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Webinar: Connected Vehicle System Design for Signalized Arterials

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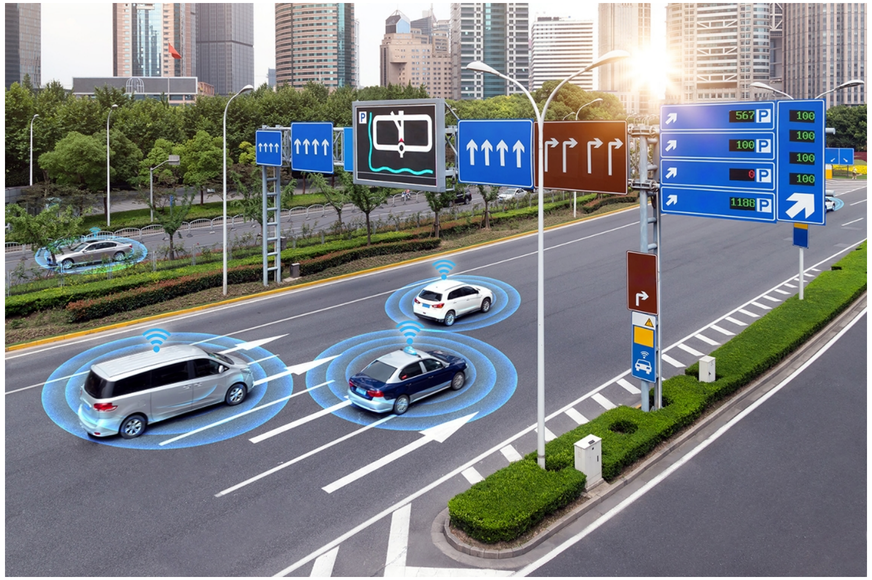

Connected Vehicle System Design for Signalized Arterials

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Outline

- ❖ Background
- ❖ CV System Architecture
- ❖ Data Collection
- ❖ Dynamic Signal Control
- ❖ Smart Traffic Signal Control
- ❖ More Discussions

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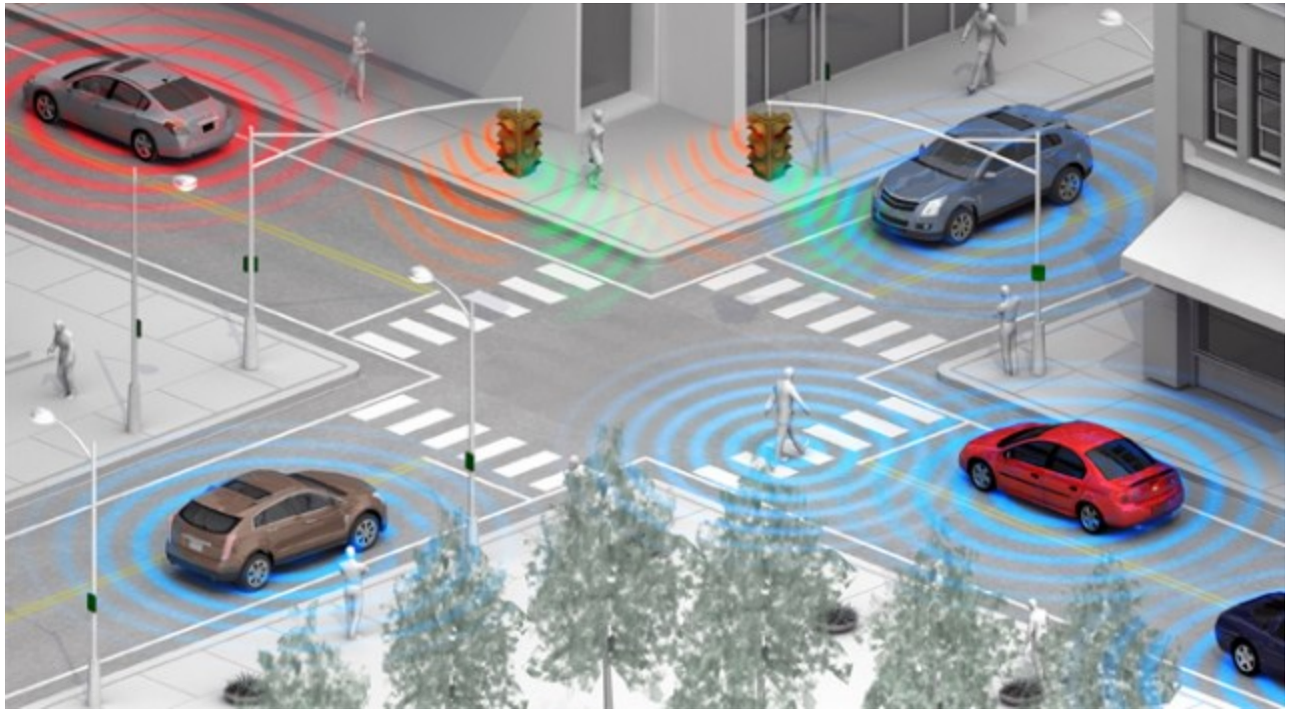
- ❖ **Background**
- ❖ CV System Architecture
- ❖ Data Collection
- ❖ Dynamic Signal Control
- ❖ Smart Traffic Signal Control
- ❖ More Discussions

Background: Connected Vehicle (CV)

- Connectivity technologies
  - DSRC
  - C-V2X
  - 5G
  - DMB

  - V2X : V2V, V2I, V2P,
  - Etc.



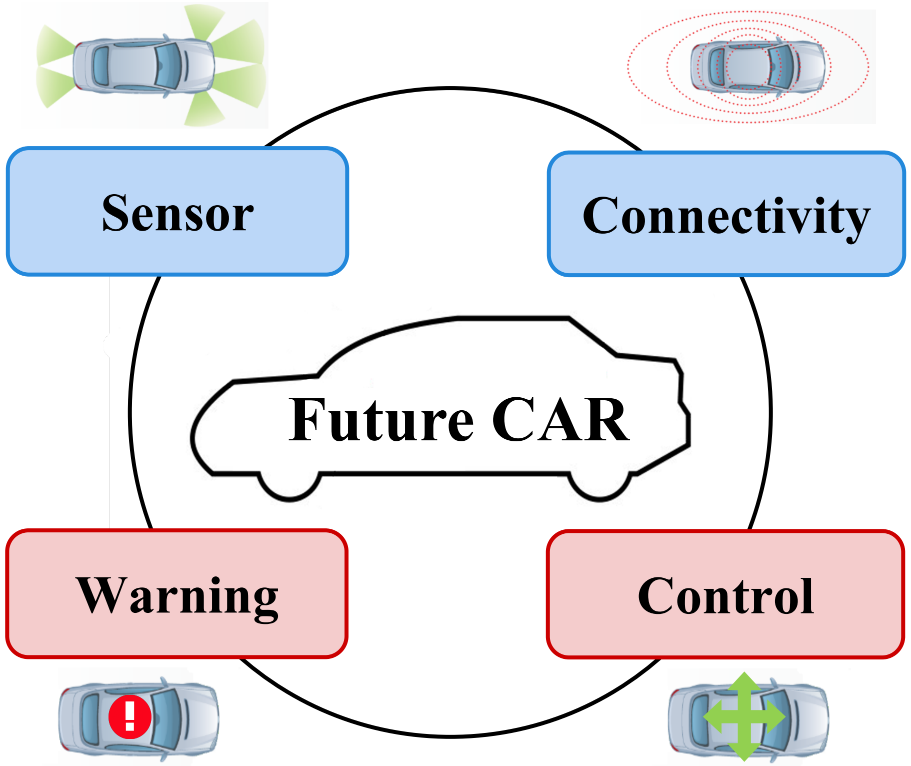
Background: Automated & Autonomous Vehicle (AV)

- **Six levels of vehicle automation**

SAE Level	SAE Name	Definition	Automation Controls...	Example(s)
0	No Automation	Human performs entire driving task	—	
1	Driver Assistance	Automation controls one vehicle function (steering OR speed)	OR	Adaptive Cruise Control Lane Keep Assist
2	Partial Automation	Automation controls BOTH steering and speed; driver responsible for monitoring and immediate reengagement	AND	Tesla Autopilot Audi Traffic Jam Assistant
3	Conditional Automation	Automation controls BOTH steering and speed and monitors environment; driver may be notified to reengage		Volvo DriveMe
4	High Automation	Automation performs all aspects of dynamic driving task in SOME driving modes; driver not required to reengage		Closed Campus Driverless Shuttle Driverless Valet
5	Full Automation	Automation performs all aspects of dynamic driving task under ALL roadway and environmental conditions		Driverless Taxi

Background: Connected Automated Vehicle (CAV)

- The connectivity technology of CAVs allows the exchange of traffic information between vehicles and infrastructure.
- The automated driving system (ADS) will control the vehicle trajectory based on the real-time data from on-board sensors and CV communication.



Outline

- ❖ Background
- ❖ **CV System Architecture**
- ❖ Data Collection
- ❖ Dynamic Signal Control
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- ❖ More Discussions

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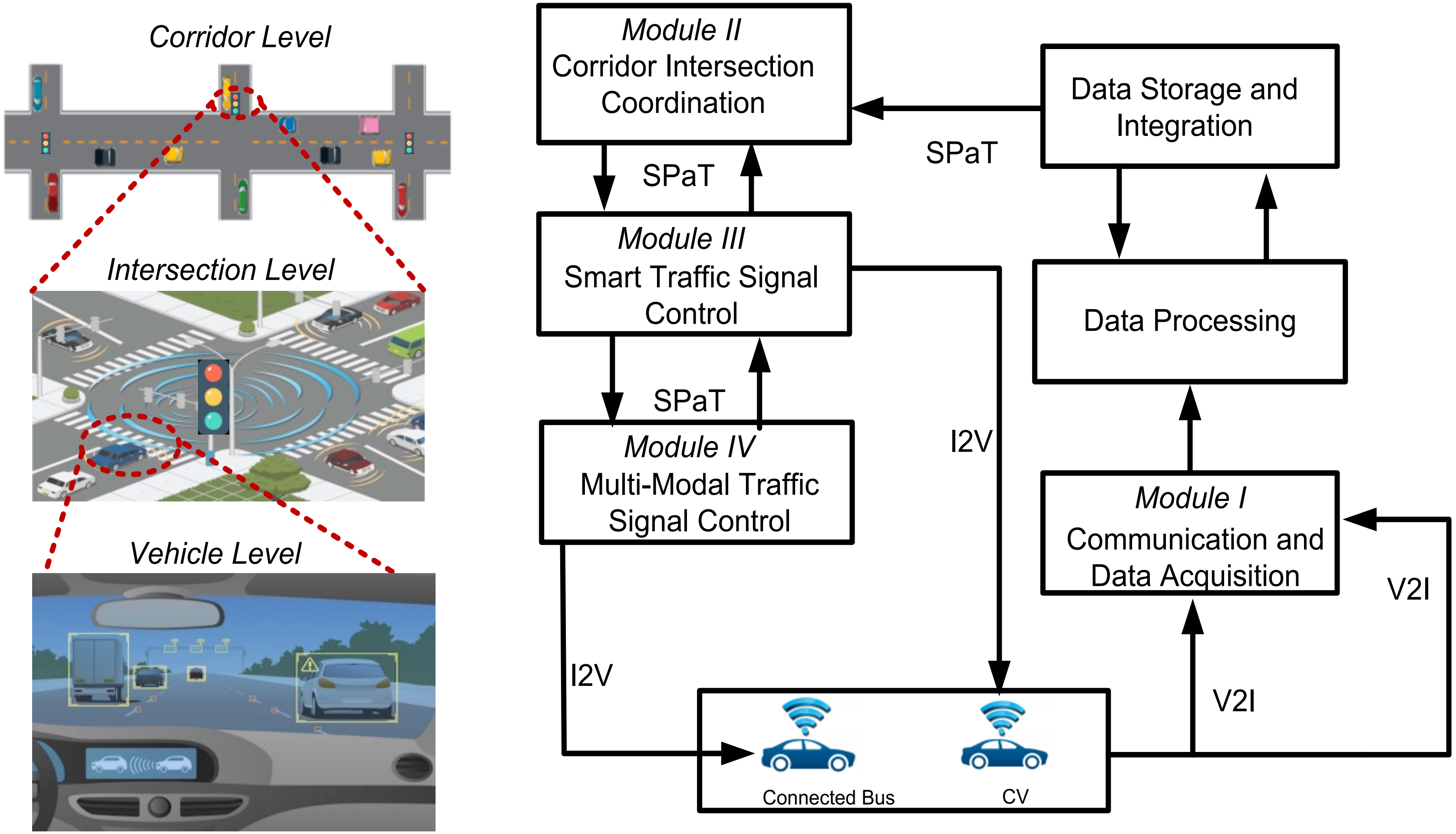
System Architecture

Control Levels



Outline

- ❖ Background
- ❖ CV System Architecture
- ❖ **Data Collection**
- ❖ Dynamic Signal Coordination
- ❖ Smart Traffic Signal Control
- ❖ Multi-Modal Systems
- ❖ More Discussions

Data Collection: DSRC v.s. C-V2X

At present, there are two very different technologies enabling V2X:

- **DSRC** stands for dedicated short-range communications. It is also called ITS-G5 in Europe. In the US, DSRC is contained in a 75 MHz segment of the 5.9 GHz band. It is often used for direct communications in a local environment.
- **C-V2X** stands for cellular V2X. It utilizes cellular technology to provide the link between the vehicle and the rest of the world, including other vehicles and the traffic control system.

