A Coordinated Signal Control System for Commuting Arterials with Highly Asymmetric Directional Flows

Ph.D. Dissertation Defense

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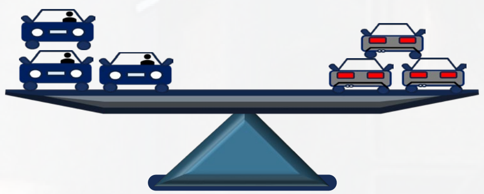
08/26/2025

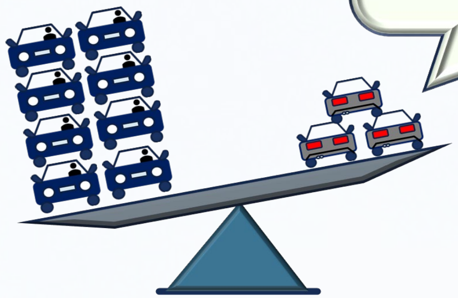
Vorsicht!

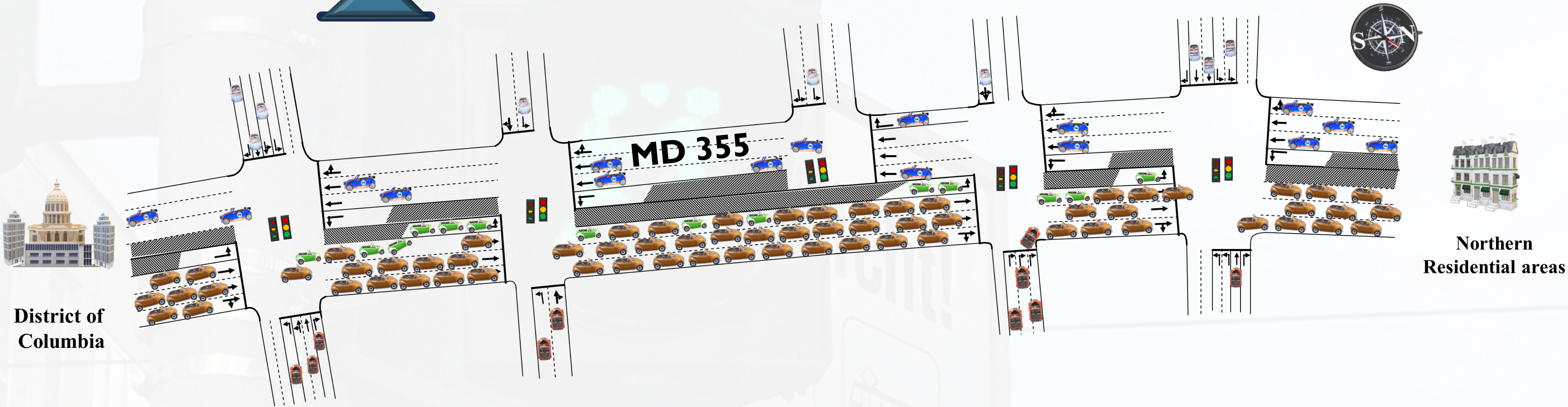
Traffic Patterns of Commuting Arterials

Off-peak hours:
balanced traffic distribution

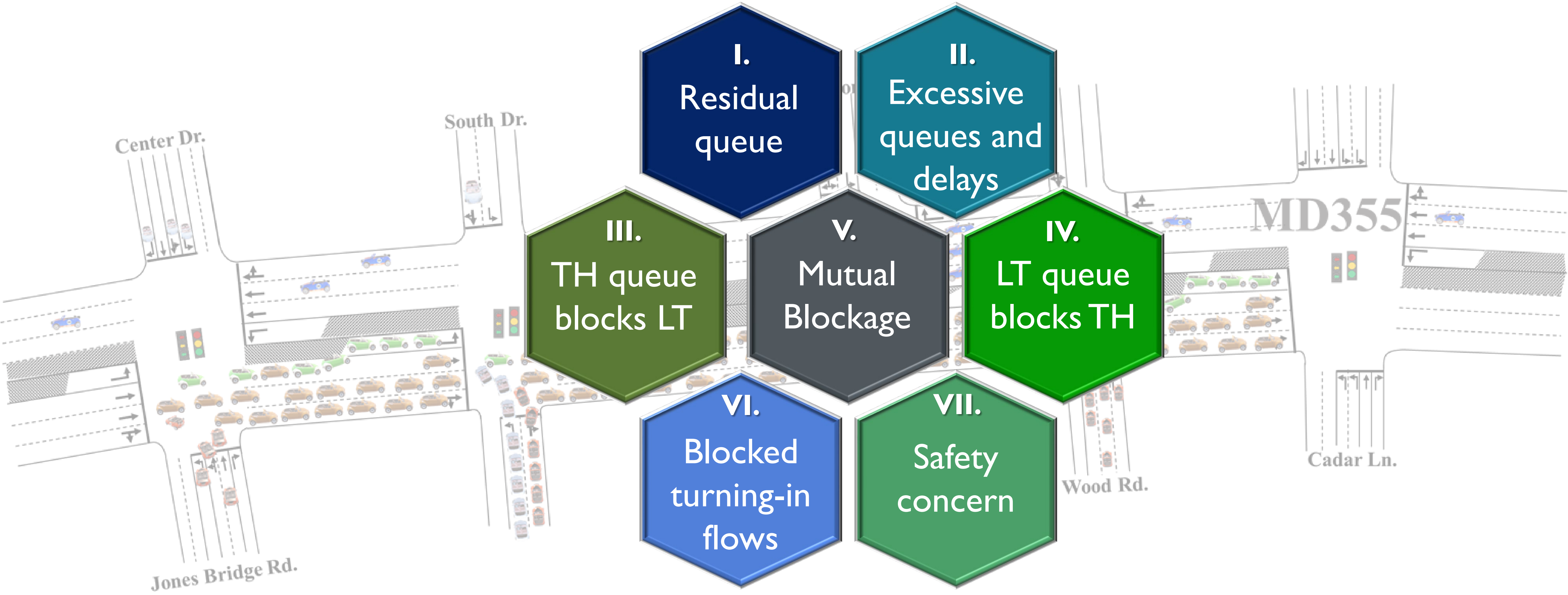


Peak hours:
highly asymmetric directional flows





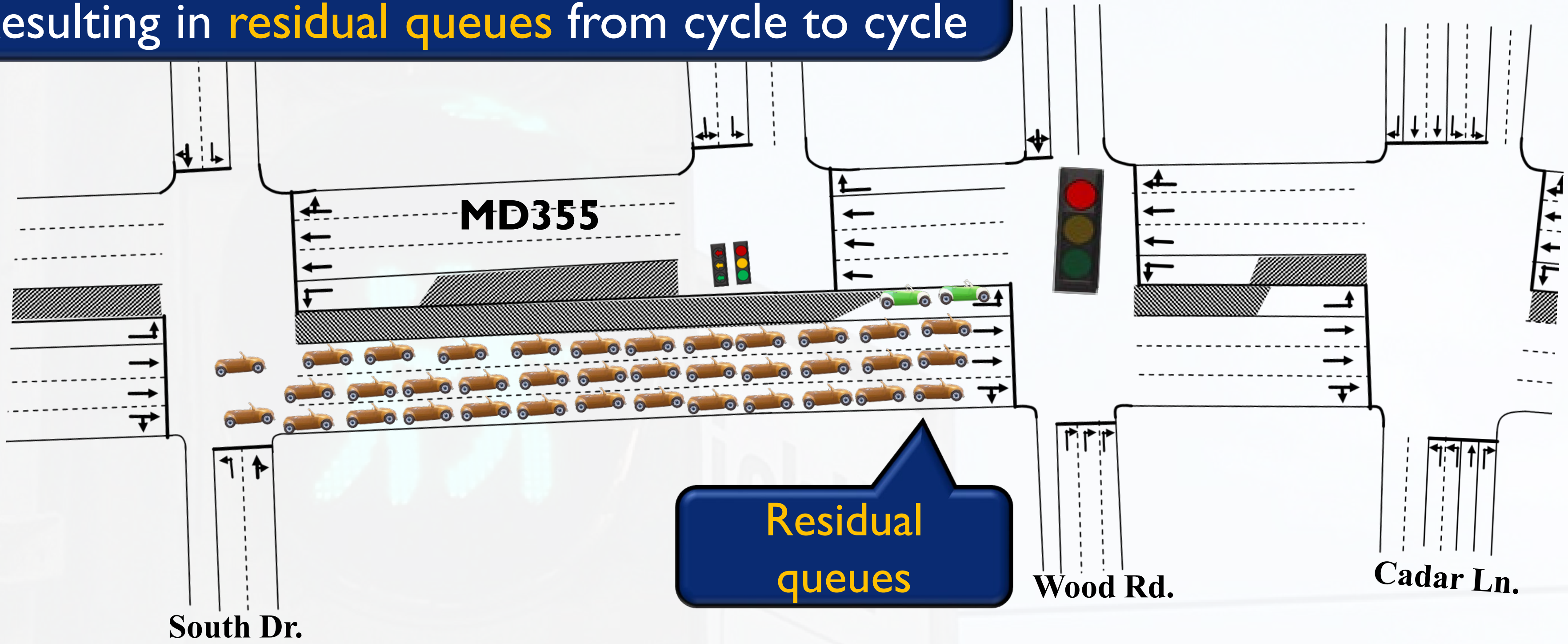
Critical Issues in Design of a Signal Control System for Commuting Arterials



Critical Issues in Design of a Signal Control System for Commuting Arterials

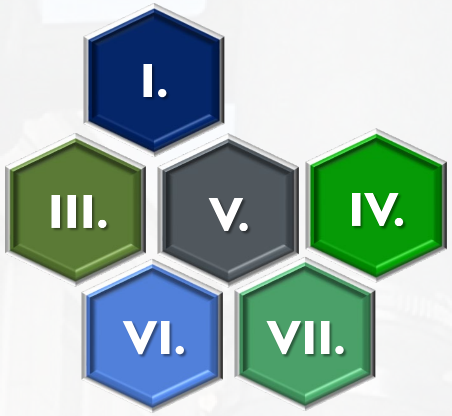
I. Residual queue

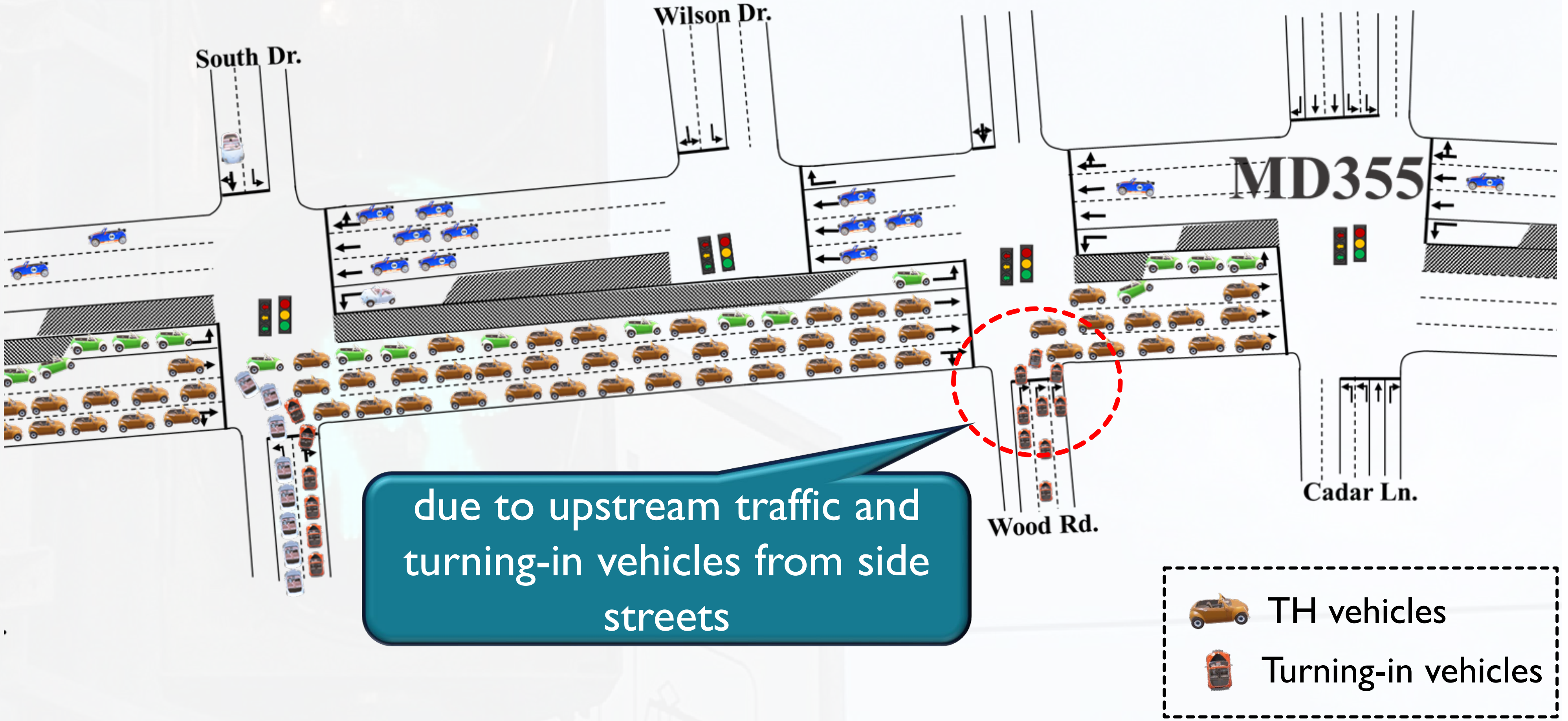
Steady high volume may surpass the capacity of some intersections
→ Resulting in residual queues from cycle to cycle



