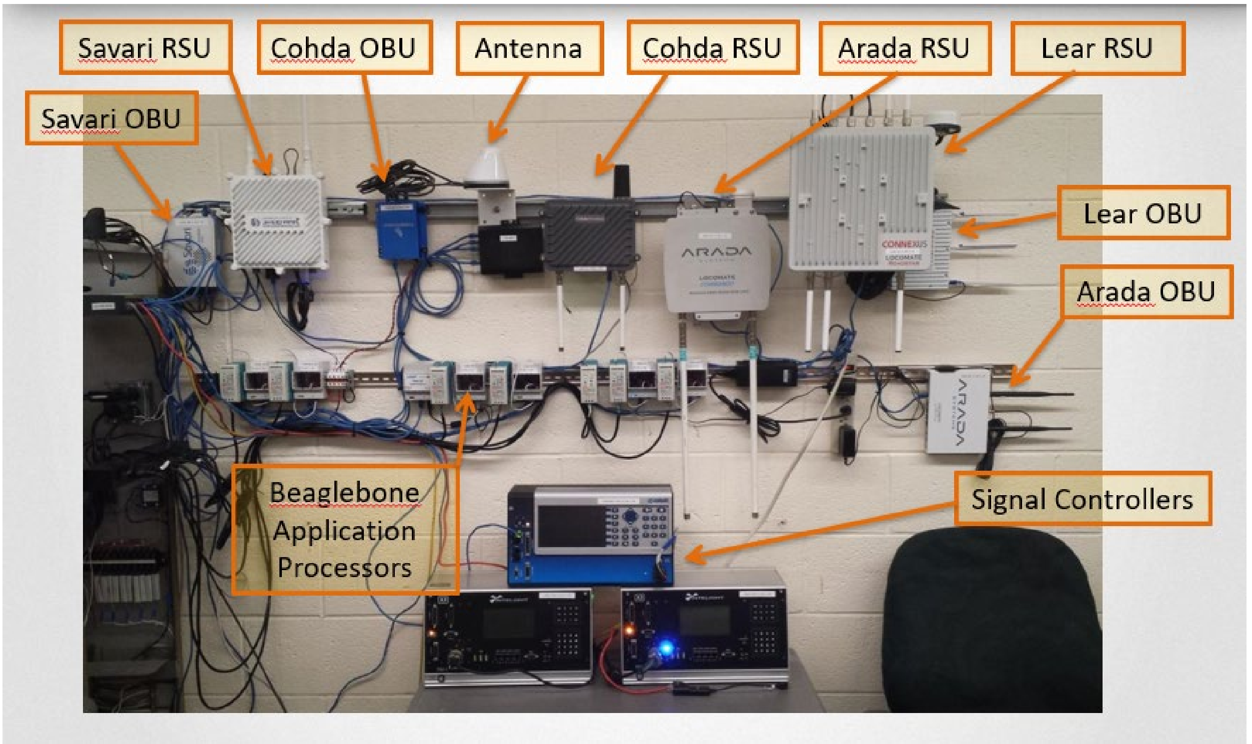
Connected vehicle (CV)

Vehicle to vehicle (v2v)

Vehicle to infrastructure (v2I)

On-board Sensors equipped in vehicles are providing various vehicle sensor data (VSD) such as the CAV's GPS location, speed and moving direction (trajectory)





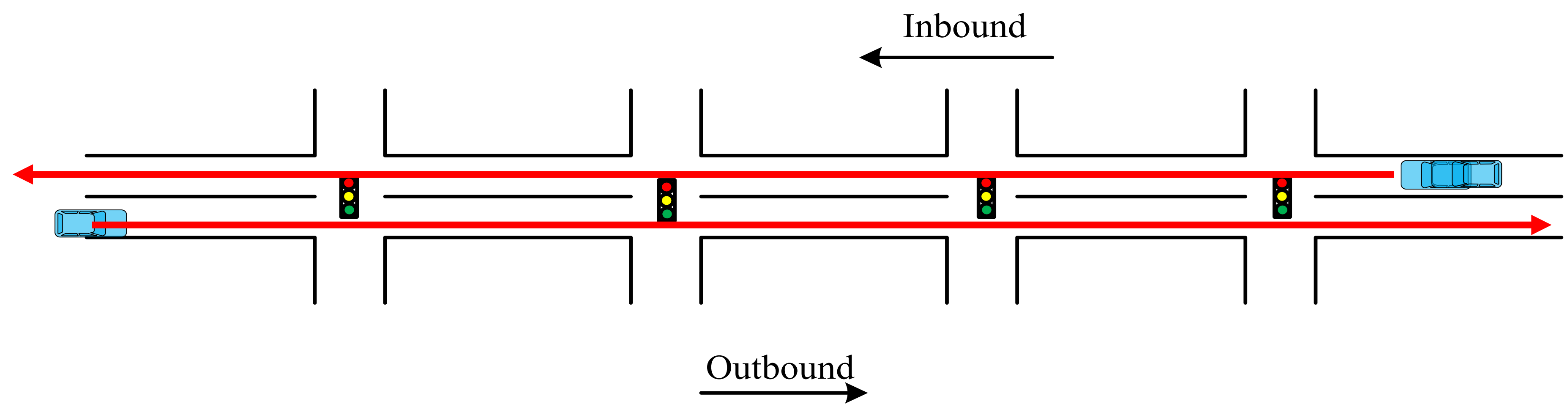
Roadside Sensors can provide various information, such as traffic signal timing information, for vehicle control.

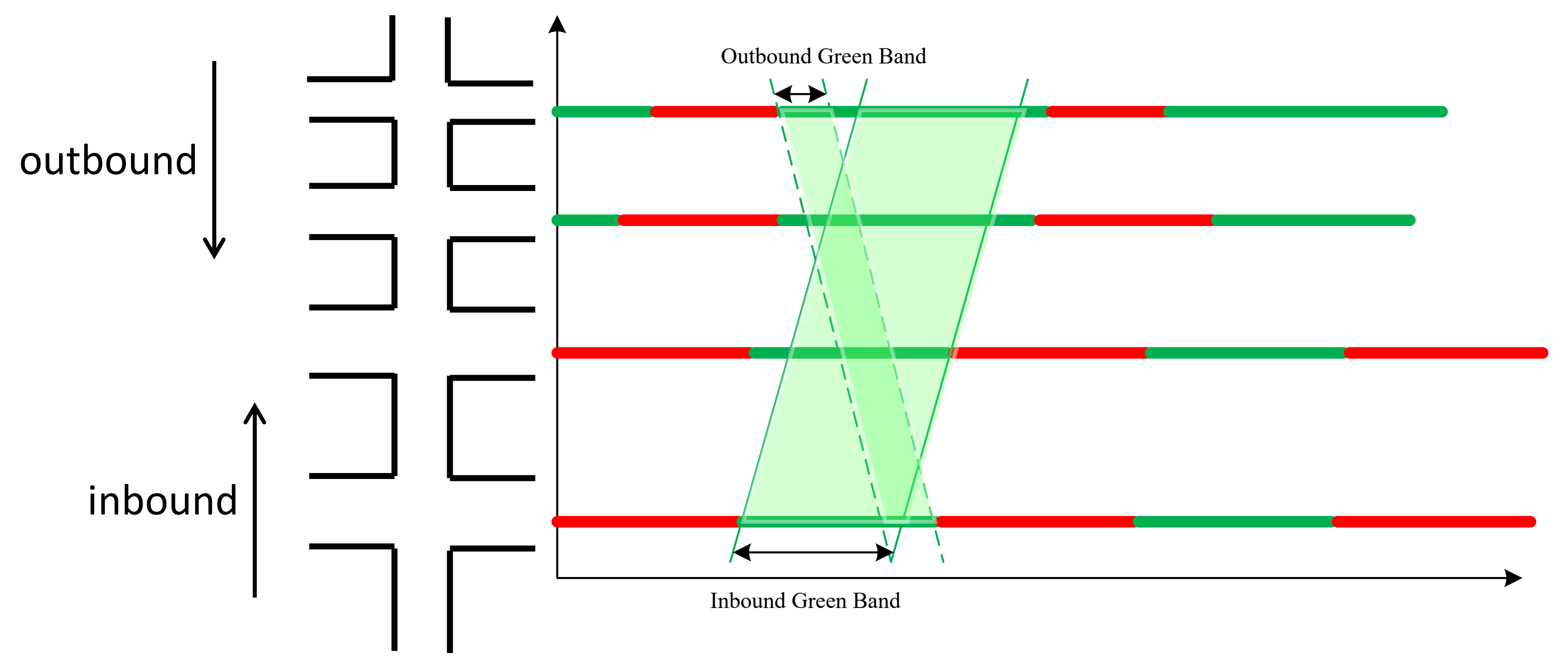
Background and Motivations

Signal coordination: a method of timing groups of traffic signals along an arterial to provide for the smooth movement of traffic with minimal stops.

- Provided progression for one through path or two through paths and assuming that flows along those paths (OD flow) are highest.

