Department of Civil & Environmental Engineering
University of Maryland

Integrating of Arterial Signal and Freeway Off-ramp Controls for Commuting Corridors

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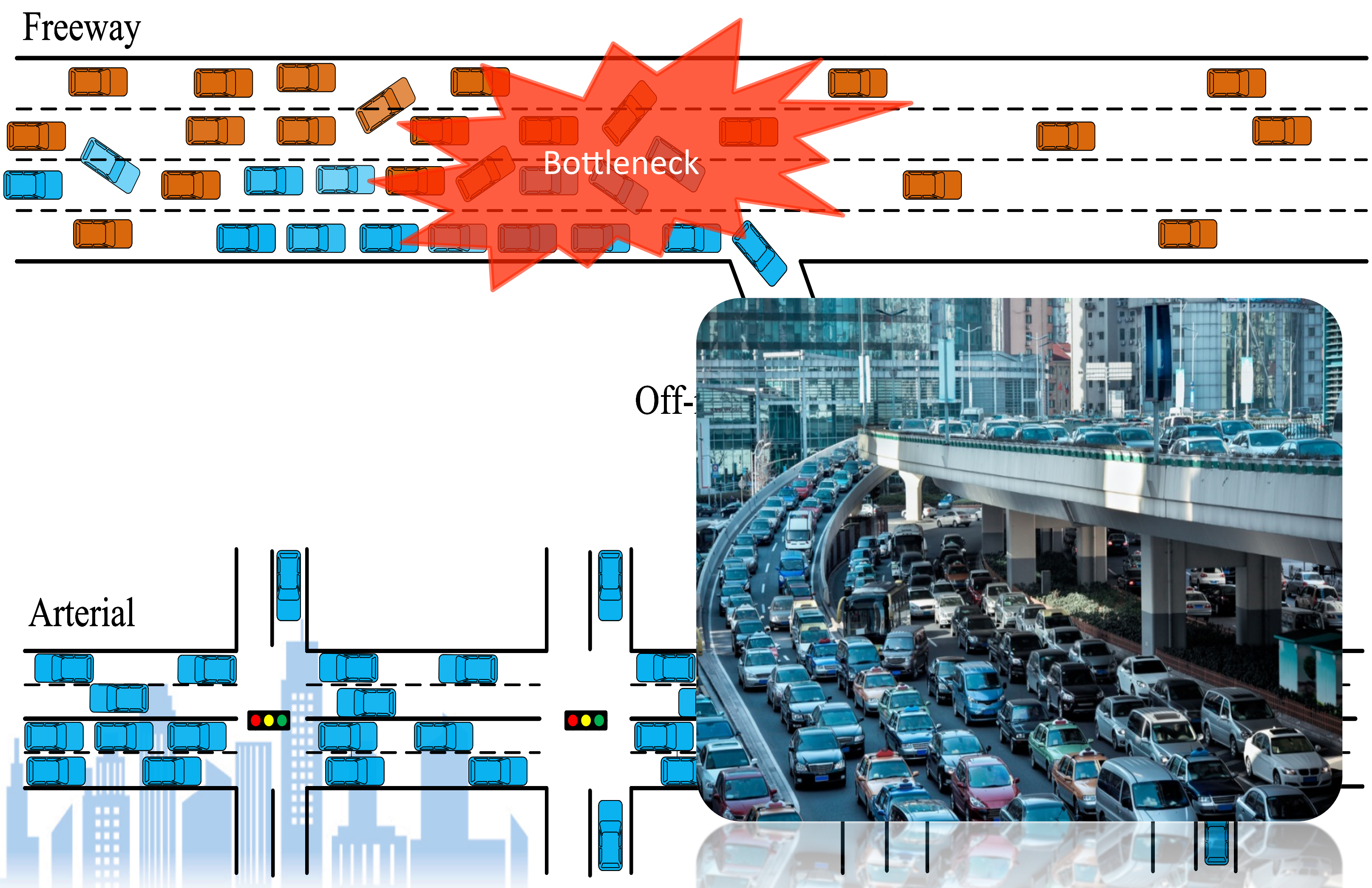
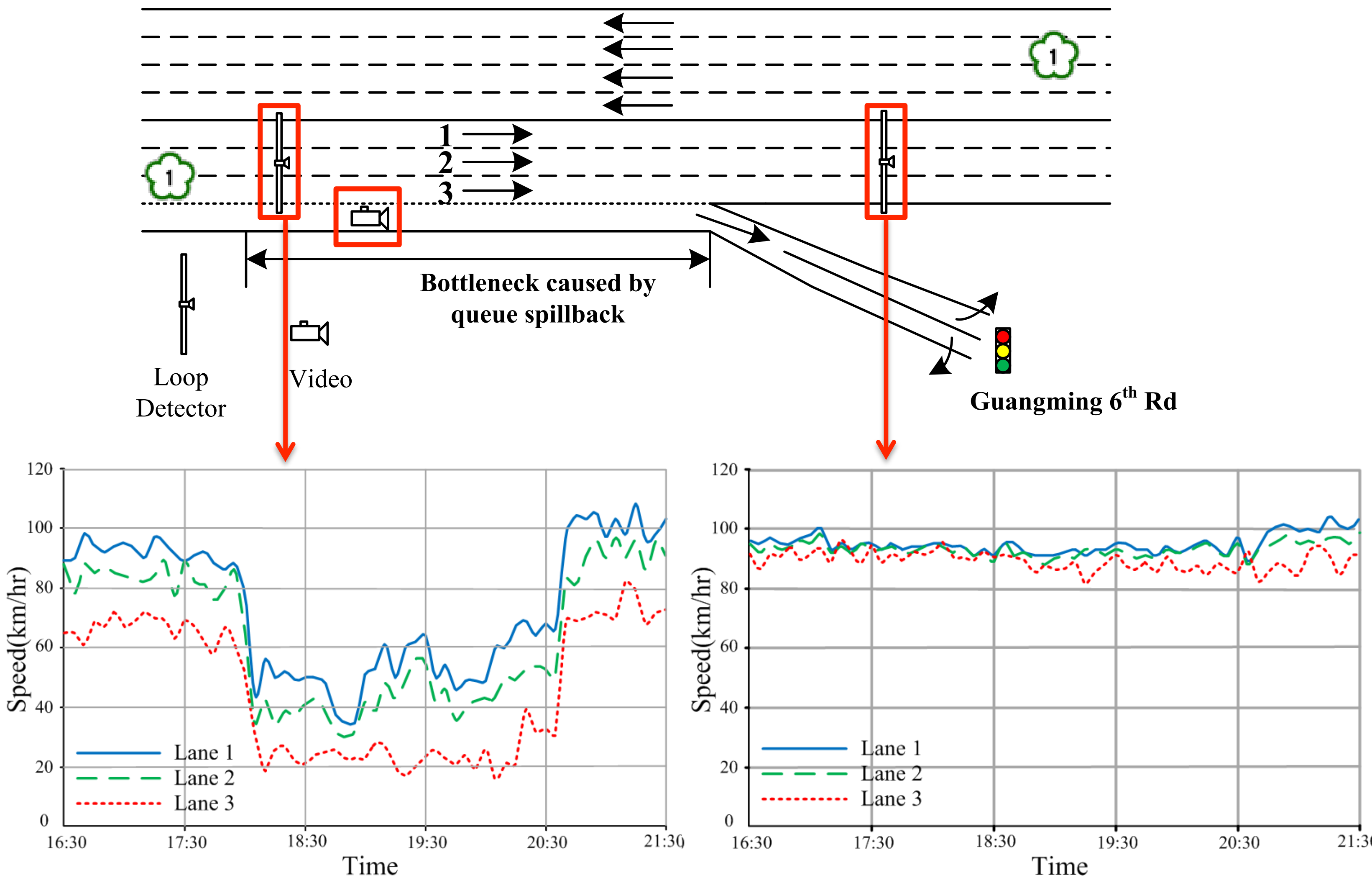
Outline

1. Research Background & Literature Review
2. Primary Tasks & System Framework
3. Model Formulations
4. Conclusions and Future Research Directions

Congestion at Off-ramp Interchanged Area



Field Observations
(National Highway No. 1, Chupei, Taiwan)



(A) Speed obtained by upstream detectors

(B) Speed obtained by downstream detectors

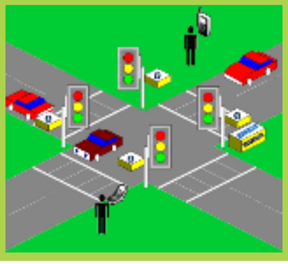
Integrated Off-Ramp Controls

Freeway

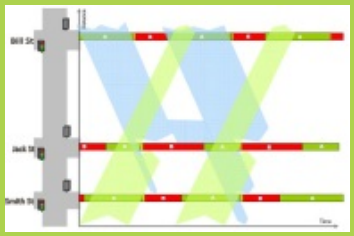
Arterial

Off-Ramp Interchange

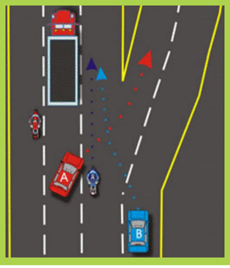
Intersection Signal Control



Signal Coordination Control



Off- Ramp Queue Spillover Prevention



Integrated Off-ramp Traffic Control

Literature Reviews

Existing Studies

- Pre-timed Signal Optimization Models
- Real-time Signal Control Models
- Integrated Control Models

Literature Reviews

Pre-timed Signal Optimization Models

↓

Signal optimization at isolated intersections

Delay Minimization Model	Mathematical Programming Model
Matson et al. (1955), Webster (1958), Miller (1963), Robertson, (1969), Allsop (1971, 1972, 1975, 1981), Tully (1976) and Burrow (1987), Chang and Lin (2000)	Silcock, (1997,) Wong et al., (2003), Lan (2004), Yang et al., (2014)

Literature Reviews

Pre-timed Signal Optimization Models

Signal optimization at arterial level

Minimizing Total Traffic Delay	Maximizing Progression Efficiency
TRANSYT (Robertson, 1969); ***TRANSYT 7-F*** (Wallace et al., 1988); ***Simulation-based*** (Yun and Park ,2006, Stevanovic et al., 2007); ***CTM-based*** (Lo, 1999; Lo et al., 2001; and Lo and Chow 2004); *Others* (Aboudolas et al., 2010; Zhang and Yin 2010, Li, 2012, Liu and Chang, 2011)	Morgan and Litter (1964), Litter (1966), Little et al., (1981), Gartner et al. (1991), Chaudhary et al. (2002), Tian and Urbanik (2007), Li (2014)

Literature Reviews

Real-time Signal Control Models

Actuated Signal Control	Adaptive Signal Control
System Introduction (Boillot et al. 1992; ITE, 1997) ***Min green time selection*** (Kell and Fullerton, 1998) ***Max green time selection*** (Lin, 1985; Courage et al., 1989; Orcutt , 1993; Kell and Fullerton, 1998; Courage , 2003; Zhang and Wang, 2011)	**SCOOT** (Hunt et al. 1982; Ian et al., 1998; Dennis et al., 1991; Bretherton et al., 2005) **SCATS** (Luke, 1984, Gross, 2000, Gao, 2011) **OPAC** (Gartner et al., 1979; Gartner, 1983; Gartner et al., 1995; Gartner et al., 2001) **RHODES** (Mirchandani et al., 1995, 2000, 2001, 2004)

Literature Reviews

Integrated Control Models

Integrated Corridor Control	Off-ramp Control
Integration of multiple strategies such as: ▪ ***traffic diversion*** ▪ ***on-ramp metering*** ▪ ***speed limit control*** ▪ ***signal timing controls*** (Cremer and Schoof , 1989; Zhang and Hobeika, 1997; Wu and Chang, 1999; Chang et al., 1993; Papageorgiou, 1995; Berg et al., 2001; Li, 2010; Haddad et al. , 2013)	***Eliminating the lane changing maneuvers*** (Daganzo et al., 2002; Rudjanakanoknad, 2012; Di et al., 2013) ***Detouring the flows to other non-congested areas*** (Gunther et al., 2012; Spiliopoulou et al., 2013, 2014) ***Optimizing signal timing at neighboring intersections*** (Messer, 1998; Tian et al., 2002; Li et al., 2009; Lim et al., 2011; Yang et al., 2014)

Findings of Literature

❑ *Signal controls at arterial level (pre-timed & real-time)*:
may fall short of providing efficiency control at the off-ramp interchanged area;

❑ *Integrated corridor control*:
may not be able to find the optimal solution for system control variables;

❑ *Off-ramp control with restricting lane changing or detouring flows*:
may not be applicable in practice;

❑ *Off-ramp control with signal optimization at neighboring intersections*:
more practical but many critical issues remain to be solved!