Critical Issues in Design of a Signal Control System for Commuting Arterials

II. Excessive queues and delays

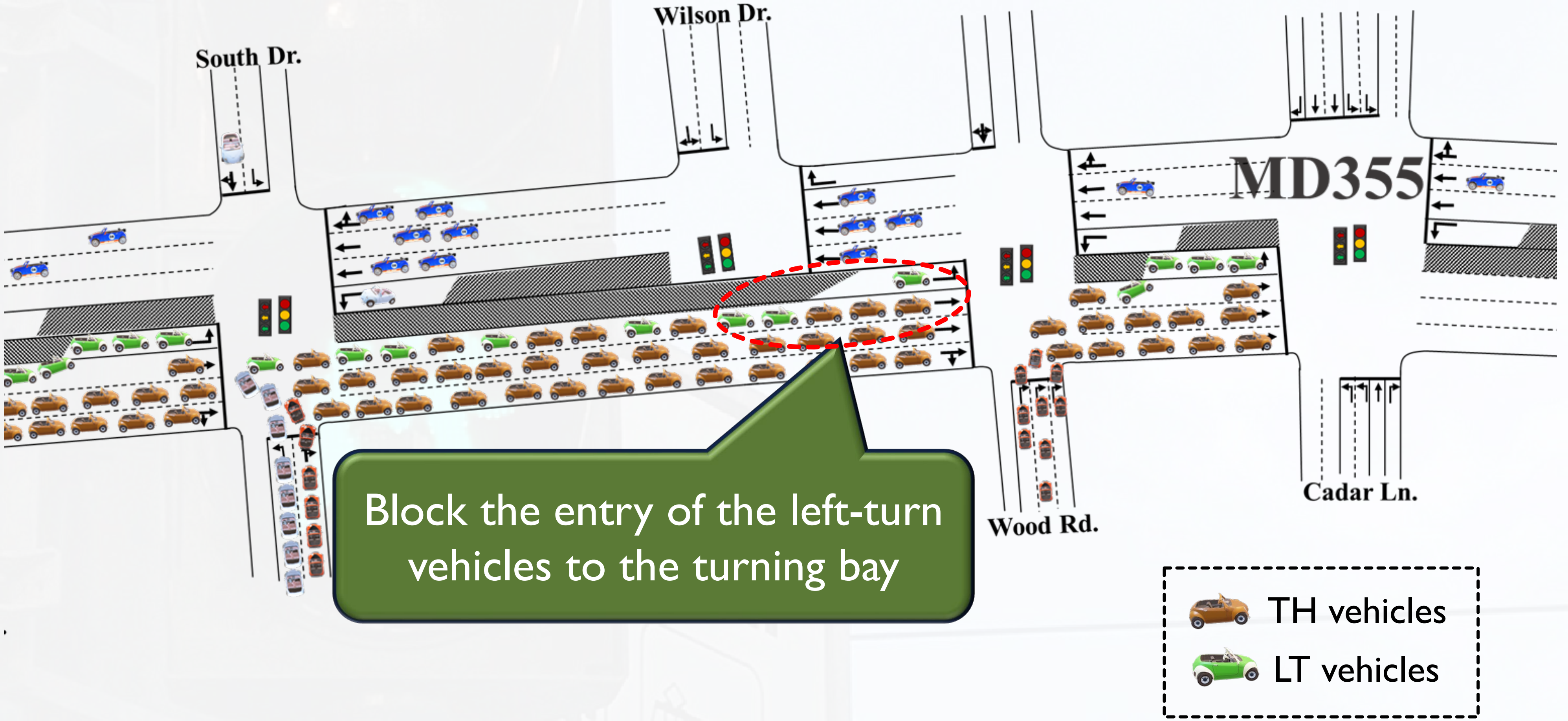




Critical Issues in Design of a Signal Control System for Commuting Arterials

III.
TH queue blocks LT

I. II. V. IV. VI. VII.

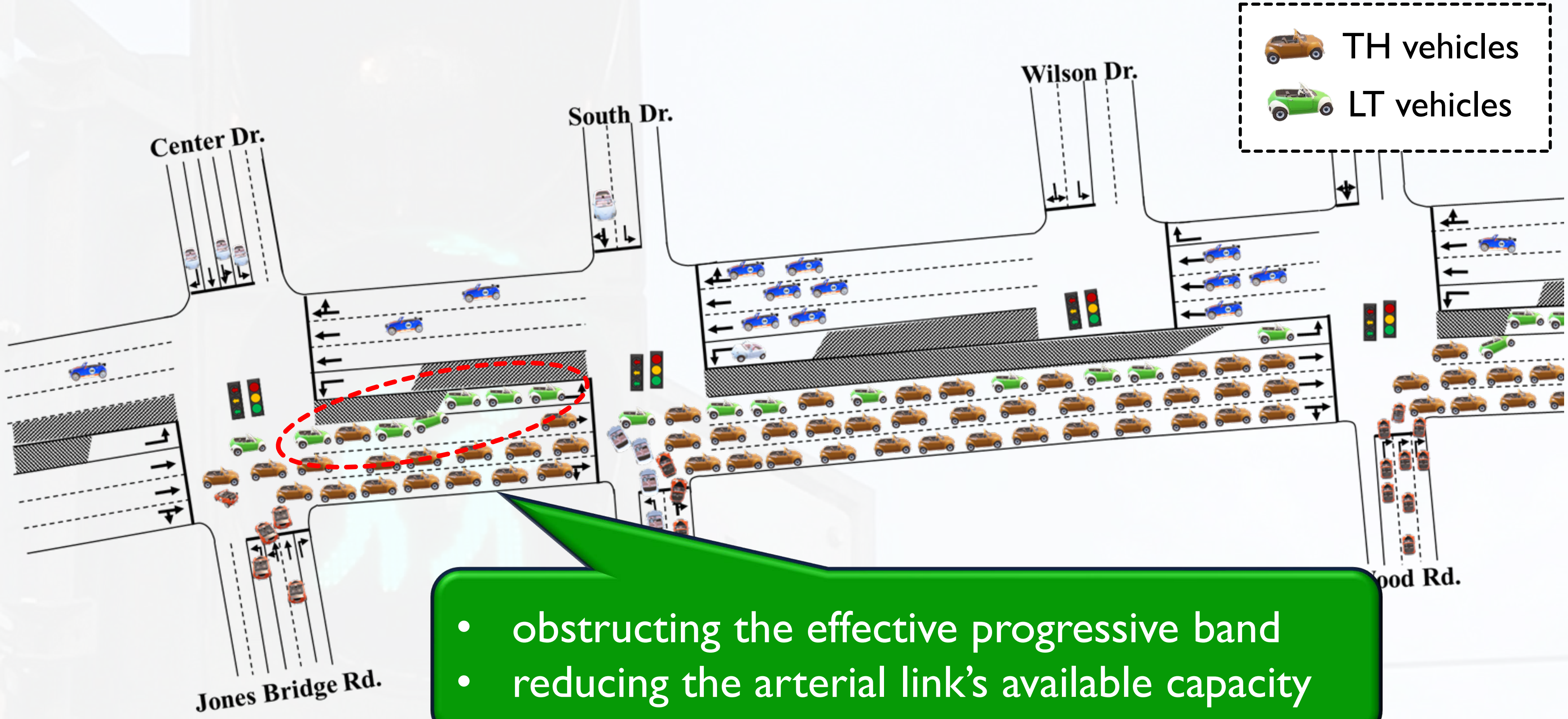


Block the entry of the left-turn vehicles to the turning bay

Critical Issues in Design of a Signal Control System for Commuting Arterials

IV.
LT queue blocks TH

I. II. III. V. VI. VII.

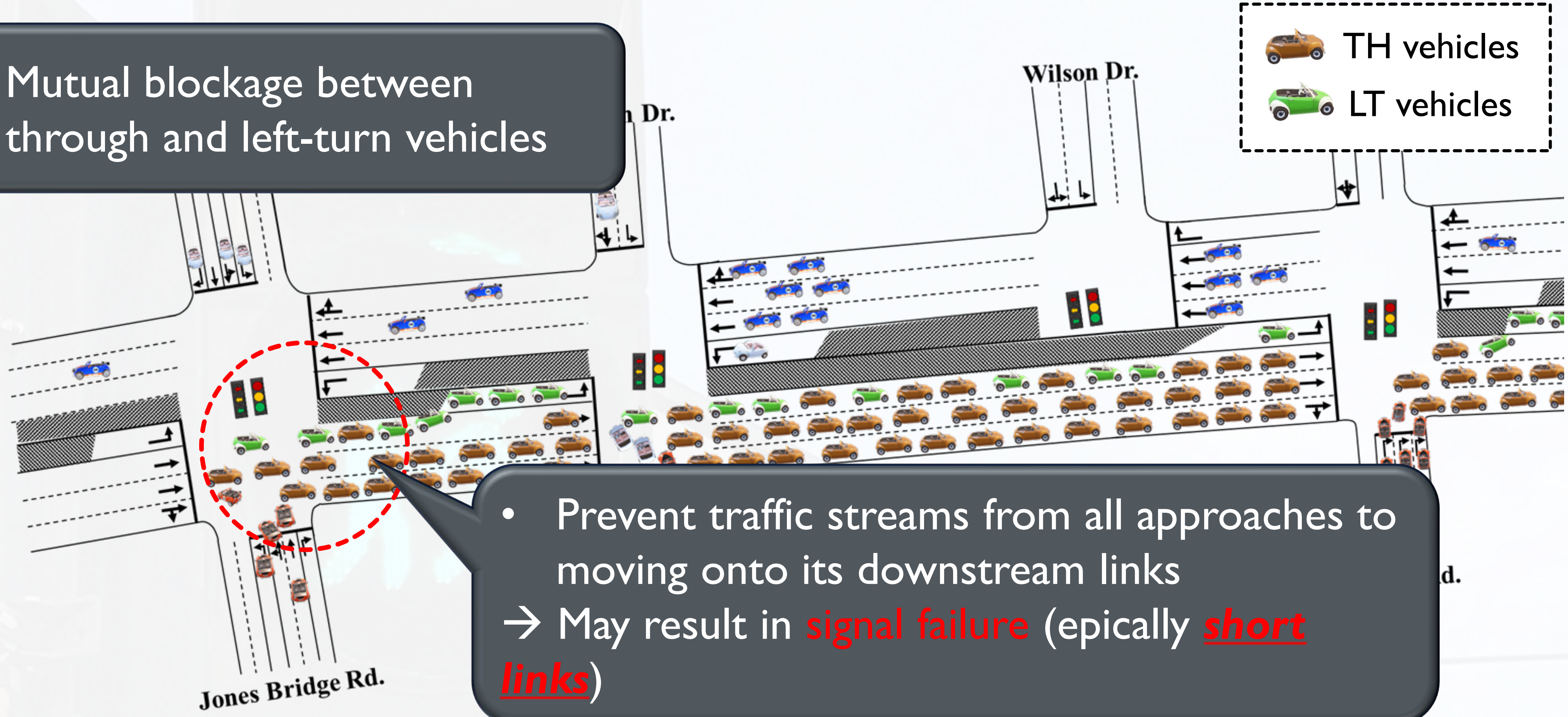


- obstructing the effective progressive band
- reducing the arterial link's available capacity

Critical Issues in Design of a Signal Control System for Commuting Arterials

V. Mutual Blockage

- Mutual blockage between through and left-turn vehicles

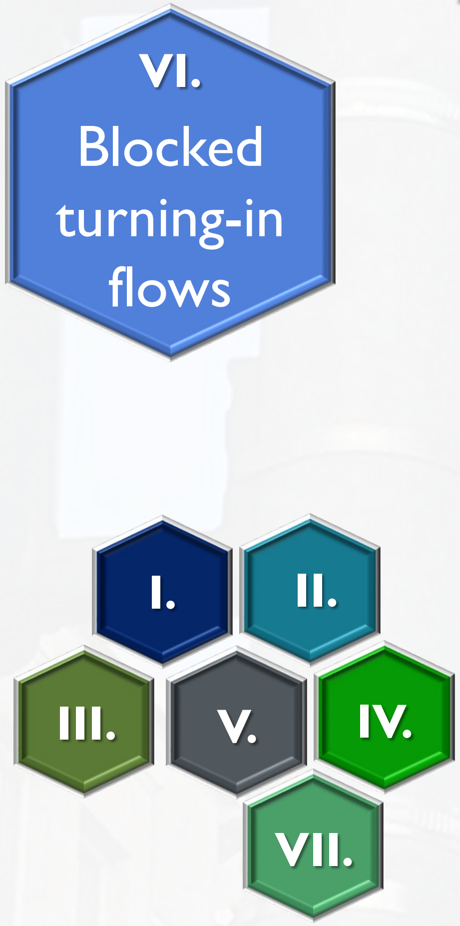


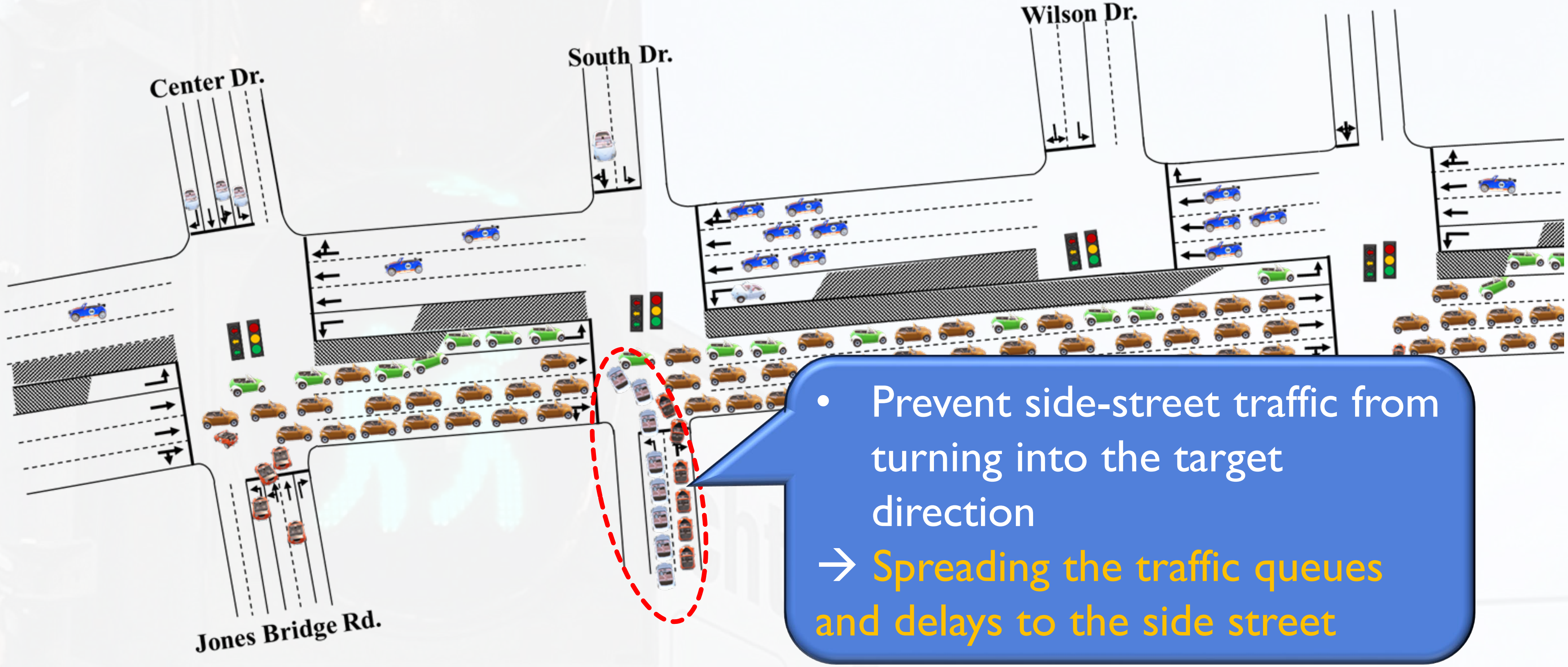
- Prevent traffic streams from all approaches to moving onto its downstream links

→ May result in signal failure (epically ***short links***)

I. II. III. IV. VI. VII.

Critical Issues in Design of a Signal Control System for Commuting Arterials



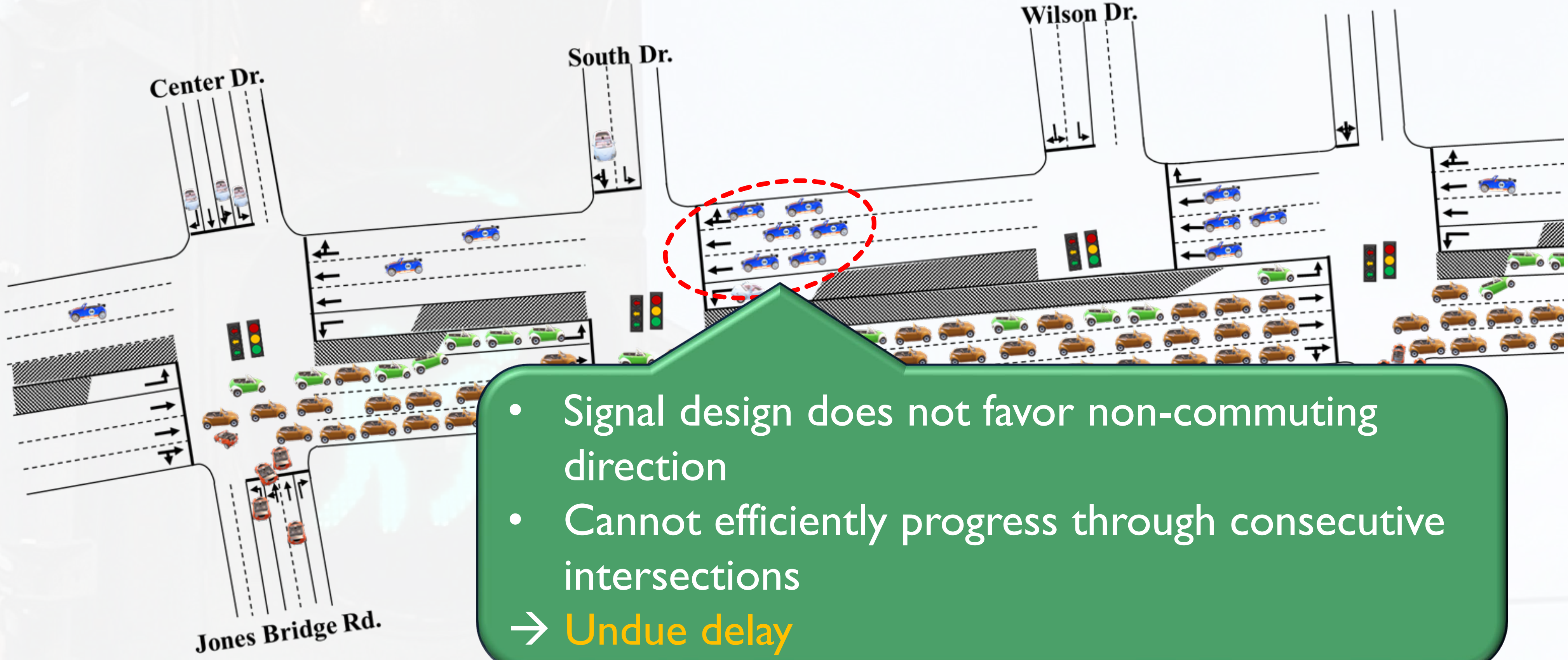


- Prevent side-street traffic from turning into the target direction

→ Spreading the traffic queues and delays to the side street

Critical Issues in Design of a Signal Control System for Commuting Arterials

VII.
Safety concern

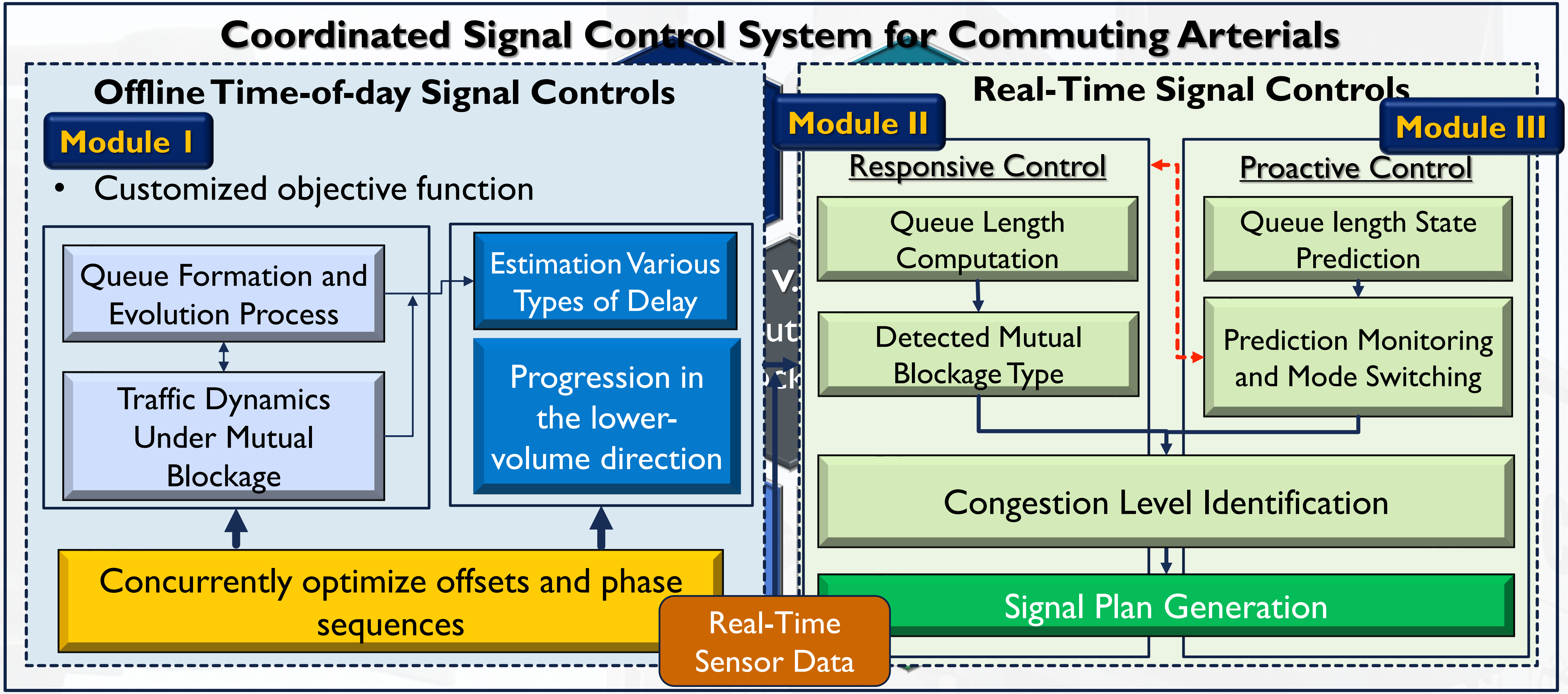


- Signal design does not favor non-commuting direction
- Cannot efficiently progress through consecutive intersections

→ Undue delay

I. II. III. V. IV. VI.

Structure of the Coordinated Signal Control System for Commuting Arterials



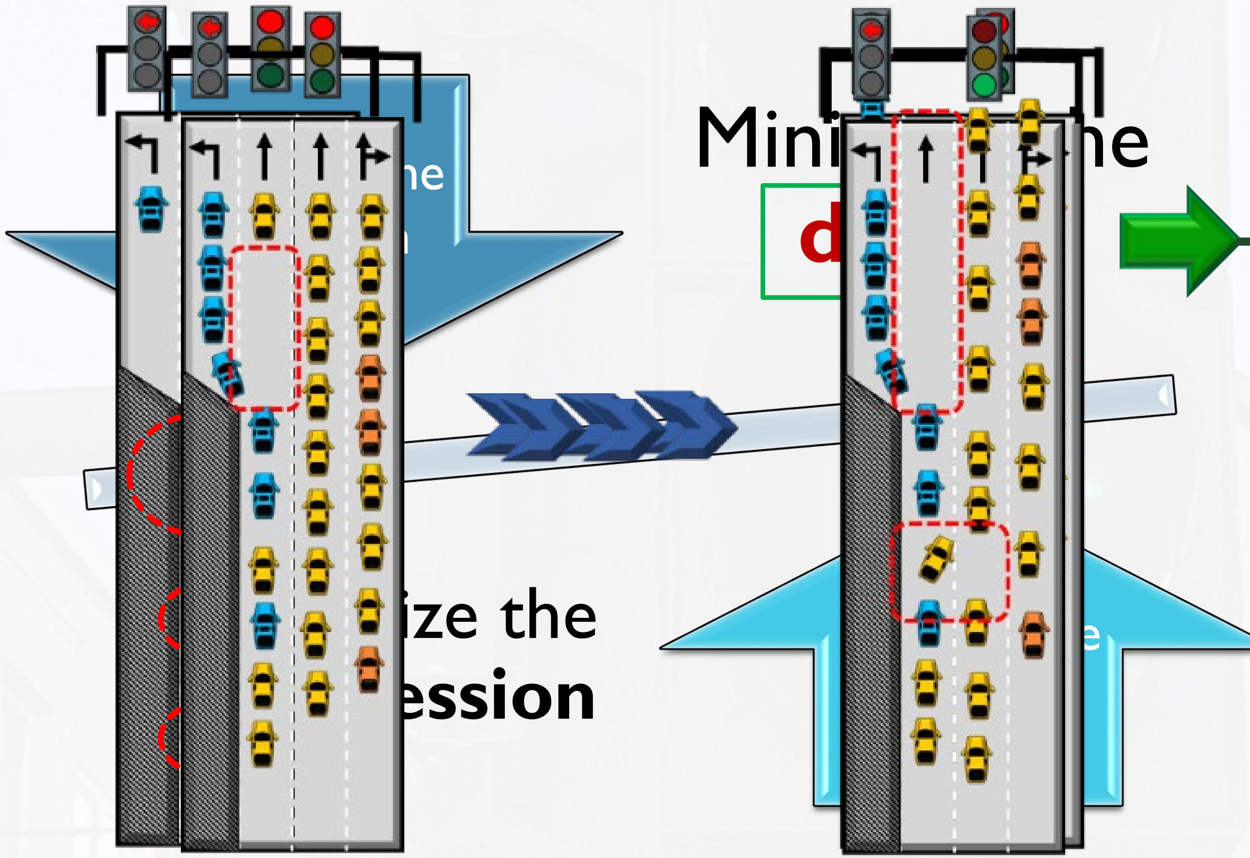
Module I:
Time-of-Day Signal Controls

Lin, Y. T., Cheng, Y., & Chang, G. L. (2024). Integration of progression maximization and delay minimization controls for commuting arterials accommodating highly asymmetric directional traffic flows. *Journal of Intelligent Transportation Systems*, 1-17.