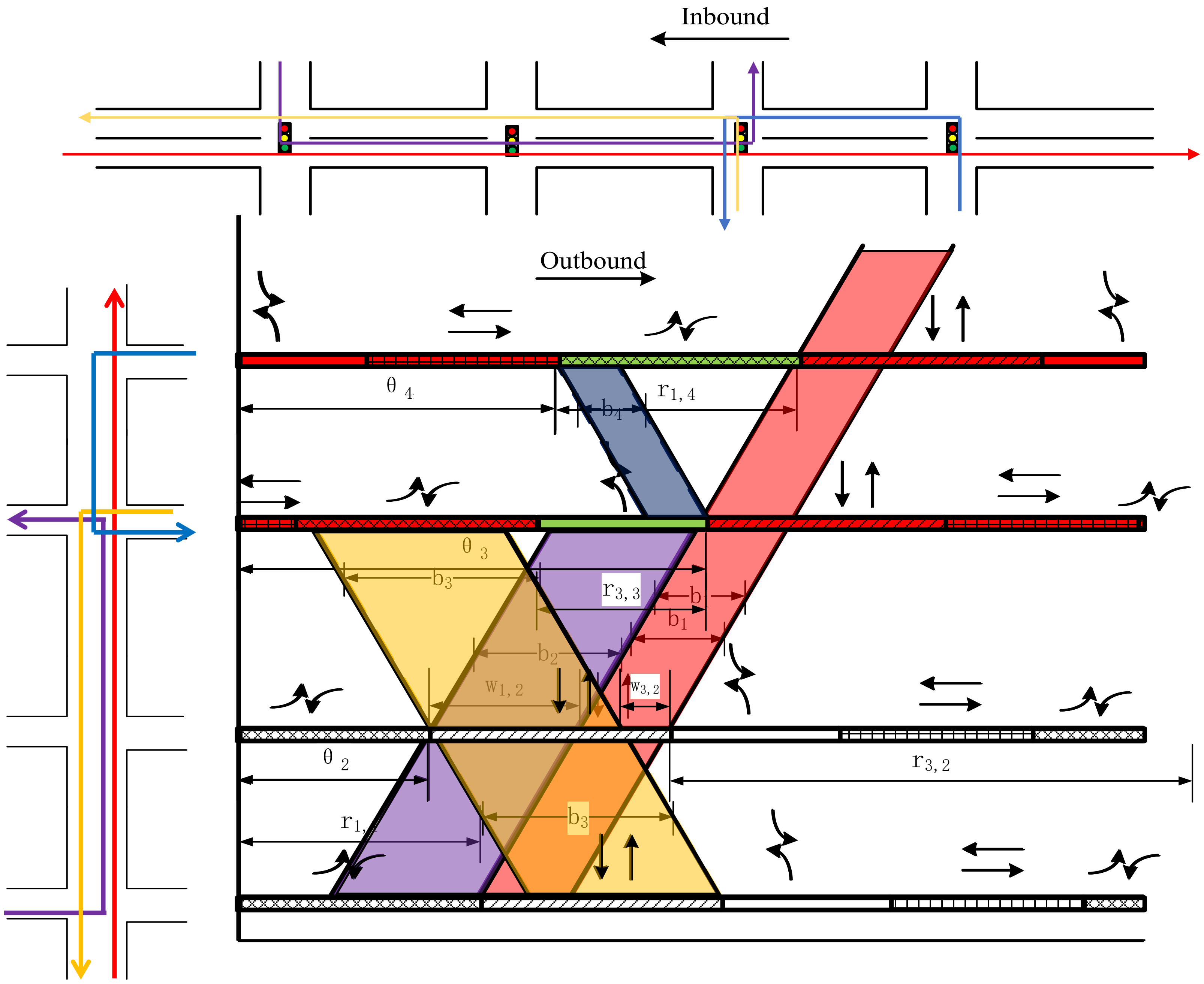
- Design a fixed offset plan during the whole control period.





Background and Motivations

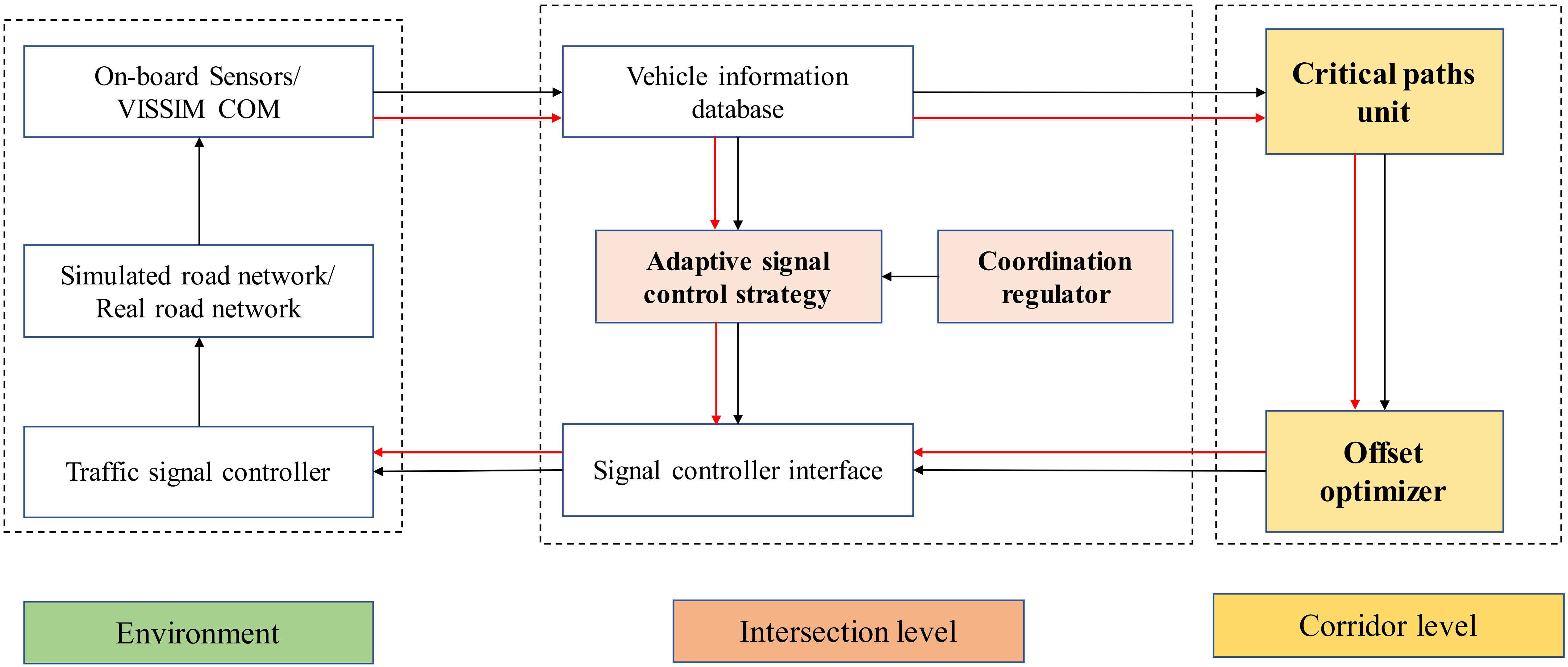
- Provide progression to multiple paths with high volume (critical paths).
- Change coordination plan.



OUTLINE

1. **Background and Motivations**
2. **Sensor-based Traffic Signal Control**
3. **Numerical Examples**
4. **Conclusions**

Sensor-based Traffic Signal Control



Sensor-based Traffic Signal Control

Intersection Level

Vehicle arrival flow rate:

$$\mu_{l,i}(k,j) = \frac{1}{C} * q_{l,i}(j) \quad \forall l, j \tag{1}$$

Turning flow:

$$q_{l,i}(j) = \frac{1}{N} \sum_{n=1}^{N} q_{i,j}(j-n) \tag{2}$$

$$q_{l,i}(j) = \frac{q_{l,i}^{c}(j)}{p_{l,i}(j)} \tag{3}$$

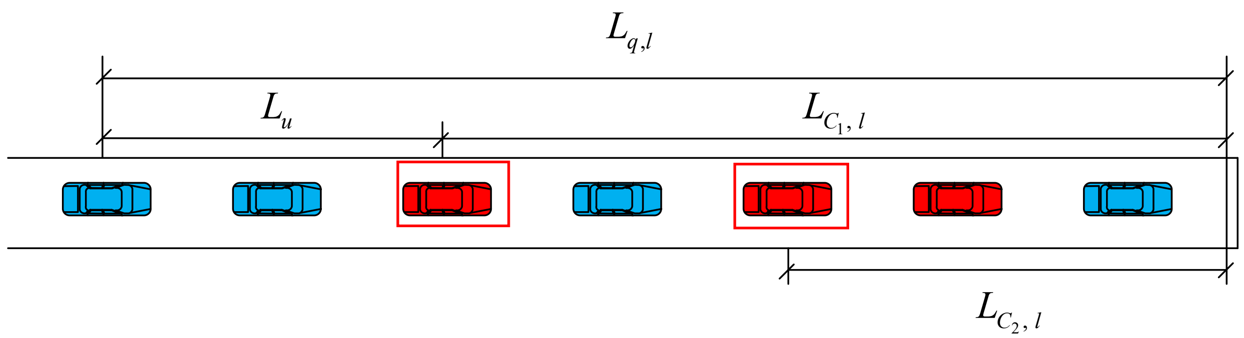
Market penetration rate

$$p_{l,i}(j) = \frac{N_{c,j}}{N_{all,j}} \tag{4}$$

$$N_{all,j} = \frac{L_{q,j}}{L_{eff}} \tag{5}$$

Sensor-based Traffic Signal Control

Case 1: More than one CAV in the queue

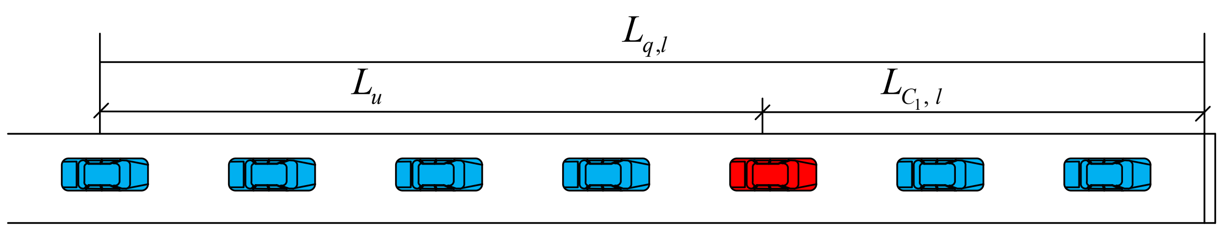


$$L_u = v_{q,l} * (t - t_{c1,l}) \tag{6}$$

$$v_{q,l} = \frac{L_{c1,l} - L_{c2,l}}{t_{c1,l} - t_{c2,l}} \tag{7}$$

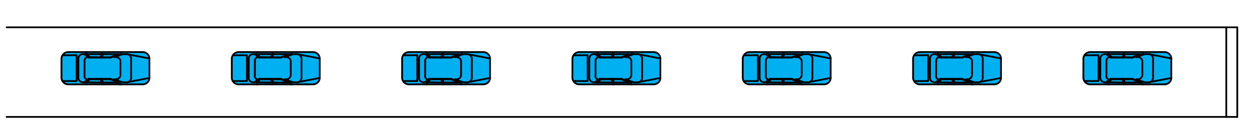
$$L_{q,l} = L_{c1,l} + L_u \tag{8}$$

Case 2: Only one CAV in the queue



$$v_{q,l} = \frac{L_{c1,l}}{t_{c1,l} - t_{r,l}} \tag{9}$$

Case 3: No CAV in the queue



We simplify the lane flow of current cycle under this condition by the average lane flow of previous several cycles.

Sensor-based Traffic Signal Control

Model 1

$$\min \sum_{j=1}^{J} d_i(j) \quad (10)$$

s.t.

$$d_i(j) = \sum_{l=1}^{L}\sum_{k=1}^{c} Q_{l,i}(k,j) * \Delta t \qquad \forall l,j \quad (11)$$

Total intersection delay

$$Q_{l,i}(k,j) = \max\big(Q_{i,j}(k-1,j) + \mu_{l,i}(k,j) - r_{l,i}(k,j), 0\big) \quad \forall l,j \quad (12)$$

Queue length

$$\mu_{l,i}(k,j) = \frac{1}{c} * q_{l,i}(j) \quad \forall l,j \quad (13)$$

Vehicle arrival rate

$$r_{l,i}(k,j) = \begin{cases} s_{l,i} * \Delta t \\ 0 \end{cases} \quad \forall l,j \quad (14)$$

Saturation flow rate

$$Q_{l,i}(0,j) = \tau_{l,i}(0,j-1) \quad \forall l,j \quad (15)$$

Initial queue length at the start of each cycle

$$\sum_{p=1}^{p=N} \big(g_{i,p}(k) + l_{i,p}(k)\big) = c(k) \quad (16)$$

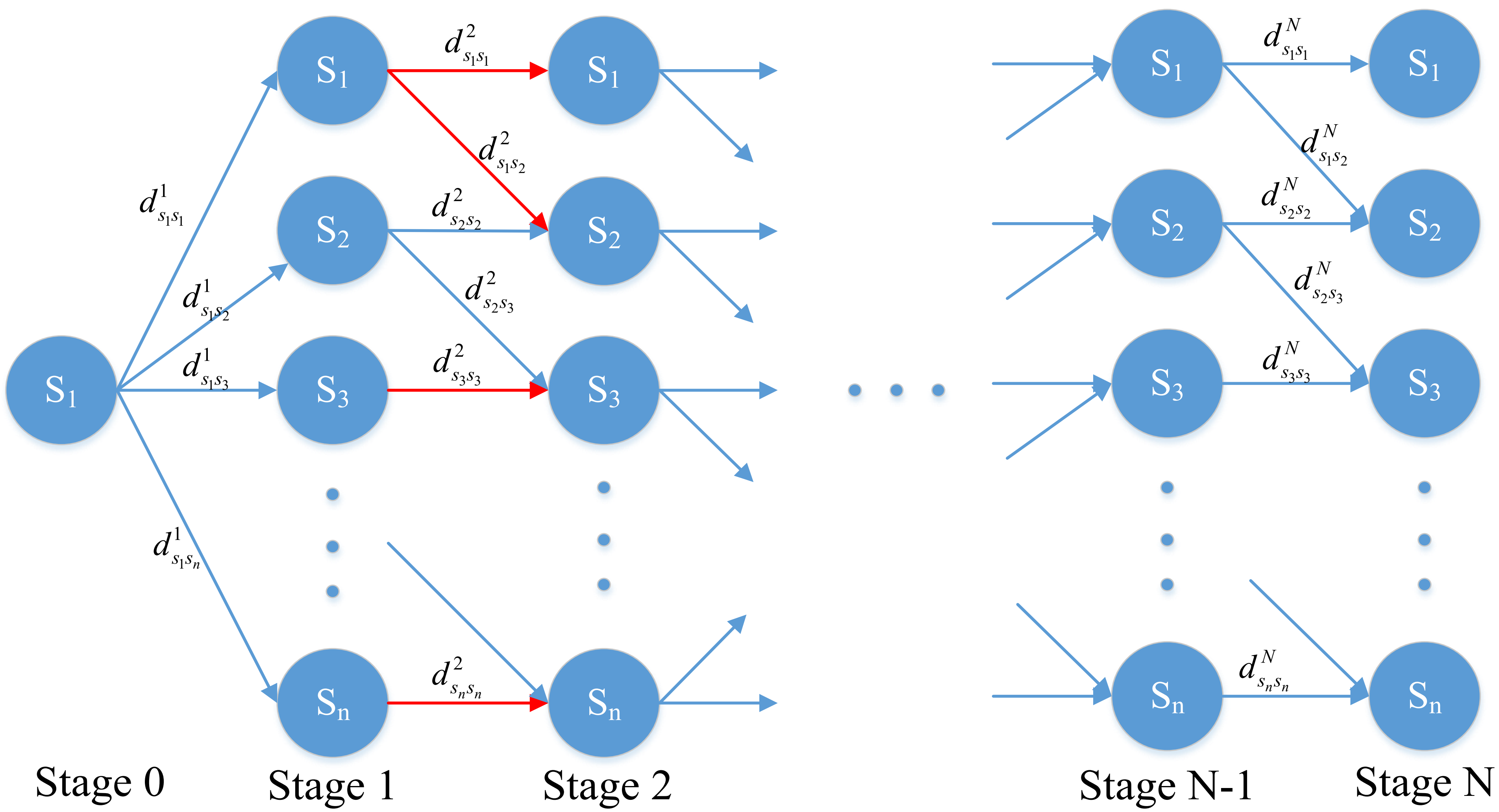
$$g_{min} \le g_{i,m}(k) \le g_{max} \quad (17)$$

$$g_{i,m}(k-1) - \Delta g_i \le g_{i,m}(k) \le g_{i,m}(k-1) + \Delta g_i \quad (18)$$

Timing plan constraints

Dynamic programming

Basic features: stage; state variable; decision variable; value function



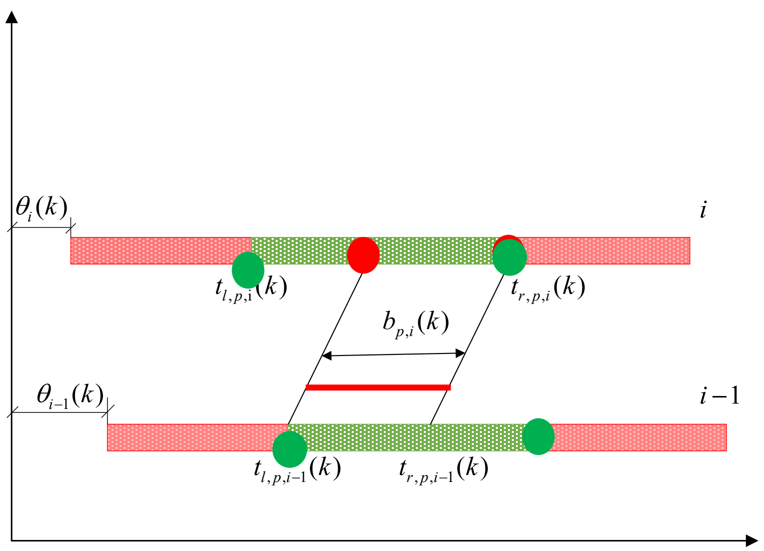
Stage: phases

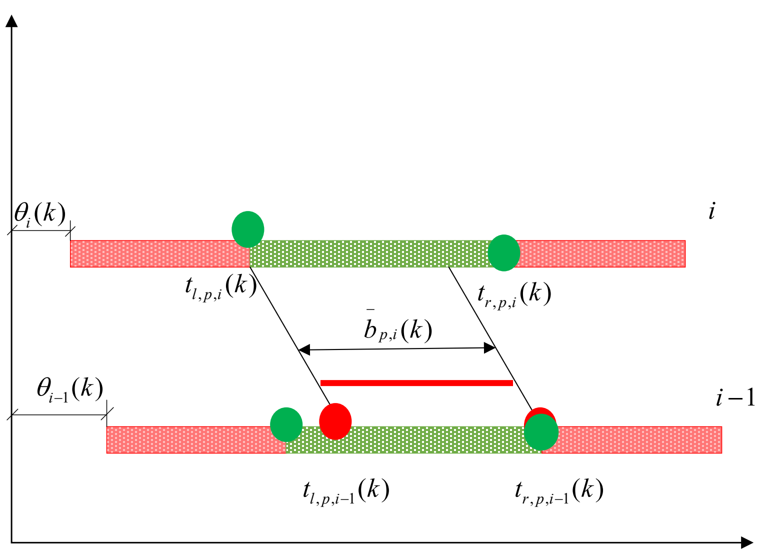
Decision variable: green time

State variable: total allocated time when each stage is completed

Value function: total delay

Coordination level





$$\max\left(\sum_i \sum_p \omega_p(h) b_{p,i}(j) + \sum_i \sum_p \bar{\omega}_p(h) \bar{b}_{p,i}(h)\right) \quad (19)$$