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- Primary Tasks & System Framework

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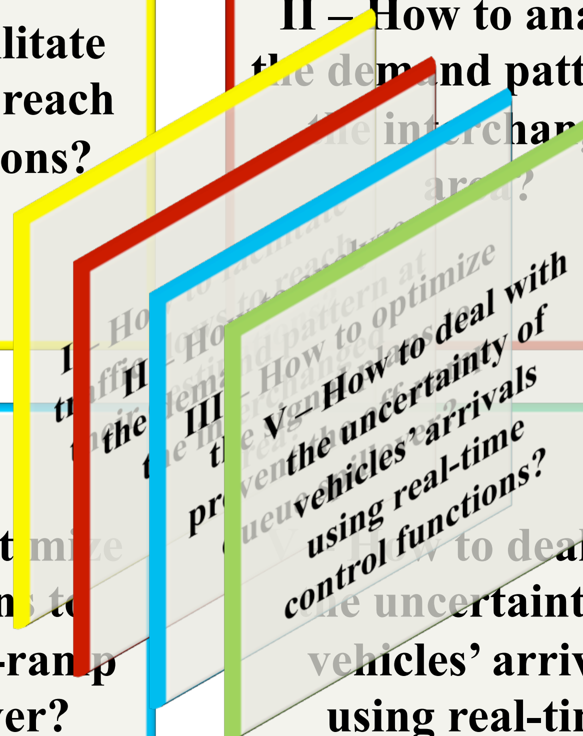
- Model Formulations

3
- Conclusions and Future Research Directions

Critical Research Issues

I – How to facilitate traffic flows to reach their destinations?

II – How to analyze the demand pattern at the interchanged area?



III – How to optimize the signal plans to prevent the off-ramp queue spillover?

V – How to deal with the uncertainty of vehicles' arrivals using real-time control functions?

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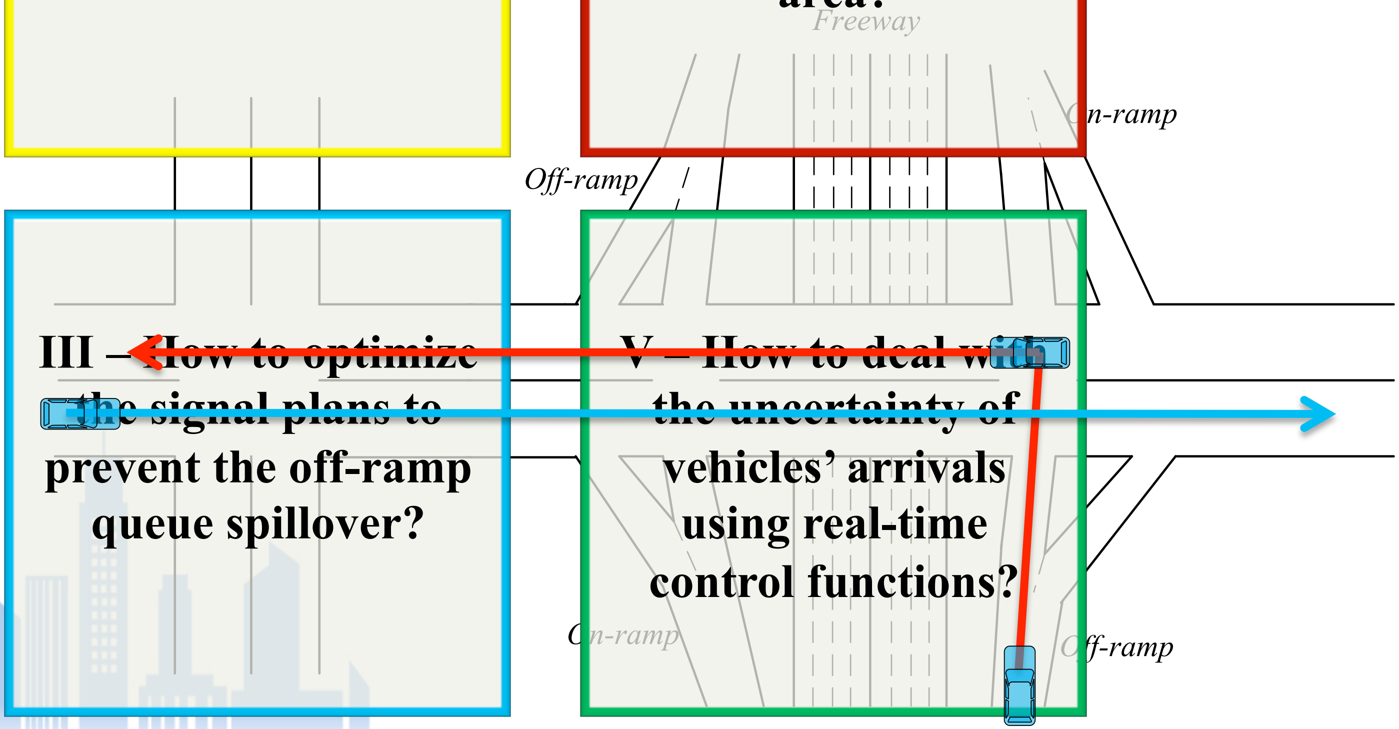

Critical Research Issues

I – How to facilitate traffic flows to reach their destinations?

II – I… the demand pattern a… the interchanged area?

Identify traffic flows' origins and destinations

O-D Estimation Model

Identify Critical Path

III – How to optimize the signal plans to prevent the off-ramp queue spillover?

V – H… the uncertainty of vehicles' arrivals using real-time control functions?

Critical Research Issues

I – How to facilitate traffic flows to reach their destinations?

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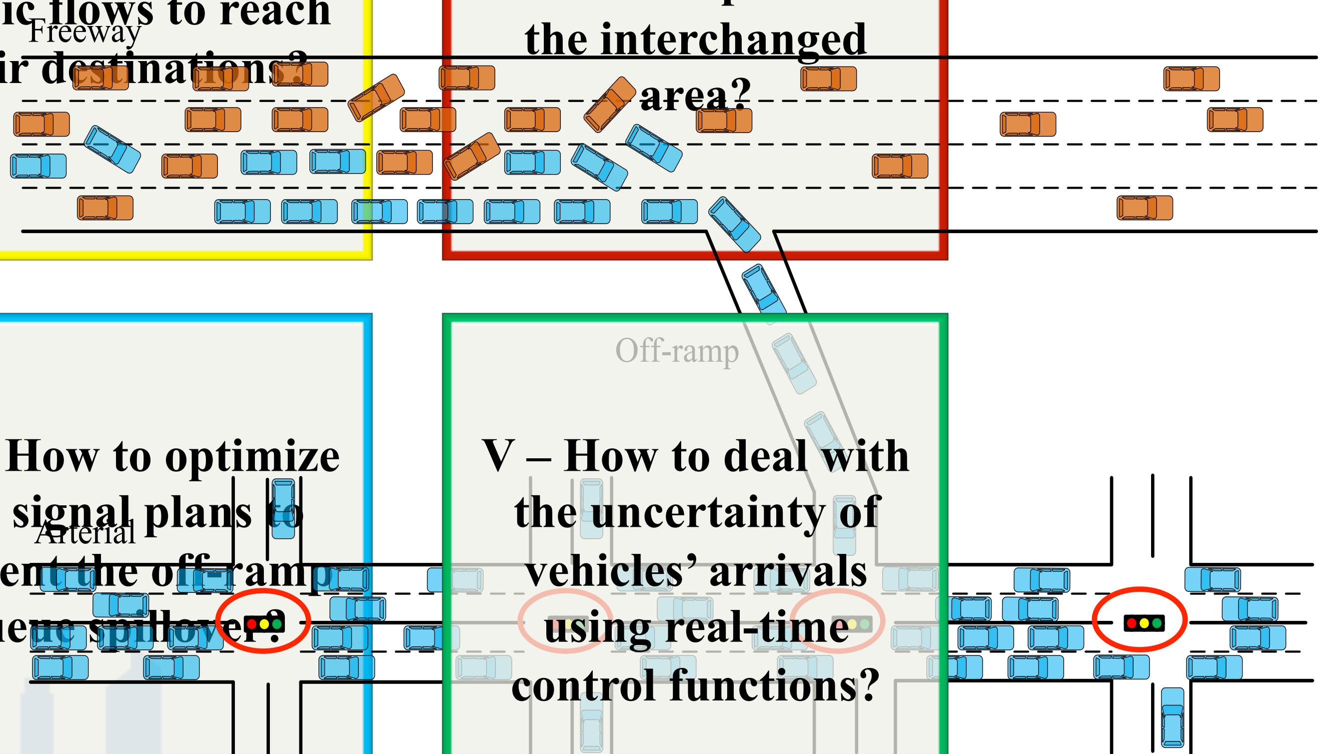

Critical Research Issues

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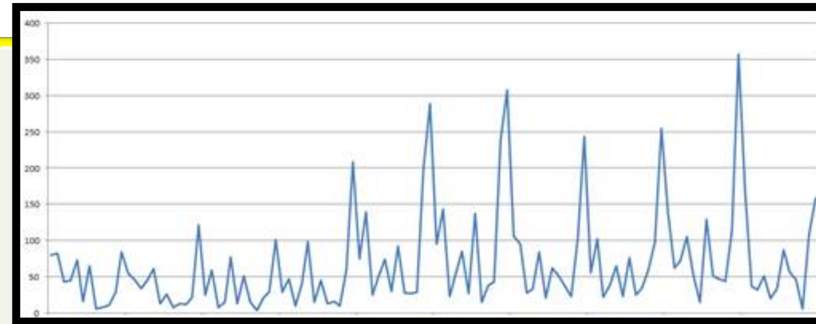
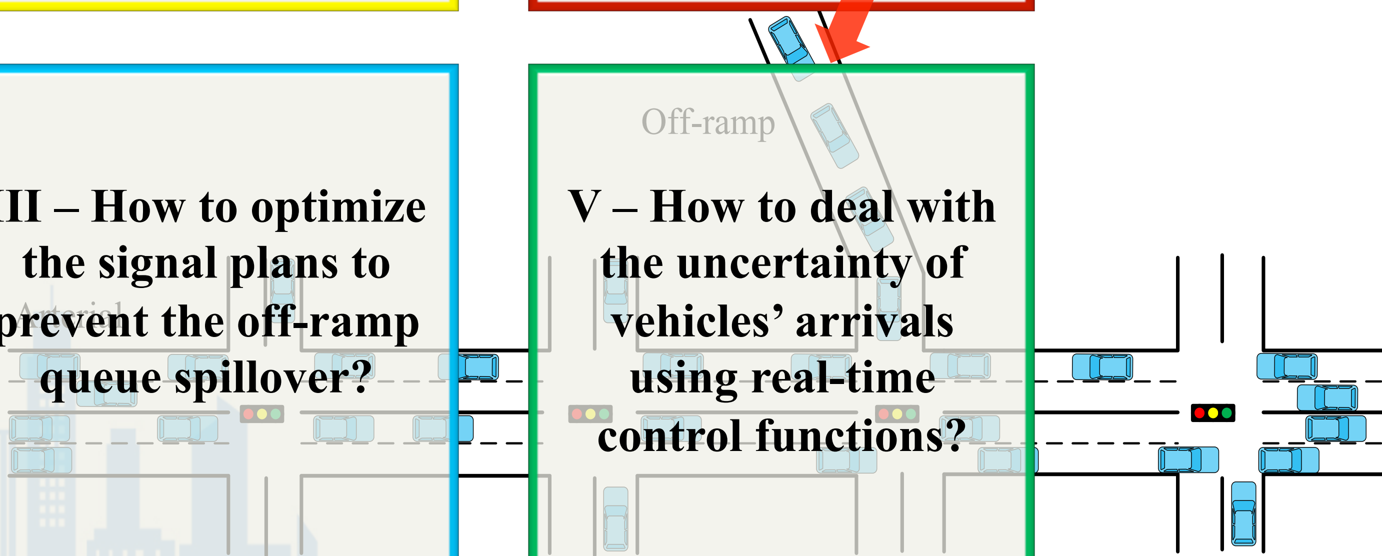