Module I

Time-of-day controls for commuting arterials with asymmetric directional flows

- Customized Signal Control:
  - Objective function:



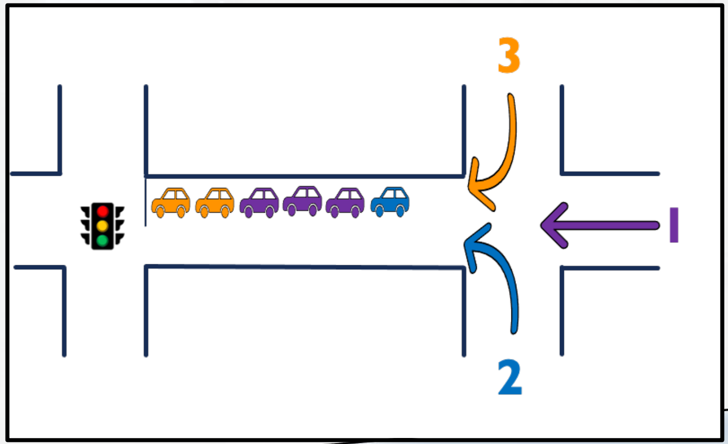
- **Through-vehicle delays**
- **Delays caused by mutual blockage**
  - delays of blocked left-turn vehicles
    - longer queue
    - residual queue
  - delays of blocked through vehicles
    - capacity drop

Concurrently optimize **offsets** and **phase sequences**

Module I

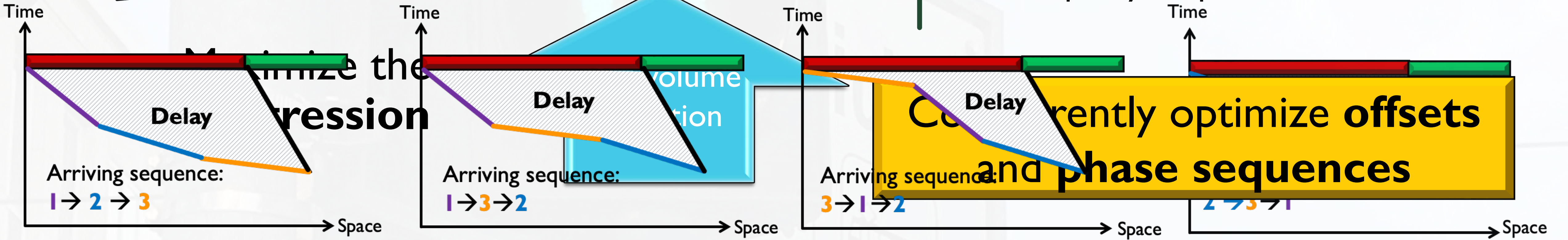
Time-of-day controls for commuting arterials with asymmetric directional flows

- Customized Signal Control:
  - Objective function:



Minimize the **delays**

- **Through-vehicle delays**
- **Delays caused by mutual blockage**
  - delays of blocked left-turn vehicles
    - longer queue
    - residual queue
  - delays of blocked through vehicles
    - capacity drop



and phase sequences

Module I

Time-of-day controls for commuting arterials with asymmetric directional flows

Impacts of optimized offsets

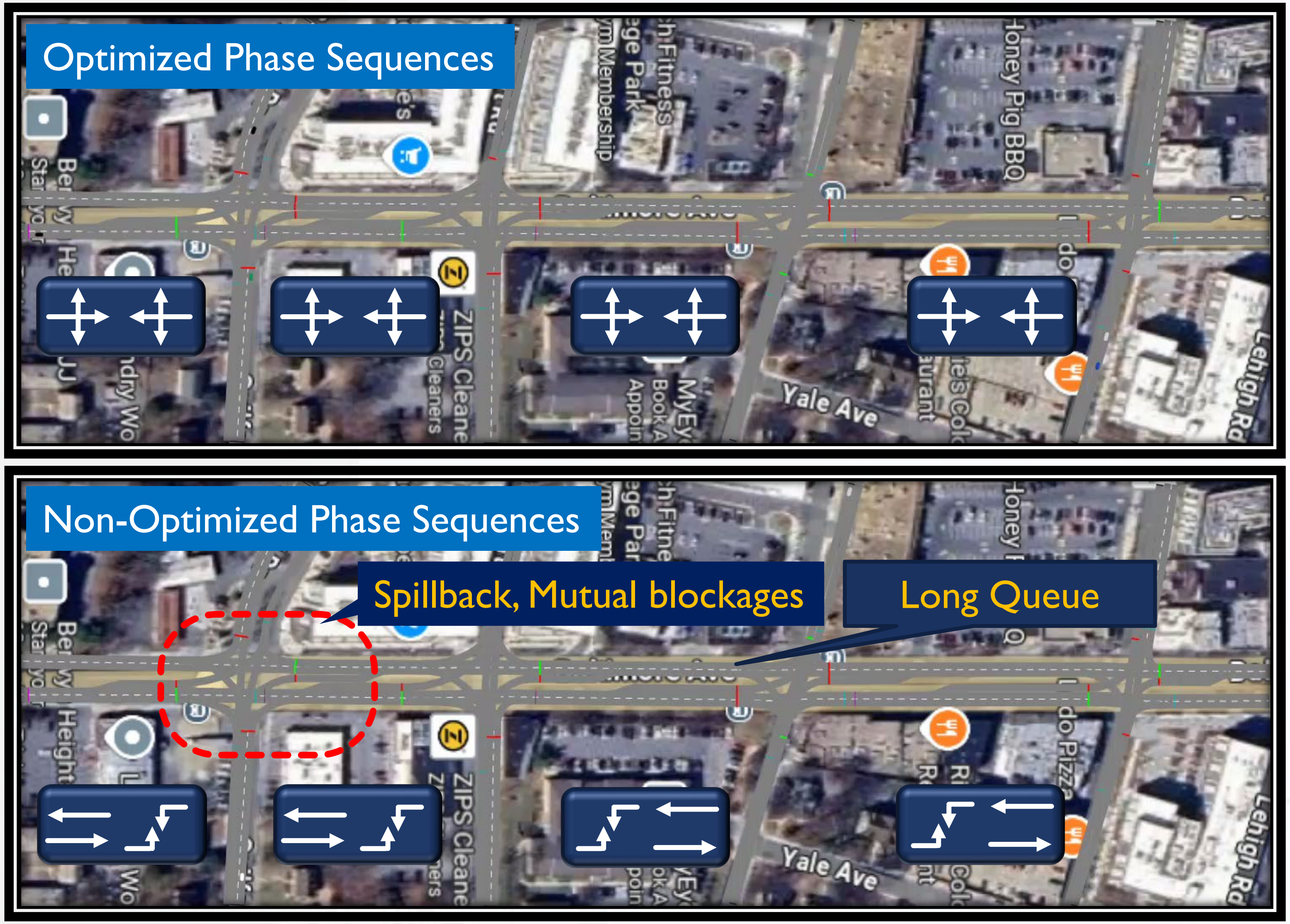
- ✓ Same signal timing
- ✓ Same signal phase sequence
- ✓ Same volume input
- ✓ Same turning ratio
- ✓ Same site
- ✓ Only the offsets are different

Module I

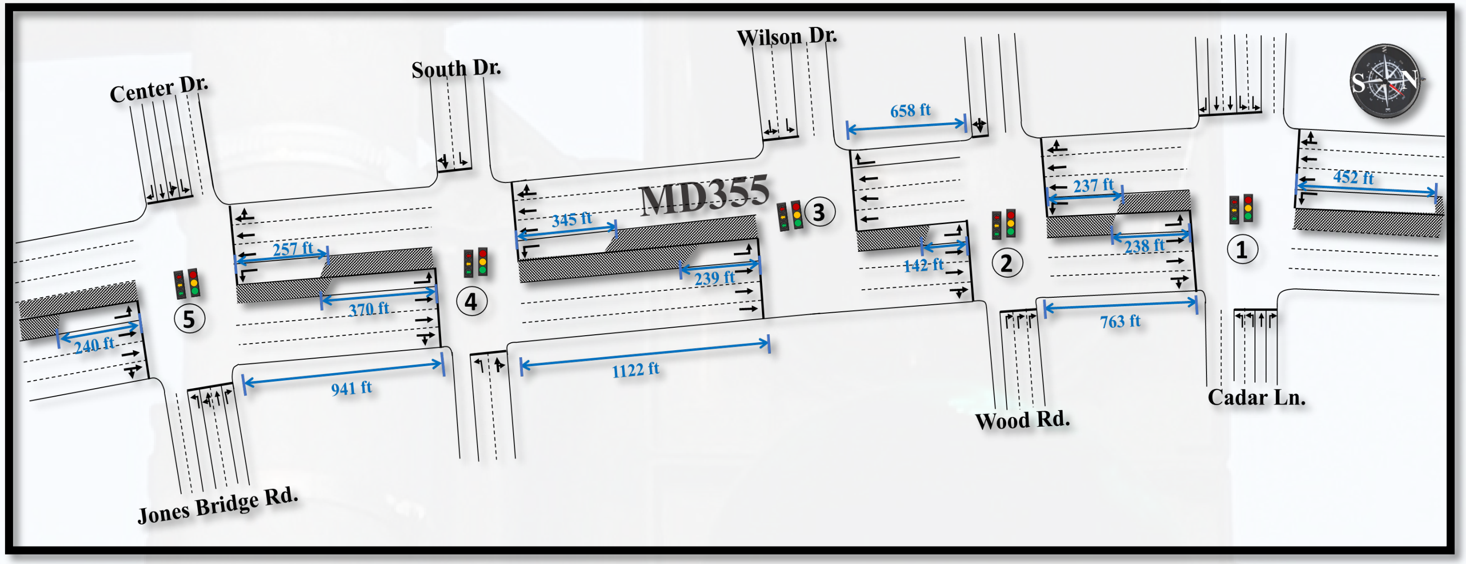
Time-of-day controls for commuting arterials with asymmetric directional flows

Impacts of optimized phase sequences

- ✓ Same signal timing
- ✓ Same offsets
- ✓ Same volume input
- ✓ Same turning ratio
- ✓ Same site
- ✓ Only the signal phase sequences are different

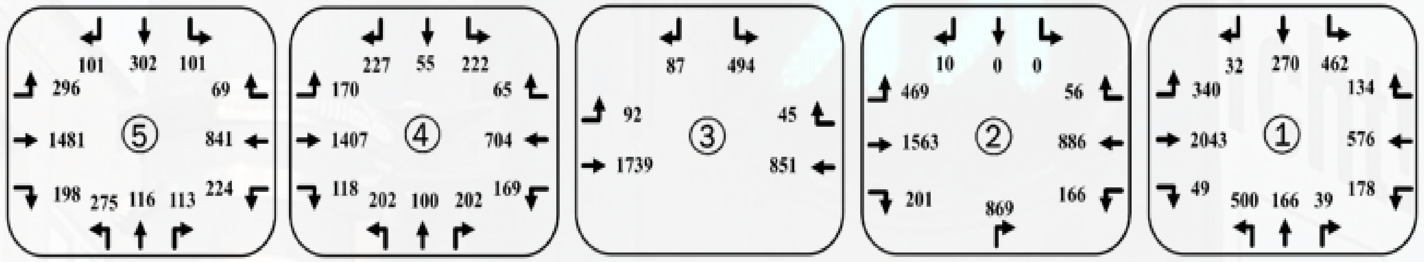


Recap: Module 1 Performance Comparison



- MD 355 Rockville Pike in Bethesda
- PM Peak hour (ITMS)
- Commuting direction: northbound
- VISSIM simulation

Hourly Volume
(Maryland SHA Internet Traffic Monitoring System (ITMS))



Evaluation Results:

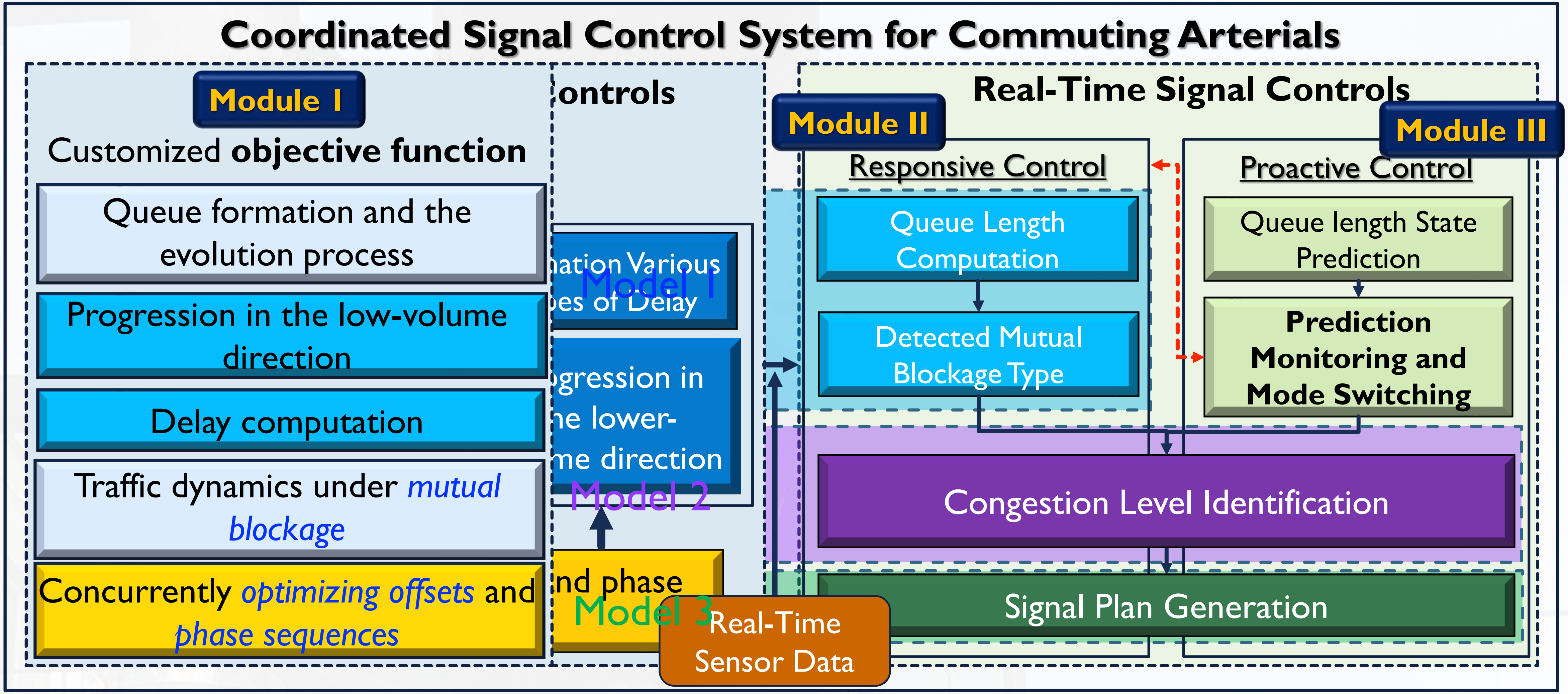
- NB Through Average Delay
  - 12.19% reduction vs. TRANSYT-7F
  - 8.39% reduction vs. MUTLIBAND
  - 1.85% reduction vs. Synchro
- Network Average Delay
  - 11.31% reduction vs. TRANSYT-7F
  - 3.84% reduction vs. MUTLIBAND
  - 3.79% reduction vs. Synchro

Module II:
Responsive Real-Time Signal Control

Lin, Y. T., Huang, Y. L., & Chang, G. L. (2025). A Real-Time Responsive Signal Control System for Commuting Arterials Plagued by Highly-Congested Traffic, Turning-Bay Overflows, and Mutual Queue Blockages. IEEE Transactions on Intelligent Transportation Systems.

Module II

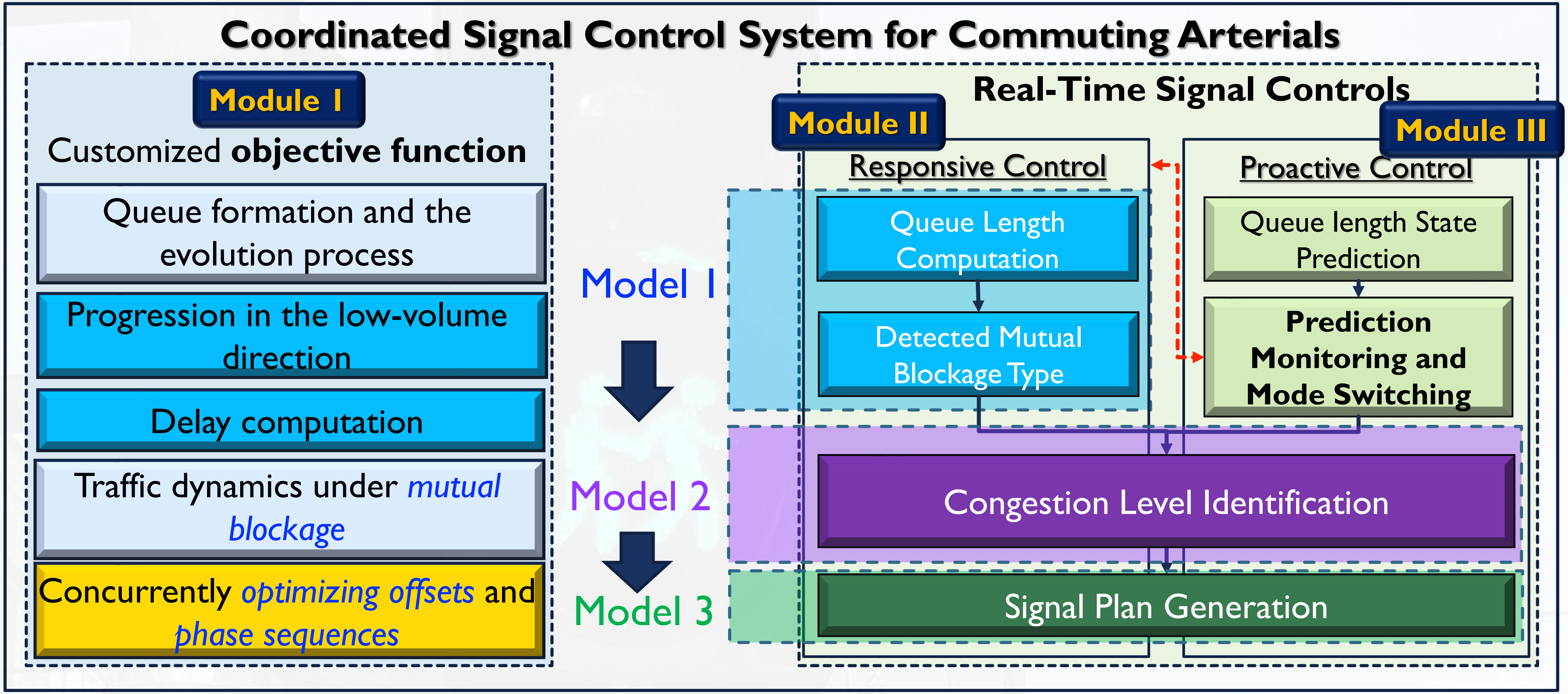
Responsive Real-Time Control Module



Module II

Responsive Real-Time Control Module

Model I: Queue Length Computation $Q_i^n(t)$



Module II

Responsive Real-Time Control Module

Model I: Queue Length Computation $Q_i^n(t)$

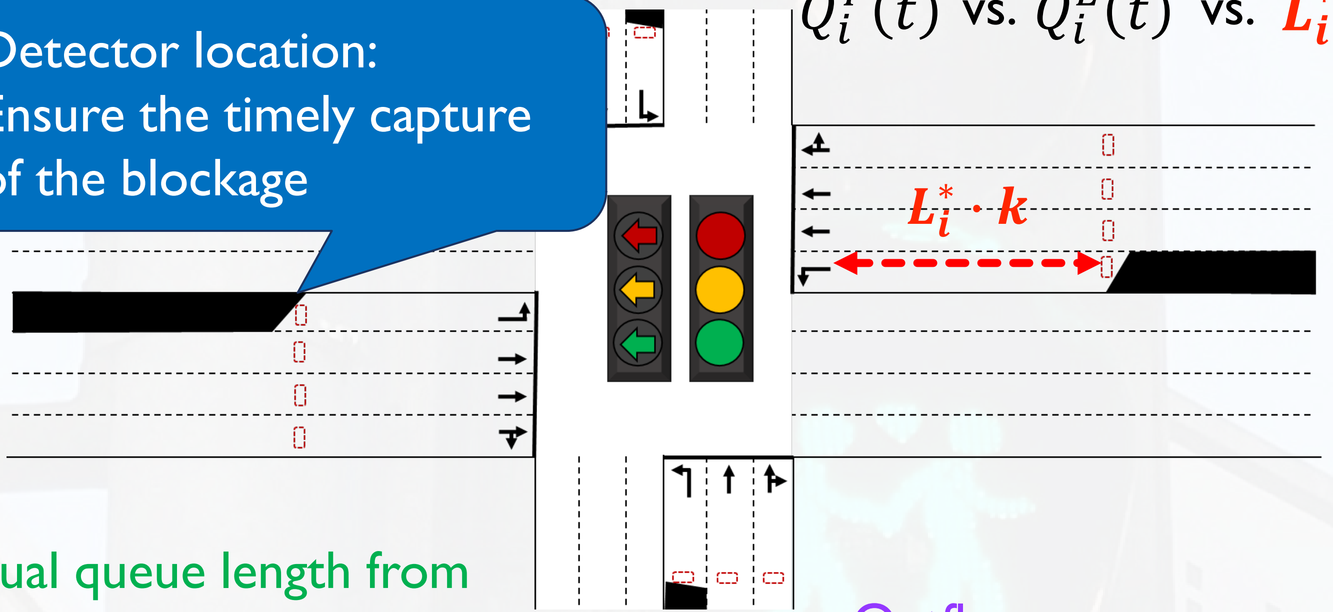
2

3

→ identify the queue blockage type and onset time using the detected inflow rate $\hat{x}_t^n$