Data Collection: The Engineer's Dilemma

- ❑ In the midst of a platform war, engineers must choose which platform to commit their development time and costs to.
- ❑ Possible solution: combining DSRC and C-V2X

Data Collection: Other Challenges

Communication Jam/Congestion

- ❑ Imaging all vehicles on the road are CV and CAVs…
- ❑ Some communication priorities may be given to CAVs.

Outline

- ❖ Background
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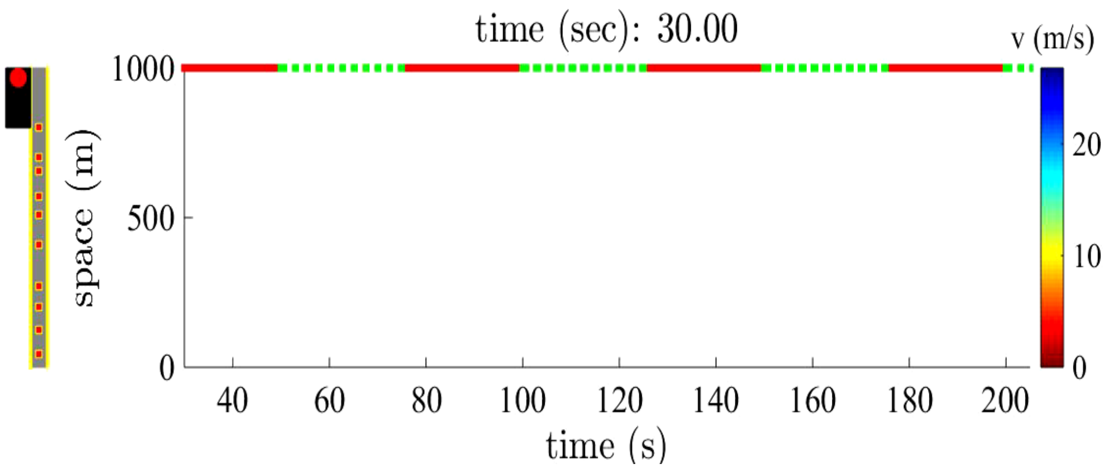
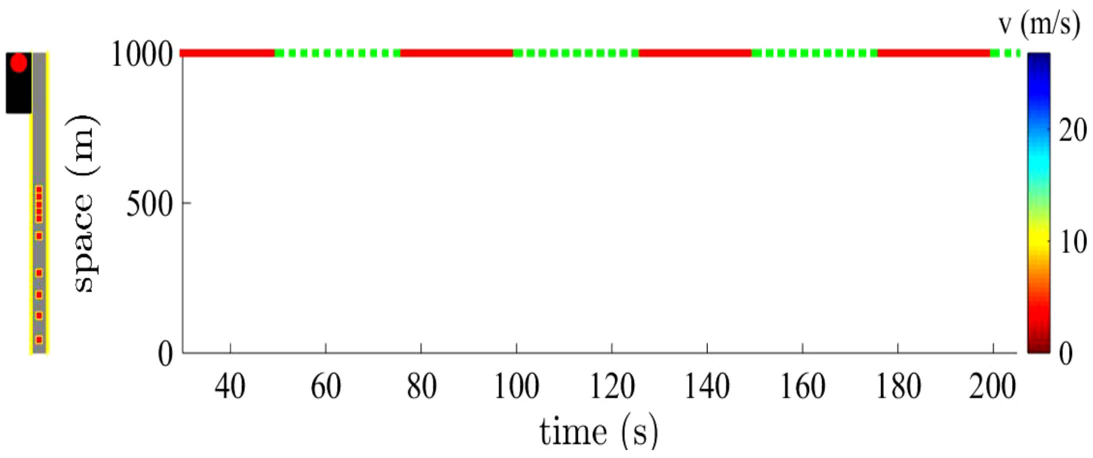
- ❖ Data Collection
- ❖ **Dynamic Signal Control**
- ❖ Smart Traffic Signal Control
- ❖ More Discussions

Dynamic Traffic Signal Coordination: Concept

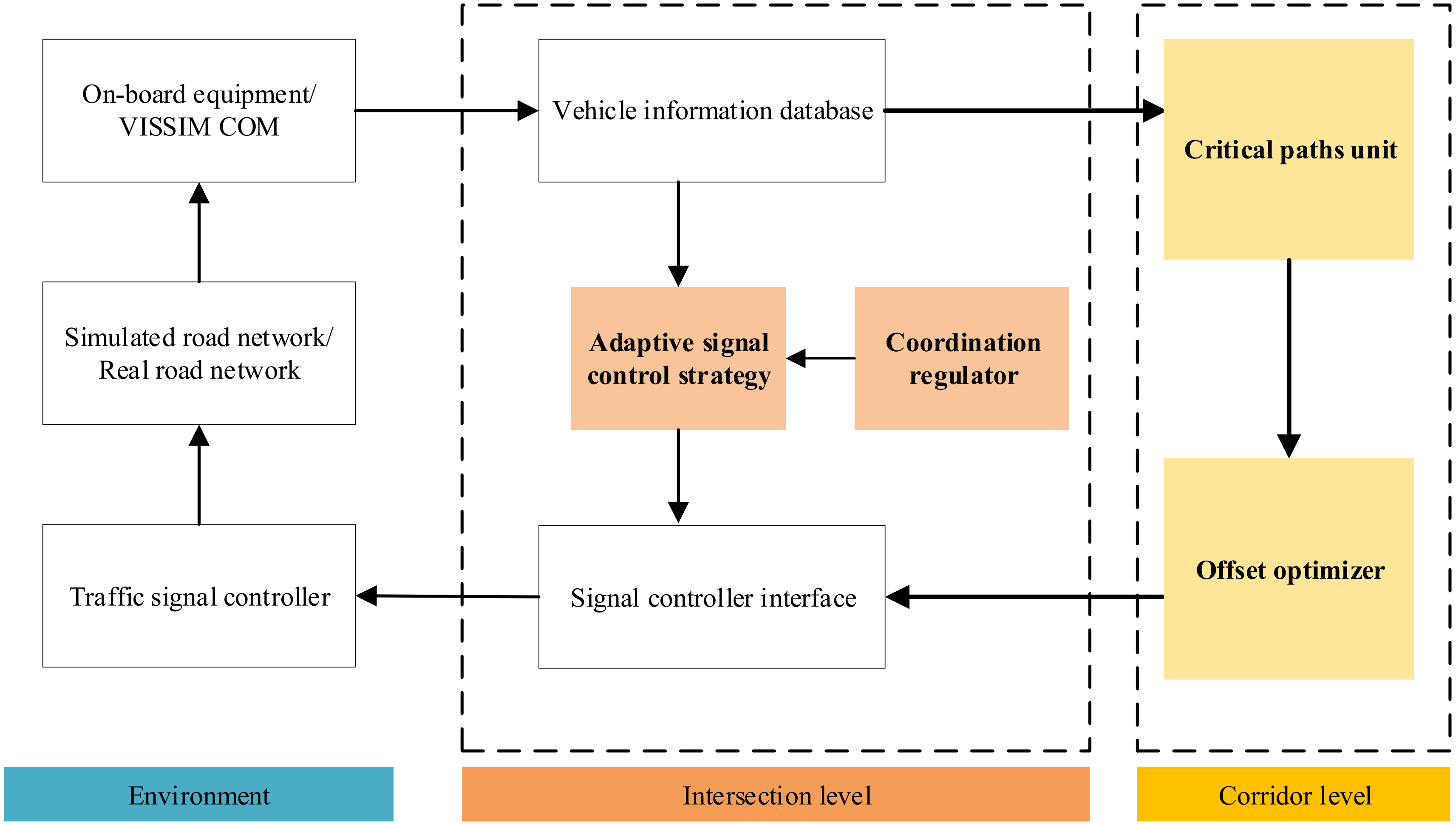
CAV Speed Harmonization

- Design vehicle trajectories and corresponding signal timing (i.e., final boundary conditions)
- Maximize throughput and driving comfort, minimize energy consumption, ensure safety
- Core problem – Trajectory planning + Scheduling





Dynamic Traffic Signal Control: System Design

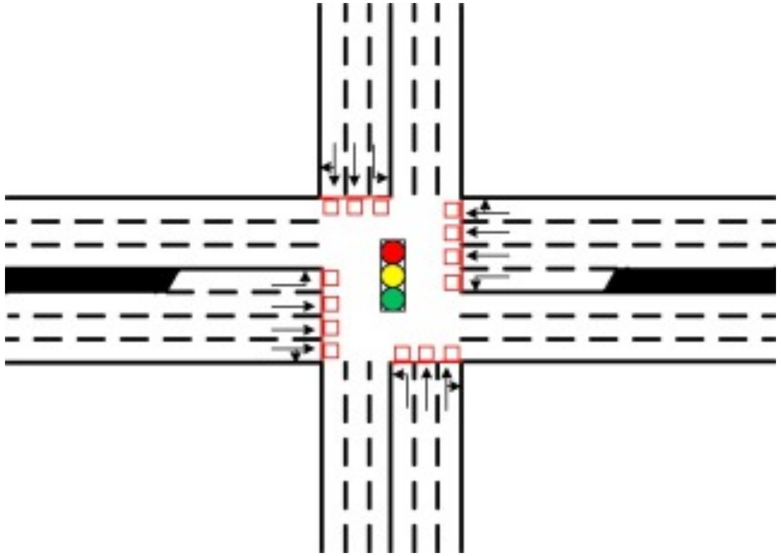


Intersection Level: Signal Timing Optimization

The input information of vehicle arrival and departure at intersections are crucial.

Vehicle arrival flow rate: $$\mu_{l,i}(k,j) = \frac{1}{C} * q_{l,i}(j) \quad \forall l,j$$

Turning flow: $$q_{l,i}(j) = \frac{1}{N}\sum_{n=1}^{N} q_{i,j}(j-n)$$



Installation and maintenance cost is high.

Intersection Level: Model & Algorithm

Market penetration rate (MPR) : the ratio of the number of CAVs to the number of traffic travelling through the network over a period of time.

When the market penetration rate is low:

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

O.W.