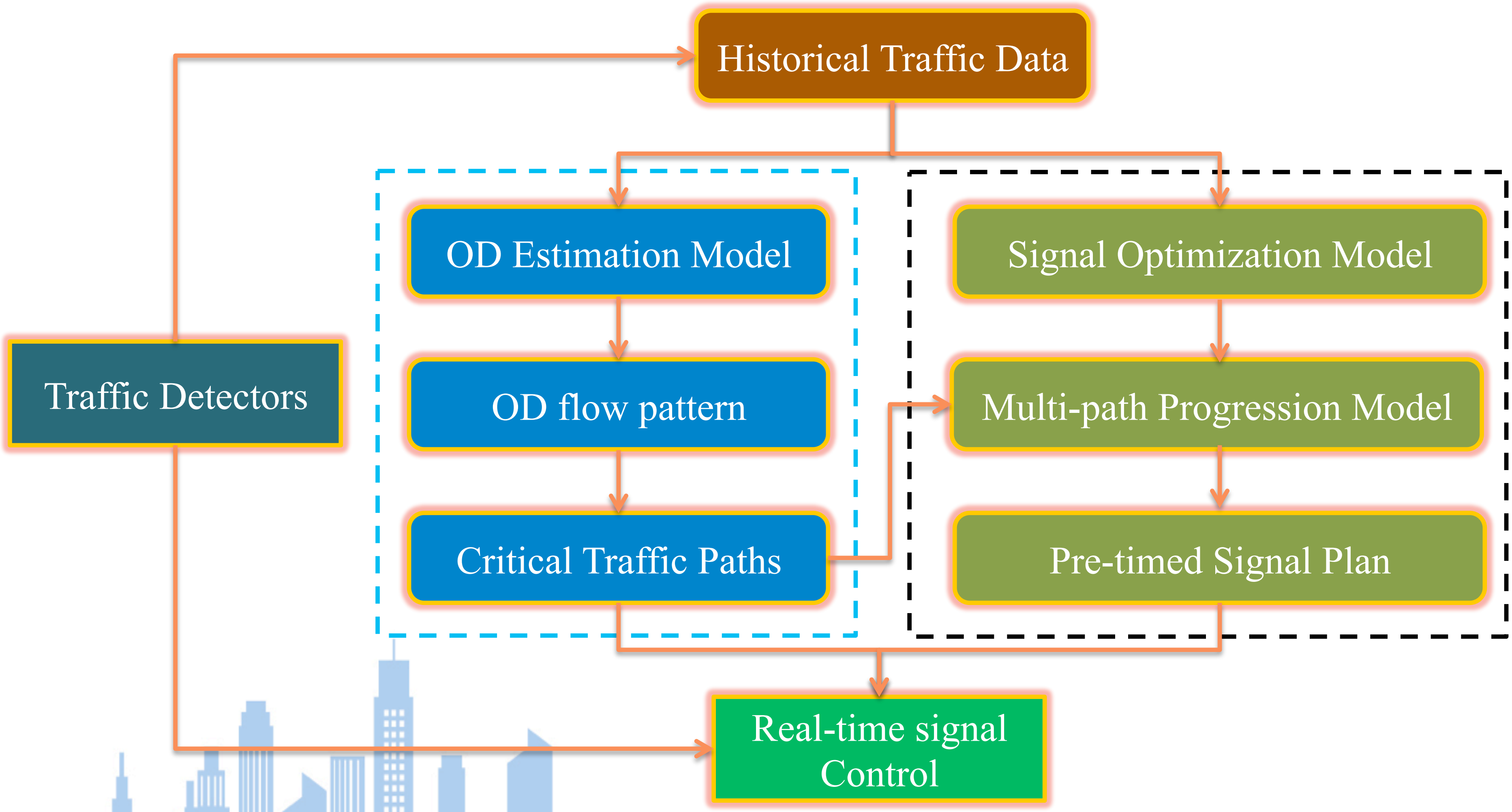
area?



III – How to optimize the signal plans to prevent the off-ramp queue spillover?

V – How to deal with the uncertainty of vehicles' arrivals using real-time control functions?

System Framework



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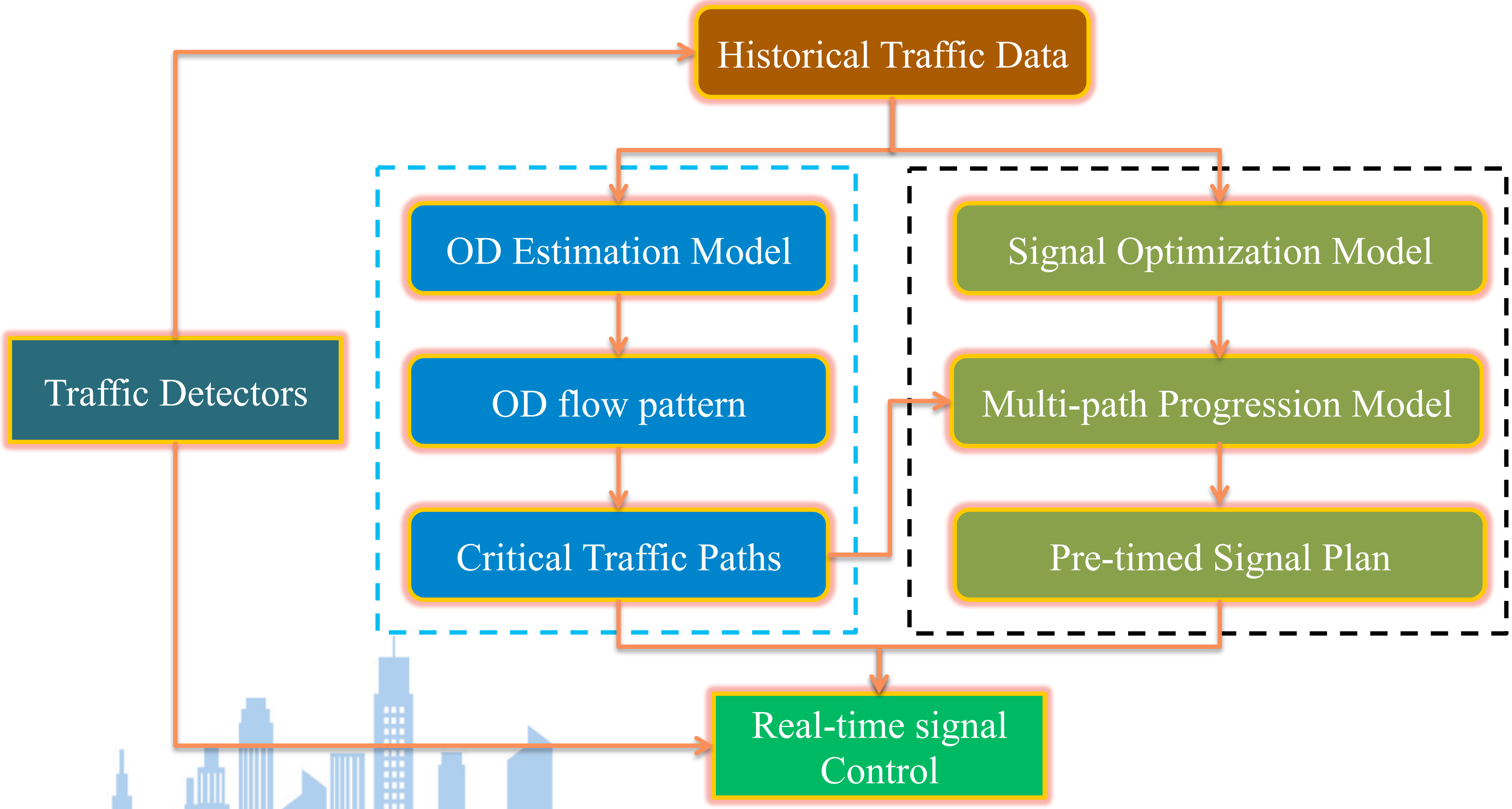
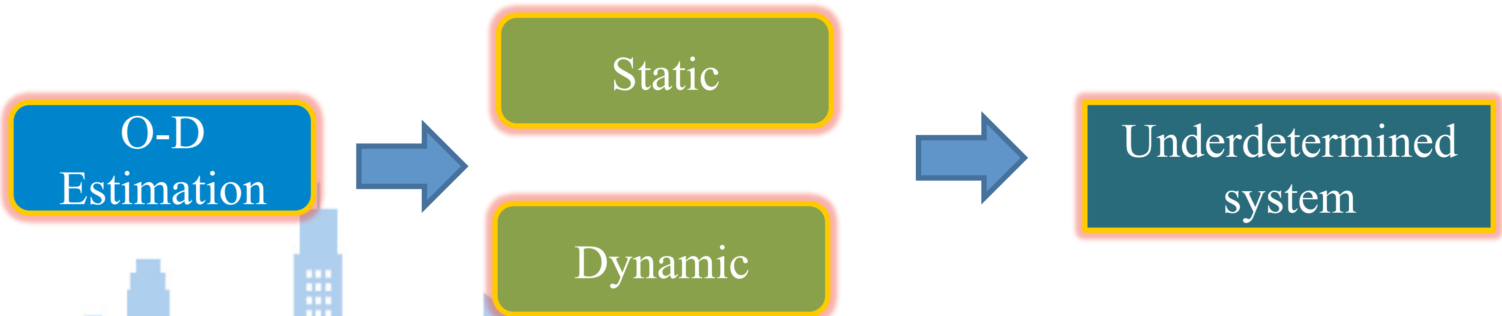
Model Development



Origin-Destination Estimation

- In the literature, the main purpose of most O-D estimation models is providing essential information for **traffic assignment** or **network simulation**.

- However, designing of signal plan at the off-ramp interchanged area have also raised the need of using O-D estimation for identifying **critical traffic paths**.