Detector location:
Ensure the timely capture of the blockage

$Q_i^T(t)$ vs. $Q_i^L(t)$ vs. $L_i^* \cdot k$



$$Q_i^T(m_i^T) \geq L_i^* \cdot k$$

- Through queue exceeds the turning bay length at time step m_i^T

$$Q_i^L(m_i^L) \geq L_i^* \cdot k$$

- Left-turn queue exceeds the turning bay length at time step m_i^L

$$0 < m_i^L < m_i^T$$

→ Know the sequence of the blockages

→ Left-turn queue block through vehicles, then through queue blocks left-turn vehicles

Residual queue length from the previous time step

Inflow

Outflow

$$Q_i^n(t) = Q_i^n(t-1) + \hat{x}_t^n - \left(\tau_i^n(t) \times \Delta t \times \frac{1}{h}\right)$$

a binary variable to identify whether movement n has a green phase at a given time step t

I

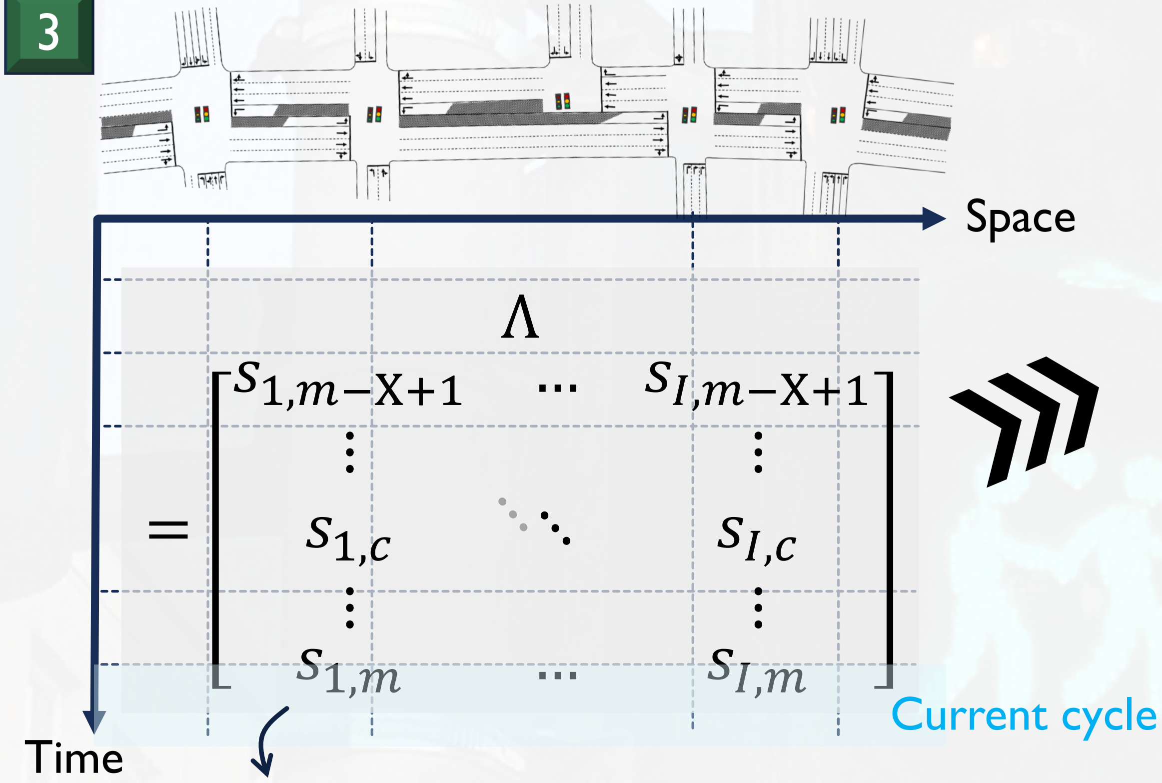
Module II

Responsive Real-Time Control Module

3

Model 2: Congestion Level Identification

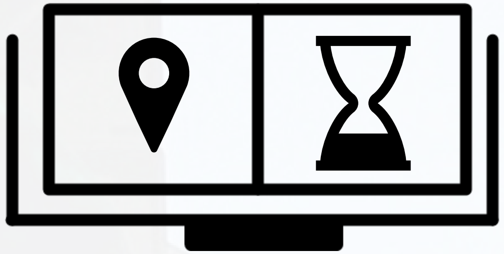
→ Evaluates arterial congestion severity using <u>spatial-temporal rules</u> that consider the timing and location of queue blockages identified by Model I



$$\Lambda = \begin{bmatrix} s_{1,m-X+1} & \cdots & s_{I,m-X+1} \\ \vdots & & \vdots \\ s_{1,c} & \ddots & s_{I,c} \\ \vdots & & \vdots \\ s_{1,m} & \cdots & s_{I,m} \end{bmatrix}$$

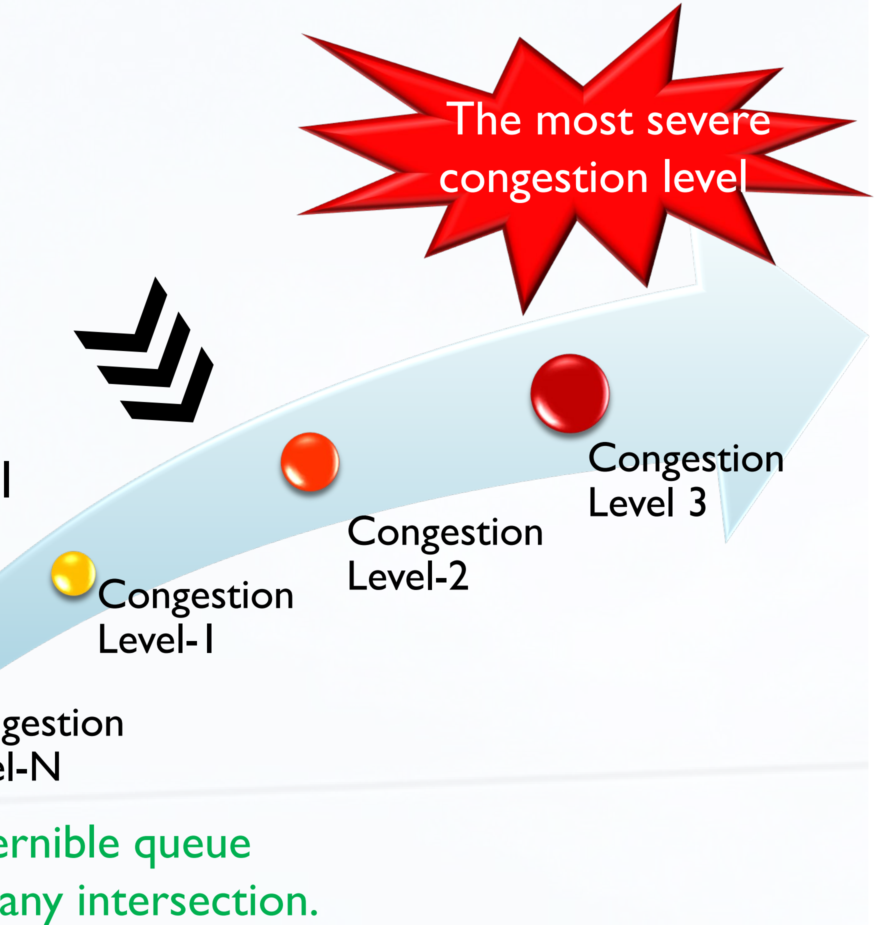
Every cell ($s_{i,c}$) fills in: whether a queue blockage occurred at **intersection *i*** during **cycle c** (1 = blockage, 0 = no blockage)

If-Then RULES



✓ Spatial ✓ Temporal

✓ Spatial + Temporal



Module II

I

Model 2: Congestion Level Identification

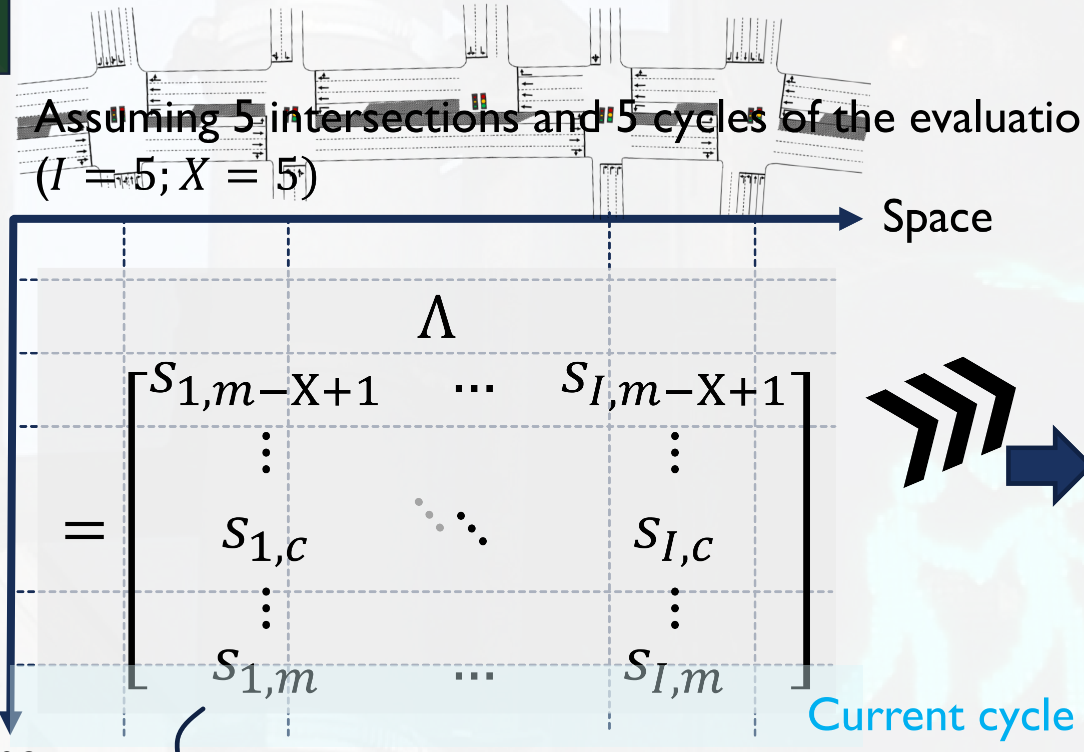
3

Responsive Real-Time Control Module

→ Evaluates arterial congestion severity using spatial-temporal rules that consider the timing and location of queue blockages identified by Model I.

- $s_{i,c} = 1$ if a blockage was present
- $s_{i,c} = 0$ if there is no blockage

Assuming 5 intersections and 5 cycles of the evaluation period ($I = 5; X = 5$)



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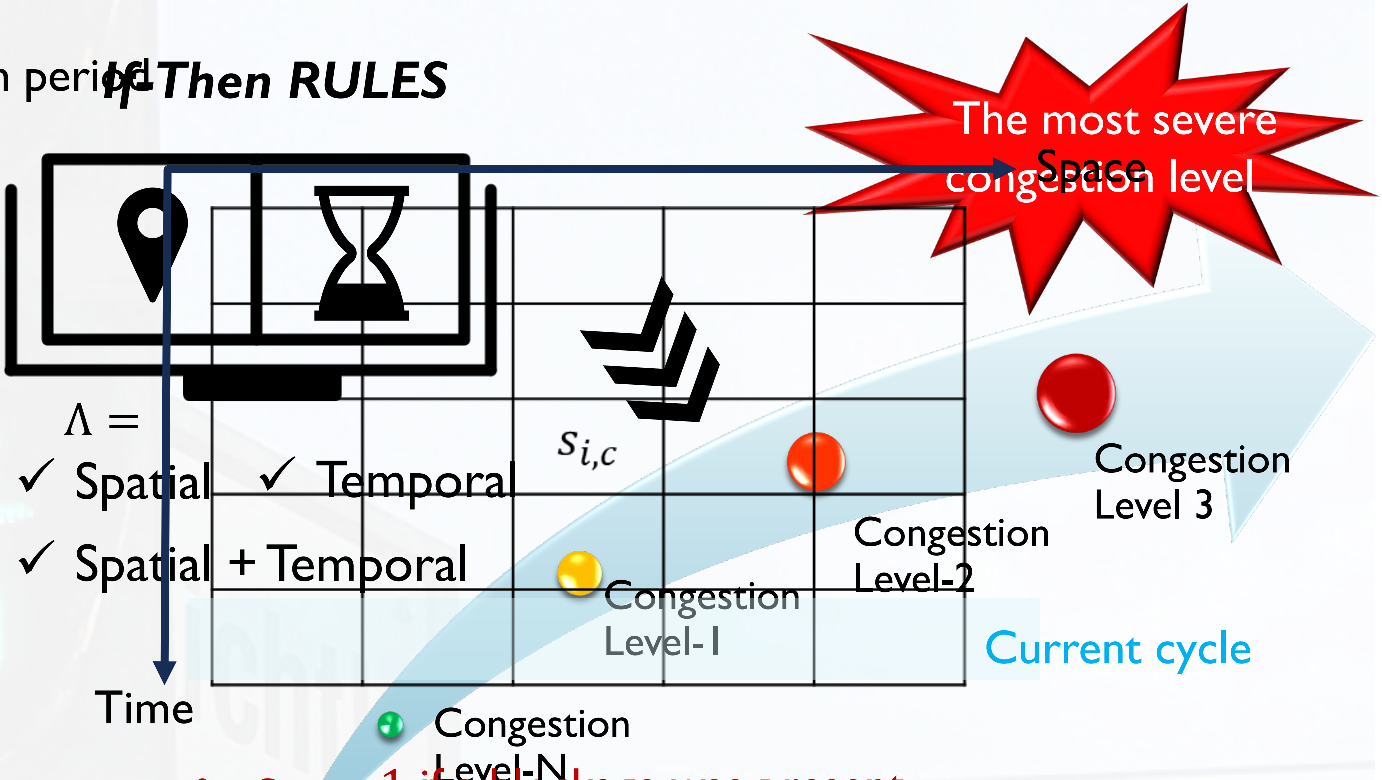
Every cell ($s_{i,c}$) fills in: whether a queue blockage occurred at **intersection *i*** during **cycle c** (1 = blockage, 0 = no blockage)

If-Then RULES

$\Lambda =$

- ✓ Spatial
- ✓ Temporal
- ✓ Spatial + Temporal



- $s_{i,c} = 1$ if a blockage was present
- $s_{i,c} = 0$ if there is no blockage

✓ No discernible queue blockage at any intersection.

Module II

I

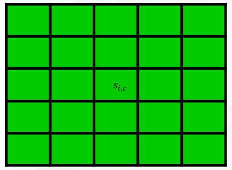
Model 2: Congestion Level Identification

3

If-Then RULES

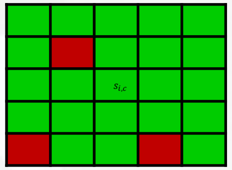
Assuming 5 intersections and 5 cycles
$(I = 5; X = 5)$

Rule 1: N



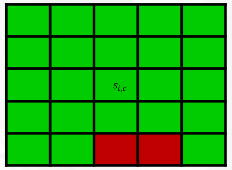
$$\sum_{i=1}^{I} \sum_{c=m-X+1}^{m} s_{i,c} = 0$$

Rule 2: 1



$$0 < \sum_{i=1}^{I} s_{i,c} < \frac{1}{2} I \qquad \forall c \in [m - X + 1, m]$$

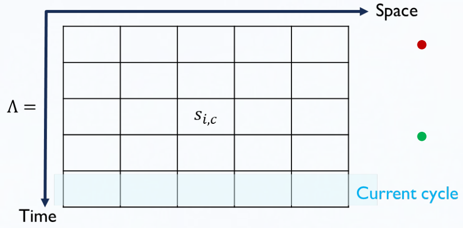
Rule 3: 2



$$s_{i,c} + s_{i+1,c} = 2 \qquad \forall i \in [1, I - 1]; \; \forall c \in [m - X + 1, m]$$

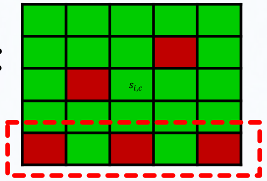
Responsive Real-Time Control Module

N 1 2 3



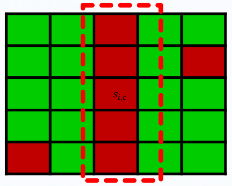
- $s_{i,c} = 1$ if a blockage was present
- $s_{i,c} = 0$ if there is no blockage

Rule 4: 2



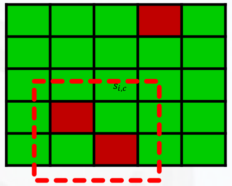
$$\sum_{i=1}^{I} s_{i,c} \geq \frac{1}{2} I \qquad \forall c \in [m - X + 1, m]$$

Rule 5: 2



$$\sum_{c=m-X+1}^{m} s_{i,c} = X \qquad \forall i \in [1, I]$$

Rule 6: 2



$$s_{i,c} + s_{i+1,c+1} = 2 \qquad \forall i \in [1, I - 1]; \; \forall c \in [m - X + 1, m]$$

Rule 7: If Level-1 congestion persists across ***X*** consecutive cycles → 2

Rule 8: If Level-2 congestion persists across ***X*** consecutive cycles → 3

Module II

Responsive Real-Time Control Module

1

2

N 1 2 3

Model 3: Responsive Strategy Generator : selecting and executing signal control strategies

- Response Plan-N → maintains the current signal timing plan
- Response Plan-1
- Response Plan-2
- Response Plan-3

The control strategy matches congestion severity — using minor local tweaks for mild congestion, and full arterial re-optimization for severe, widespread gridlock.

Module II

Responsive Real-Time Control Module

1 2 N 1 2 3

Model 3: Responsive Strategy Generator : selecting and executing signal control strategies

Response Plan-1

The control strategy matches congestion severity — using minor local tweaks for mild congestion, and full arterial re-optimization for severe, widespread gridlock.