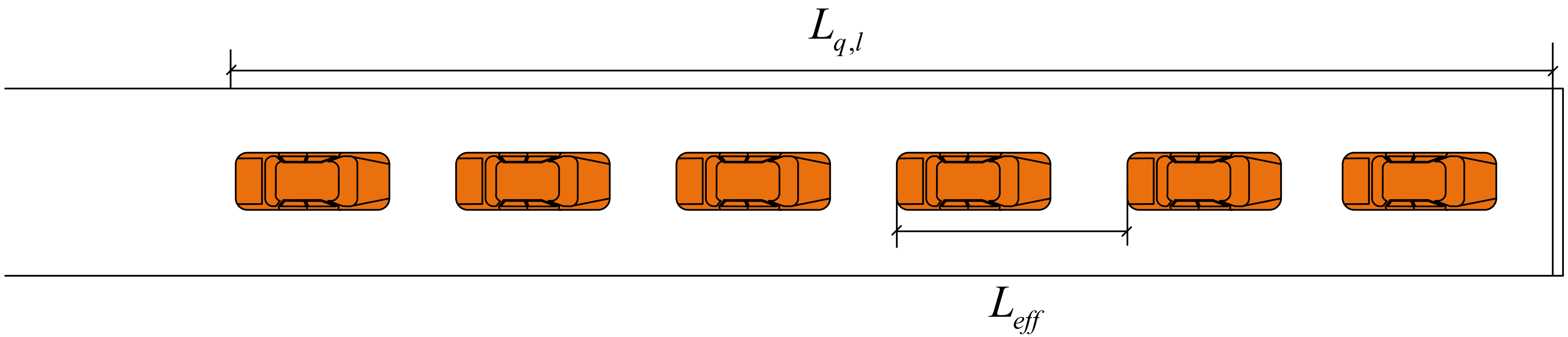
$$p_{l,i}(j) = \frac{N_{c,l}}{N_{all,l}}$$

Intersection Level: Model & Algorithm

Number of CAVs and all vehicles waited in the queue:

$N_{c,l}$ Can be observed

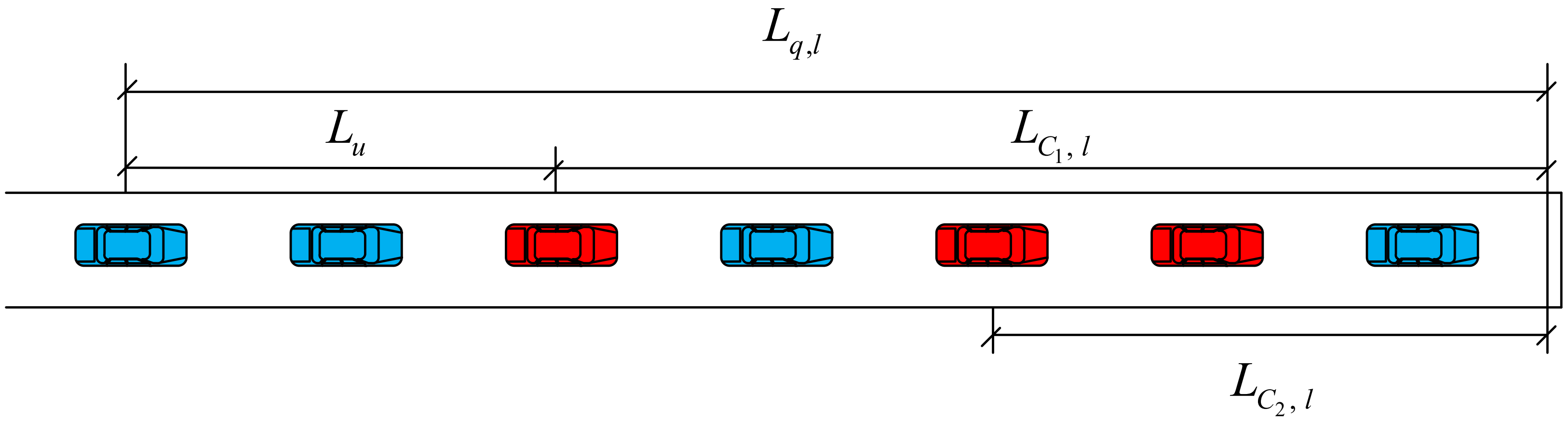
$N_{all,,l}$ Can be estimated by $N_{all,j} = \frac{L_{q,j}}{L_{eff}}$



Intersection Level: Model & Algorithm

Three queuing cases with CAVs and non-CAVs

Case 1: More than one CV in the queue



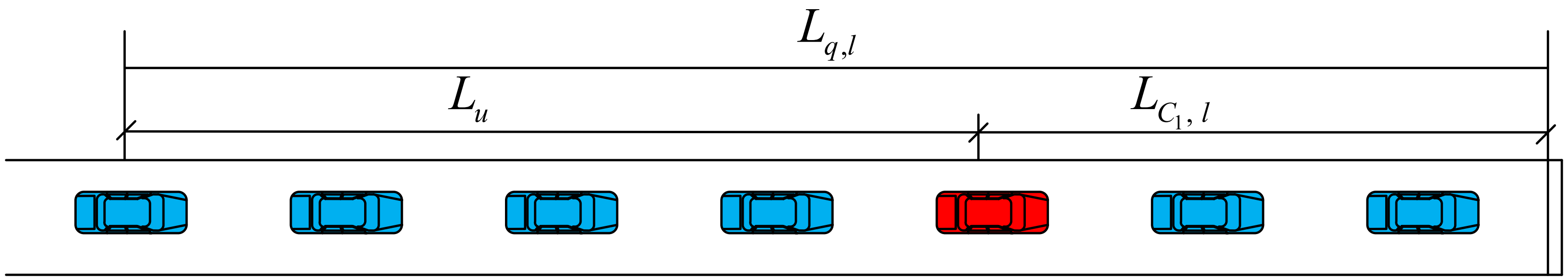
$$L_{q,l} = L_{c1,l} + L_u$$

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

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

Intersection Level: Model & Algorithm

Case 2: Only one CV in the queue



$$L_{q,l} = L_{c1,l} + L_u$$

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

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

Case 3: No CVs in the queue

the only information that can be used is the historical information. We simplify the lane flow of current cycle under this condition by the average lane flow of previous several cycles.

Intersection Level: Model & Algorithm

Model 1

$$\min d_i(j) \quad (1)$$

$$d_i(j) = \sum_{l=1}^{L} \sum_{k=1}^{c} Q_{l,i}(k,j) * \Delta t \qquad \forall l,j \quad (2)$$

Total intersection delay

$$Q_{l,i}(k,j) = \max\left(Q_{i,j}(k-1,j) + \mu_{l,i}(k,j) - r_{l,i}(k,j), 0\right) \quad \forall l,j \quad (3)$$

Queue length

$$\mu_{l,i}(k,j) = \frac{1}{c} * q_{l,i}(j) \quad \forall l,j \quad (4)$$

Vehicle arrival rate

$$r_{l,i}(k,j) = \begin{cases} s_{l,i} * \Delta t \\ 0 \end{cases} \quad \forall l,j \quad (5)$$

Saturation flow rate

$$Q_{l,i}(0,j) = \tau_{l,i}(0,j-1) \quad \forall l,j \quad (6)$$

$$\sum_{p=1}^{p=N} \left(g_{i,p}(k) + l_{i,p}(k)\right) = c(k) \quad (7)$$

$$g_{i,m}(k-1) - \Delta g_i \le g_{i,m}(k) \le g_{i,m}(k-1) + \Delta g_i \quad (8)$$

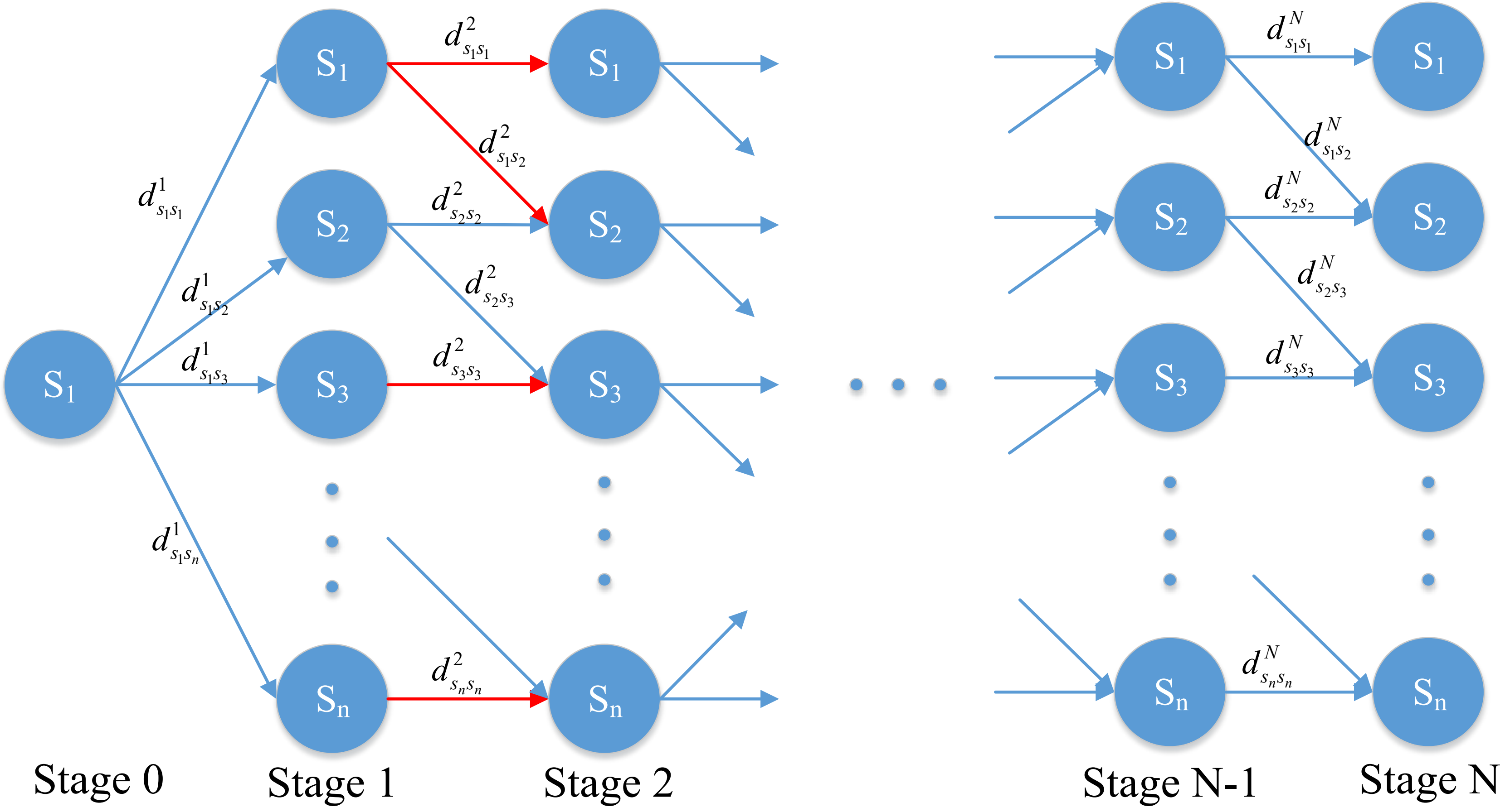
$$g_{min} \le g_{i,m}(k) \le g_{max} \quad (9)$$

Timing plan constraints

Intersection Level: Model & Algorithm

Dynamic programming

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



Intersection Level: Model & Algorithm

Algorithm

Stage: discrete time step.

State variable: total allocated time to each phase.

$$S_i(p,j) = \{\max\left(g_{min}, g_{i,p}(j-1) - \Delta g_i\right) + l_{i,p}(j), \ldots \min\left(g_{max}, g_{i,p}(j-1) + \Delta g_i\right) + l_{i,p}(j)\}$$

Decision variable: green time allocated to each phase.