Green bandwidth

$$\bar{b}_{p,i}(h) = max\left(\bar{b}_{r,p,i}(h) - \bar{b}_{l,p,i}(h), 0\right) \quad (20)$$

$$\bar{b}_{p,i}(h) = max\left(\bar{b}_{r,p,i}(h) - \bar{b}_{l,p,i}(h), 0\right) \quad (21)$$

Right edge and left edge of the green band

$$b_{r,p,i}(h) = min(t_{r,p,i}(h) + t_{i,i+1}(h), t_{r,p,i+1}(h)) \quad (22)$$

$$b_{l,p,i}(h) = max(t_{l,p,i}(h) + t_{i,i+1}(h), t_{l,p,i+1}(h)) \quad (23)$$

$$\bar{b}_{r,p,i}(h) = min(t_{r,p,i+1}(h) + t_{i,i+1}(h), t_{r,p,i}(h)) \quad (24)$$

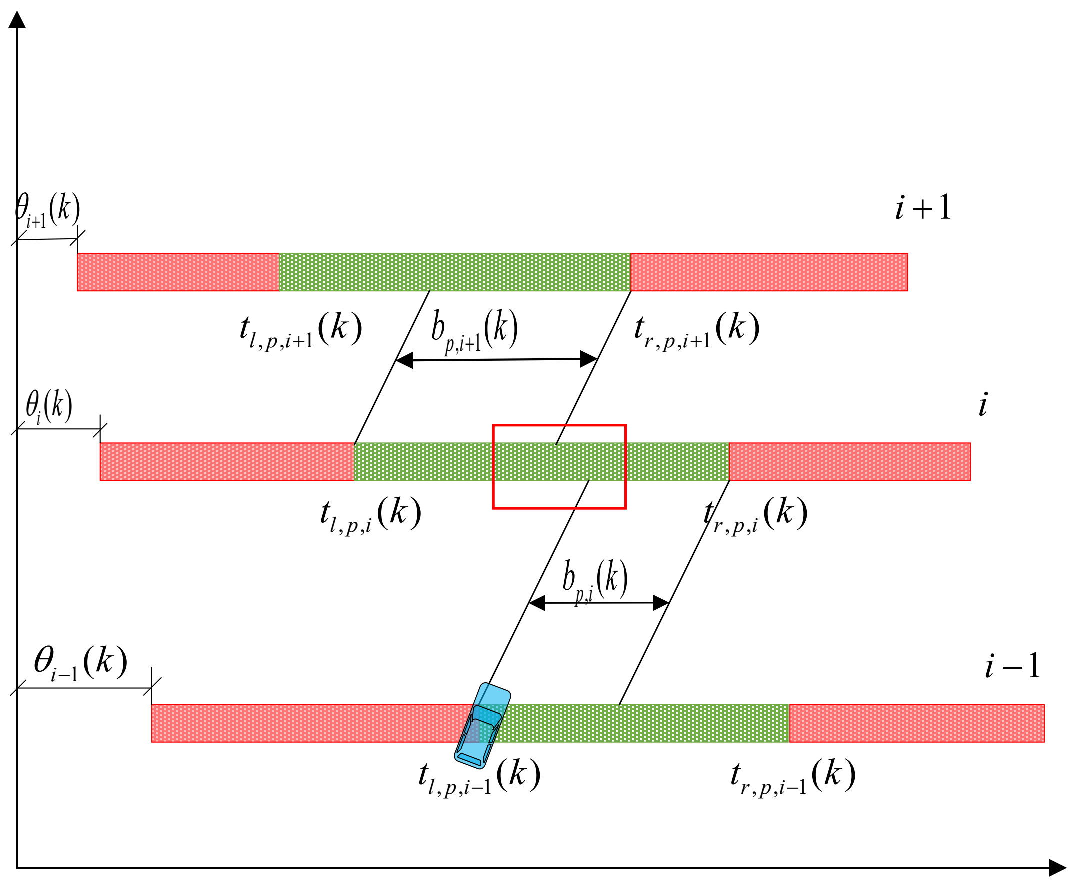
$$\bar{b}_{l,p,i}(h) = max(t_{l,p,i+1}(h) + t_{i,i+1}(h), t_{l,p,i}(h)) \quad (25)$$

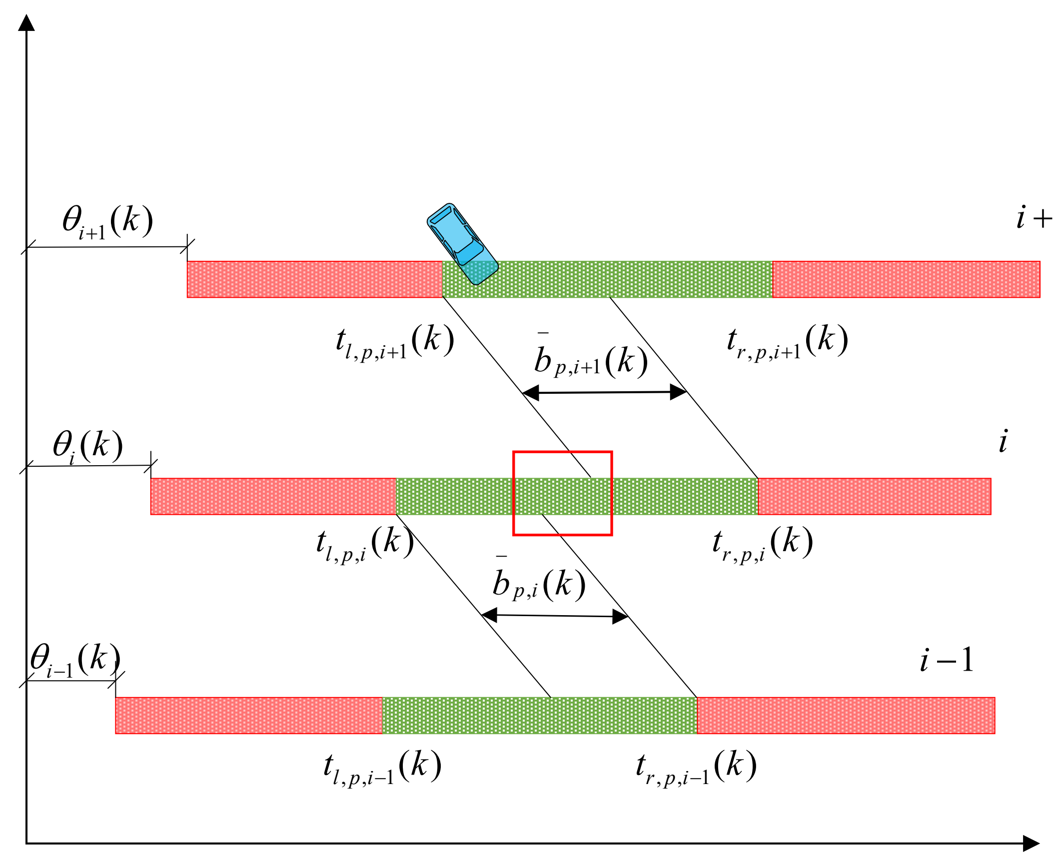
Start and end of the green times

$$t_{l,p,i}(h) = \sum_m \sum_n \beta_{m,p,i} * \varphi_{m,n} * g_{i,m}(h) + \theta_i(h) \quad (26)$$

$$t_{r,p,i}(h) = \sum_m \sum_n \beta_{m,p,i} * \varphi_{m,n} * g_{i,m}(h) + \sum_m \beta_{m,p,i} * g_{i,m}(h) + \theta_i(h) \quad (27)$$