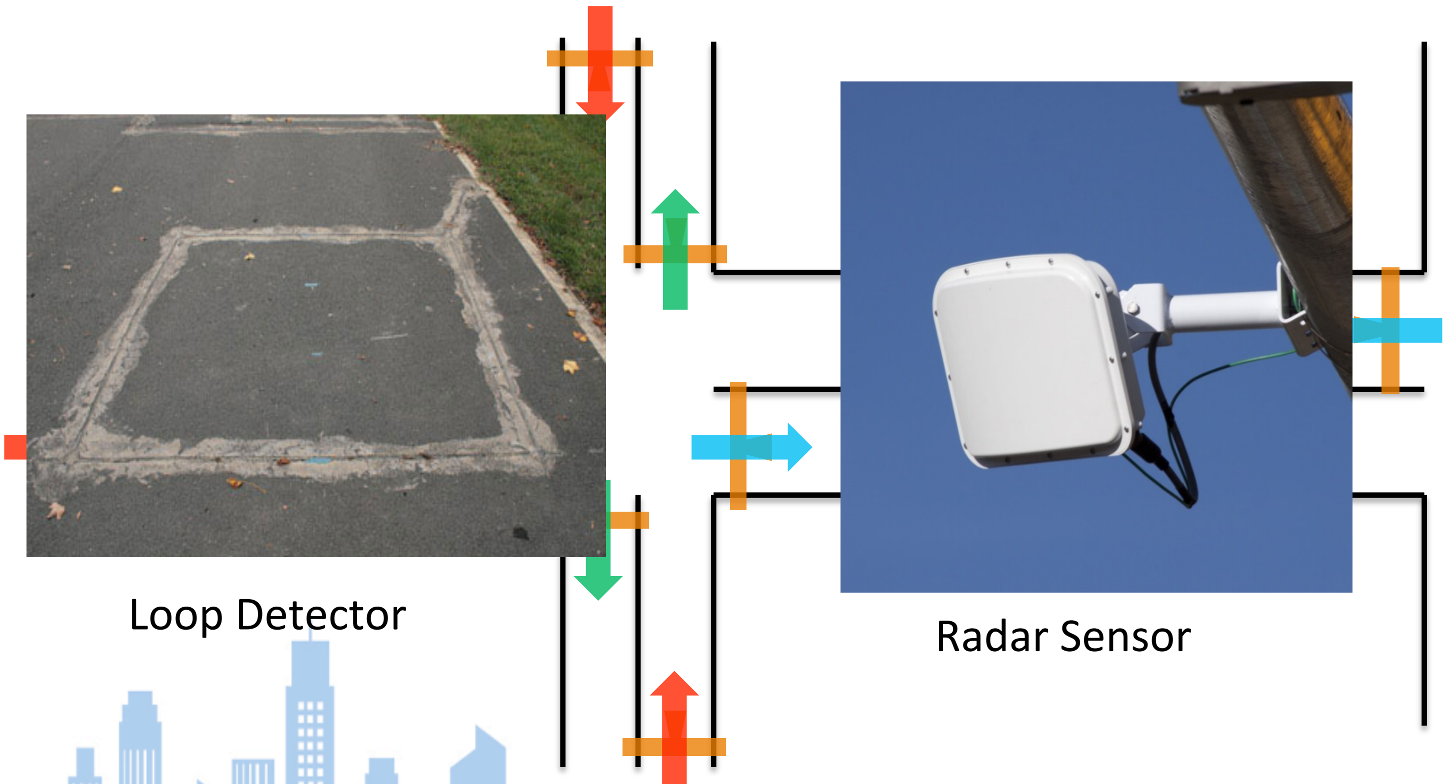
Origin-Destination Estimation

Based on the dynamic O-D estimation technique, this study proposed three models with different measurement inputs:

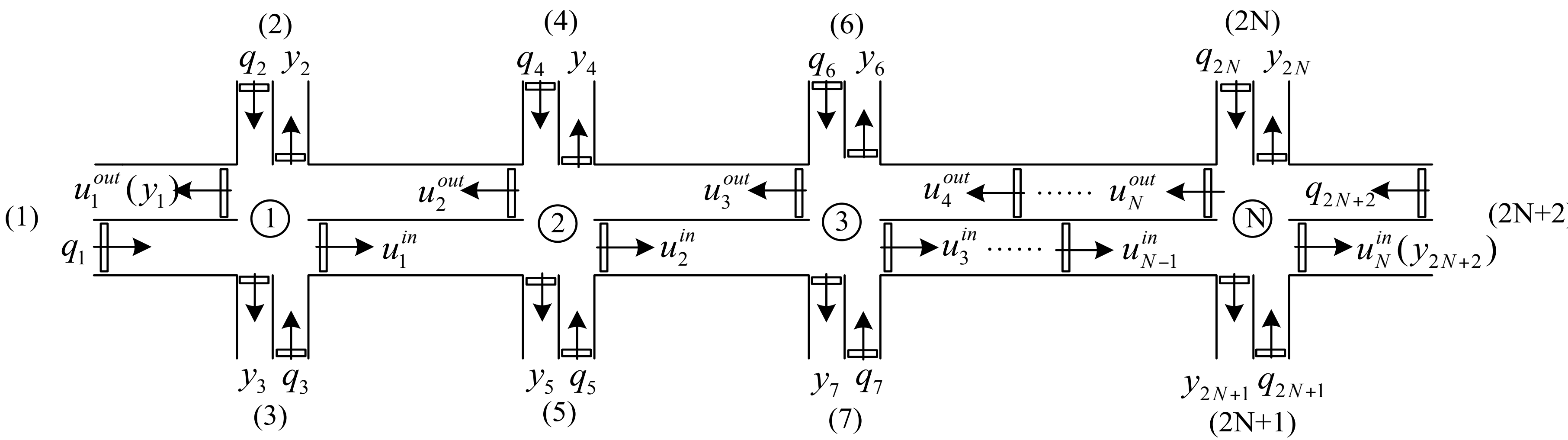
- ❑Model I: only the **link count** data are available;
- ❑Model II: **turning volumes** at each intersection are available;
- ❑Model III: both intersection **turning flows** and **real-time queue information** are obtainable for model estimation.

O-D Estimation: Model I

Only the **link count** data are available



O-D Estimation: Model I



(i): Node i (i): Intersection i ‖: Detector

Flow conservations and diversions

$$y_j(k) = \sum_{i=1}^{2N+2} \left[q_i(k-\tau_{ij}^{k+})\rho_{ij}^{+}(k-\tau_{ij}^{k+})b_{ij}(k-\tau_{ij}^{k+}) + q_i(k-\tau_{ij}^{k-})\rho_{ij}^{-}(k-\tau_{ij}^{k-})b_{ij}(k-\tau_{ij}^{k-}) \right]$$

$$\rho_{ij}^{+}(k) + \rho_{ij}^{-}(k) = 1$$

$$u_l^{in}(k) = \sum_{i=1}^{2l+1} \sum_{j=2l+2}^{2N+2} \left[q_i(k-\tau_{il}^{k+})\theta_{il}^{+}(k-\tau_{il}^{k+})b_{ij}(k-\tau_{il}^{k+}) + q_i(k-\tau_{il}^{k-})\theta_{il}^{-}(k-\tau_{il}^{k-})b_{ij}(k-\tau_{il}^{k-}) \right]$$

$$u_l^{out}(k) = \sum_{i=2l}^{2N+2} \sum_{j=0}^{2l-1} \left[q_i(k-\tau_{il}^{k-})\theta_{il}^{-}(k-\tau_{il}^{k-})b_{ij}(k-\tau_{il}^{k-}) + q_i(k-\tau_{il}^{k-})\theta_{il}^{-}(k-\tau_{il}^{k-})b_{ij}(k-\tau_{il}^{k-}) \right]$$

$$\sum_{m=0}^{M} \theta_{ij}^{m}(k$$

$$\theta_{il}^{+}(k) + \theta_{il}^{-}(k) = 1$$

Estimation Algorithm

The dynamic O-D variables are assumed to follow the random walk process between successive time intervals:

$$b_{ij}(k+1) = b_{ij}(k) + w_{ij}^{b}(k), \quad 1 \le i, j \le 2N+2$$

$$\rho_{ij}^{-}(k+1) = \rho_{ij}^{-}(k) + w_{ij}^{\rho}(k), \quad 1 \le i, j \le 2N+2$$

$$\theta_{il}^{-}(k+1) = \theta_{il}^{-}(k) + w_{il}^{\theta}(k), \quad 1 \le i \le 2N+2; 1 \le l \le N$$

Estimation Algorithm

Initialization

Compute the mean link travel time

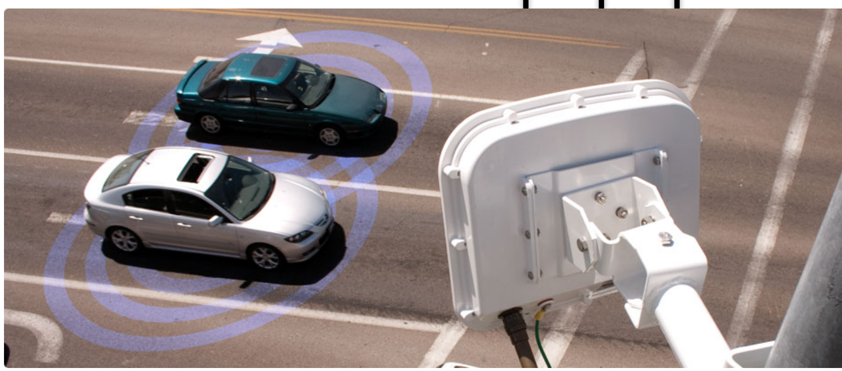
Compute the linearized transformation matrix H(k)

Update the estimation with extended Kalman filter

- $\mathbf{X}^{-}(k) = \mathbf{X}(k-1);\ \ \mathbf{P}^{-}(k) = \mathbf{P}(k-1) + \mathbf{Q}$
- $\mathbf{K}(k) = \mathbf{P}^{-}(k)\mathbf{H}^{T}(k)(\mathbf{H}(k)\mathbf{P}^{-}(k)\mathbf{H}^{T}(k) + \mathbf{R})^{-1}$
- $\mathbf{X}(k) = \mathbf{X}^{-}(k) + \mathbf{K}(k)\left[\mathbf{z}(k) - h(\mathbf{X}^{-}(k))\right]$
- $\mathbf{P}(k) = \left[\mathbf{I} - \mathbf{K}(k)\mathbf{H}(k)\right]\mathbf{P}^{-}(k)$

O-D Estimation: Model II

Turning volumes at each intersection are available

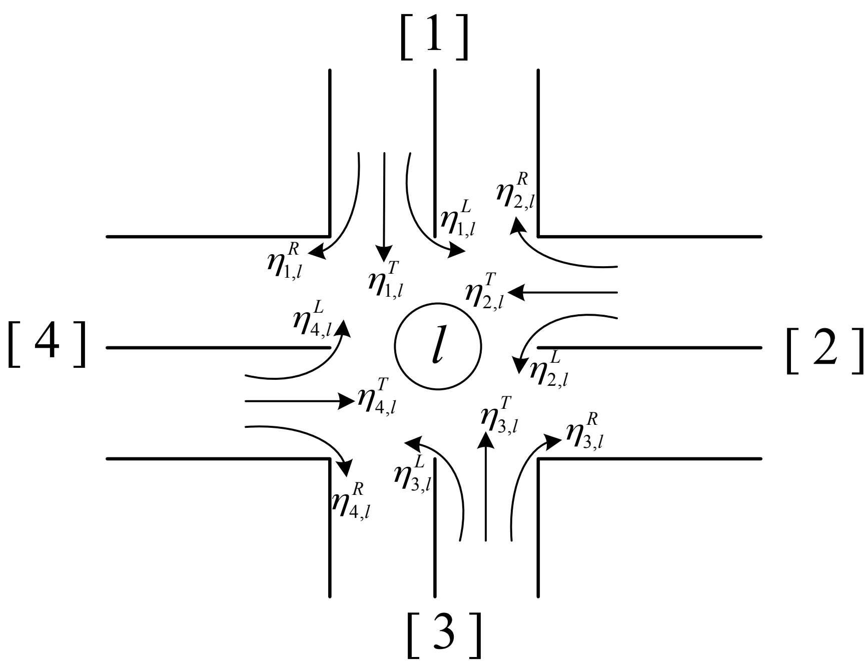


Lane-based Radar Sensor

To / From	1	2	3	4	5	6
1	7	7	0	0	0	0
2	6	29	1	0	0	0
3	0	10	2	4	0	0
4	6	0	7	22	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0

Fisheye camera

O-D Estimation: Model II



Turning flows at intersection l

Flow conservations and diversions

For approach 2 and 4:

$$\eta^L_{2l}(k)=\sum_{i=2l+2}^{2N+2}\sum_{m=\tau_{ij}^-}^{\tau_{ij}^-+1} q_i(k-m)\theta^m_{i,l}(k-m)b_{i,2l+1}(k-m)$$

$$\eta^T_{2l}(k)=\sum_{i=2l+2}^{2N+2}\sum_{m=\tau_{ij}^-}^{\tau_{ij}^-+1}\sum_{j=1}^{2l-1} q_i(k-m)\theta^m_{i,l}(k-m)b_{ij}(k-m)$$

$$\eta^R_{2l}(k)=\sum_{i=2l+2}^{2N+2}\sum_{m=\tau_{ij}^-}^{\tau_{ij}^-+1} q_i(k-m)\theta^m_{i,l}(k-m)b_{i,2l}(k-m)$$

$$\eta^L_{4l}(k)=\sum_{i=1}^{2l-1}\sum_{m=\tau_{il}^-}^{\tau_{il}^-+1} q_i(k-m)\theta^m_{i,l}(k-m)b_{i,2l}(k-m)$$