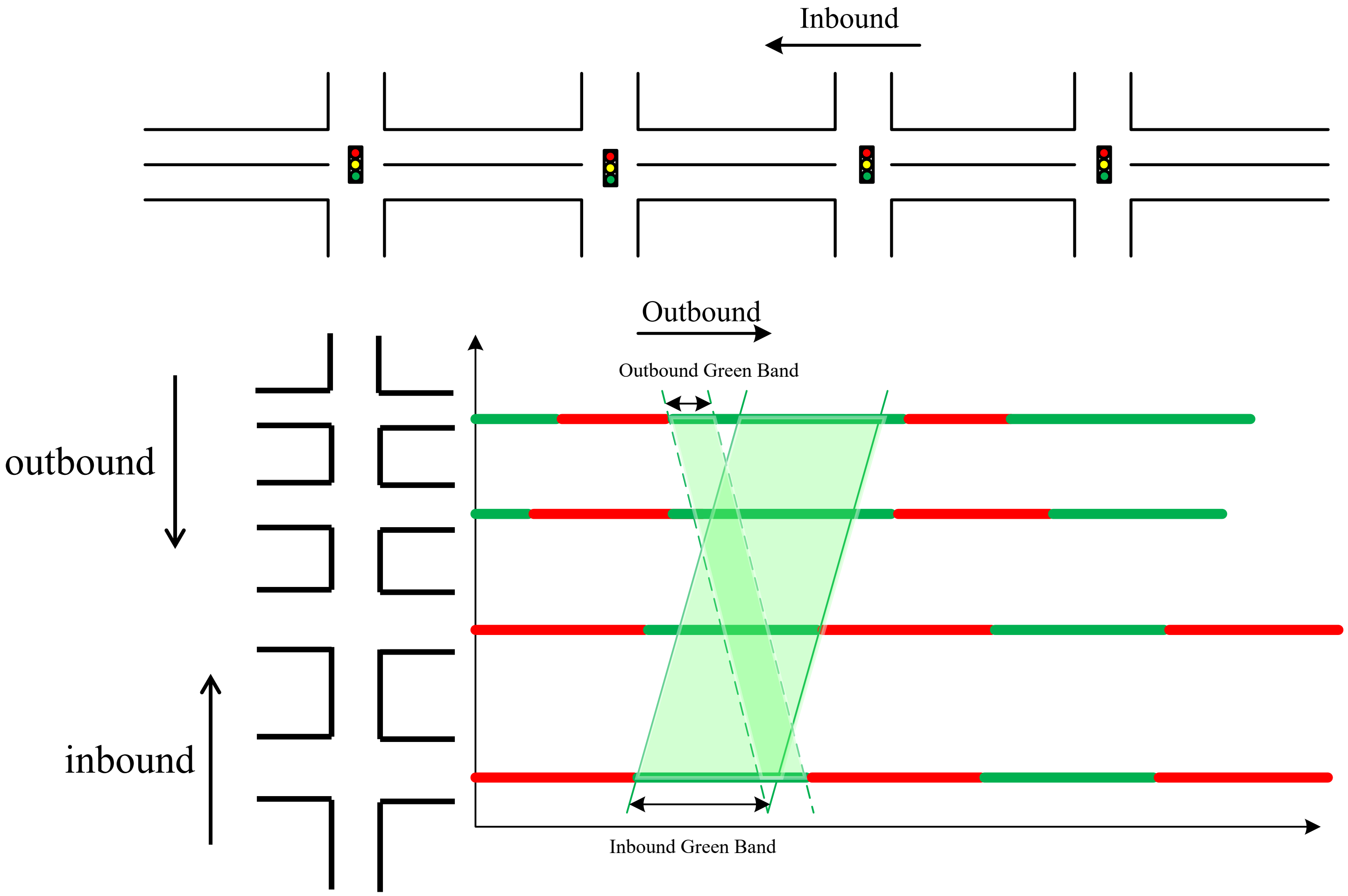
$$X_i(p,j) = \{\max\left(g_{min}, g_{i,p}(j-1) - \Delta g_i\right), \ldots \min\left(g_{max}, g_{i,p}(j-1) + \Delta g_i\right)\}$$

Value function: total delay.

Step 1: define $p = 1, v_i(0) = 0$;
Step 2: $p = p + 1$; update value function $v_i(s_i(p,j)) = \{v_{i-1}(s_i(p-1,j)) + d_i(x_i(p,j)) | x_i(p,j) \in X_i(p,j)\}$ and determine the optimal value function; Then find the optimal solution at this stage, denoted as $\theta_i^*(j)$.
Step 3: if $i < N_i$, go to step 2; Else, trace back to find the optimal solution for each stage.

Arterial Level: System Coordination

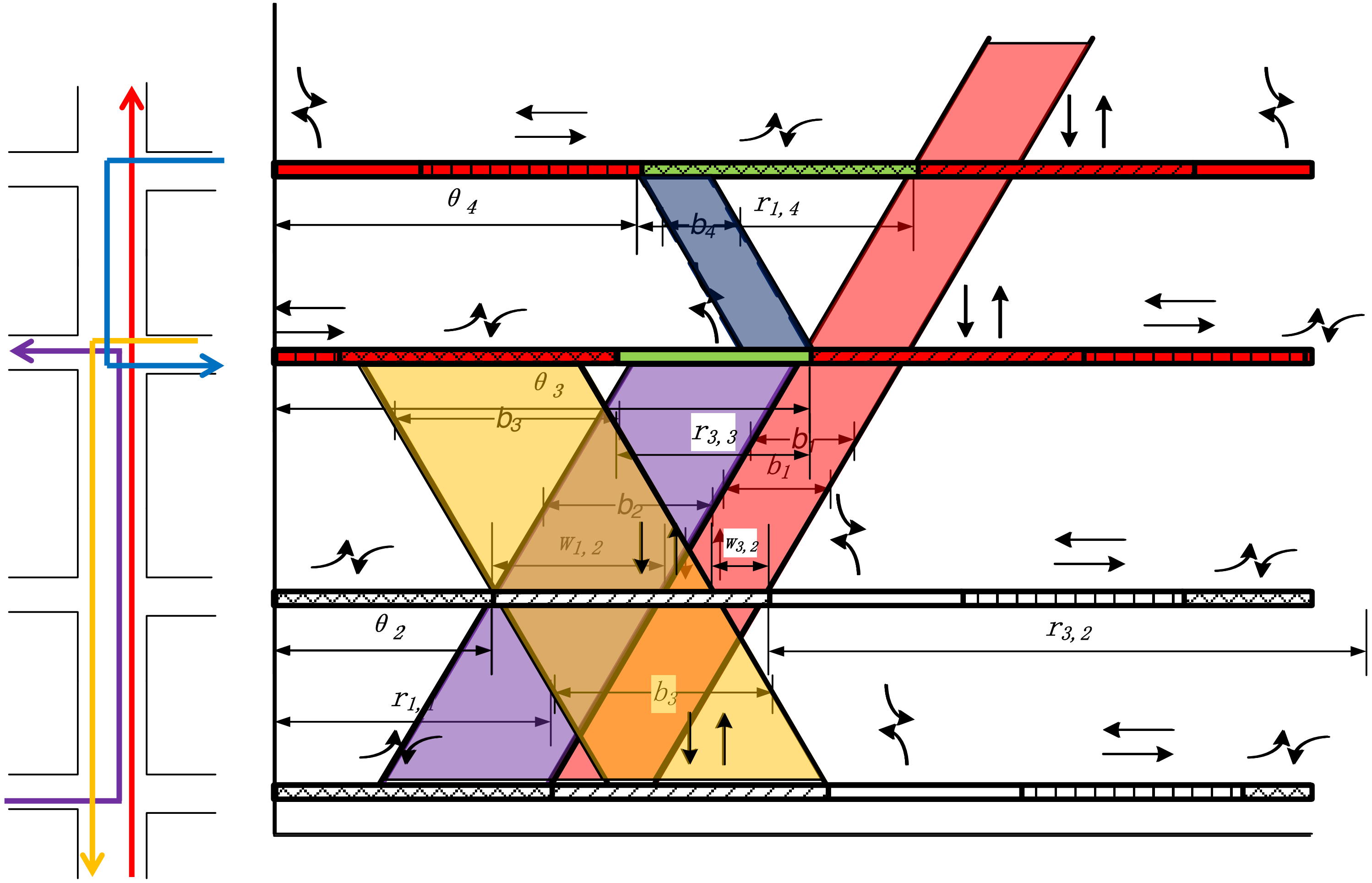
Traditional Two-way Signal Progression



Within the green band, vehicles can pass the intersections without any stops.