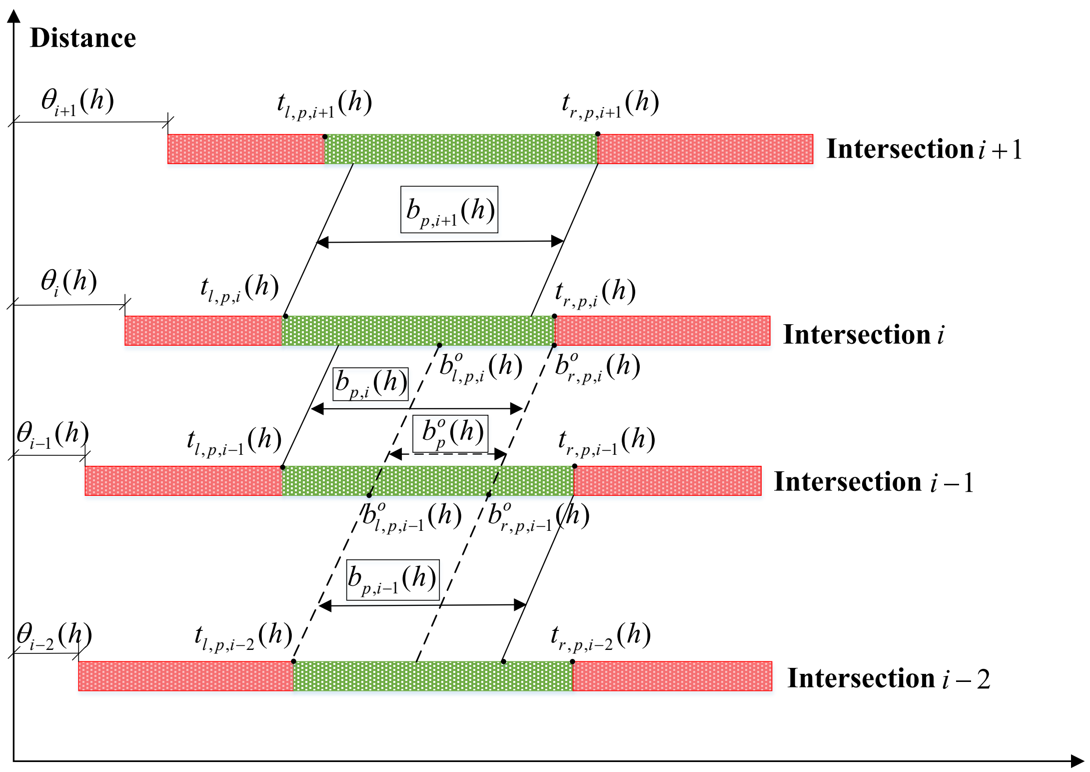
Sensor-based Traffic Signal Control

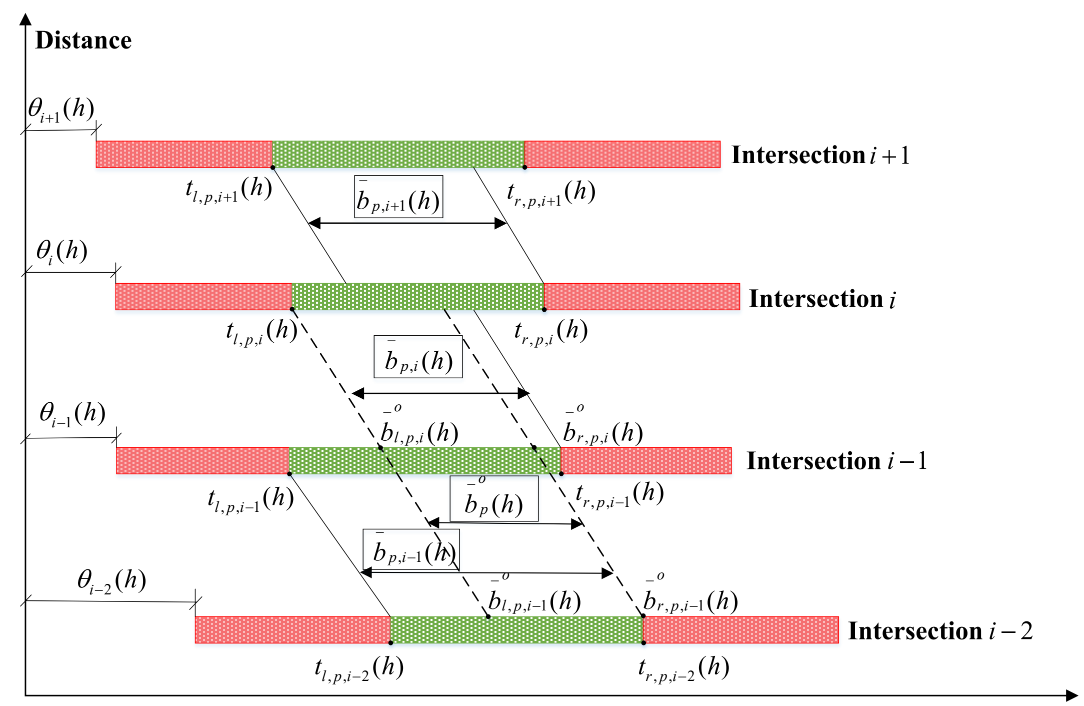




If the green band for a path is not continuous between intersections along an arterial, vehicles may need to stop several times when traveling along this path, which negatively impacts on the effectiveness of the coordination system.

Sensor-based Traffic Signal Control





$$b_{l,p,i}(h) < b_{r,p,i+1}(h) - t_{i,i+1}(h) \quad (28)$$

$$b_{r,p,i}(h) > b_{l,p,i+1}(h) - t_{i,i+1}(h) \quad (29)$$

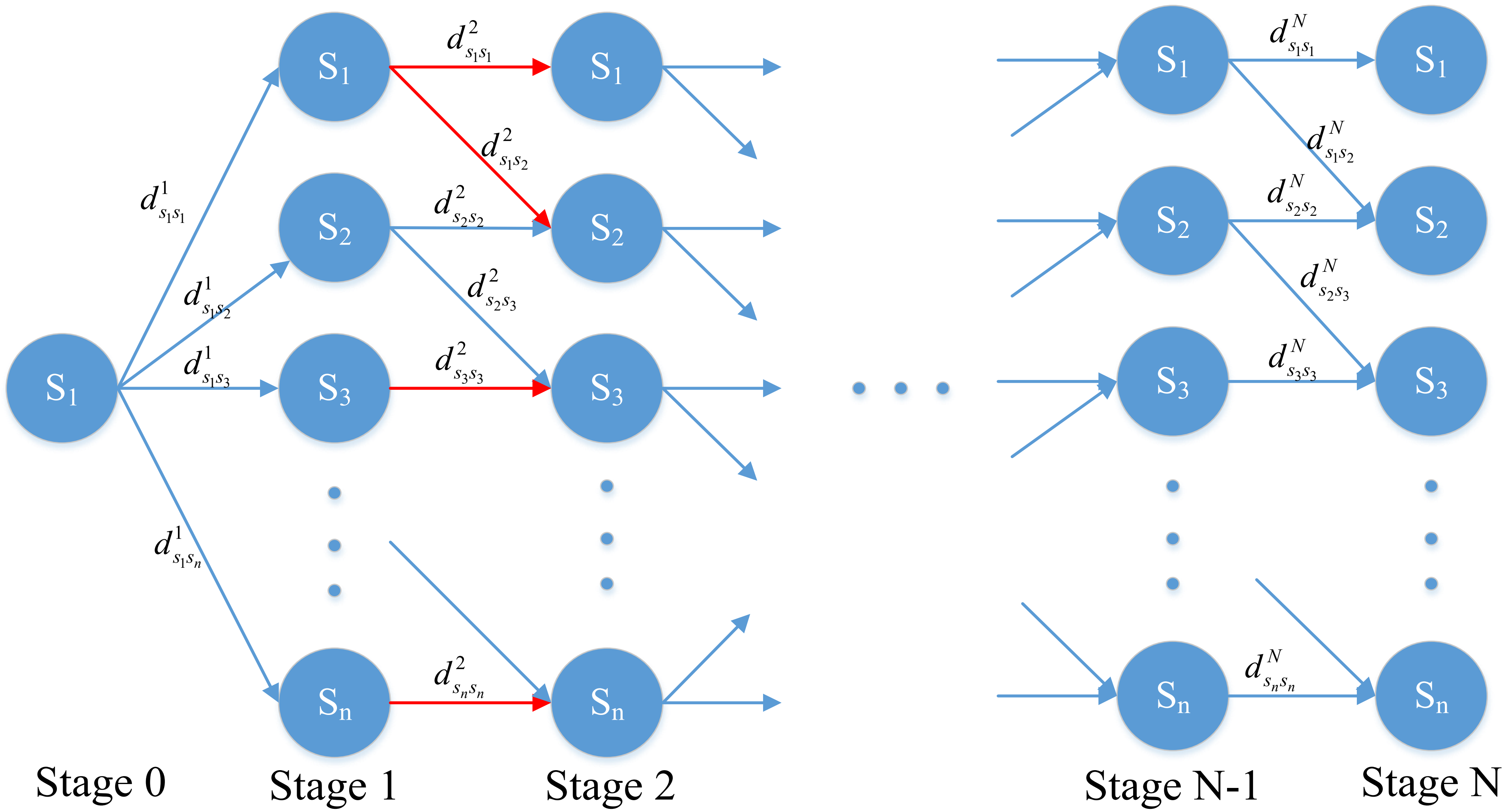
$$\bar{b}_{l,p,i+1}(h) < \bar{b}_{r,p,i}(h) - t_{i,i+1}(h) \quad (30)$$

$$\bar{b}_{l,p,i+1}(h) < \bar{b}_{r,p,i}(h) - t_{i,i+1}(h) \quad (31)$$

$$\theta_{i-1}(h) - \Delta\theta_i \le \theta_i(h) \le \theta_{i-1}(h) + \Delta\theta_i \quad (32)$$