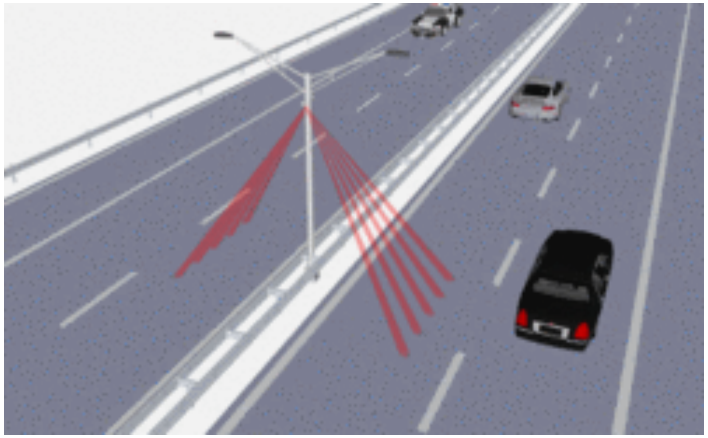
$$\eta^T_{4l}(k)=\sum_{i=1}^{2l-1}\sum_{m=\tau_{ij}^-}^{\tau_{ij}^-+1}\sum_{j=2l+2}^{2N+2} q_i(k-m)\theta^m_{i,l}(k-m)b_{ij}(k-m)$$

$$\eta^R_{4l}(k)=\sum_{i=1}^{2l-1}\sum_{m=\tau_{il}^-}^{\tau_{il}^-+1} q_i(k-m)\theta^m_{i,l}(k-m)b_{i,2l+1}(k-m)$$

O-D Estimation: Model III

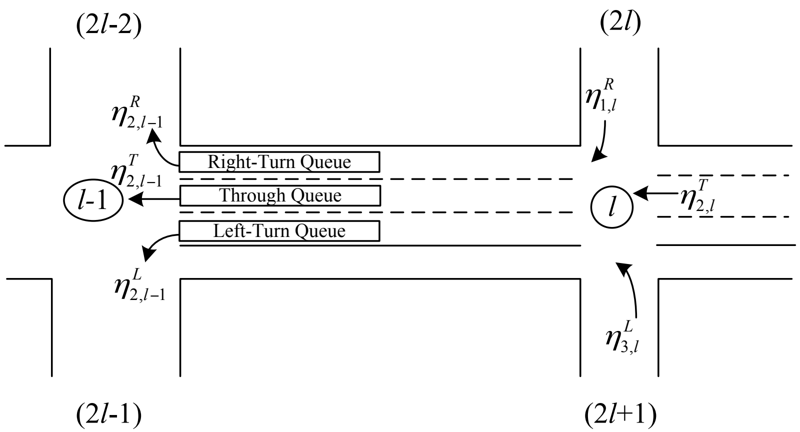
Both intersection **turning flows** and **real-time queue information** are obtainable for model estimation

Camera Sensors



Radar Sensors

O-D Estimation: Model III



Queue Length Estimation

$$\delta^T_{l,l-1}(k) = \sigma^T_{l,l-1}(k) + \varphi_T(\eta^R_{1,l}\xi^T_{1,l}r^T_{1,l} + \eta^T_{2,l}\xi^T_{2,l}r^T_{2,l} + \eta^L_{3,l}\xi^T_{3,l}r^T_{3,l})$$

$$\delta^L_{l,l-1}(k) = \sigma^L_{l,l-1}(k) + \varphi_L(\eta^R_{1,l}\xi^L_{1,l}r^L_{1,l} + \eta^T_{2,l}\xi^L_{2,l}r^L_{2,l} + \eta^L_{3,l}\xi^L_{3,l}r^L_{3,l})$$

$$\delta^R_{l,l-1}(k) = \sigma^R_{l,l-1}(k) + \varphi_R(\eta^R_{1,l}\xi^R_{1,l}r^R_{1,l} + \eta^T_{2,l}\xi^R_{2,l}r^R_{2,l} + \eta^L_{3,l}\xi^R_{3,l}r^R_{3,l})$$

$\delta^i_{l,l-1}(k)$ is the queue length at the end of red phase on lane group i;

$\sigma^i_{l,l-1}(k)$ is the queue length at the start of red phase on lane group i;

φ_i is the lane use factor for lane group i;

$\xi^j_{i,l}$ is a ratio which represents the portion of flow $\eta^m_{i,l}$ that will join downstream flow $\eta^j_{2,l-1}$:

$r^j_{i,l}$ is a ratio which represents the portion of uncoordinated flows;

O-D Estimation: Model III

Queue Length Estimation

For outbound direction:

$$\delta^{p}_{l,l-1}(k)=\sigma^{p}_{l,l-1}(k)+\varphi_{p}[(\sum_{j=1}^{2l-1}\sum_{m=\tau^{-}_{2l,l}}^{\tau^{-}_{2l,l}+1} q_{2l}(k-m)\theta^{m}_{2l,l}(k-m)b_{2l,j}(k-m))\xi^{p}_{1,l}r_{1}^{p}$$

$$+(\sum_{i=2l+2}^{2N+2}\sum_{m=\tau^{-}_{il}}^{\tau^{-}_{il}+1}\sum_{j=1}^{2l-1} q_{i}(k-m)\theta^{m}_{i,l}(k-m)b_{ij}(k-m))\xi^{p}_{2,l}r^{p}_{2,l}$$

$$+(\sum_{j=1}^{2l-1}\sum_{m=\tau^{-}_{2l+1,l}}^{\tau^{-}_{2l+1,l}+1} q_{2l+1}(k-m)\theta^{m}_{2l+1,l}(k-m)b_{2l+1,j}(k-m))\xi^{p}_{3,l}r^{p}_{3,l}];\ \forall p\in\{L,T,R\}$$

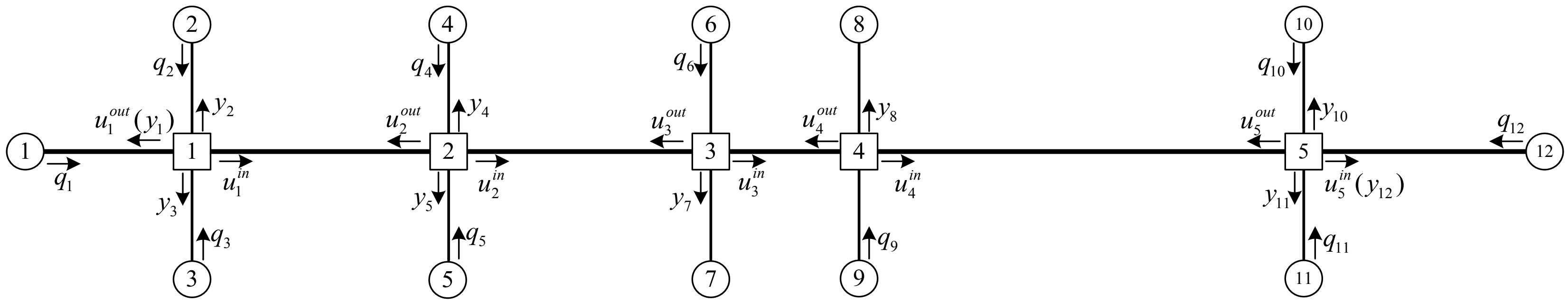
For inbound direction:

$$\delta^{p}_{l,l+1}(k)=\sigma^{p}_{l,l+1}(k)+\varphi_{T}[(\sum_{j=2l+2}^{2N+2}\sum_{m=\tau^{-}_{2l,l}}^{\tau^{-}_{2l,l}+1} q_{2l}(k-m)\theta^{m}_{2l,l}(k-m)b_{2l,j}(k-m))\xi^{p}_{1,l}r_{1}^{p}$$

$$+(\sum_{i=1}^{2l-1}\sum_{m=\tau^{-}_{il}}^{\tau^{-}_{il}+1}\sum_{j=2l+2}^{2N+2} q_{i}(k-m)\theta^{m}_{i,l}(k-m)b_{ij}(k-m))\xi^{p}_{2,l}r^{p}_{2,l}$$

$$+(\sum_{j=2l+2}^{2N+2}\sum_{m=\tau^{-}_{2l+1,l}}^{\tau^{-}_{2l+1,l}+1} q_{2l+1}(k-m)\theta^{m}_{2l+1,l}(k-m)b_{2l+1,j}(k-m))\xi^{p}_{3,l}r^{p}_{3,l}];\ \forall p\in\{L,T,R\}$$