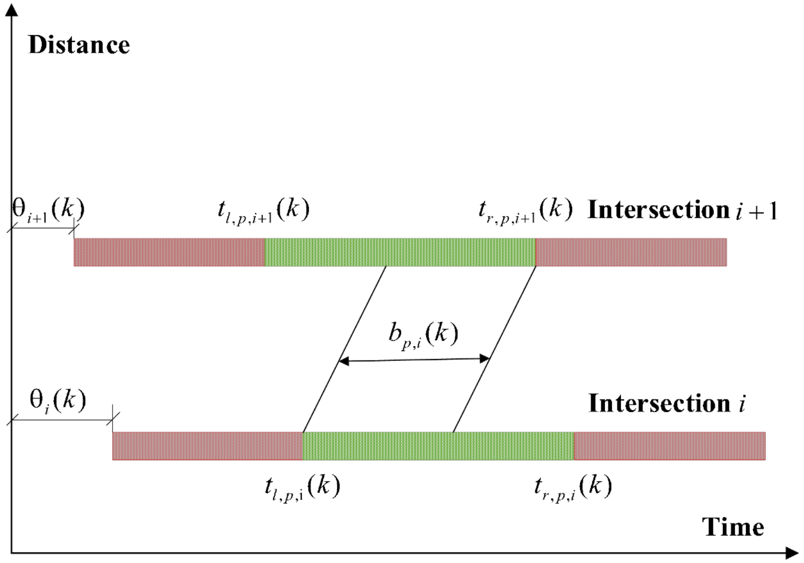
Arterial Level: System Coordination

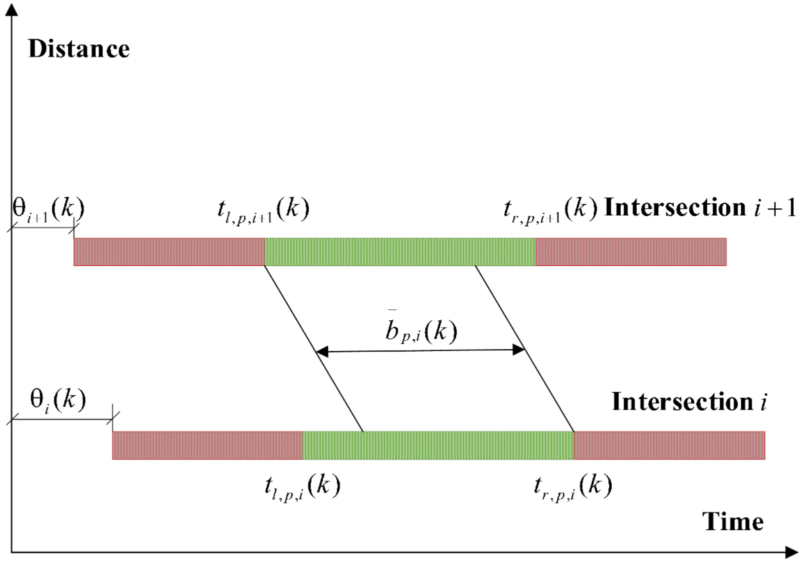
Multi-Path Progression



Arterial Level: System Coordination

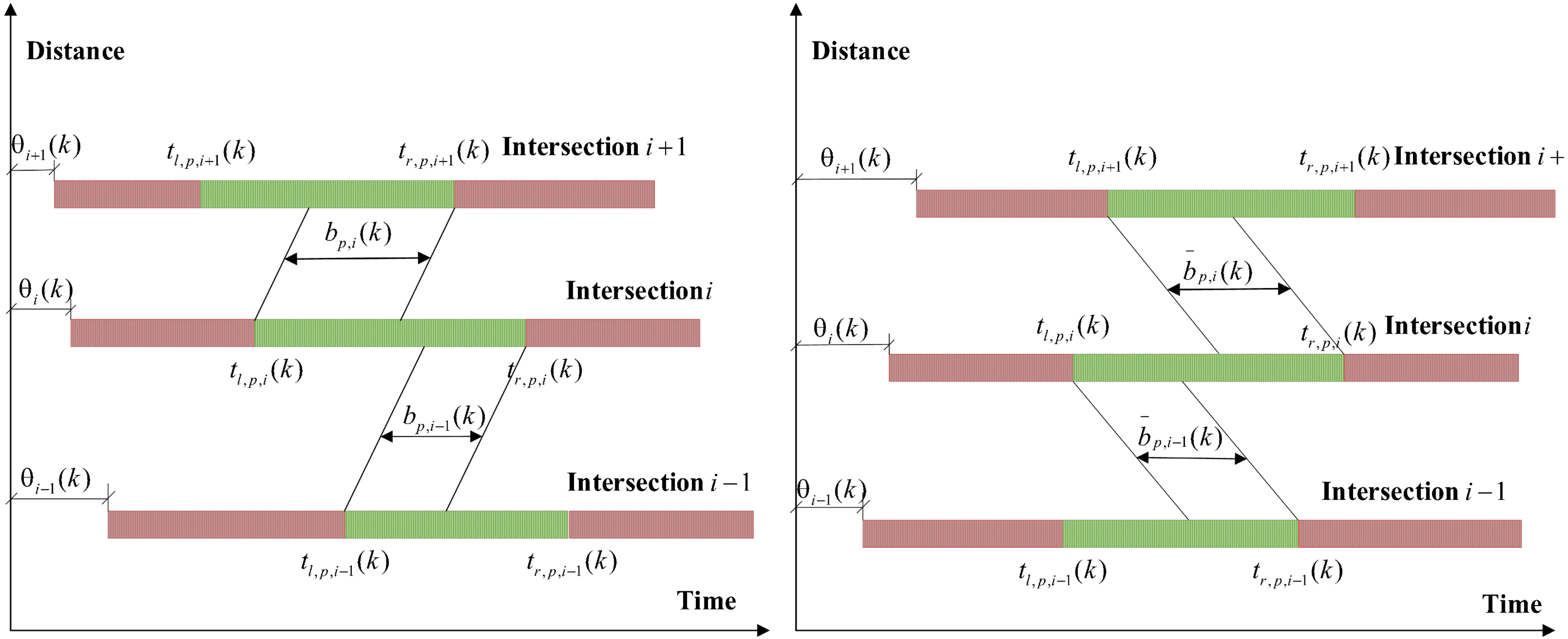
Modeling Concept: simplified formulation





The outbound & inbound green band along one critical path

Modeling Concept: Potential Issues



Non-continuous of green band in two directions

Arterial Level: Model & Algorithm

Model 2

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

$$b_{p,i}(h) = max\left(b_{r,p,i}(h) - b_{l,p,i}(h), 0\right)$$

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

→ green band for an outbound and inbound path-flow

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

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

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

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

→ the right bound and left bound of the green band of path p for outbound and inbound

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

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

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

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

↗ ensure the continuity of the green band for a path along multiple intersections

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

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

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

start and end of the green band for critical path

Arterial Level: Model & Algorithm

Solution Algorithm

Stage: index of intersections

State variable: feasible new offset of each control period at each intersection

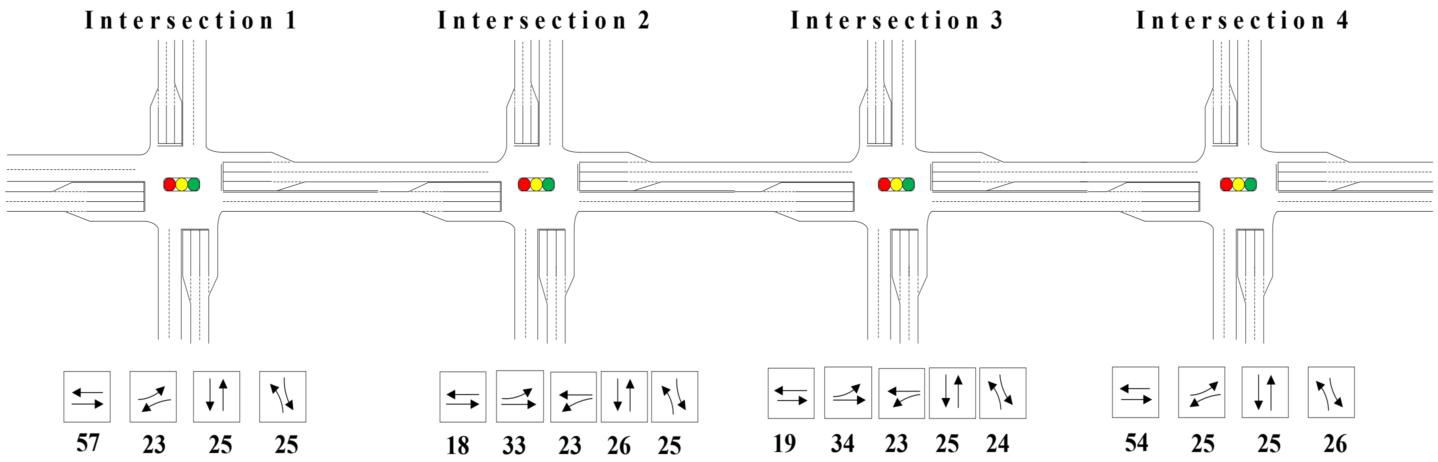
$$S_i(h) = \{\theta_i(h-1) - \Delta\theta_i, \theta_i(h-1) - \Delta\theta_i + 1, \dots, \theta_i(h-1) + \Delta\theta_i \}$$

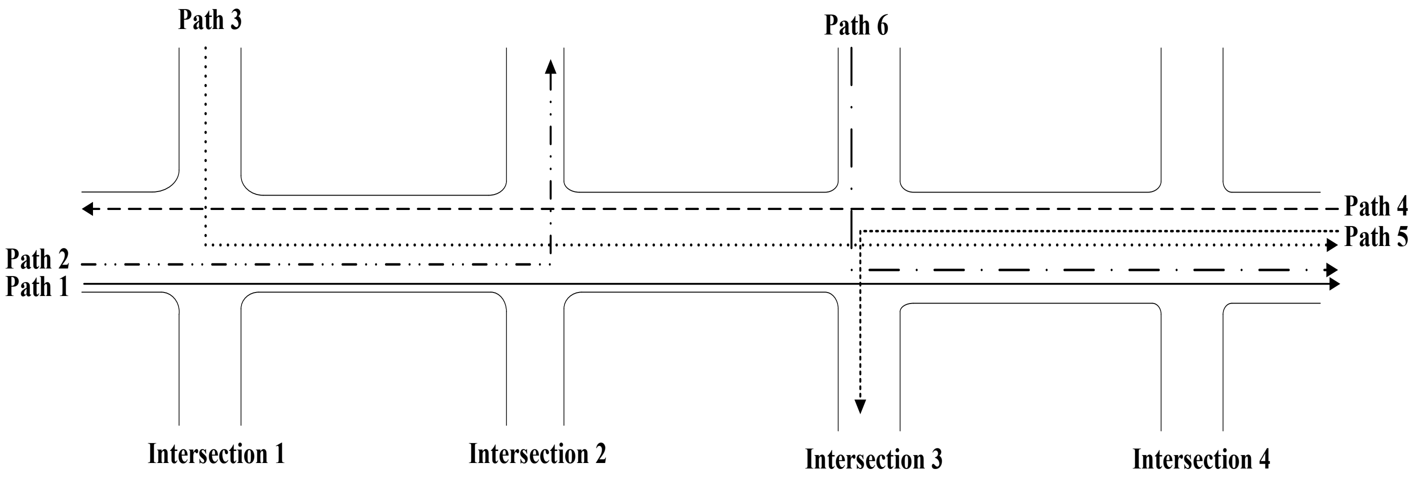
Value function: Total green bandwidth

Step 1: define $i = 1$, $\theta_1(h) = 0$, and $V_i(0) = 0$;
Step 2: $i = i + 1$; update value function with Eq. (33) and determine the optimal value function $V_i\big(\theta_i^*(h)\big) = min_{\theta_{i(k)}}\{V_{i-1}\big(\theta_{i-1}^*(h)\big) + B_i(\theta_i(h))|\theta_i(h) \in S_i(h)\}$; Find the optimal solution at this stage, denoted as $\theta_i^*(j)$.
Step 3: if $i < N_i$, go to step 2; Else, trace back to find the optimal solution for each stage.

Numerical Examples: Case Setup

Four intersections on State Street, Salt Lake City, UT





Numerical Examples: Critical Paths

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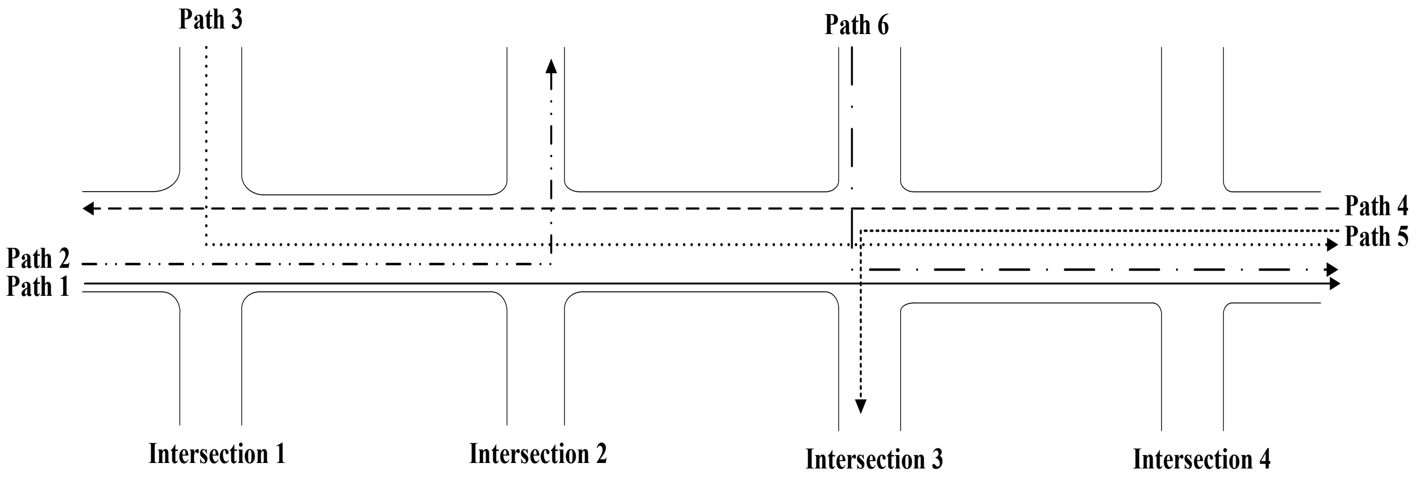
Four intersections on State Street, Salt Lake City, UT



Time Period	Critical paths
1200 - 1800	Path 1; path 2; path 3; path 4; path 5
1800 - 2400	Path 1; path 2; path 3; path 4; path 5
2400 - 3000	Path 1; path 2; path 3; path 4; path 5
3000 - 3600	Path 1; path 2; path 3; path 4; path 5
3600 - 4200	Path 1; path 3; path 4; path 5; path 6
4200 - 4800	Path 1; path 3; path 4; path 5; path 6