Local Green Extensions for needed movements (TH and/or LT)

Step 1: Check Minimum Green Time
Ensure the side street has the minimum required green time.

$$G_i^* = g_i - \tilde{g}_i$$

G_i^*: allowable green extension
g_i: side-street green duration
$\tilde{g}_i$: the minimum side-street green duration

Step 2: Compute Blockage Duration
Compute how long the queue was blocked during the red phase

$$\bar{G}_i^n = (\tilde{m}_i^n - m_i^n) \times \Delta t$$

$\bar{G}_i^n$: target green extension
$\tilde{m}_i^n$: the time step at the onset of the green light for the overflow stream n.

Step 3: Adjust Green Splits
Extended green for the needed movement based on blockage duration

$$G_i = \begin{cases} \min(G_i^*, \bar{G}_i^n), & G_i^* > 0 \\ \text{Responsive Plan 2}, & G_i^* = 0 \end{cases}$$

G_i: finally adopted green extensions

If the side-street green time is fully utilized, proceed with Response Plan 2 instead

Module II

Responsive Real-Time Control Module

I

2 N I 2 3

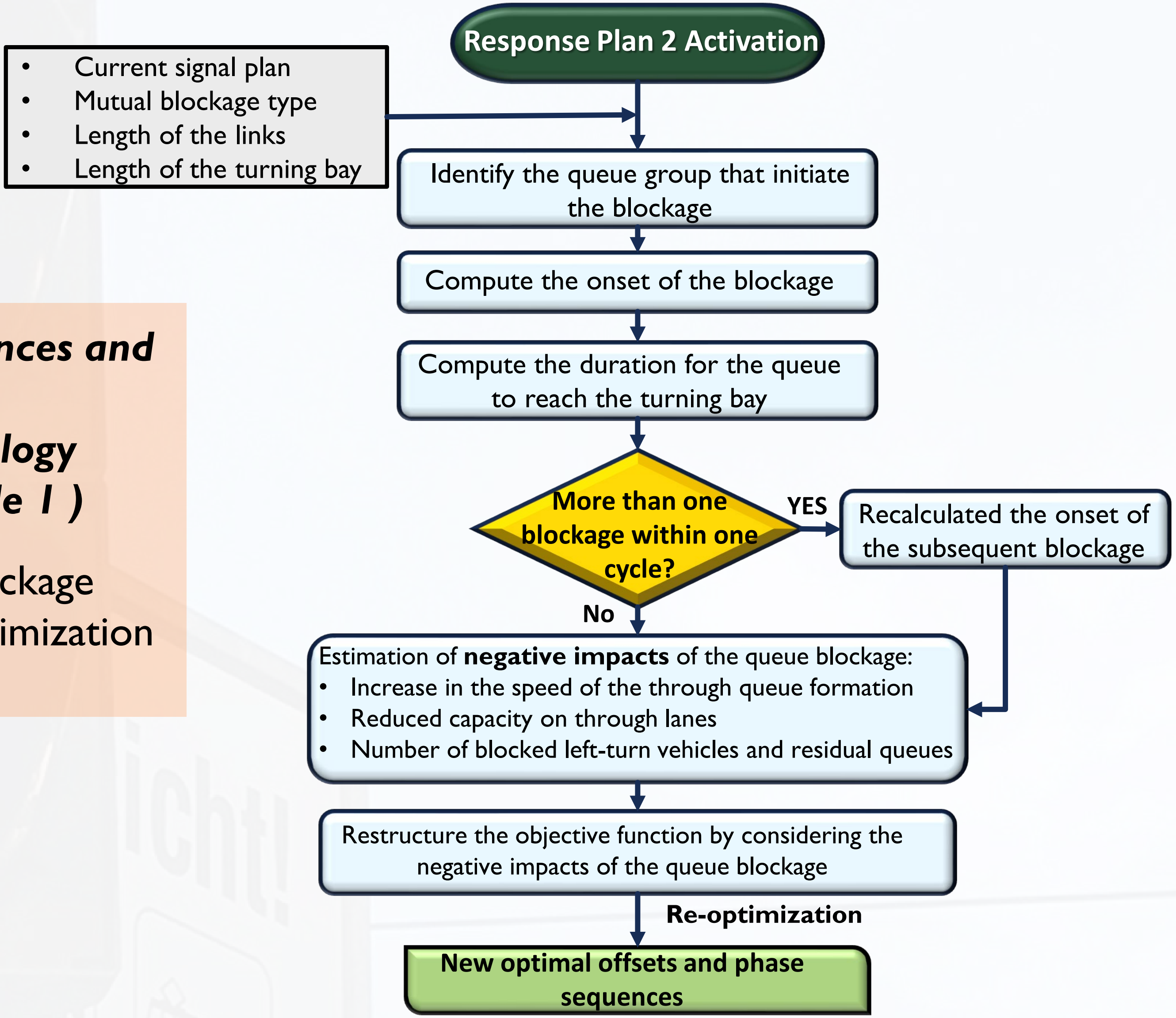
Model 3: Responsive Strategy Generator

Response Plan-2

The control strategy matches congestion severity — using minor local tweaks for mild congestion, and full arterial re-optimization for severe, widespread gridlock.

Re-optimize phase sequences and offsets (follows the methodology established for Module I)

✓ embedding real-time blockage information into the optimization logic



Module II

1

2 N 1 2 3

Responsive Real-Time Control Module

Adjust cycle lengths and green splits, then re-optimize phase sequences and offset

- to be activated for the most severe congestion level (Level-3)

Model 3: Responsive Strategy Generator

Response Plan-3

The control strategy matches congestion severity — using minor local tweaks for mild congestion, and full arterial re-optimization for severe, widespread gridlock.

Step 1: Adjust the Cycle length

Gradually reduce cycle length to limit queue growth under severe congestion.

$$C_{min} = \frac{1}{\epsilon} \times L$$

ϵ: a pre-defined percentage
L: the total lost time per cycle (sec/cycle)
(Roger et al., 2004)

- ✓ adjusted cycle length should not be shorter than the pre-defined threshold
- ✓ because a shorter cycle length inherently results in a higher proportion of lost time, and thus a lower intersection capacity utilization.

Step 2: Adjust Green Splits

Adjust green splits based on upstream entry flows to better match time-varying demands under the new, shorter cycle length

$$g_i = g_{TOT} \cdot \left(\frac{V_{ci}}{V_c}\right)$$

(Roger et al., 2004)

g_i: effective green time for Phase i (sec)
g_{TOT}: total effective green time for the cycle (sec)
V_{ci}: critical lane volume for Phase i (veh/h);
V_c: the sum of the critical-lane volumes (veh/h).

Step 3: Reoptimize Offsets and Phase Sequence

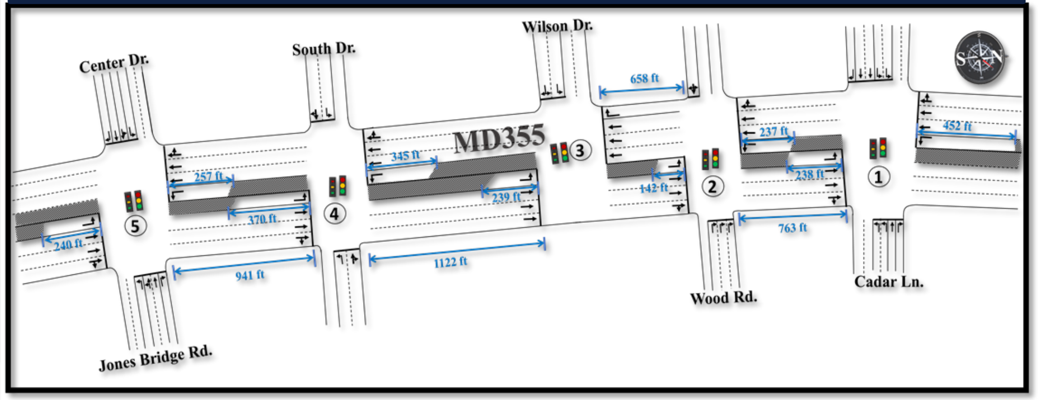
- Ensuring delay minimization and progression while accounting for mutual blockage effects
- using the methodology from Module 1 (Response Plan 2)

Summary of Module II: Responsive Control

Model 1: Queue length computation

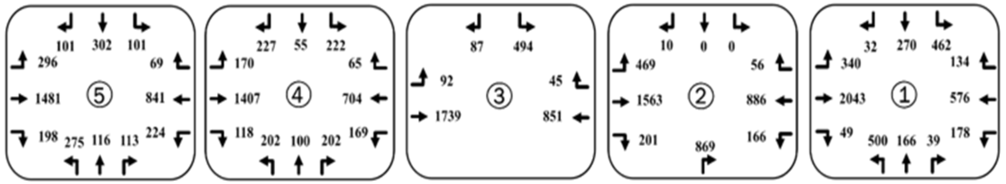
- Queue length estimation
- Mutual blockage type identification

Model 2: Congestion level identification



Hourly Volume

(Maryland SHA Internet Traffic Monitoring System (ITMS))



uation

1. Detection capability (Model 1)

- Validate the developed module's ability to accurately and promptly detect various types of queue blockages

2. Control performance (Models 2 & 3)

- Evaluate the effectiveness in generating and executing real-time responsive signal plans to mitigate queue propagation and reduce delays.

Setup

- Module I outperformed TRANSYT-7F, MULTIBAND, and Synchro, and is thus used as the baseline for comparison.

→ evening peak hour, a 2.55% increase was applied to each of the four 15-minute field volumes.

Performance Evaluation

Detection of mutual blockages at each intersection								
Cycle	Intersection 1		Intersection 2		Intersection 3		Intersection 4	
	[illegible]	[illegible]	Module II (responsive)	Module I (time-of-day)	Module II (responsive)	Module I (time-of-day)	Module II (responsive)	Module I (time-of-day)
1-12	[illegible]	[illegible]	-	-	-	-	-	-
13	[illegible]	[illegible]	S_1	S_1	-	-	[illegible]	[illegible]
14	S_1	S_1	S_1	S_1	-	-	[illegible]	[illegible]
15	[illegible]	[illegible]	S_1	S_1	S_1	S_1	-	-
16	[illegible]	[illegible]	S_1	S_1	-	-	-	-
17	-	-	-	S_3	S_1	S_1	-	-
18	[illegible]	[illegible]	S_1	S_1	-	-	S_1	S_1
19	[illegible]	[illegible]	S_1	S_1	S_1	S_1	S_3	S_3
20	-	S_2	-	S_1	[illegible]	[illegible]	-	S_1
21	-	S_3	-	S_1	[illegible]	[illegible]	-	S_1
22	-	-	S_1	S_3	[illegible]	[illegible]	-	[illegible]
23	-	S_1	-	S_1	-	S_1	[illegible]	[illegible]
24	-	S_1	S_1	S_1	S_1	S_2	[illegible]	[illegible]

Note: S_i denotes the observed Blockage type-i; the cell without any letter represents no mutual blockage observed

- Classified as Congestion Level-2
- Response Plan 2 is triggered

An optimal signal plan is produced

An optimal signal plan is implemented

S_1: Through queue blocks left-turn vehicles.

S_3: Through queue blocks left-turns, which then block the returning through flow.

S_2: Left-turn queue blocks through vehicles.

S_1: Through queue blocks left-turn vehicles. S_2: Left-turn queue blocks through vehicles. S_3: Through queue blocks left-turns, which then block the returning through flow.

S_4: Left-turn queue blocks through traffic, which then forms queues that block subsequent left-turns.

Performance Evaluation

Detection of mutual blockages at each intersection								
Cycle	Intersection 1		Intersection 2		Intersection 3		Intersection 4	
	Module II (responsive)	Module I (time-of-day)	Module II (responsive)	Module I (time-of-day)	Module II (responsive)	Module I (time-of-day)	Module II (responsive)	Module I (time-of-day)
1-12	-	-	-	-	-	-	-	-
13	-	-	S_1	S_1	-	-	-	-
14	S_1	S_1	S_1	S_1	-	-	-	-
15	-	-	S_1	S_1	S_1	S_1	-	-
[illegible]	[illegible]	-	[illegible]	[illegible]	-	-	-	-
[illegible]	[illegible]	-	-	S_3	S_1	S_1	-	-
[illegible]	S_1	S_1	S_1	S_1	-	-	S_1	S_1
19	S_1	S_1	S_1	S_1	S_1	S_1	S_3	S_3
20	-	S_2	-	S_1	-	-	-	S_1
21	[illegible]	S_3	-	S_1	-	S_1	-	S_1
22	[illegible]	-	S_1	S_3	-	S_1	-	S_1
23	-	S_1	-	S_1	-	S_1	S_1	S_1
24	-	S_1	S_1	S_1	S_1	S_2	-	S_1
Note: S_i denotes the observed Blockage type-i; the cell without any letter represents no mutual blockage observed								

New signal plan computation

Congestion Level-2

New signal plan

S_1: Through queue blocks left-turn vehicles.

S_2: Left-turn queue blocks through vehicles.

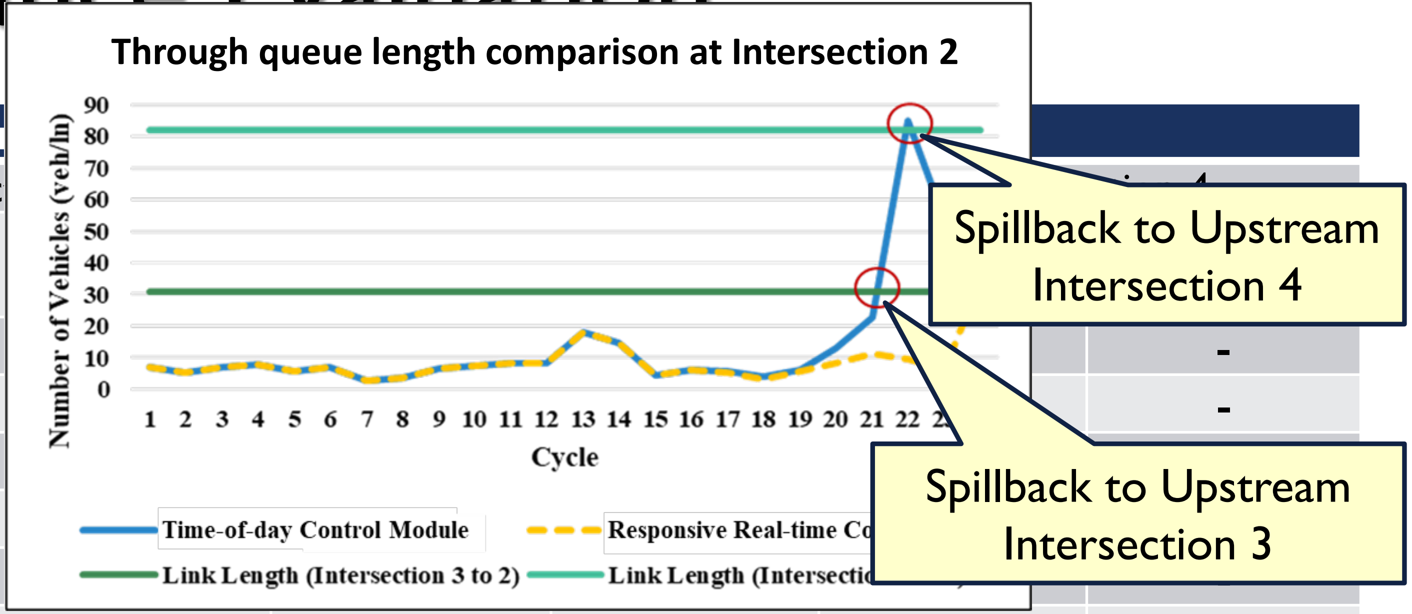
S_3: Through queue blocks left-turns, which then block the returning through flow.

S_4: Left-turn queue blocks through traffic, which then forms queues that block subsequent left-turns.

Performance Evaluation

Detection of mutu								
Cycle	Intersection 1		Intersec					
	Module II (responsive)	Module I (time-of-day)	Module II (responsive)					
1-12	-	-	-					-
13	-	-	S_1					-
14	S_1	S_1	S_1					
15	-	-	S_1					
16	-	-	S_1					
17	-	-	-	S_3	S_1	S_1	-	-
18	S_1	S_1	S_1	S_1	-	-	S_1	S_1
19	S_1	S_1	S_1	S_1	S_1	S_1	S_3	S_3
20	-	S_2	-	S_1	-	-	-	S_1
21		S_3	-	S_1	-	S_1	-	S_1
22		-	S_1	S_3	-	S_1	-	S_1
23	-	S_1	-	S_1	-	S_1	S_1	S_1
24	-	S_1	S_1	S_1	S_1	S_2	-	S_1
Note: S_i denotes the observed Blockage type-i; the cell without any letter represents no mutual blockage observed								

New signal plan



S_1: Through queue blocks left-turn vehicles.

S_2: Left-turn queue blocks through vehicles.

S_3: Through queue blocks left-turns, which then block the returning through flow.

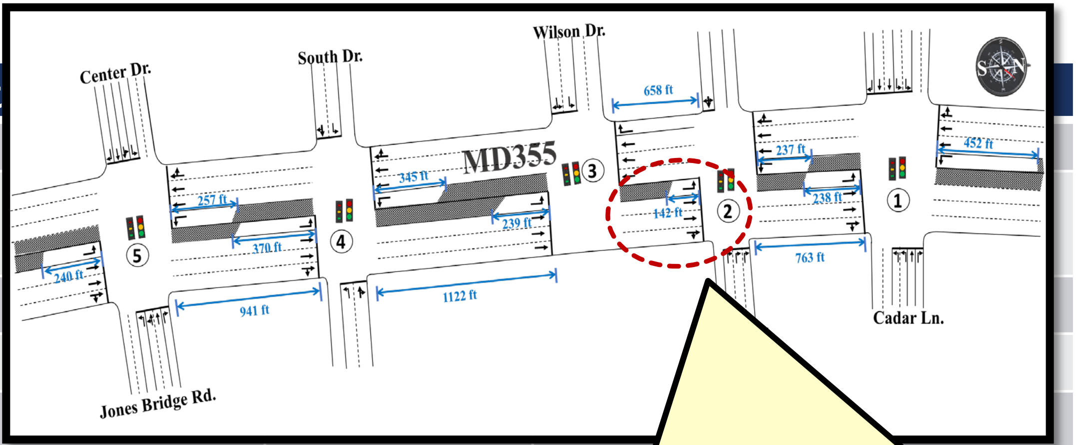
S_4: Left-turn queue blocks through traffic, which then forms queues that block subsequent left-turns.

Performance Evaluation

Detection of mutual blockages at

Cycle	Intersection 1		Intersection 2	
	Module II (responsive)	Module I (time-of-day)	Module II (responsive)	Module I (time-of-day)
1-12	-	-	-	-
13	-	-	S_1	S_1
14	S_1	S_1	S_1	S_1
15	-	-	S_1	S_1
16	-	-	S_1	S_1
17	-	-	-	S_3
18	S_1	S_1	S_1	S_1
19	S_1	S_1	S_1	S_1
20	-	S_2	-	S_1
21	-	S_3	-	S_1
22	-	-	S_1	S_3
23	-	S_1	-	S_1
24	-	S_1	S_1	S_1

Note: S_i denotes the observed Blockage type-i; the cell without any letter represents no m



shortest link, shortest turning bay

→ examined its susceptibility to mutual blockages under both modules

→ MOEs:

- ***Throughput per cycle at each intersection***: The number of vehicles passing through the stop line at the downstream intersection during each signal cycle.
- ***Queue delay***: Per vehicle's total time in the queue.

S_1: Through queue blocks left-turn vehicles.

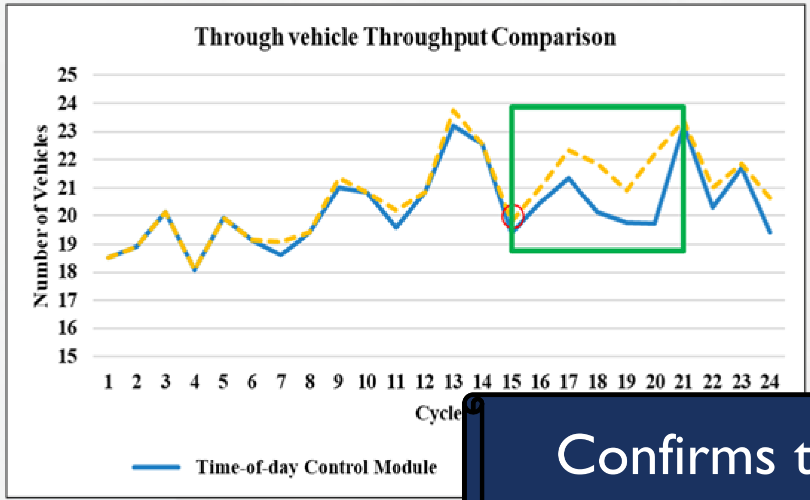
S_2: Left-turn queue blocks through vehicles.