Sensor-based Traffic Signal Control

Dynamic programming



Stage: intersections

Decision variable: offset

State variable: feasible new offset

Value function: green band width

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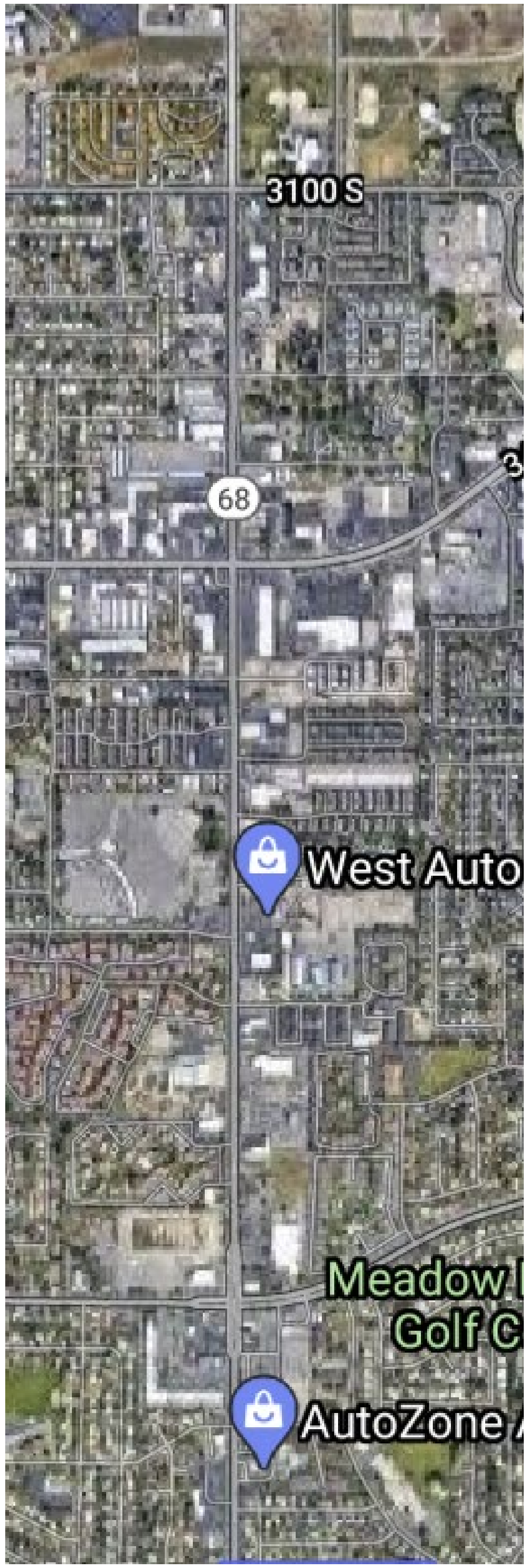
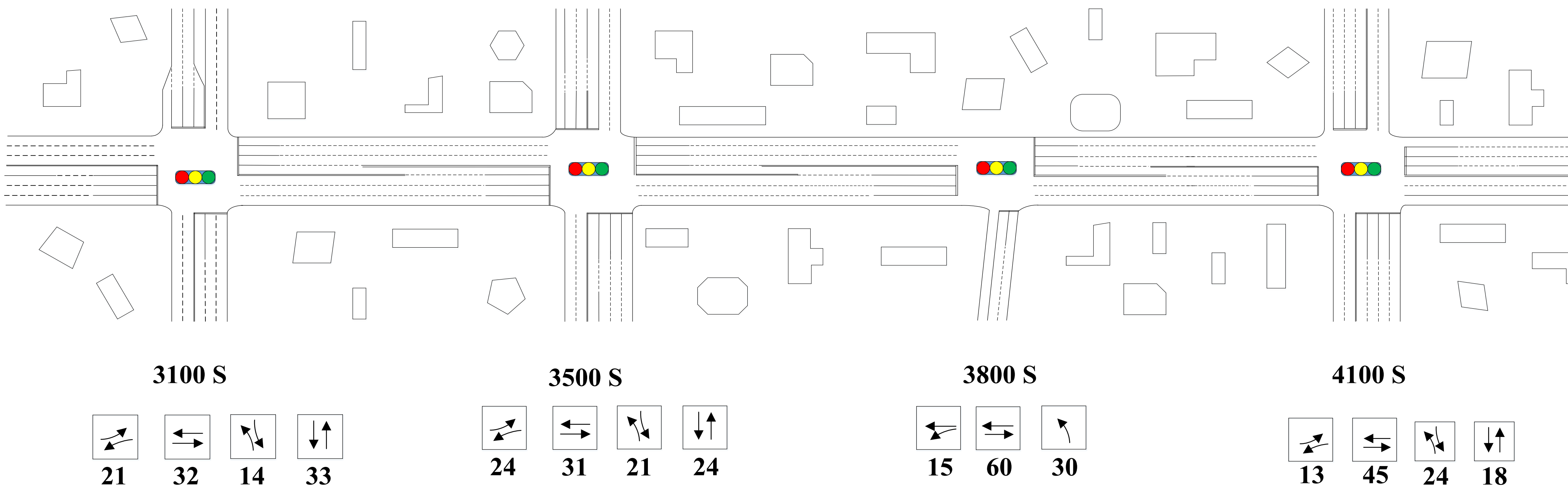
Numerical Examples





Numerical Examples

Three control systems

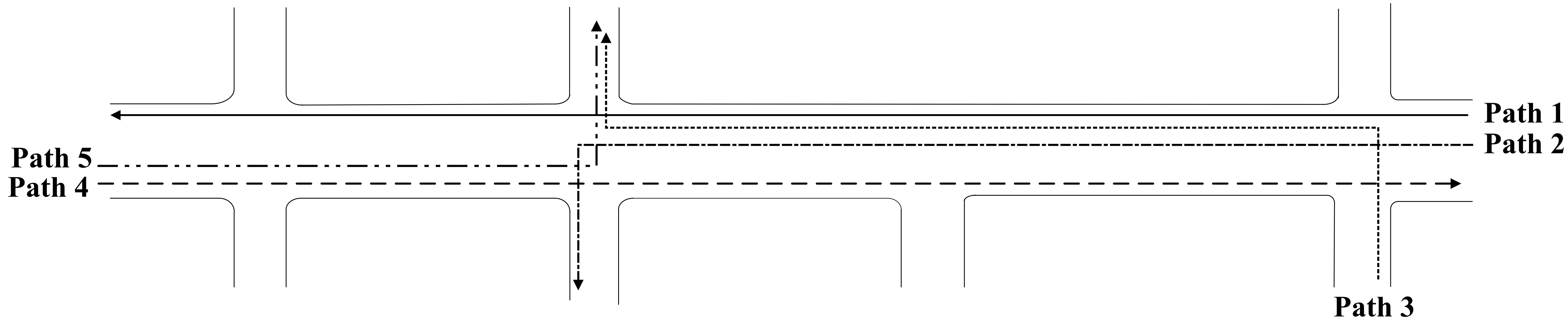
Fixed progression control system: the coordination parameters including phase split, cycle length and offset are determined by TOC and are applied in daily traffic management and operation. The signal timing plan is shown in the figure and the offset of the four intersections are 45s, 98s, 49s, and 96s from west to east, respectively.

Adaptive control system: only the developed adaptive traffic signal control system is applied in the simulated network. In this case, detectors are installed behind the stop bar to get the turning flow of each intersection.

Proposed control system: Following the control logic, adaptive traffic signal control and dynamic progression control are both implemented. The proposed control system is tested with four scenarios of 25%, 50%, 75% and 100% CAV market penetration rate.