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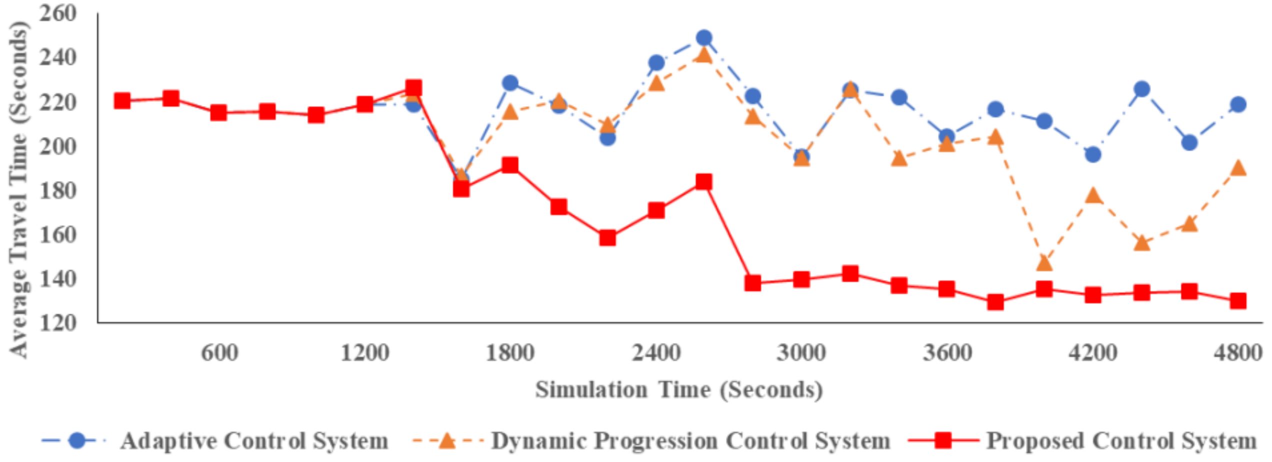
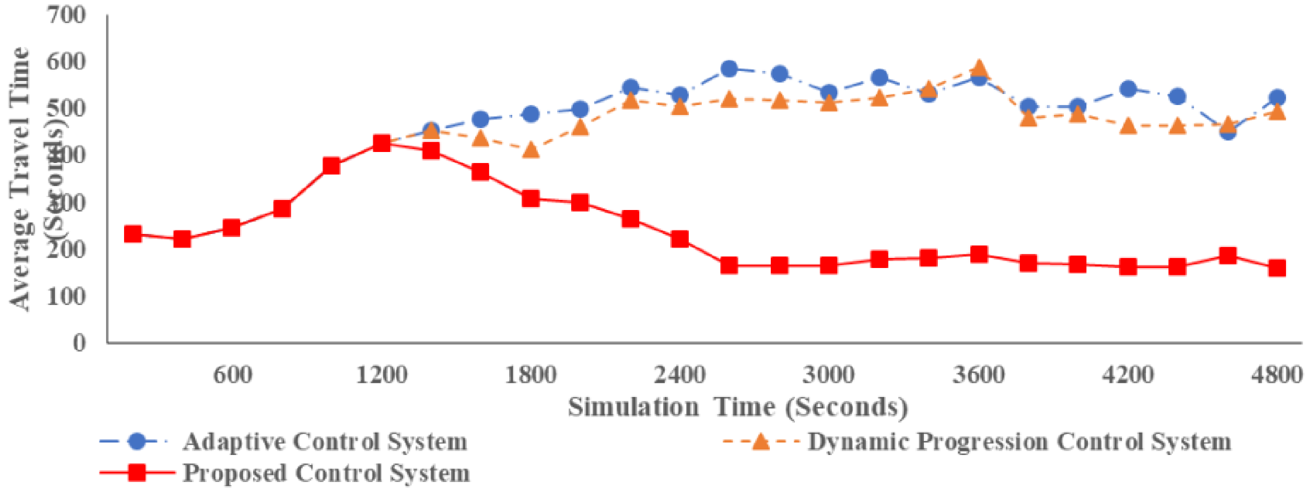
Numerical Examples: Results

Time-Dependent Travel Time along Paths



Path 1



Path 3

Numerical Examples: Results

Network Performance

Proposed control system v.s. adaptive control system

Performance Index	ACS	100% MPR	75% MPR	50% MPR	25% MPR
Average delay	104.50	94.03 (-10.02%)	96.83 (-7.34%)	103.76 (-0.71%)	113.57 (+0.08%)
Average number of stops	2.34	2.17 (-7.27%)	2.25 (-3.85%)	2.35 (+0.43%)	2.58 (+10.26%)

Proposed control system v.s. dynamic progression control system

Performance Index	DPCS	100% MPR	75% MPR	50% MPR	25% MPR
Average delay	103.06	94.03 (-8.72%)	96.83 (-6.05%)	103.76 (+0.07%)	113.57 (+0.10%)
Average number of stops	2.33	2.17 (-6.87%)	2.25 (-3.43%)	2.35 (+0.86%)	2.58 (+10.73%)

Numerical Examples: Results

Path-flow Performance

Proposed control system v.s. adaptive control system

Performance Index	ACS	100% MPR	75% MPR	50% MPR	25% MPR
Average delay	175.27	89.32 (-49.04%)	108.79 (-37.93)	109.86 (-37.32%)	123.95 (-29.28%)
Average number of stops	2.48	1.69 (-31.85%)	2.09 (-15.73%)	2.07 (-16.53%)	2.36 (-4.84%)

Proposed control system v.s. dynamic progression control system

Performance Index	DPCS	100% MPR	75% MPR	50% MPR	25% MPR
Average delay	161.79	89.32 (-44.79%)	108.79 (-32.76%)	109.86 (-32.09%)	123.95 (-23.39%)
Average number of stops	2.47	1.69 (-31.58%)	2.09 (-15.38%)	2.07 (-16.19%)	2.36 (-4.45%)

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Smart Traffic Signal Control: background

Intersection Safety

- Two types of crashes at intersections

Side-Angle Crash

Rear-End Crash

Dilemma Zone Protection System (DZPS) → ✓

Advanced Warning Systems(AWS) → ?

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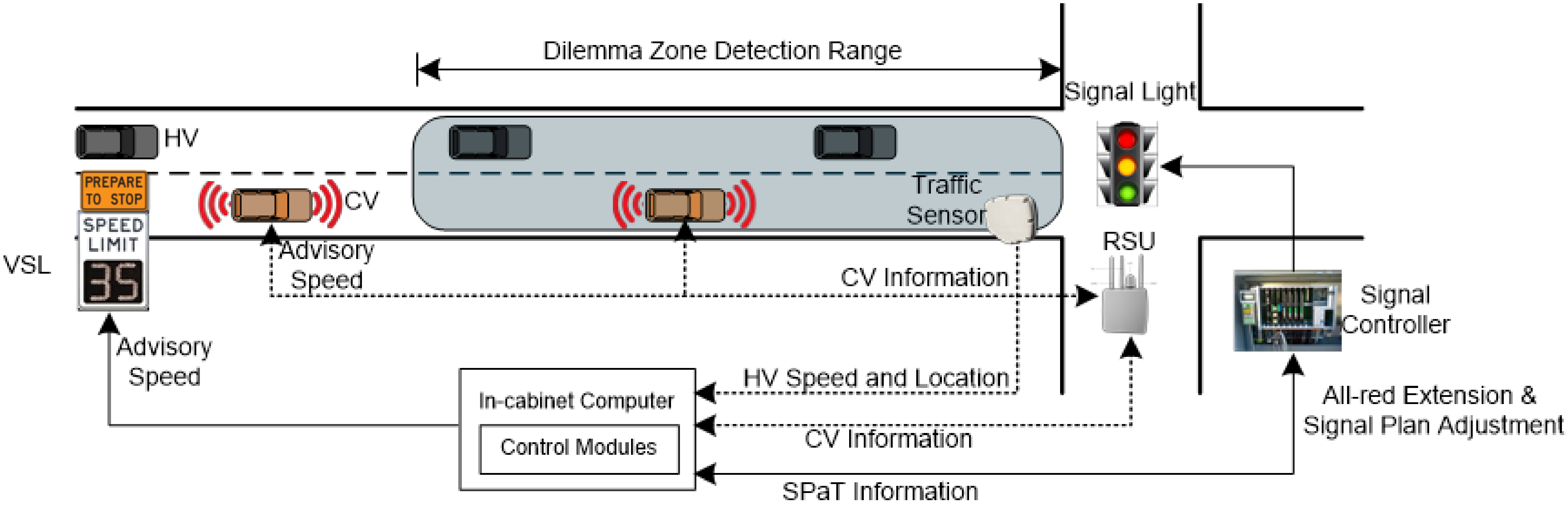
Intersection Safety & Mobility

- The prevention of rear-end collision at intersections is still an unsolved problem.
- Traffic safety and mobility are usually implemented with different control devices, and thus often compete for the limited available resources.
- Integration of control devices for both operations so as to concurrently achieve the effectiveness on those two regards has not been well-addressed yet.

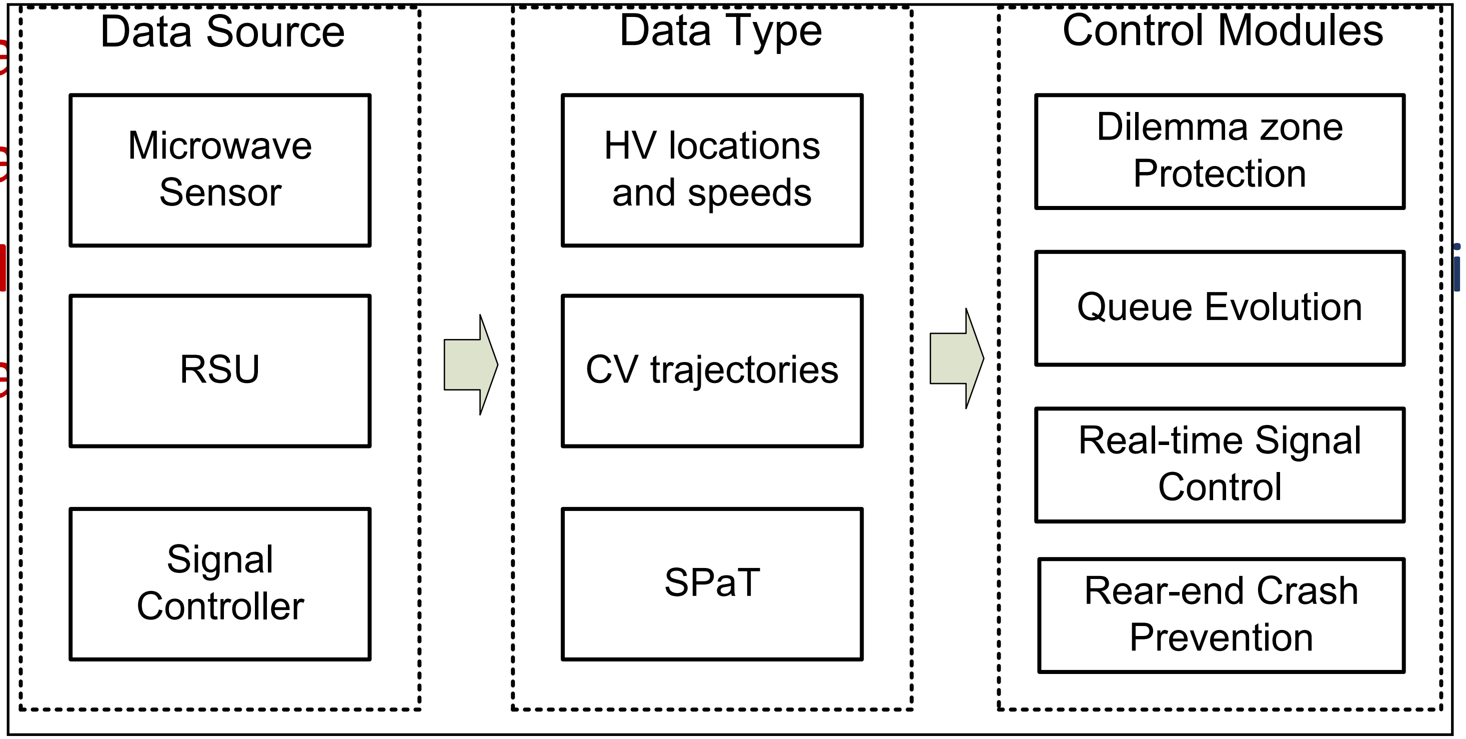
The proposed system



System Data Flow

Modules:

- Module 1 (Sa
- Module 2 (Sa
- Module 3 (M … ization
- Module 4 (Sa



Module 1: Dilemma Protection

This study aims to predict vehicles' passing probability at ε seconds before the end of yellow interval, where ε indicates the time needed for data transition and all-red extension activation:

$$P_{pass}(i,t_\varepsilon) = Max\left(\frac{1}{1-e^{-\beta_0-\beta_1 v_i(t_\varepsilon)-\beta_2 d_i(t_\varepsilon)}}, \delta_i(t_\varepsilon)\right)$$

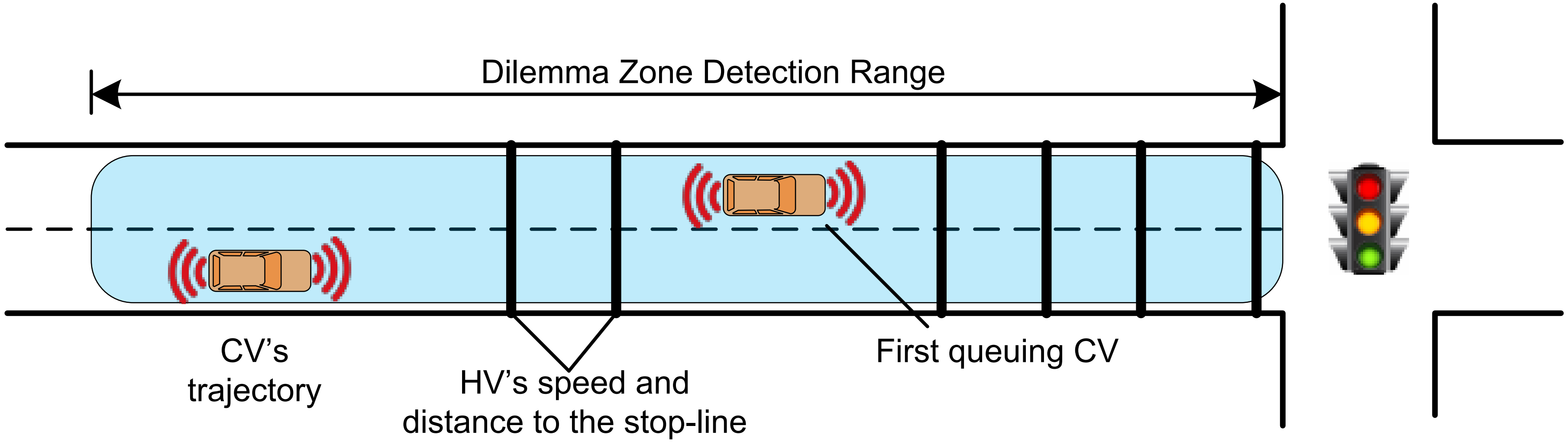
where $\delta_i(t_\varepsilon)$ is a binary variable which indicates whether vehicle i intends to accelerate:

$$\delta_i(t_\varepsilon) = \begin{cases} 1 & if\ v_i(t_\varepsilon) \geq v_i(t_\varepsilon - 1) \\ 0 & o.w. \end{cases}$$

Then the required all-red extension time, ARE, can be calculated by:

$$ARE = \max_i \left\{ \frac{d_i(t)}{v_i(t)} - \varepsilon - AR + \sigma \right\}$$

Module 2: Queue Length Estimation




: the location of vehicles


: the trajectory of CVs

Module 3: Signal Coordination & CV Speed Harmonization

$$\zeta_{out,i} = \max(\theta_i + \max_{j \in \Psi_{out}(i)} \{\tau_j\} - \frac{L_{out,i} - \max_{j \in \Psi_{out}(i)} \{q_j + \lambda_j \tau_j\}}{v_{out,i}}, 0)$$

$$\zeta_{in,i} = \max(-\theta_i + \max_{j \in \Psi_{out}(i)} \{\tau_j\} - \frac{L_i - \max_{j \in \Psi_{out}(i)} \{q_j + \lambda_j \tau_j\}}{v_{in,i}}, 0)$$

Module 4: Rear-end Crash Prevention

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Sub-Modules:

- Submodule 1 – vehicles are arriving with insufficient sight distance while intersection has uncleared initial queue after onset of green.
- Submodule 2 – vehicles are arriving with insufficient sight distance while intersection has uncleared initial queue after onset of red.
- Submodule 3 – some vehicles within the detection zone are predicted to be stopping during yellow and all-red time

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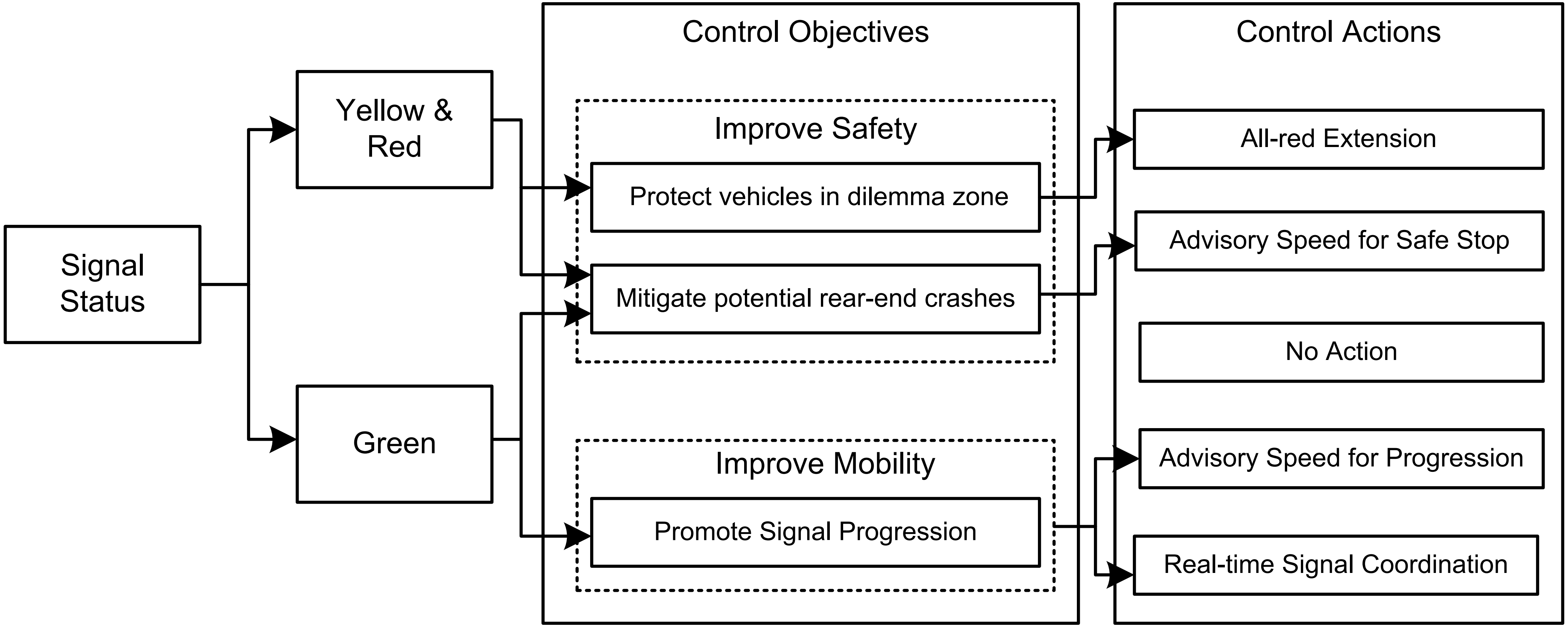
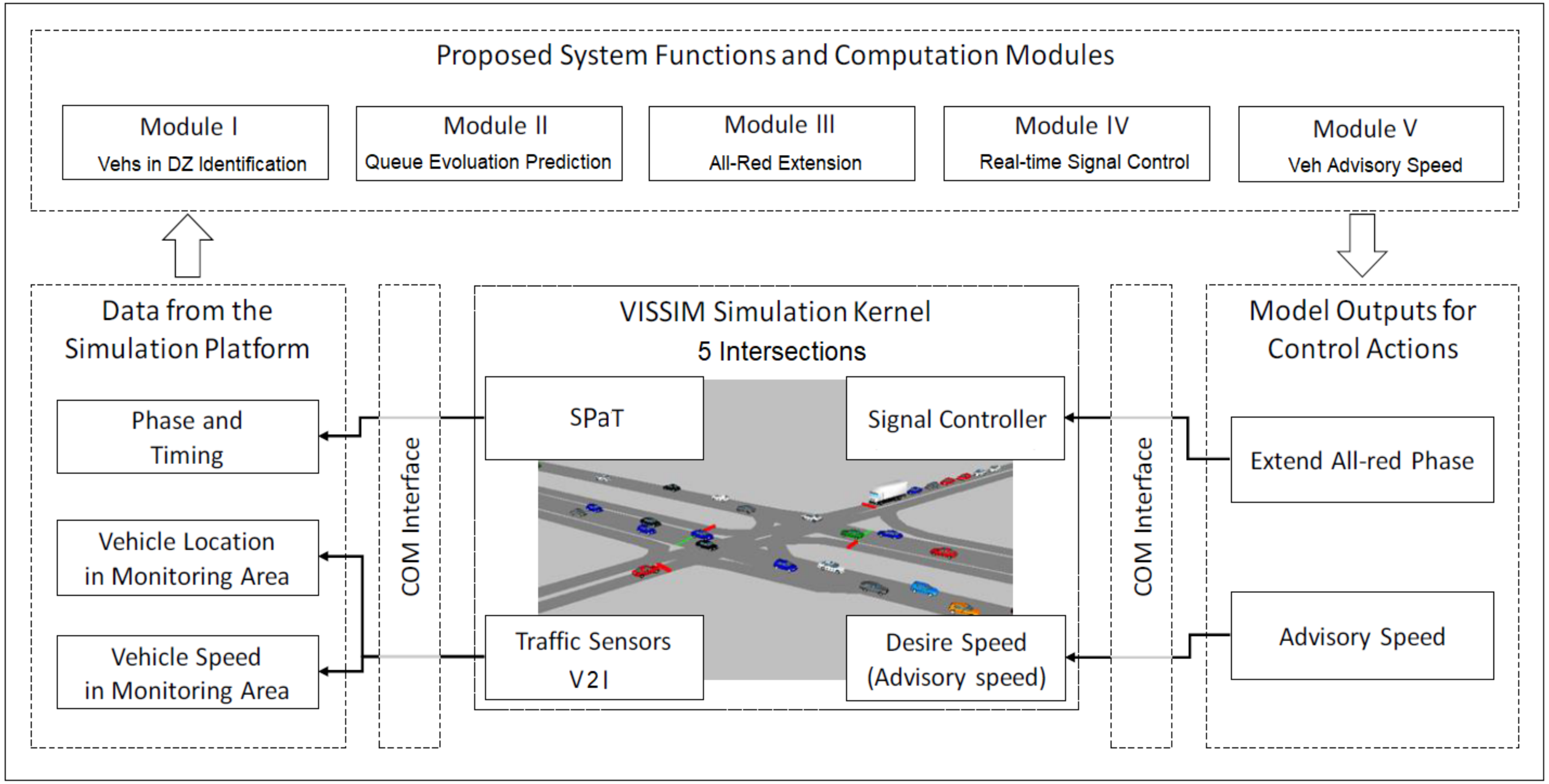
System Control Logic and Actions



Xianfeng Yang*, Zhao Zhang, Gang-Len Chang, & Pengfei Li, (2019), ”Smart Signal Con-trol System for Accident Prevention and Arterial Speed Harmonization under Connected Vehicle Environment”, Journal of Transportation Research Board: Transportation Research Record. vol 2673 (5), pp: 61-71.