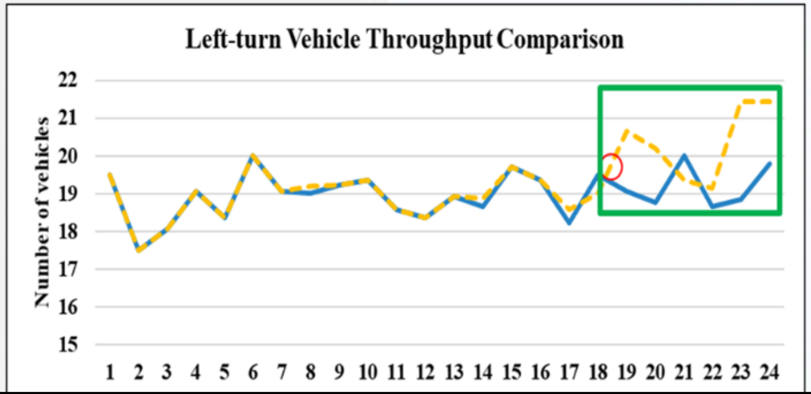
S_3: Through queue blocks left-turns, which then block the returning through flow.

S_4: Left-turn queue blocks through traffic, which then forms queues that block subsequent left-turns.

Performance Evaluation

- Throughput per cycle:

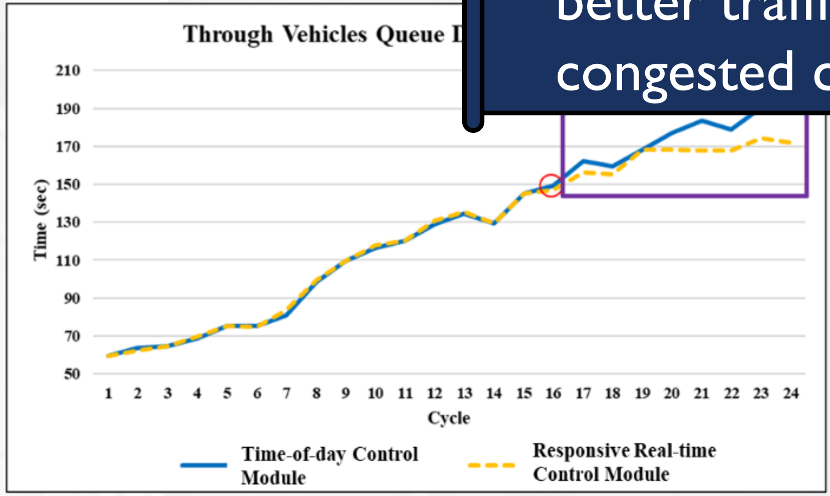


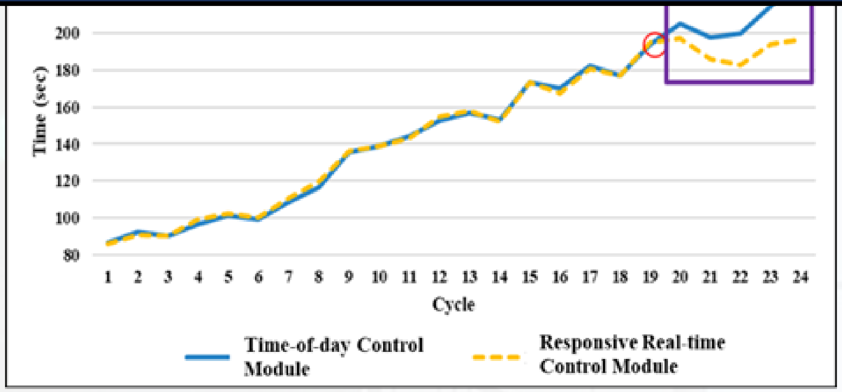


- Periods of volume surge: Cycle 13 to Cycle 24
- The Responsive module consistently achieves higher throughput compared to the time-of-day control module

Confirms the Module II's ability to minimize spillover impacts and queue propagation, ensuring better traffic progression even under highly congested conditions

- Queue delay:

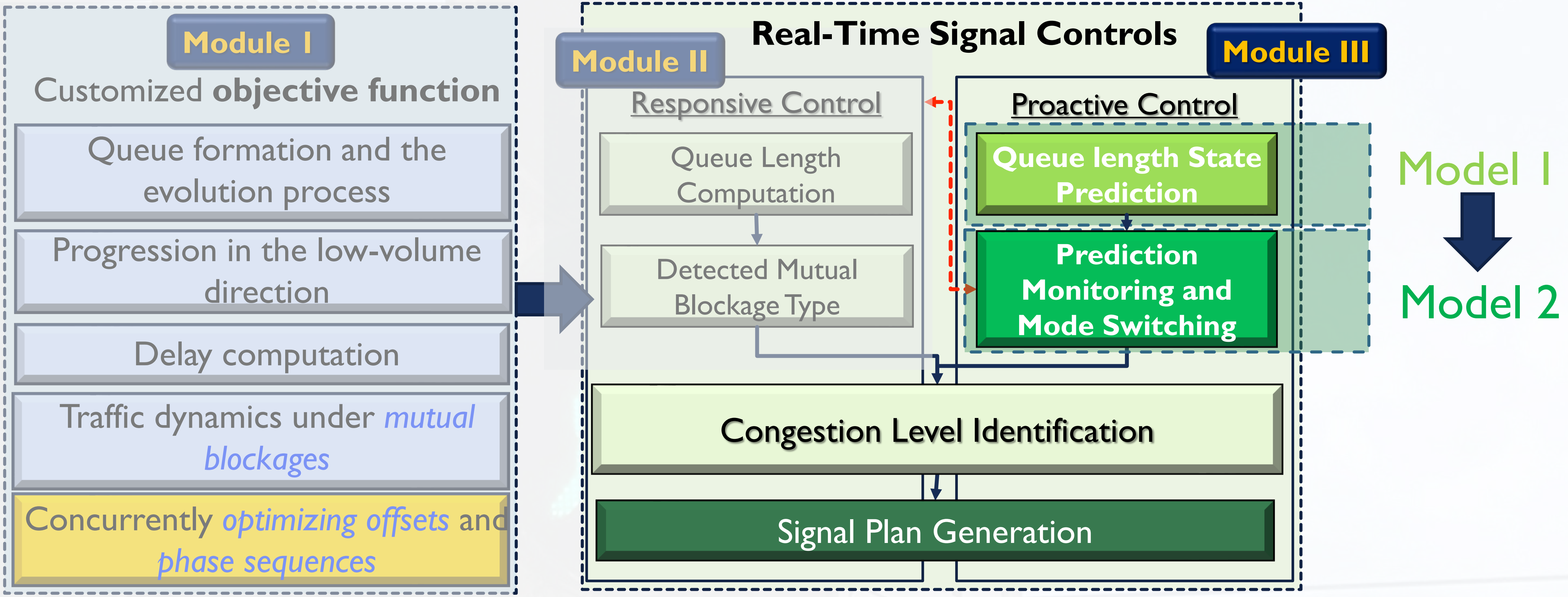




- ring mutual blockages, green ases may be underutilized, forcing some vehicles to wait across cycles and experience excessive delays.
- Responsive module consistently achieves reduced queue delays

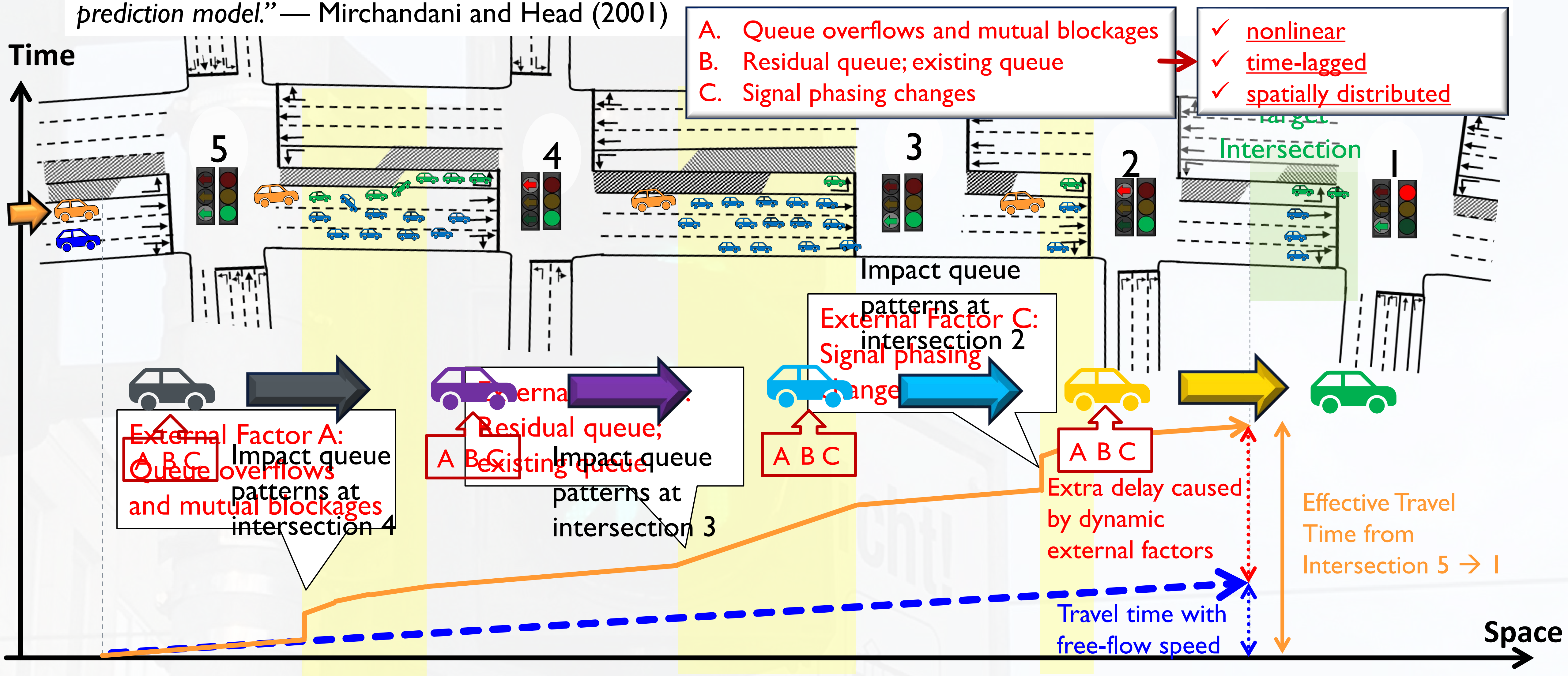
Module III:
Proactive Real-Time Signal Control

Coordinate Signal Control System



Module III: The Challenges of Predictive Queue Modeling

"The effectiveness of any proactive signal control system depends fundamentally on the reliability of its underlying traffic prediction model." — Mirchandani and Head (2001)



Module III-Model I: Queue Length State Prediction

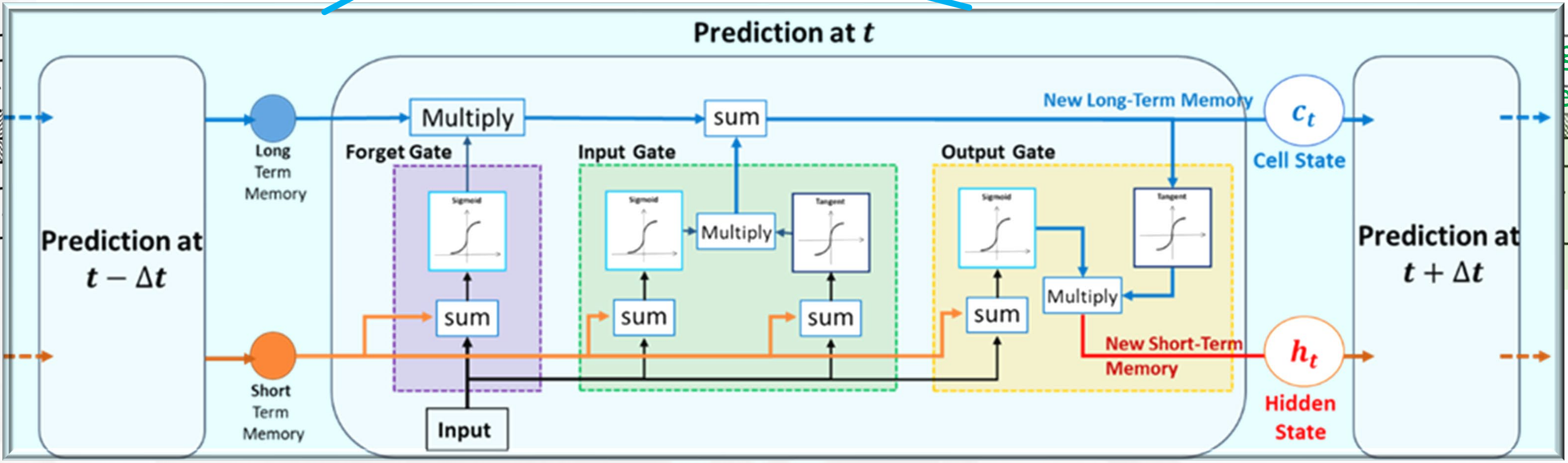
Proactive

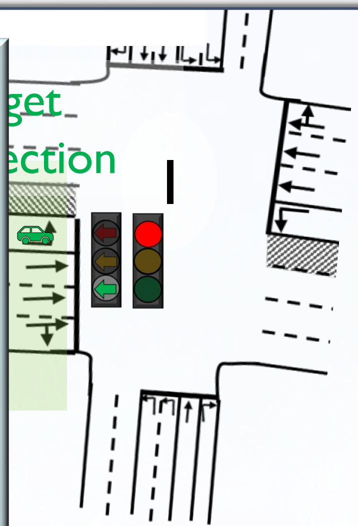
✓ multi-branch multi-head LSTM prediction model

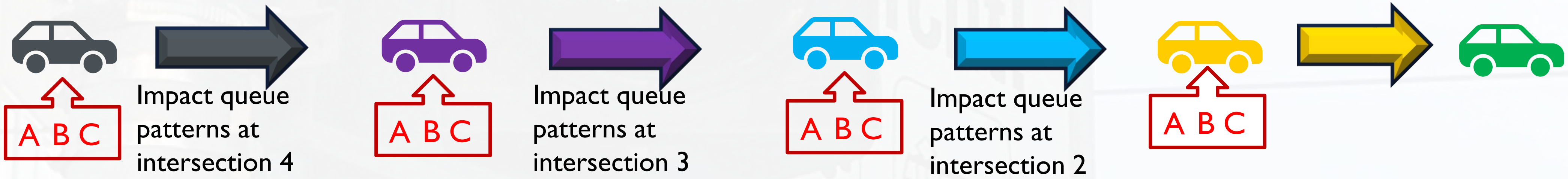
A. Queue overflows and mutual blockages
B. Residual queue; existing queue
C. Signal phasing changes

→

✓ nonlinear
✓ time-lagged
✓ spatially distributed







Module III-Model I: Queue Length State Prediction

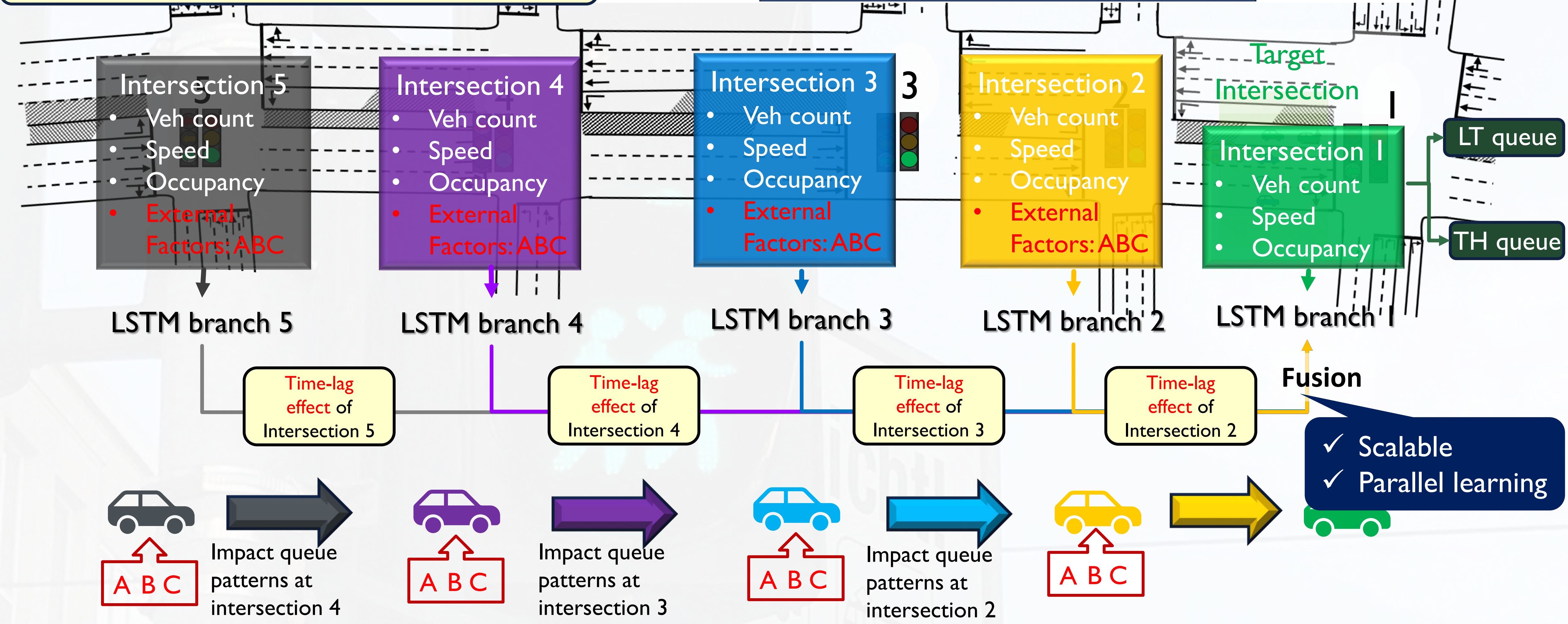
Proactive

✓ multi-branch multi-head LSTM prediction model

Adaptive Time Lag and Spatial-Temporal Input

A. Queue overflows and mutual blockages
B. Residual queue; existing queue
C. Signal phasing changes

✓ nonlinear
✓ time-lagged
✓ spatially distributed



Module III-Model I: Queue Length State Prediction

Proactive

✓ multi-branch multi-head LSTM prediction model

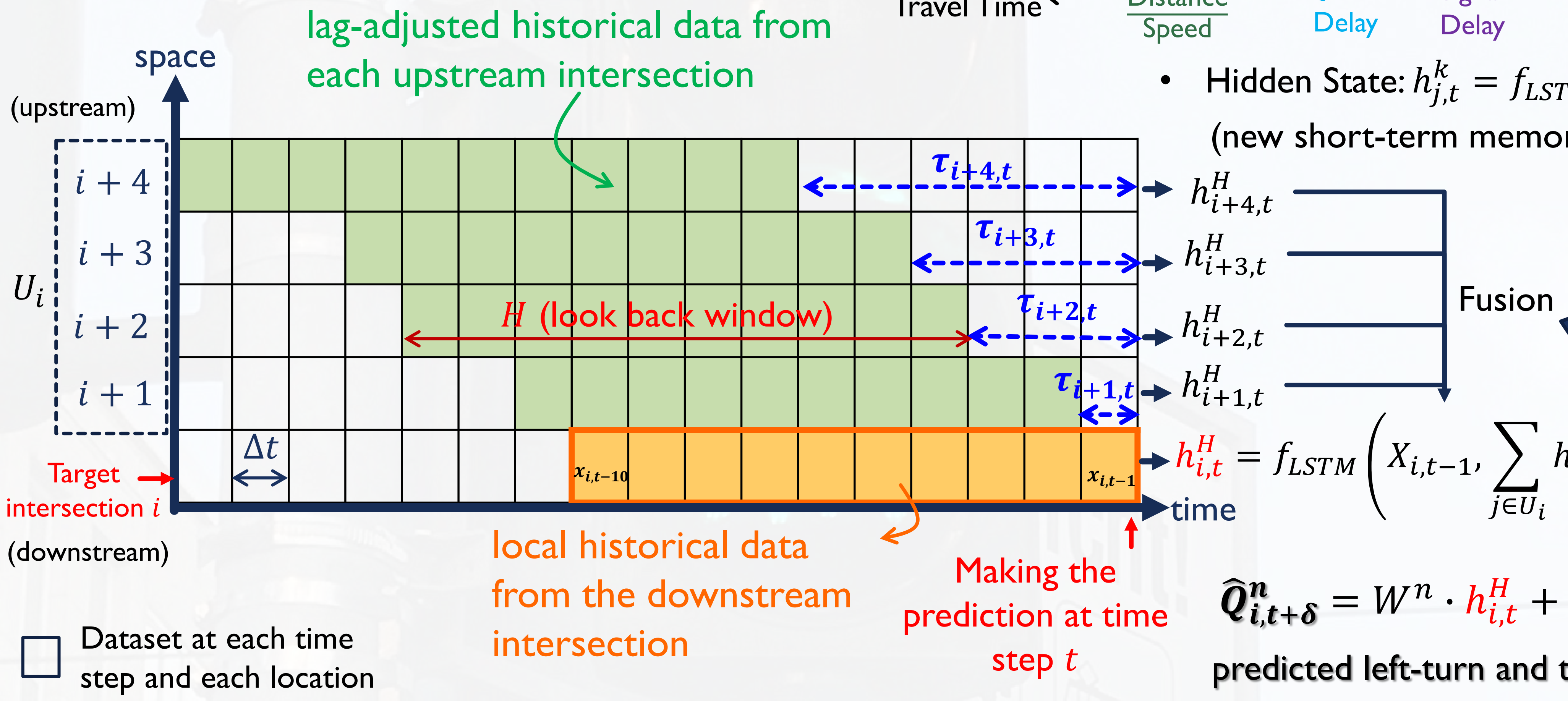
Adaptive Time Lag and Spatial-Temporal Input