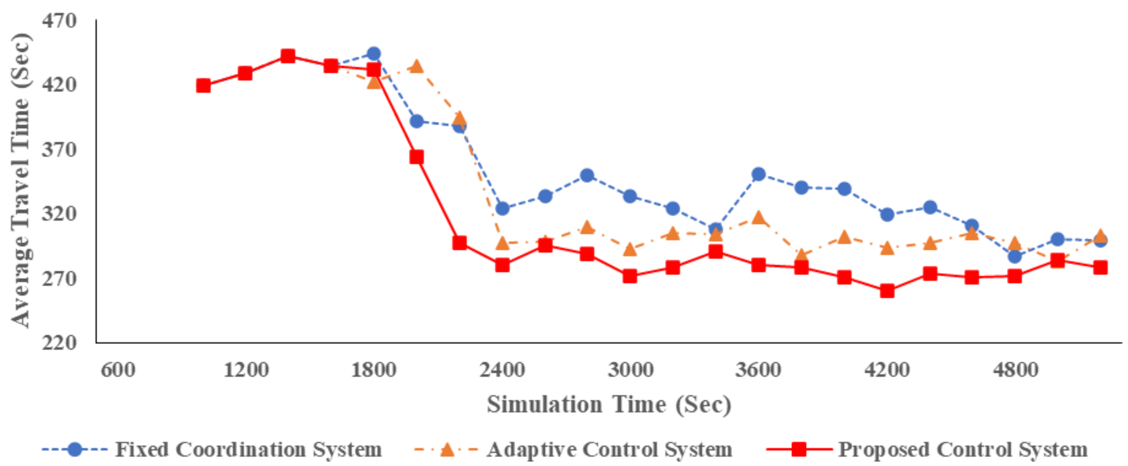
Numerical Examples

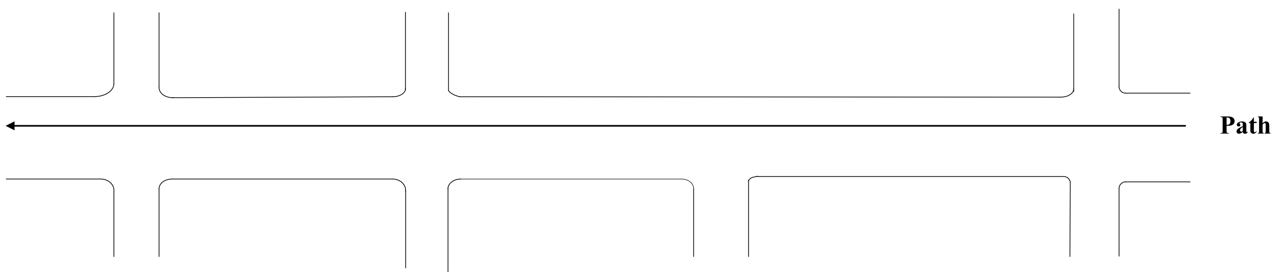
Critical paths

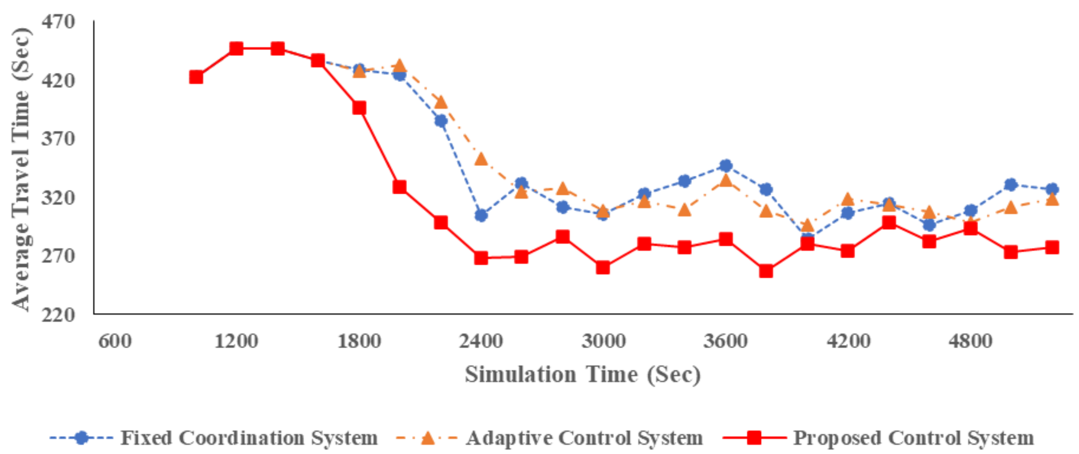


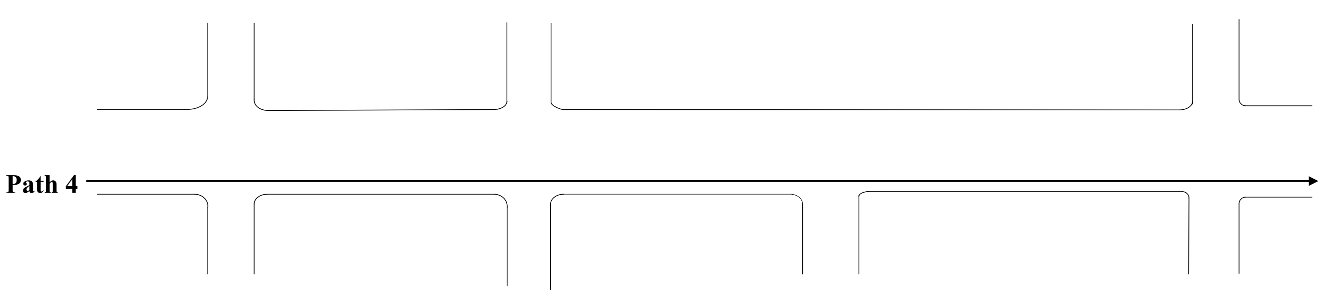
Time Period	Critical paths
1200 - 1800	Path 1; path 2; path 4; path 5
1800 - 2400	Path 1; path 2; path 4; path 5
2400 - 3000	Path 1; path 2; path 4; path 5
3000 - 3600	Path 1; path 2; path 4; path 5
3600 - 4200	Path 1; path 3; path 4; path 5
4200 - 4800	Path 1; path 3; path 4; path 5