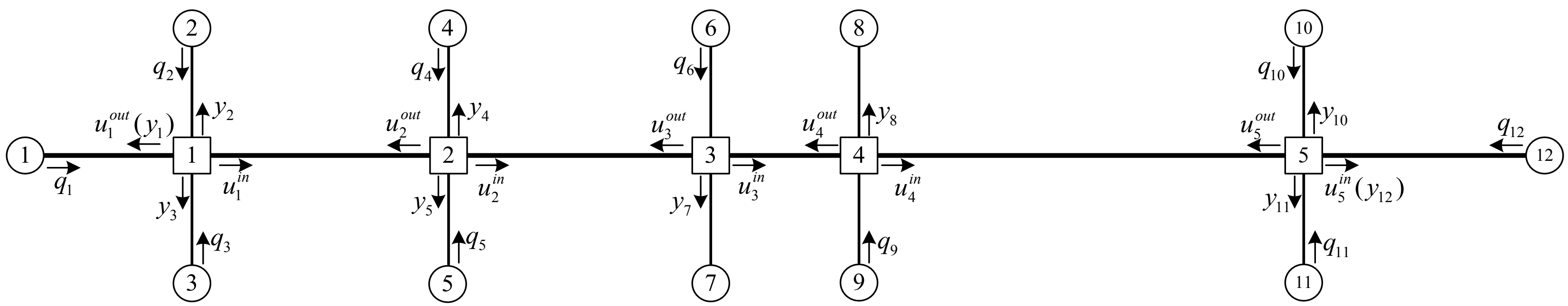
Model Evaluation



Arterial Topology of the Study Site

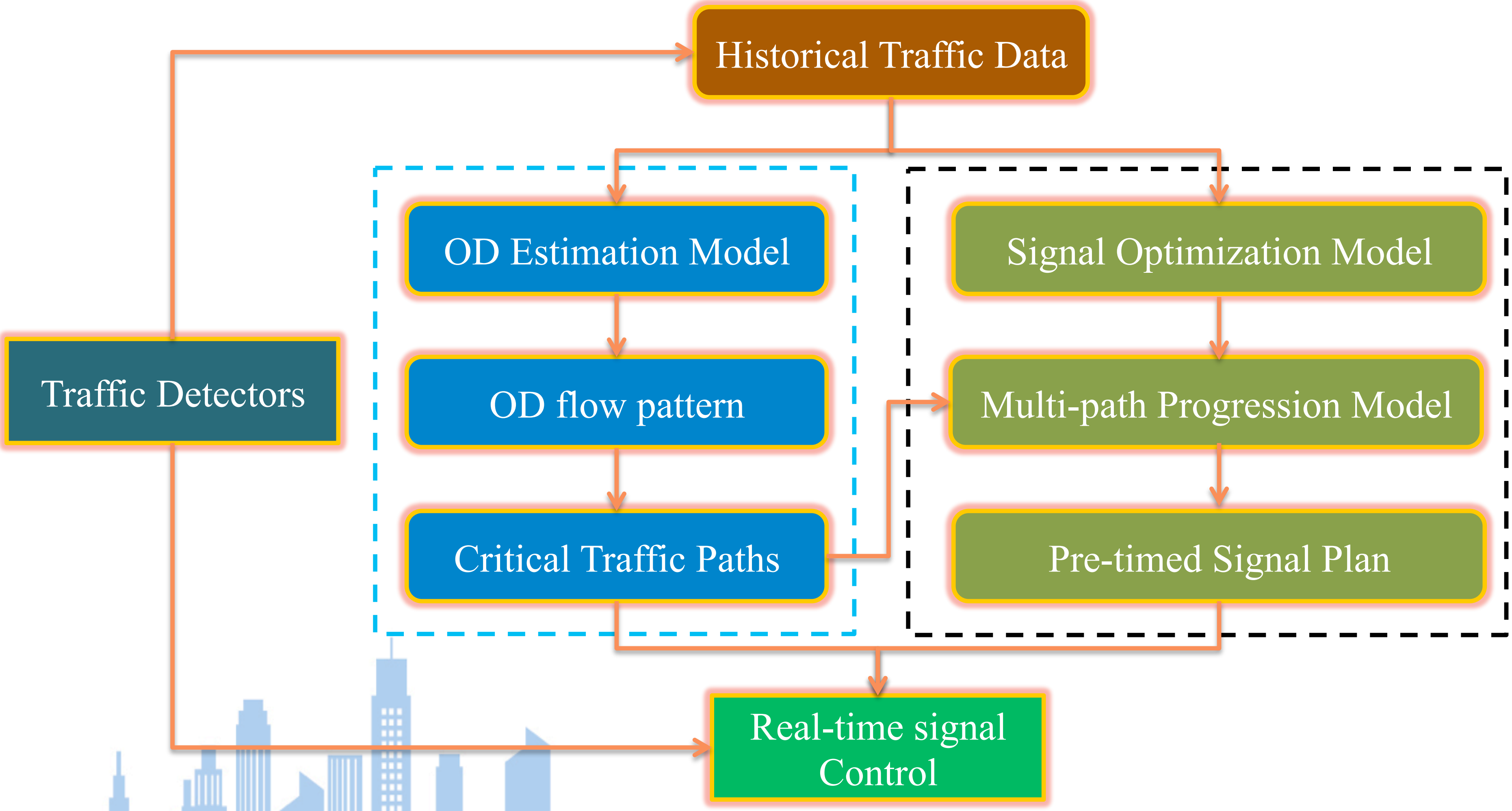
Models	Model I			Model II			Model III		
	MAE	MAPE	RMSE	MAE	MAPE	RMSE	MAE	MAPE	RMSE
Link flows	4.54	18.56%	5.48	4.10	16.31%	5.21	3.99	15.92%	4.99
Turning flows	4.02	42.39%	5.54	2.75	18.27%	4.07	2.70	17.46%	3.92
OD flows	1.885	42.02%	3.075	1.473	33.20%	2.512	1.251	28.11%	1.979

Model Evaluation



Ground Truth		Model I		Model II		Model III	
OD Pair	Total Flows	OD Pair	Total Flows	OD Pair	Total Flows	OD Pair	Total Flows
9→12	1390	**9→12**	1658	**9→12**	1372	**9→12**	1480
6→12	765	**6→12**	985	**6→12**	860	**6→12**	784
9→1	756	9→4	649	9→4	727	**9→1**	722
6→4	729	4→7	497	4→7	571	**6→4**	642
12→7	553	4→8	465	12→6	544	**12→7**	540
12→1	472	**9→1**	427	**9→1**	531	**12→1**	452

Pre-timed Signal Design



Pre-timed Signal Design

Signal Optimization Model

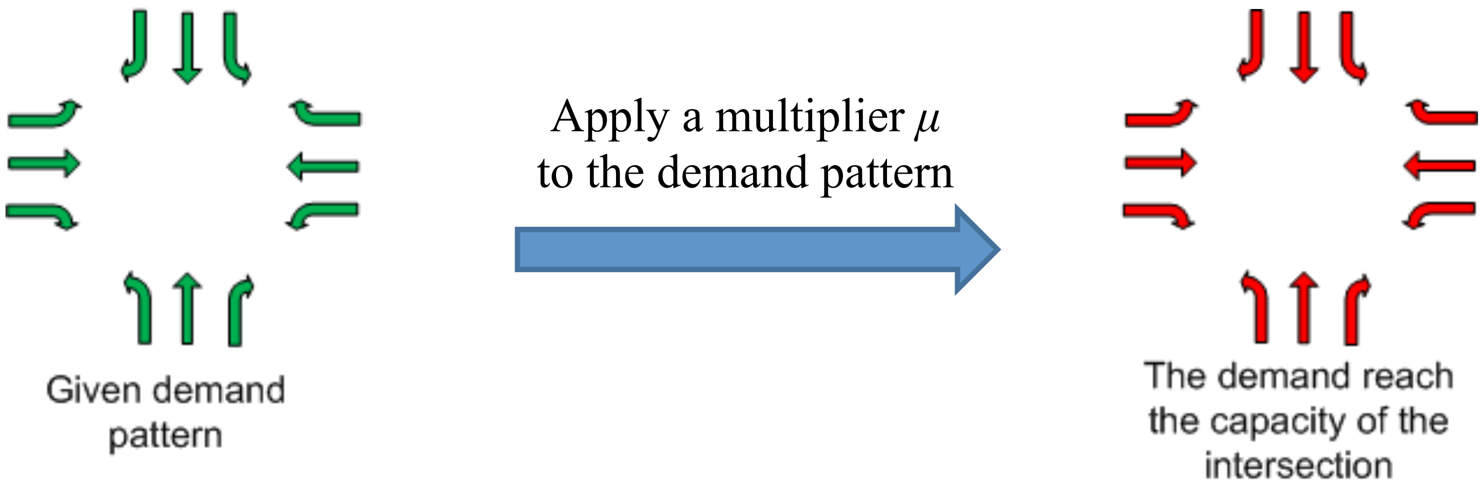
Objective:
maximizing intersection capacity
Control Variables:
common cycle length, green split

Multi-path Progression Model

Objective:
maximizing progression efficiency
Control Variables:
offsets; phase sequences

Signal Timing Optimization

Objective function: Maximization of Intersection capacity



Give arrival pattern, capacity is usefully measured by how large a multiplier μ can be applied to the demand.

Then, the capacity of the intersection could be indicated by the multiplier μ.

REF : *S.C. Wong et al.*(2003)

Signal Timing Optimization

$$M1: Maxmize \sum_i \mu_i$$ → Maximization of intersection capacities

$s.t.$

$$\mu_i \alpha_{k,i} q_{k,i} \le s_{k,i} \sum_m \beta_{k,m,i} \Phi_{m,i} - \delta \times \xi \quad \forall i,k$$ → Flow <= Link Capacity

$$\sum_m \Phi_{m,i} = 1 \quad \forall i$$ → Sum of green = cycle length

$$(1 - \sum_m \beta_{o,m,i} \Phi_{m,i} + \delta \times \xi) \cdot q_{o,i} \cdot s_{o,i} \le \tau_{o,i}^{\max} (s_{o,i} - q_{o,i}) \xi$$ → Off-ramp queue constraint: Queue < Link Length

$$\frac{1}{C_{\max}} \le \xi \le \frac{1}{C_{\min}}$$ → Min & Max cycle length

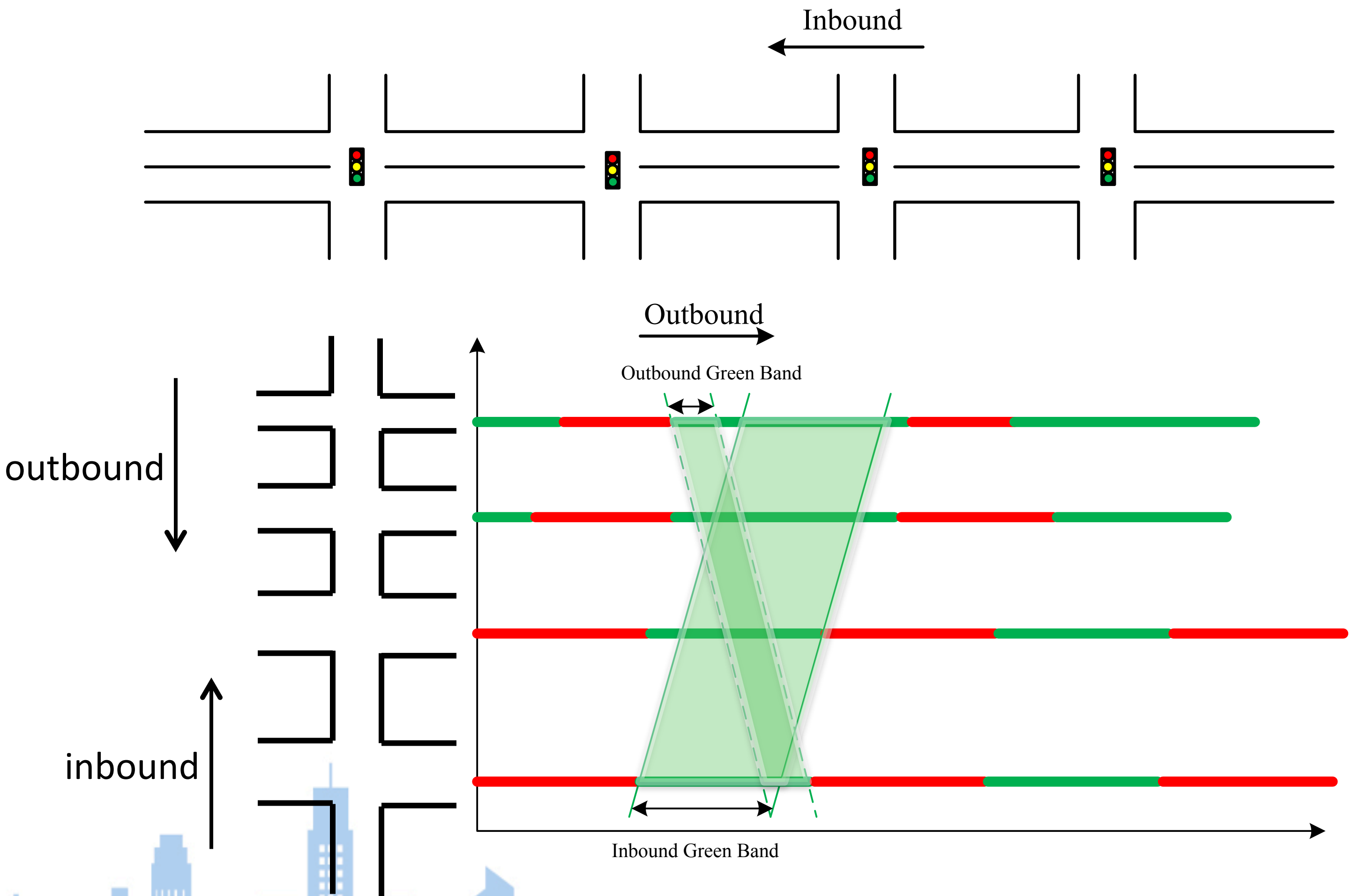
$$\xi \times g_{\min} \le \Phi_{m,i} \le \xi \times g_{\max} \quad \forall m,i$$ → Min & Max green time

Pre-timed Signal Design

Signal Optimization Model → Objective: maximizing intersection capacity; Control Variables: common cycle length, green split