- Time Lag ($\tau_{j,t}$) from upstream Intersection j to downstream i:

$$T_{j\to i,t} = \frac{L_{ji}}{u_{j,t}} + Q^*_{j,t} + s^*_{j,t} \qquad \tau_{j,t} = \left\lceil \frac{T_{j\to i,t}}{\Delta t} \right\rceil$$

Effective Travel Time; Distance / Speed; Queue Delay; Signal Delay

- Hidden State: $h^k_{j,t} = f_{LSTM}\left(X_{j,t-\tau_{j,t-k}}, h^{k-1}_{j,t}; \theta_j\right)$ (new short-term memory)



The features from each branch are concatenated together

$$h^H_{i,t} = f_{LSTM}\left(X_{i,t-1}, \sum_{j\in U_i} h^H_{j,t}, h^{k-1}_{i,t}; \theta_i\right)$$

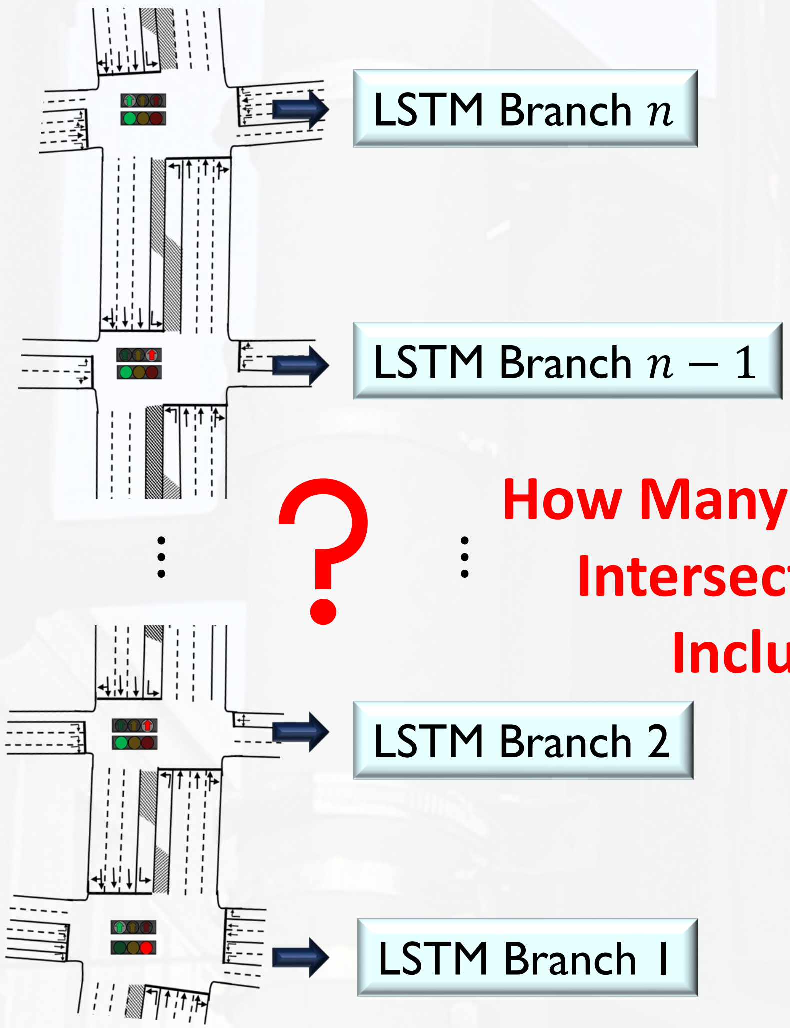
$$\hat{Q}^n_{i,t+\delta} = W^n \cdot h^H_{i,t} + b^n \qquad n \in \{LT, TH\}$$

predicted left-turn and through queue lengths

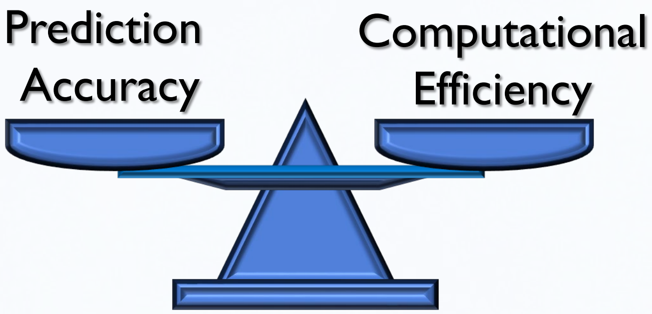
Module III-Model 1: Queue Length State Prediction

Proactive

- ✓ multi-branch multi-head LSTM prediction model
- ✓ Easily scalable



How Many Upstream Intersections to Include?



1. Step 1: Vector Autoregression (VAR) helps in modeling the relationships between multiple time series:
   - captures the overall temporal relationships among intersections
   - identifies potential upstream impacts on the downstream intersection.

Downstream queue length→ / Upstream traffic features →

$$\begin{bmatrix} Q_t \\ X_{j,t} \end{bmatrix} = \sum_{k=1}^{p} \begin{bmatrix} A_{11}^k & A_{12}^k \\ A_{21}^k & A_{22}^k \end{bmatrix} \begin{bmatrix} Q_{t-k} \\ X_{j,t-k} \end{bmatrix} + \begin{bmatrix} \varepsilon Q_t \\ \varepsilon X_{j,t} \end{bmatrix}$$

2. Step 2: Granger Causality- A test to determine whether one time series can predict another.

$$H_0\colon A_{12}^1 = A_{12}^2 = \cdots = A_{12}^p = 0$$

✓Granger Causality refines the selection by determining whether an upstream intersection's past data uniquely improves downstream predictions

Performance Evaluation of Module III-Model I

Proactive

- Assess the model's suitability for real-time operations
- Examine the accuracy of queue states (spillback/blockage or not) prediction—key triggers for control adaptation

MOEs:

- ✓ *Event Detection Rate*

% of actual spillovers/blockages correctly predicted

- ✓ *Average Duration Deviation*
- ✓ *False Alarm Rate*

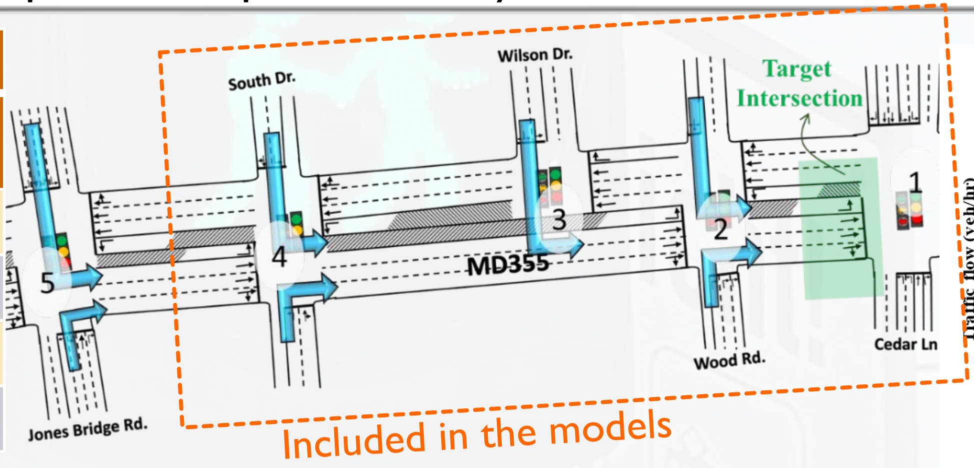
% of normal queue states incorrectly classified as spillover/blockage events

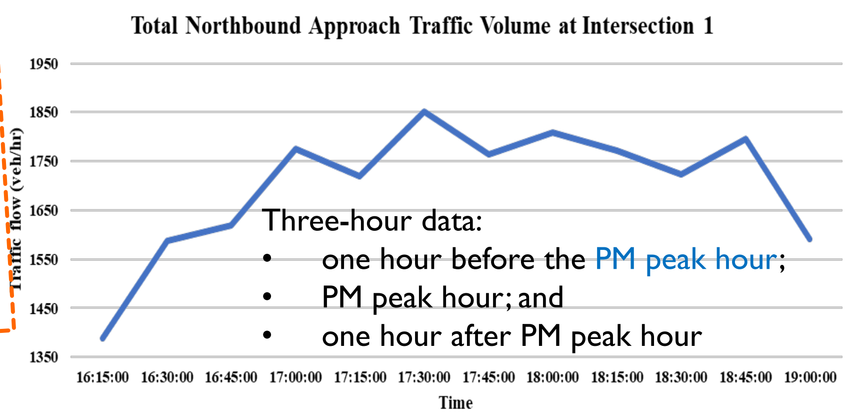
- ✓ *Average Start Time Deviation*

Why does it matter?
Even with the same number of predicted spillovers, *delay detection* or *duration deviation* can impair proactive response

Results of the Granger Causality Test

Upstream Intersection (X)	P-value	Intepretation
Intersection 2	0.000	Reject H_o
Intersection 3	0.000	Reject H_o
Intersection 4	0.000	Reject H_o
Intersection 5	0.208	Fails to reject H_o



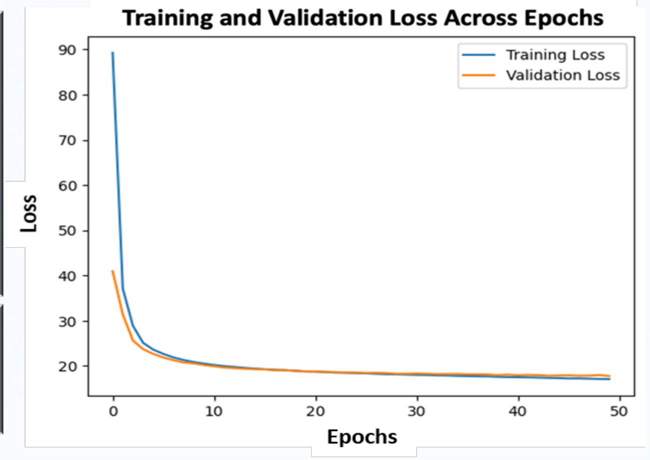


Performance Evaluation of Module III-Model I

Proactive

Benchmark models:
- Extended Kalman Filter (EKF): Recursive state estimator; smooths noise but oversimplifies nonlinear dynamics → baseline traditional method
- Standard Recurrent Neural Network (RNN): Neural network for sequential data; captures temporal patterns but unstable long-term → baseline deep learning model

Setup:
- Prediction interval: Every 30 seconds
- Horizon: 300 seconds (2 cycles)



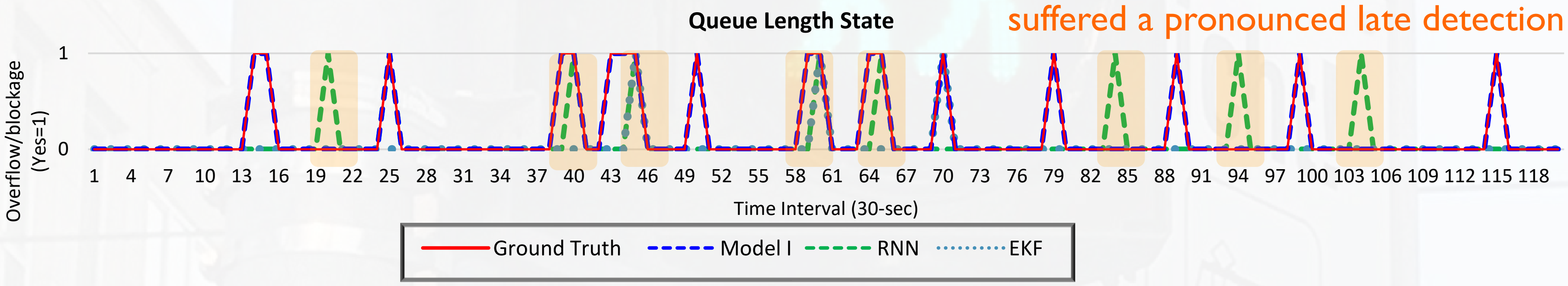
Summary of Spillover/Blockage Prediction Performance

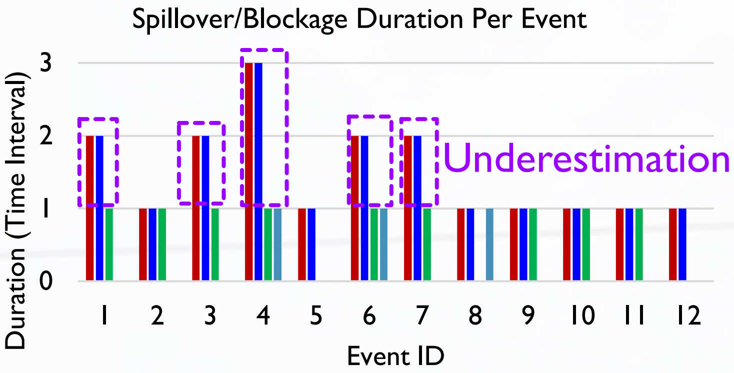
Metric	Model I	RNN	EKF
Event Detection Rate	100%	75%	25%
False alarm rate	0%	0%	0%
Average Start Time Deviation (sec/event)	0	87[a]	40[a]
Average Duration Deviation (sec/event)	0	-20[b]	-30[b]

a) A positive (negative) value indicates that the detected event is predicted to take place later (earlier) than its actual onset time.
b) A positive (negative) value implies an overestimation (underestimation) of the blockage duration.

✓ The multi-branch LSTM achieved perfect accuracy in both event detection and duration estimation.

✓ Reflecting its limited responsiveness to abrupt traffic state transitions, due in part to its reliance on local linearization and recursive filtering





Module III-Model I: Queue Length State Prediction

Proactive

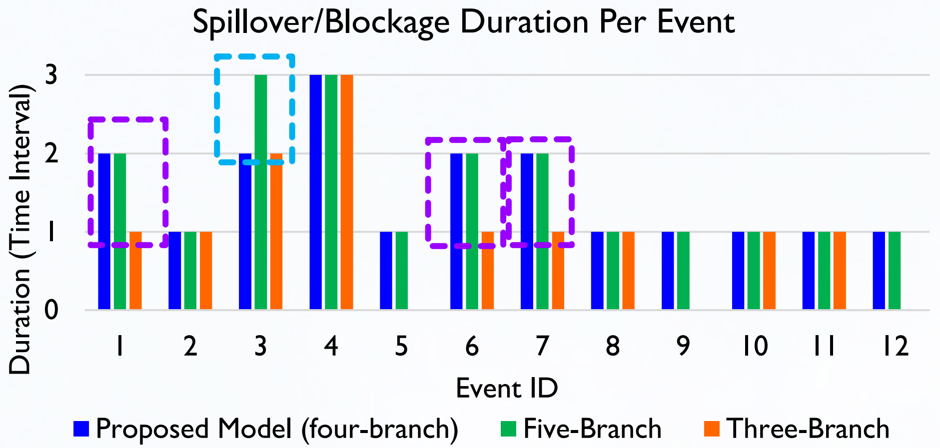
Numerical Experiment: Sensitivity of upstream traffic information coverage on the prediction accuracy

Three-branch model: Target Intersection+ 2 upstream intersections	Four-branch model (Model I): Target Intersection+ 3 upstream intersections	Five-branch model: Target Intersection+ 4 upstream intersections

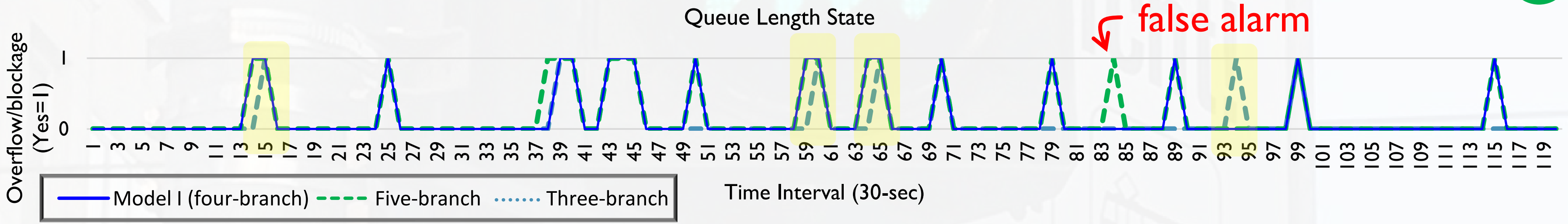
Summary of Spillover/Blockage Prediction Performance

Metric	Three-branch Model	Developed Model I (Four-branch)	Five-branch Model
Event Detection Rate	75%	100%	100%
False alarm rate	0%	0%	**7.7%**
Average Start Time Deviation (sec/event)	27[a]	0	-2.5[a]
Average Duration Deviation (sec/event)	-20[b]	0	2.5[b]

a) A positive (negative) value indicates that the detected event is predicted to take place later (earlier) than its actual onset time.
b) A positive (negative) value implies an overestimation (underestimation) of the blockage duration.