Travel time of critical path

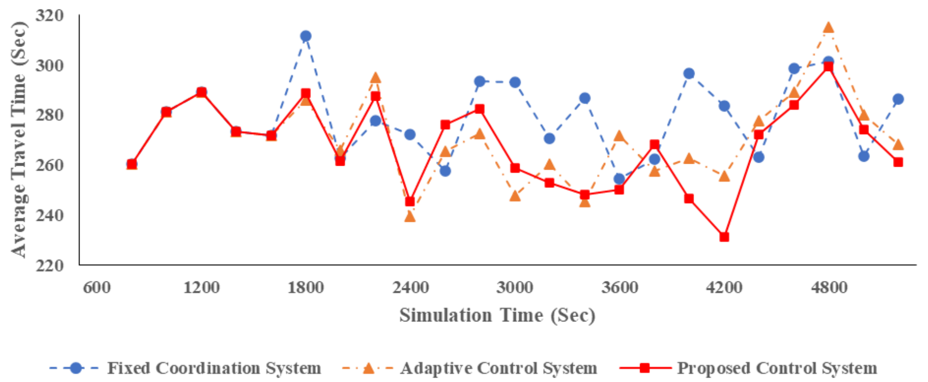


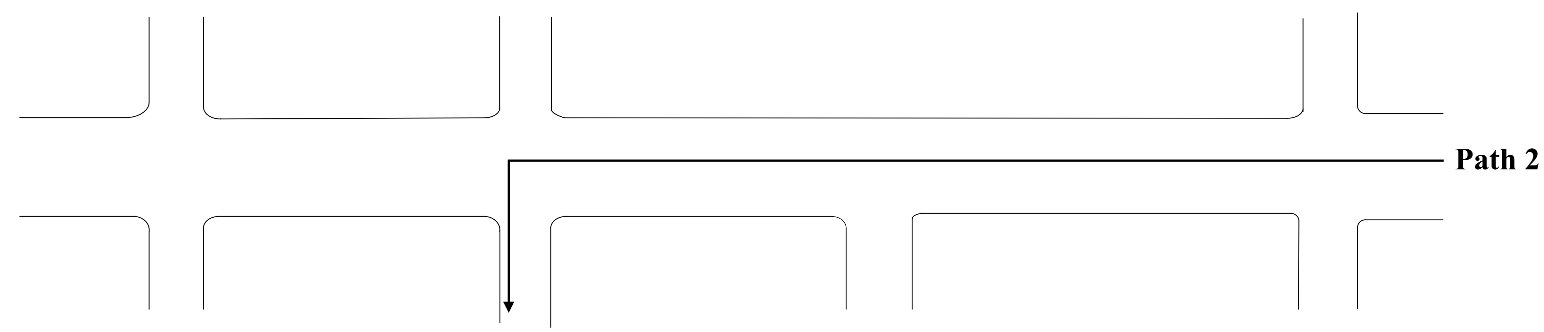


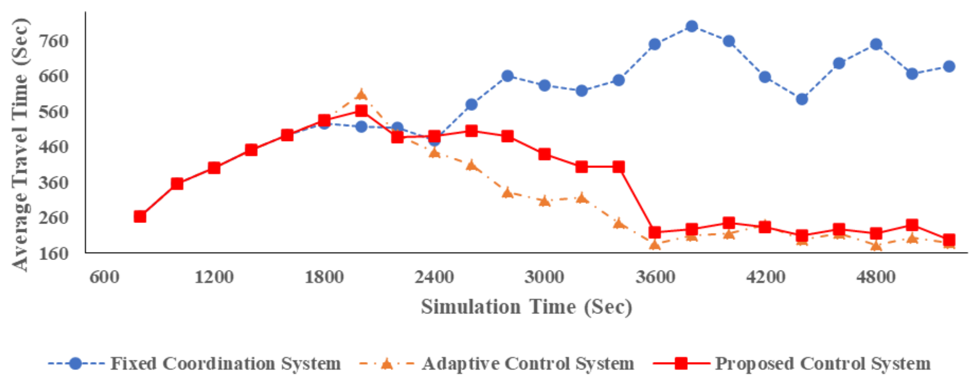


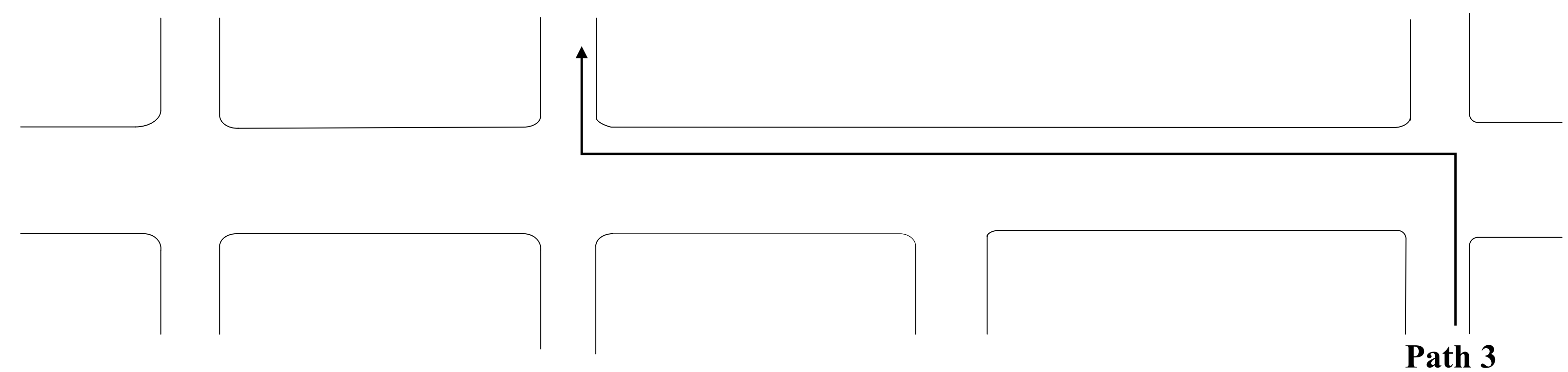


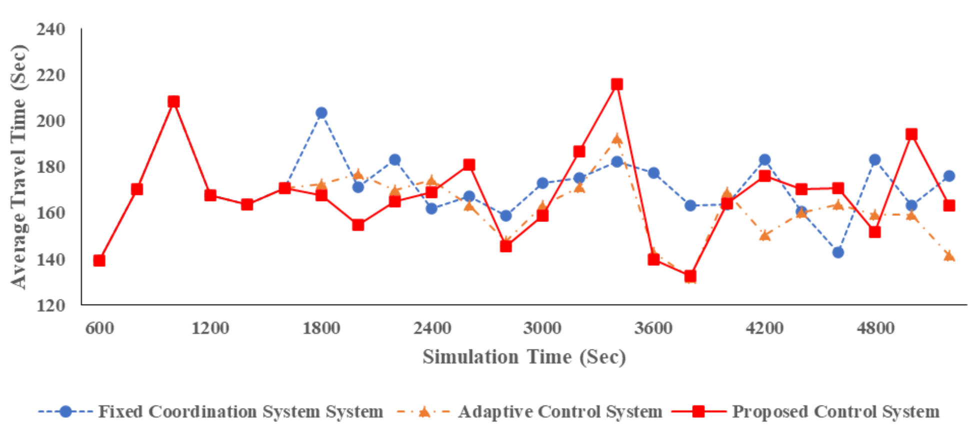
Numerical Examples

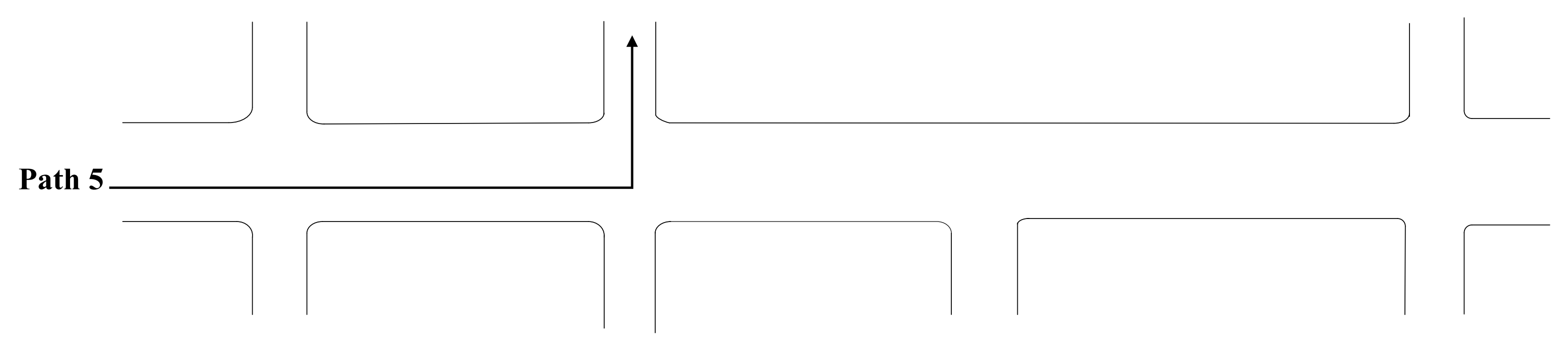












Numerical Examples

Arterial performance

Arterial performance of proposed and fixed coordination control system

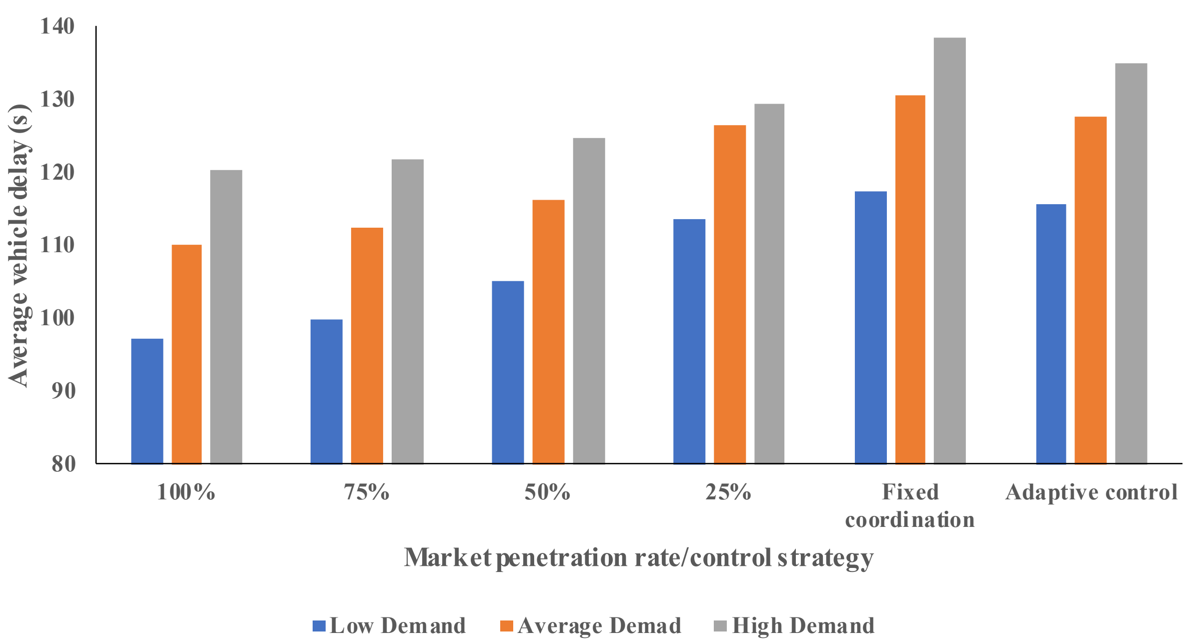
Performance Index	FCCS	100% MPR	75% MPR	50% MPR	25% MPR
Average delay	130.43	109.99 (-15.67%)	112.32 (-13.89%)	116.12 (-10.97%)	126.40 (-3.09%)
Average number of stops	2.56	2.03 (-20.70%)	2.20 (-14.06%)	2.24 (-12.50%)	2.34 (-8.59%)

Arterial performance of proposed and adaptive signal control system

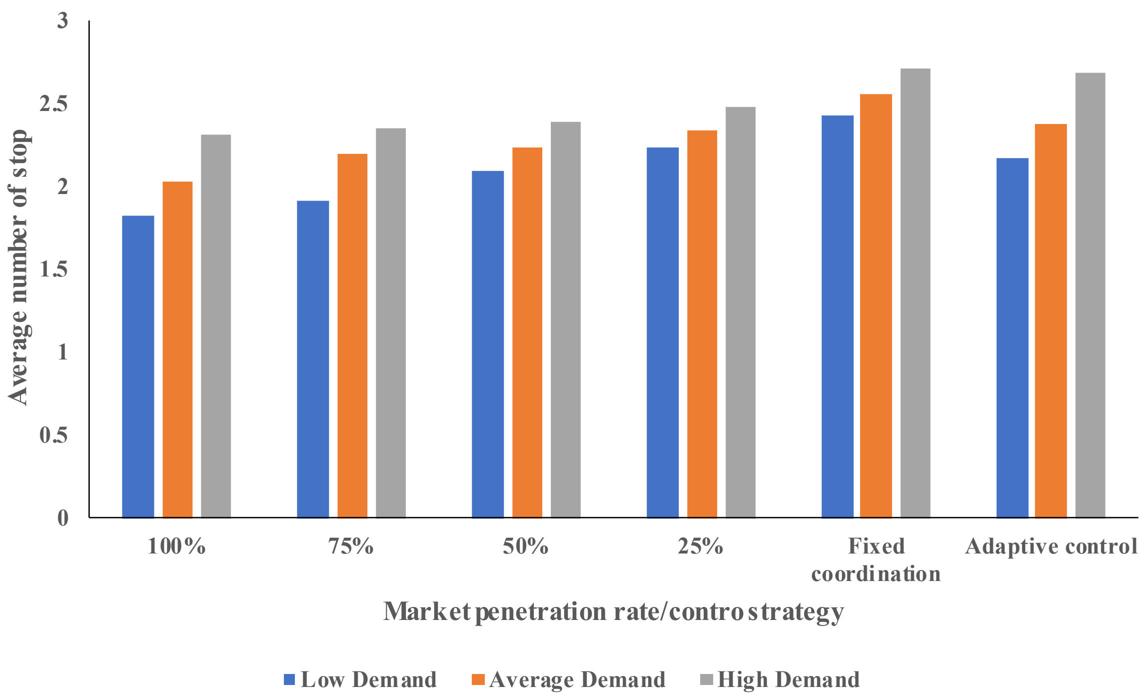
Performance Index	ACS	100% MPR	75% MPR	50% MPR	25% MPR
Average delay	127.62	109.99 (-13.81%)	112.32 (-11.99%)	116.12 (-9.01%)	126.40 (-0.95%)
Average number of stops	2.38	2.03 (-14.71%)	2.20 (-7.56%)	2.24 (-5.88%)	2.34 (-1.68%)

Numerical Examples

Sensitivity analysis with various demand level



Average vehicle delay



Average vehicle stop

OUTLINE

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Conclusions

- With the advances in the sensors technology, traffic signals can collect real-time vehicle information including location, speed, acceleration, heading and other vehicle data. Leveraging these enriched data, traffic controllers are able to perform more effectively.

- Developing a real-time control system to adaptively optimize signal control plan to minimize the total vehicle delay for an isolated intersection under different market penetration rates of CAV.

- Regarding low market penetration rate and available CAV information, a method was developed to estimate the vehicle arrival information at the intersection.

- Developing a real-time control system to dynamically optimize offsets of intersections to offer green bandwidth to paths with high volume.

THANK YOU FOR TIME

Questions?