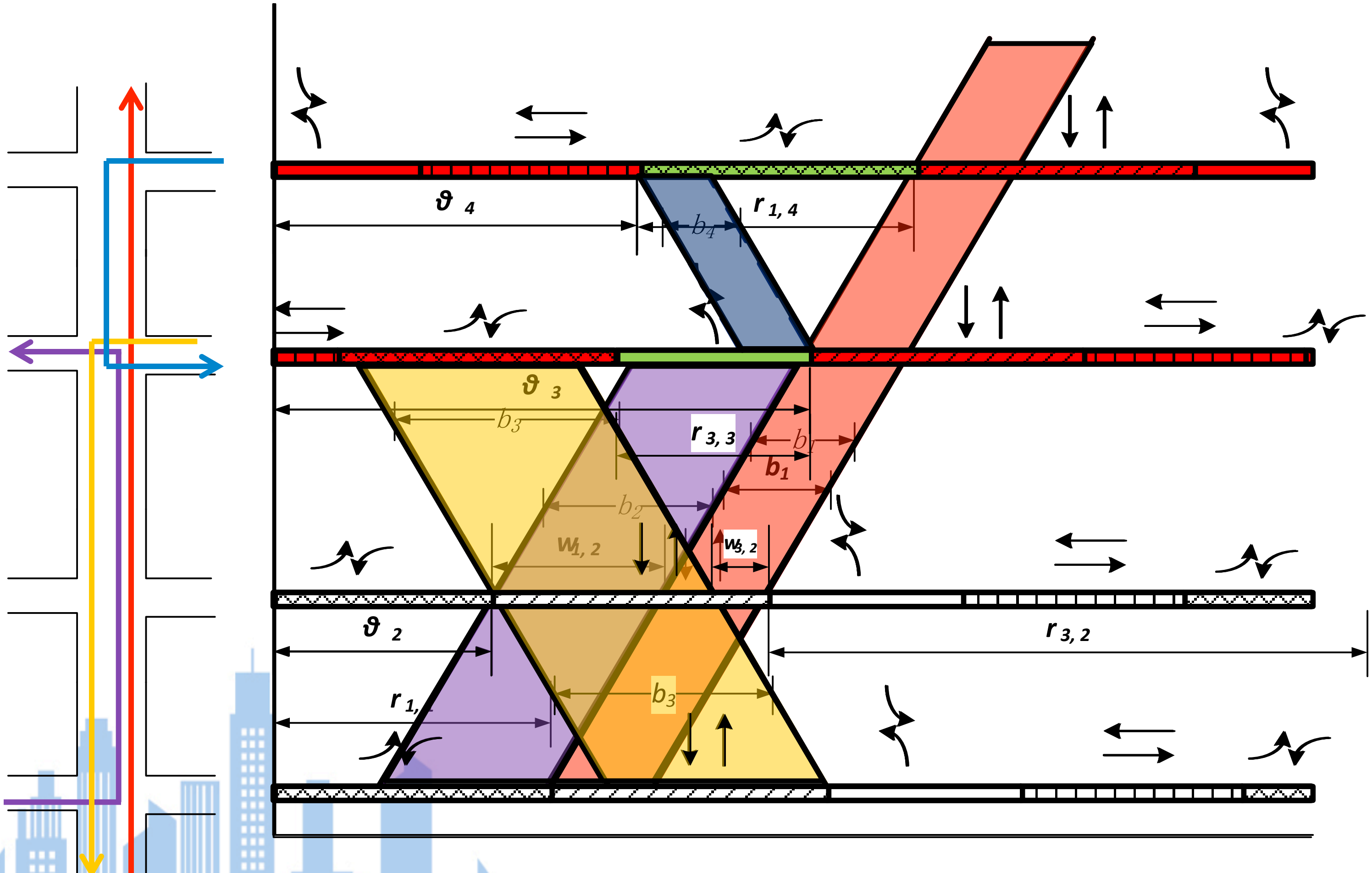
Multi-path Progression Model → Objective: maximizing progression efficiency; Control Variables: offsets; phase sequences

Review of Two-way Progression



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

What is Multi-Path Progression?



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Critical Issues in Multi-Path Progression

1
- How to formulate the optimization model to accommodate multiple traffic paths?

2
- How to concurrently optimize the phase sequences?

3
- How to effectively eliminate some paths so as to produce the maximal progression benefit?

Model I

- Control Objective:

$$Max \sum_i (\varphi_i b_i + \bar{\varphi}_i \bar{b}_i)$$

- b_i :Bandwidth of an inbound path
- b_i :Bandwidth of an outbound path
- φ_i , φ_i :weighting factors

- Interference Constraints:

$$0 \le w_{i,k} + b_i \le g_{i,k}$$
$$0 \le \bar{w}_{i,k} + \bar{b}_i \le \bar{g}_{i,k}$$

- $g_{i,k}$:green time for an inbound path *i* at intersection k
- $g_{i,k}$:green time for an outbound path *i* at intersection k

- $w_{i,k}$:part of green time that is **before** the band for an inbound path *i* at intersection *k*
- $w_{i,k}$:part of green time that is **after** the band for an outbound path *i* at intersection *k*

Model I

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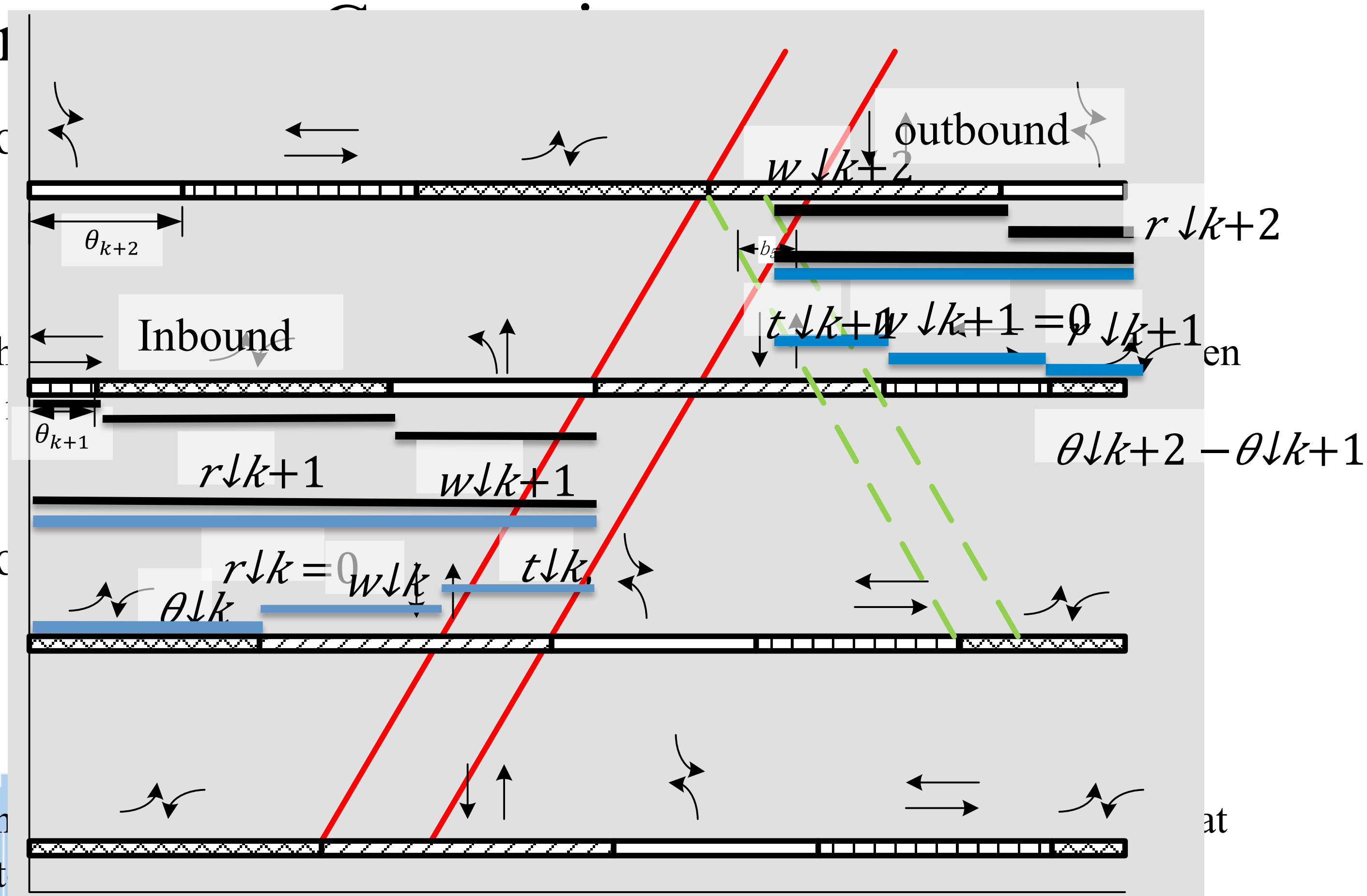

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Model II

- Model 2: To optimize the phase sequence in the multi-path progression model.

- To facilitate the phase sequence optimization, a set of binary variables are defined as follows:

$$x_{l,m,k} = \begin{cases} 1, & \text{if phase } l \text{ is before phase } m \text{ within the same cycle of intersection } k; \\ 0, & \text{o.w.} \end{cases}$$

Model II

- To ensure the feasibility of the generated phase sequence, a set of constraints are defined as follows:

$$x_{l,l,k} = 0 \quad \forall l; \forall k$$

A phase is never before itself.

$$x_{l,m,k} + x_{m,l,k} = 1 \quad \forall l \neq m; \forall k$$

Either phase l is before phase m, or phase m is before phase l.

$$x_{l,n,k} \geq x_{l,m,k} + x_{m,n,k} - 1 \quad \forall l \neq m \neq n; \forall k$$

If phase l is before phase m and phase m is before phase n, phase l must be before phase n.

$$x_{l,n,k} + x_{n,m,k} = 1 \quad l \neq m \neq n$$

(optional)Phase l and m are in a sequential order

$$x_{l,m,k} = 1 \quad l \neq m$$

(optional)Phase l must be before phase m

Model II

- The interference constraints must be re-written as follows:

A set of binary parameters are defined to represent the phasing design:

$$\beta_{i,l,k} = \begin{cases} 1, & \text{if path } i \text{ obtains green in phase } l \text{ at intersection } k; \\ 0, & \text{o.w.} \end{cases}$$

$$0 \le w_{i,k} + b_i \le \sum_l \beta_{i,l,k}\phi_{l,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$0 \le \overline{w}_{i,k} + \overline{b}_i \le \sum_l \beta_{i,l,k}\phi_{l,k} \quad \forall i \in \overline{\Omega}; \forall k \in \sigma_i$$

Model II

Similarly, the progression constraints are given as follows:

For inbound directions:

$$\theta_k + r_{i,k} + w_{i,k} + t_{i,k,k+1} + n_{i,k} = \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + n_{i,k+1}$$

(? marks above the boxed $r_{i,k}$ and $r_{i,k+1}$)

For outbound directions:

$$\theta_{k+1} - \theta_k + \bar{r}_{i,k} + \bar{w}_{i,k} + \bar{t}_{i,k,k+1} + \bar{n}_{i,k} = \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1}$$

(? marks above the boxed $\bar{r}_{i,k}$ and $\bar{r}_{i,k+1}$)

$$r_{i,k} \le \sum_l \beta_{i,m,k} x_{l,m,k} \cdot \phi_{l,k} + M(1-\beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i; \forall m$$

$$\bar{r}_{i,k} \le \sum_l \beta_{i,m,k} x_{m,l,k} \cdot \phi_{l,k} + M(1-\beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i; \forall m$$

$$r_{i,k} + \bar{r}_{i,k} + \sum_l \beta_{i,l,k} \cdot \phi_{k,n} = 1 \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i$$

- $w_{i,k}$:portion of green time that is **before** the band for an inbound path i at intersection k
- $\bar{w}_{i,k}$:portion of green time that is **after** the band for an inbound path i at intersection k
- t_k :travel time between intersection k and k+1
- $\bar{t}_{k+1}$:travel time between intersection k+1 and k

Model III

- Progression competition between different critical paths
  - In practice, the identified critical paths may compete for the progression band.
  - Thus, it might be infeasible or ineffective to find a synchronization plan which can offer reasonable bandwidths for all the critical paths.
  - Hence, it is essential to eliminate some infeasible paths when designing signal progression.