Numerical Test

The arterial segment includes five intersections and it is a part of the CV corridor operated by UDOT. All intersections are installed with DSRC RSUs for supporting V2I communications



Scenario Settings

Basic Settings:

- 40% regular vehicles' compliance rate to VSL
- 10% CV penetration rate

Control Types for Comparison:

- Pre-timed traffic control
- Dilemma zone protection system (safety module only)
- Proposed system (safety module + mobility module)

Performance Evaluations

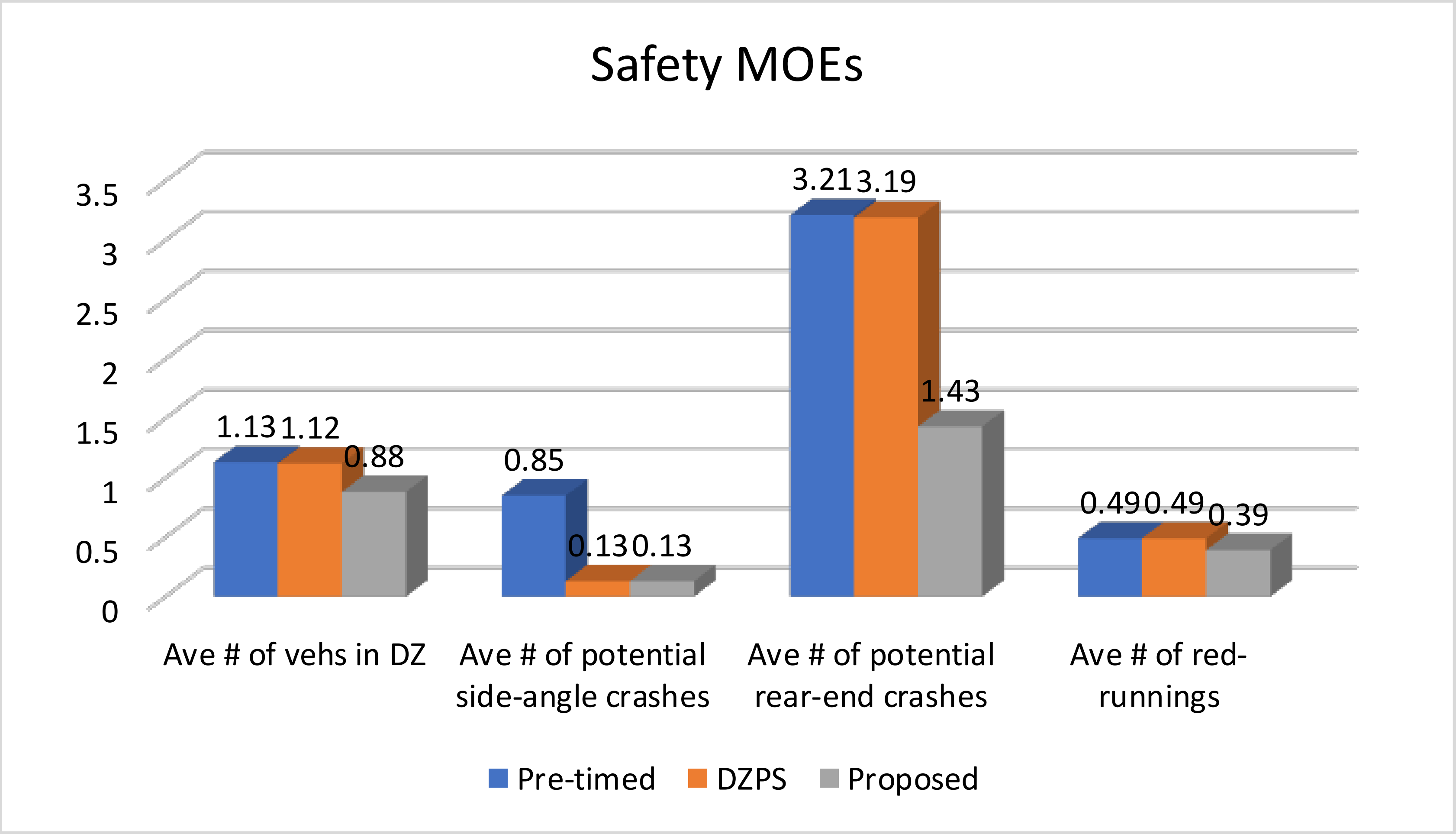
❑Safety MOEs

- Average number of vehicles trapped in the dilemma zone per signal cycle;
- Average number of potential side-angle crashes per signal cycle measured by vehicle trajectories;
- Average number of potential real-end crashes per signal cycle measured by the number of hard-braking vehicles (deceleration rate > $10ft/s^2$);
- Average number of red-light running vehicles per signal cycle.

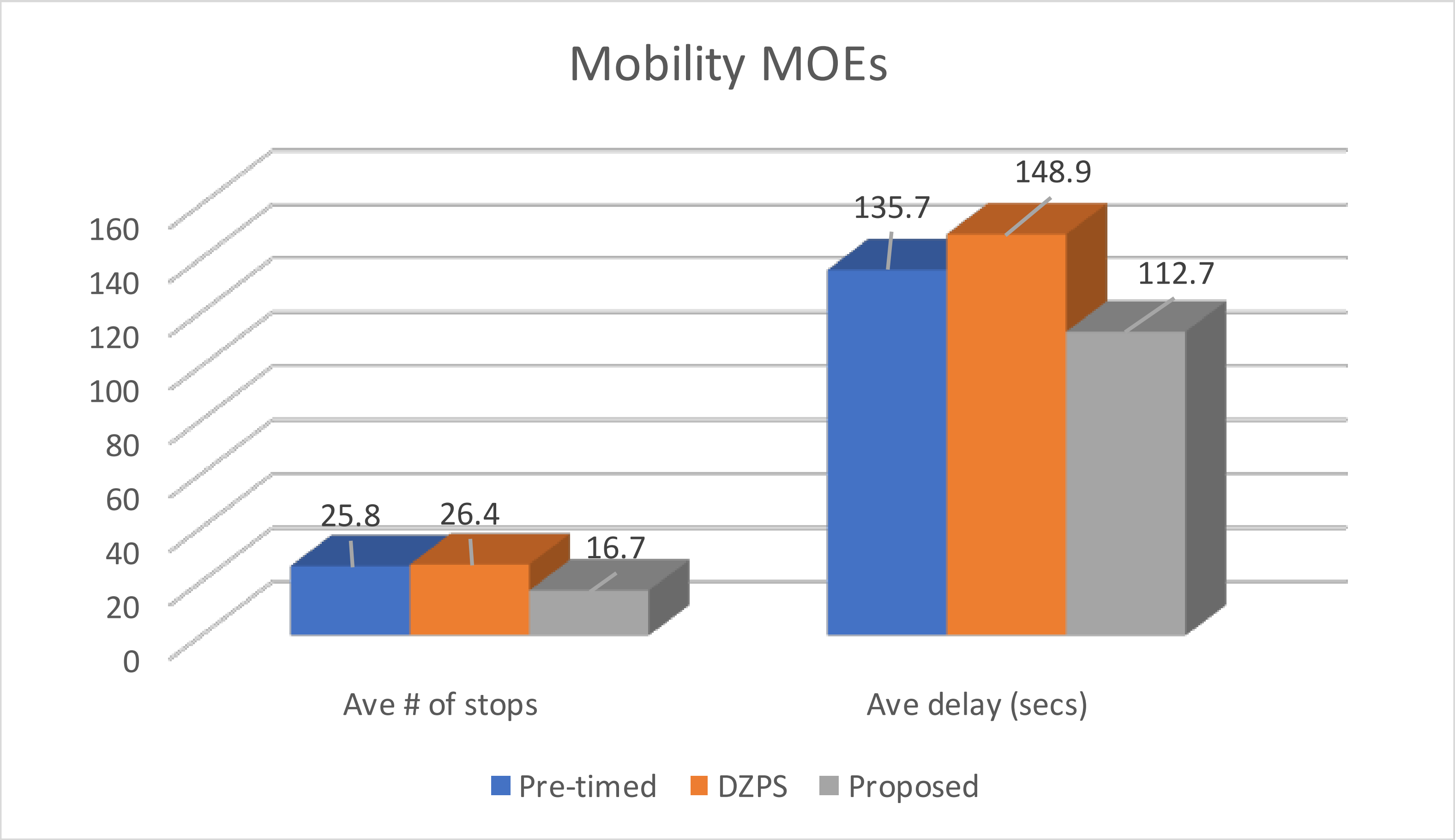
❑Mobility MOEs:

- Average number of stops;
- Average of vehicle delay.

Safety Performance



Mobility Performance



Outline

- ❖ Background
- ❖ CV System Architecture
- ❖ Data Collection
- ❖ Dynamic Signal Coordination
- ❖ Smart Traffic Signal Control
- ❖ **More Discussions**

More Discussions

Roles of Governments?

- Do nothing – Let the operations of AVs without connection
- Promote CAVs
  - CV pilot program
  - CAV (Connected Vehicles) demonstration grants
  - CARMA platform
  - Utah CV corridor
  - Standard & regulations
- Opportunities vs. liabilities
  - Demonstrate benefits of CAV over AV alone
  - Construct, manage and maintain CV infrastructure
  - Potential liabilities of providing CV data
  - AV/CAV "drivers license"
  - Data management from CAV/AV

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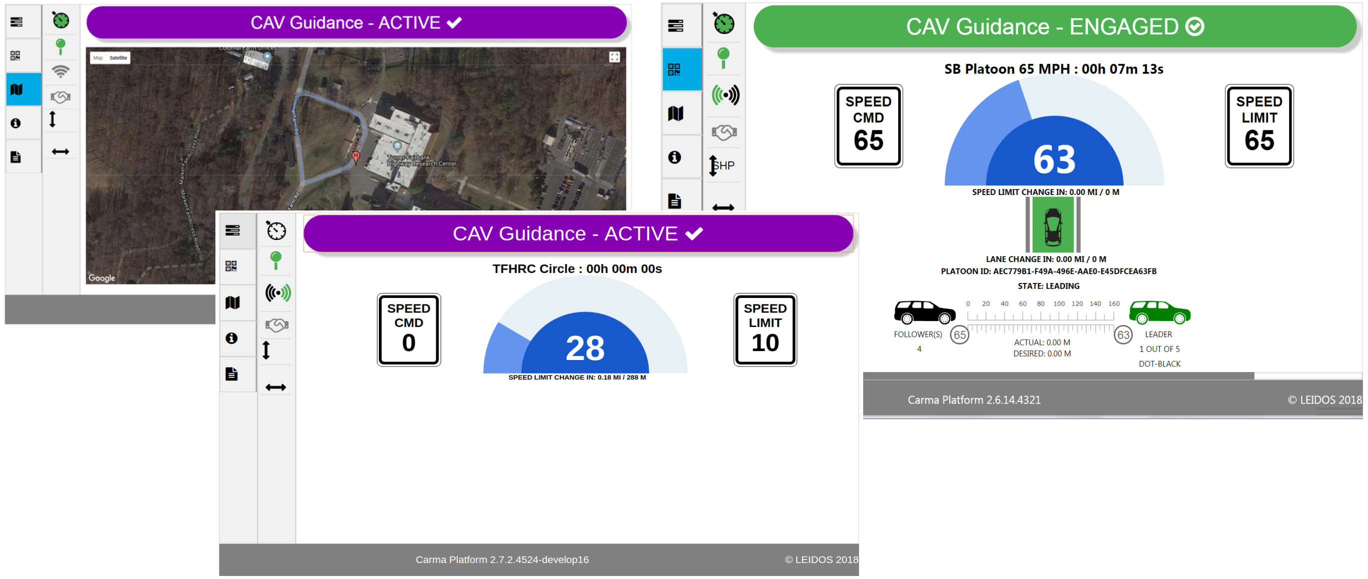
More Discussions

More to come…

CARMA 1tenth



CARMA Cloud

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Acknowledgement

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U.S. Department of Transportation
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UDOT
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Thanks & Questions?

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