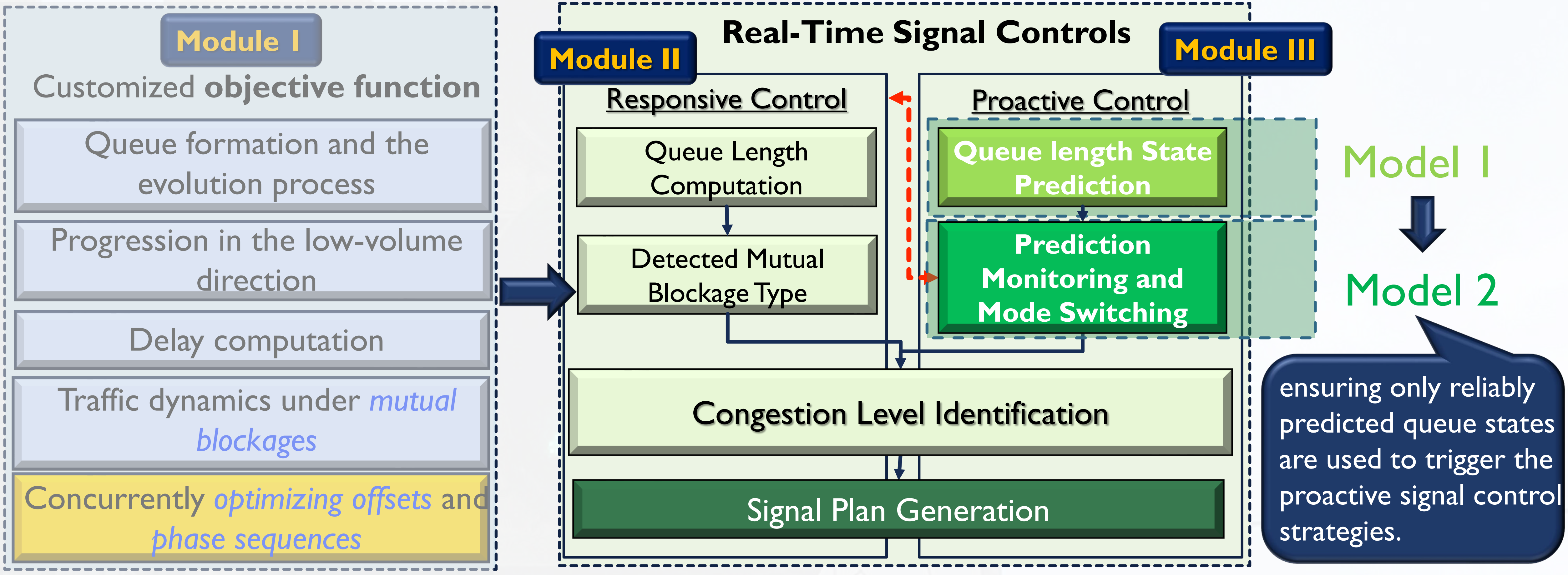
- Three-branch Model: lag detection, underestimation of blockage duration
→ diminishing sensitivity to upstream congestion due to limited spatial input.
- Five-branch Model: false alarm, overestimation of blockage duration
→ introduces some noise or weakly correlated information.



The four-branch model has achieved the optimal balance of spatial coverage and prediction accuracy

Coordinate Signal Control System

- ✓ If significant and sustained deviations are detected, the system will temporarily deactivate the proactive control path and redirect the operations back to the responsive control module



Module III-Model 2: Monitoring and Mode Switching

Proactive

Monitoring Rules

Normalized absolute prediction error:

$$\epsilon_{i,t}^{n} = \left| \frac{\hat{Q}_{i,t}^{n} - Q_{i,t}^{n}}{q_{i}^{n}} \right|$$

facilitates fair comparisons across movements and intersections with different geometric configurations

- $\hat{Q}_{i,t}^{n}$: predicted queue length for movement n at intersection i and time step t
- $Q_{i,t}^{n}$: the corresponding detected (actual) queue length
- q_{i}^{n}: the maximum physical storage capacity

Rule 1: Instantaneous Threshold Violation

$\exists t \in W: \epsilon_{i,t}^{n} > \theta_1$ → flag (prediction window: W)

Rule 2: Temporal Violation Count

More than k time steps with $\epsilon_{i,t}^{n} > \theta_2$ →flag

$$\sum_{t \in W} \mathbf{1}(\epsilon_{i,t}^{n} > \theta_2) > k$$

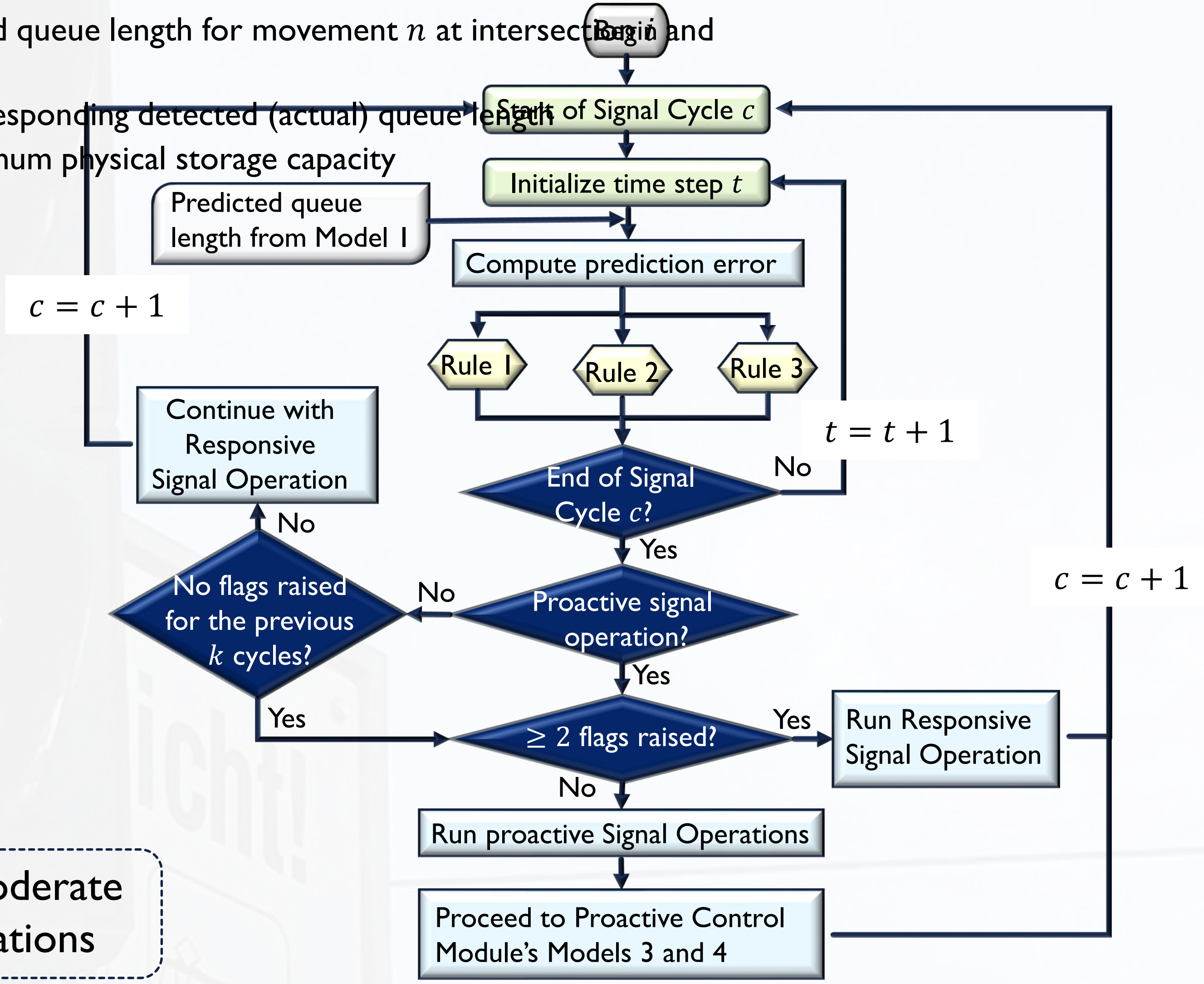
Rule 3: Consecutive Error Violation

Two or more steps with $\epsilon_{i,t}^{n} > \theta_3$ →flag

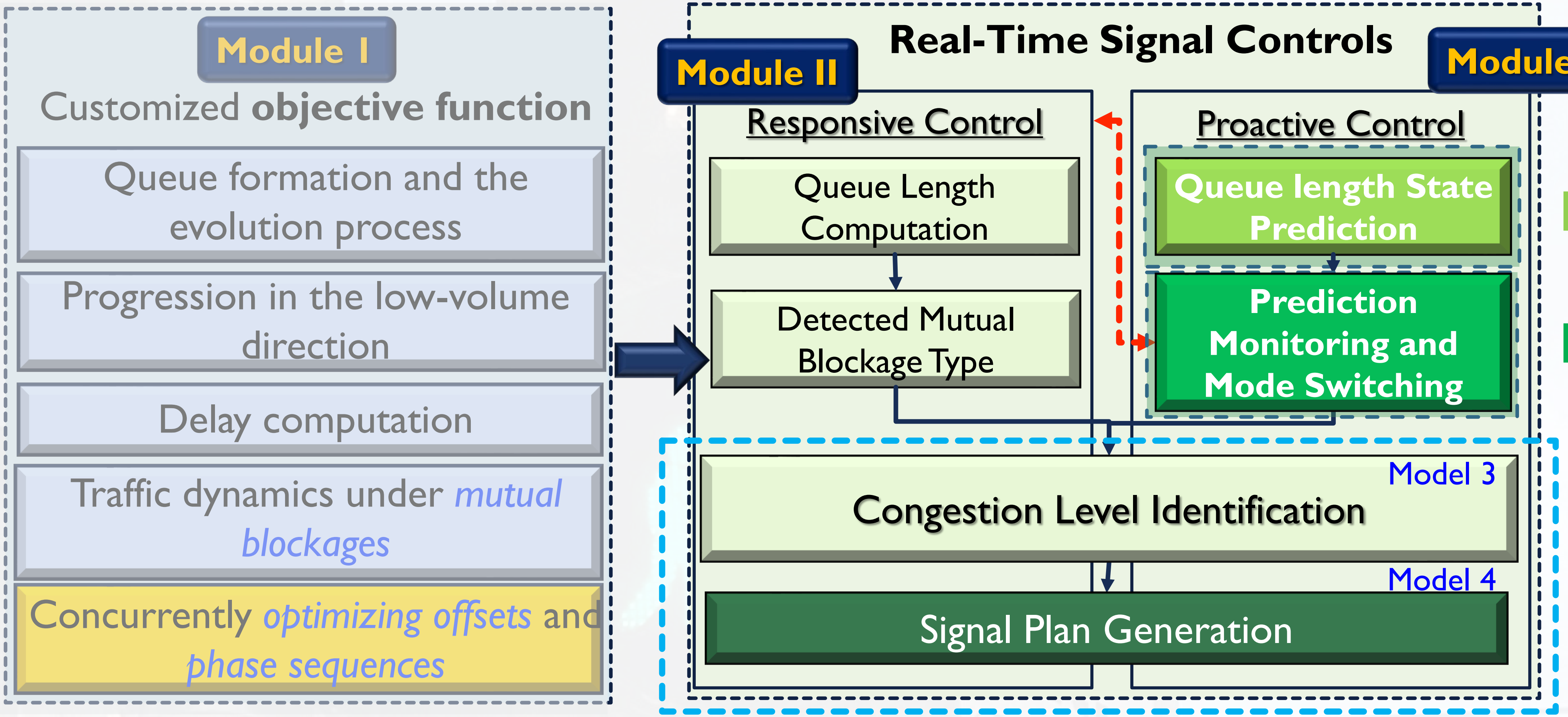
$$\exists t \in W: \epsilon_{i,t}^{n} > \theta_3 \text{ and } \epsilon_{i,t+1}^{n} > \theta_3$$

$\theta_1 > \theta_2 > \theta_3$ → distinguish between sharp outliers, moderate error frequencies, and persistent deviations

Switching Logic



Coordinate Signal Control System



Model 1

Model 2

Structurally Consistent

Module II: detected blockage types

vs.

Module III: predicted blockage types

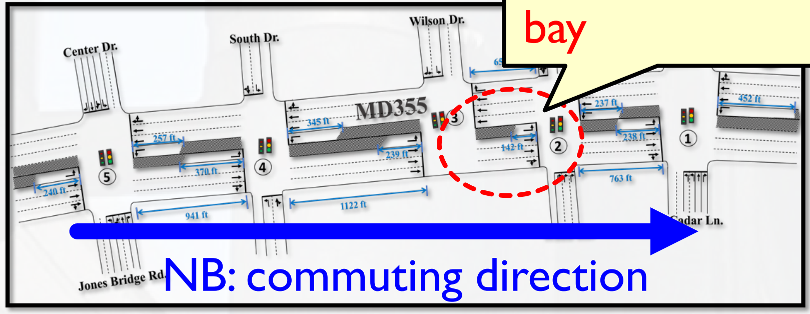
Effectiveness in Preventing Mutual Blockages

using the same site (MD 355 in Bethesda)

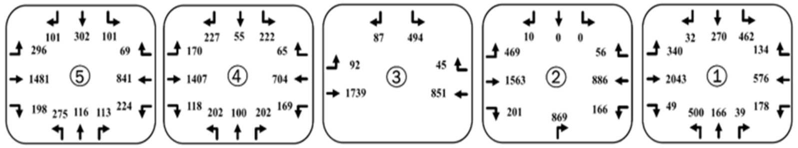
evening peak hour

a **2.55% increase** was applied to each of the four 15-minute field volumes to simulate … congestion conditio…

shortest link, shortest turning bay



Hourly Volume
(Maryland SHA Internet Traffic Monitoring System (ITMS))



- Assess the benefits of preemptively mitigating mutual queue blockages
- Compare their … *proactive (Module III)* and responsive *(Module II)* control strategies across 24 signal cycles

The proactive control module, guided by prediction, significantly reduces both the frequency and severity of mutual queue blockages—especially in locations with geometric constraints

✓ Better Handling of Complex Blockages
- Responsive: Type 3 blockage
- Proactive: Downgraded to Type 2

→ Proactive strategy mitigates cascading disruptions

Blockage Type Observations under Responsive vs. Proactive Control Strategies

Cycle	Intersection 1		Intersection 2		Intersection 3		Intersection 4	
	Responsive M…	Proactive M…	Responsive M…	Proactive M…	Responsive M…	Proactive M…ule III	Responsive Module II	Proactive Module III
1-12							-	-
13							-	-
14							-	-
15							-	-
16							-	-
17							-	-
18							S_1	-
19	S		S	S	S		S_3	S_2
20								-
21							-	-
22							-	-
23							S_1	-
24							-	-

Note: S_i denotes the observed Blockage type-i; the cell without any letter represents no mutual blockage observed

Type 3 blockage:
Two blockages per cycle, where the through queue first blocked left-turn vehicles, and then incoming through vehicles in turn are impeded by those blocked left-turn queues

Type 2 blockage:
One blockage per cycle, where the left-turn queue blocked through vehicles

Case Study:
Overall performance evaluation

Module I vs. Module II vs. Module III

Case Study - Effectiveness in Preventing Mutual Blockages

- Overall Performance Evaluation: key operational metrics

* indicates the significance level of at least 0.05

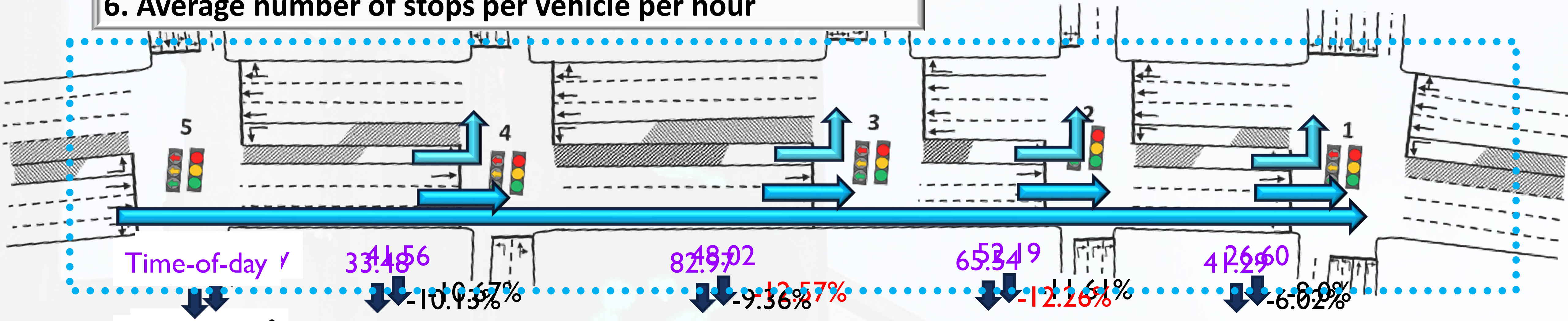
Simulation results for performance comparison						
Direction		Proactive Module III	Responsive Module II	Time-of-Day Module I	% change (Module II vs. Module III)	% change (Module I vs. Module II)
Average delay of through vehicles along the arterial per vehicle per hour (sec)						
Northbound	⑤→①	204.12	217.01	234.32	-5.94%*	-7.39%*
Southbound	①→⑤	141.43	141.46	161.65	-0.02%	-0.13%
Average number of stops of through vehicles along the arterial per vehicle per hour						
Northbound	⑤→①	5.89	6.22	6.61	-5.31%*	-5.87%*
Southbound	①→⑤	1.99	1.98	2	0.51%	-0.90%
Average delay of through vehicles from all upstream streams on individual links per vehicle per hour (sec)						
Northbound	②→①	22.09	24.19	26.60	-8.68%*	-9.05%*
	③→②	40.16	46.13	52.19	-12.94%*	-11.61%*
	④→③	37.72	41.98	48.02	-10.15%*	-12.57%*
	⑤→④	34.26	37.12	41.56	-7.70%*	-10.67%*
Average delay of left-turn vehicles from all upstream streams on individual links per vehicle per hour (sec)						
Northbound	②→①	36.09	38.80	41.29	-6.98%*	-6.02%*
	③→②	50.14	56.62	64.54	-11.44%*	-12.26%*
	④→③	67.97	75.20	82.97	-9.61%*	-9.36%*
	⑤→④	26.84	30.09	33.48	-10.80%*	-10.13%
Average delay per vehicle per hour (sec)						
Network		116.87	124.00	131.16	-5.75%*	-5.46%*
Average number of stops per vehicle per hour						
Network		2.94	3.09	3.19	-4.85%*	-3.38%*

Case Study - Effectiveness in Preventing Mutual Blockages

- Overall Performance Evaluation: key operational metrics

5. Average delay per vehicle per hour (sec)
6. Average number of stops per vehicle per hour

NB: commuting direction



Network-Wide Improvements

Northbound Delay Reduction

Improved Progression Quality (Stops)

Link-Level Delay Improvements

Through Delay Reductions on All Links (Northbound)

… significantly reduce commuting delays without … **mutual blockages**.

→ Strongest gains at Intersection 3 → 2, where the **turning bay is shortest** and most vulnerable.

→ Most improvement at **critical intersection**.

→ Gradual control upgrades yield **stepwise improvements** across the entire network.

Research Summary & Future Research

Research Summary

Goal: mutual queue blockages, asymmetric flows, and short turning bays

Module I: Time-of-Day Control Module

- Pre-timed coordination;
- Identify & classify mutual blockage types;
- Optimizes offsets/phase sequences.

Module II: Responsive Real-Time Control Module

- Detect blockage patterns in real time;
- IF-THEN rules assess congestion levels;
- Dynamically applies adjustments.

monitoring function

Module III: Proactive Real-Time Control Module

- Multi-branch, multi-head LSTM model to predict queue states;
- Enable preemptive control actions;
- A rule-based monitoring function.

Outcome: reducing delays, mitigating spillbacks, and improving progression

Future Research

System Enhancement

- Real-time Cycle Length Optimization:
Move from rule-based to optimization-based (e.g., MILP, RL, GA) for adaptive cycle length & green split tuning.

- Multimodal Integration:
Extend to transit flows; model bus-traffic interactions & mitigate right-lane blockages

- Non-Recurrent Event Response:
Add anomaly detection & adaptive logic for incidents/disruptions.

- CAV Integrations:
Use V2I data, such as precise queue positions and acceleration profiles, to enhance the granularity of control

Advanced Traffic Management System (ATMS) Application

- Queue Warning Systems:
The system's real-time queue predictions can power Dynamic Message Signs to warn drivers of upcoming congestion, providing queue length, severity, and clearance time to improve safety and reduce rear-end collision risks.

- Conditional Transit Signal Priority:
The system can enable condition-based Transit Signal Priority by using real-time bus data and congestion predictions to grant priority only when it improves transit reliability without causing major traffic disruptions, supporting balanced multimodal operations.

Thank You