Model III

To deal with the progression conflicts between critical paths, another set of constraints are introduced as follows to the model:

$$y_i = \begin{cases} 1 & \text{if path i obtains signal progression with non-zero green band} \\ 0 & \text{o.w.} \end{cases}$$

$$b_i \le y_i \qquad \bar{b}_i \le y_i$$

For inbound directions:

$$\theta_k + r_{i,k} + w_{i,k} + t_{i,k} + n_{i,k} \ge \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + n_{i,k+1} - M(1 - y_i)$$

$$\theta_{k+1} - \theta_k + r_{i,k} + w_{i,k} + t_{i,k} + n_{i,k} = r_{i,k+1} + w_{i,k+1} + n_{i,k+1}$$

$$\theta_k + r_{i,k} + w_{i,k} + t_{i,k} + n_{i,k} \le \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + n_{i,k+1} + M(1 + y_i)$$

It is similar for outbound directions.

Model Summary

Model III

$$Max \sum_i (\varphi_i b_i) + \sum_i (\bar{\varphi}_i \bar{b}_i)$$

s.t.

$$0 \le w_{i,k} + b_i \le g_{i,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$0 \le \bar{w}_{i,k} + \bar{b}_i \le \bar{g}_{i,k} \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$$

$$(1-k)\sum_{i\in\Omega} \bar{b}_i \ge (1-k)k\sum_{i\in\Omega} b_i$$

$$x_{l,l,k} = 0 \quad \forall l; \forall k$$

$$x_{l,m,k} + x_{m,l,k} = 1 \quad \forall l \ne m; \forall k$$

$$x_{l,n,k} \ge x_{l,m,k} + x_{m,n,k} - 1 \quad \forall l \ne m \ne n; \forall k$$

$$x_{l,n,k} + x_{n,m,k} = 1 \quad l \ne m \ne n$$

$$x_{l,m,k} = 1 \quad l \ne m$$

$$g_{i,k} = \beta_{i,l,k}\phi_{l,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$\bar{g}_{i,k} = \beta_{i,l,k}\phi_{l,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$0 \le w_{i,k} + b_i \le \sum_l \beta_{i,l,k}\phi_{l,k} \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$0 \le \bar{w}_{i,k} + \bar{b}_i \le \sum_l \beta_{i,l,k}\phi_{l,k} \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$$

$$r_{i,k} \le \sum_l \beta_{i,m,k} x_{l,m} \cdot \phi_{l,k} + M(1-\beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i; \forall m$$

$$\bar{r}_{i,k} \le \sum_l \beta_{i,m,k} x_{m,l} \cdot \phi_{l,k} + M(1-\beta_{i,m,k}) \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i; \forall m$$

$$r_{i,k} + \bar{r}_{i,k} + \sum_l \beta_{i,l,k} \cdot \phi_{k,n} = 1 \quad \forall i \in \Omega + \bar{\Omega}; \forall k \in \sigma_i$$

$$b_i \le y_i$$

$$\bar{b}_i \le \bar{y}_i$$

$$\theta_k + r_{i,k} + w_{i,k} + t_k + n_{i,k} \ge \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + \tau_{i,k+1} + n_{i,k+1} - M(1-y_i) \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$\theta_k + r_{i,k} + w_{i,k} + t_k + n_{i,k} \le \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + \tau_{i,k+1} + n_{i,k+1} + M(1-y_i) \quad \forall i \in \Omega; \forall k \in \sigma_i$$

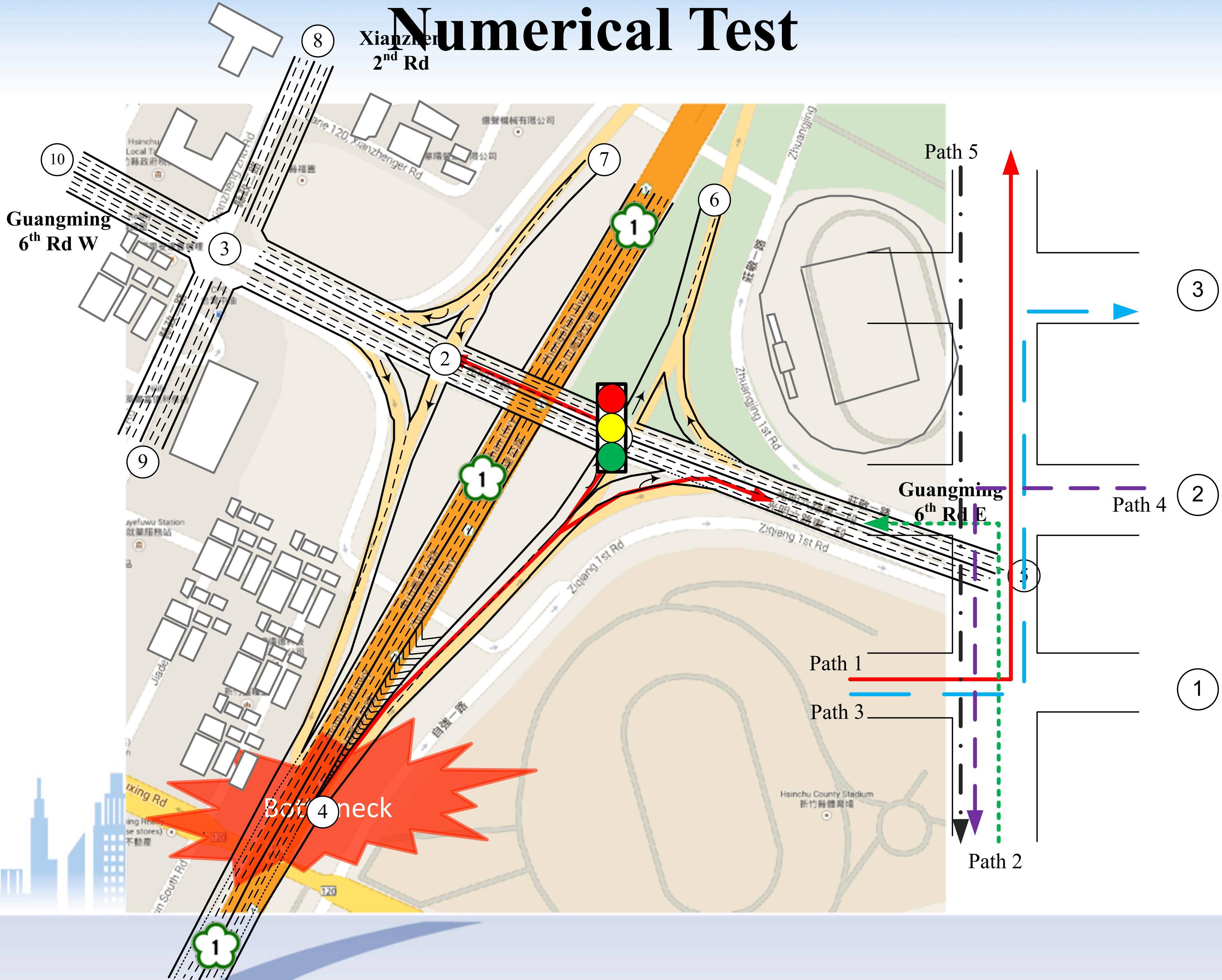
$$-\theta_k + \bar{r}_{i,k} + \bar{w}_{i,k} - \bar{\tau}_{i,k} + \bar{t}_k + \bar{n}_{i,k} \ge -\theta_{k+1} + \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1} - M(1-\bar{y}_i) \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$$

$$-\theta_k + \bar{r}_{i,k} + \bar{w}_{i,k} - \bar{\tau}_{i,k} + \bar{t}_k + \bar{n}_{i,k} \le -\theta_{k+1} + \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1} + M(1-\bar{y}_i) \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$$

$$\theta_k + r_{i,k} + w_{i,k} + t_k + n_{i,k} = \theta_{k+1} + r_{i,k+1} + w_{i,k+1} + \tau_{i,k+1} + n_{i,k+1} + M(1-y_i) \quad \forall i \in \Omega; \forall k \in \sigma_i$$

$$-\theta_k + \bar{r}_{i,k} + \bar{w}_{i,k} - \bar{\tau}_{i,k} + \bar{t}_k + \bar{n}_{i,k} = -\theta_{k+1} + \bar{r}_{i,k+1} + \bar{w}_{i,k+1} + \bar{n}_{i,k+1} - M(1-\bar{y}_i) \quad \forall i \in \bar{\Omega}; \forall k \in \sigma_i$$

Numerical Test



Numerical Test

Three models are compared:

- Model 1: TRANSYT-7F optimization Model;
- Model 2: Proposed signal optimization model with MAXBAND for progression design;
- Model 3: Proposed model;

Model	Intersection	CL	Φ1	Φ2	Φ3	Φ4	offset
Model-1	1	160	91	69	/	/	152
	2	160	41	32	60	27	0
	3	160	75	35	50	/	115
	4	160	92	37	31	/	76
Model-2	1	155	108	47	/	/	55
	2	155	39	27	63	26	85
	3	155	48	50	57	/	40
	4	155	95	32	28	/	0
Model-3	1	155	108	47	/	/	35
	2	155	39	27	63	26	47
	3	155	48	50	57	/	0
	4	155	95	32	28	/	138

Numerical Test

- To evaluate the signal plans produced by different models, a simulation network is developed with VISSIM.

- Also, the VISSIM network has been well-calibrated with field data.

Percentage difference between simulated and field volume data

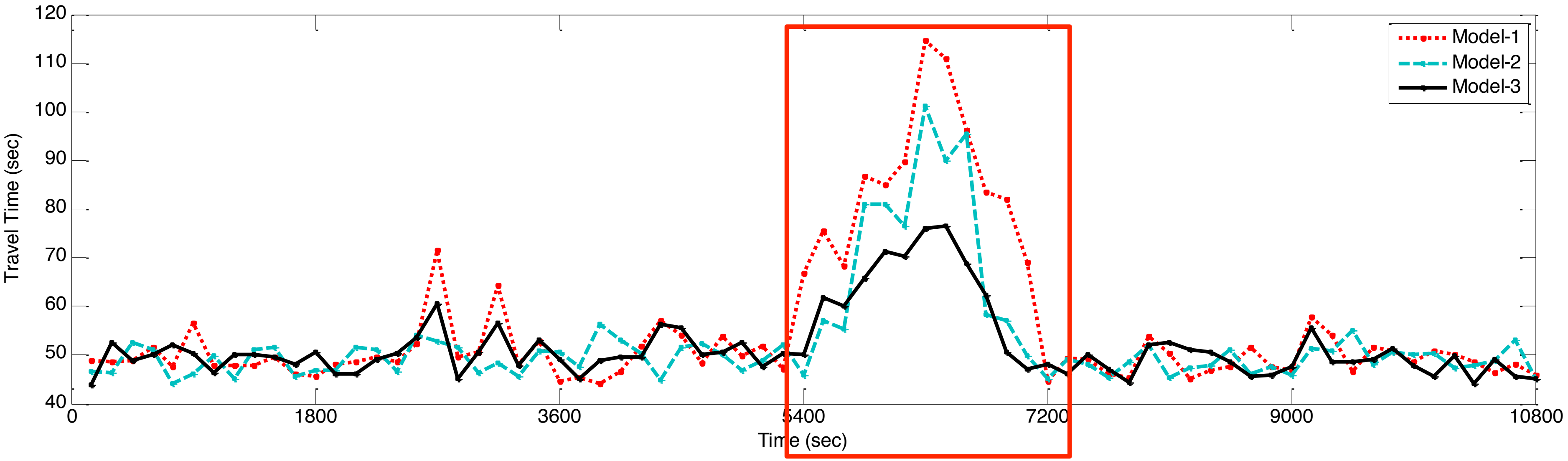
Intersection No.	Approach			
	WB	NB	EB	SB
1	1%	0.6%	2%	N/A
2	0.9%	N/A	2%	0.2%
3	2%	3%	0.6%	1%

Netowork performance under the control of different models

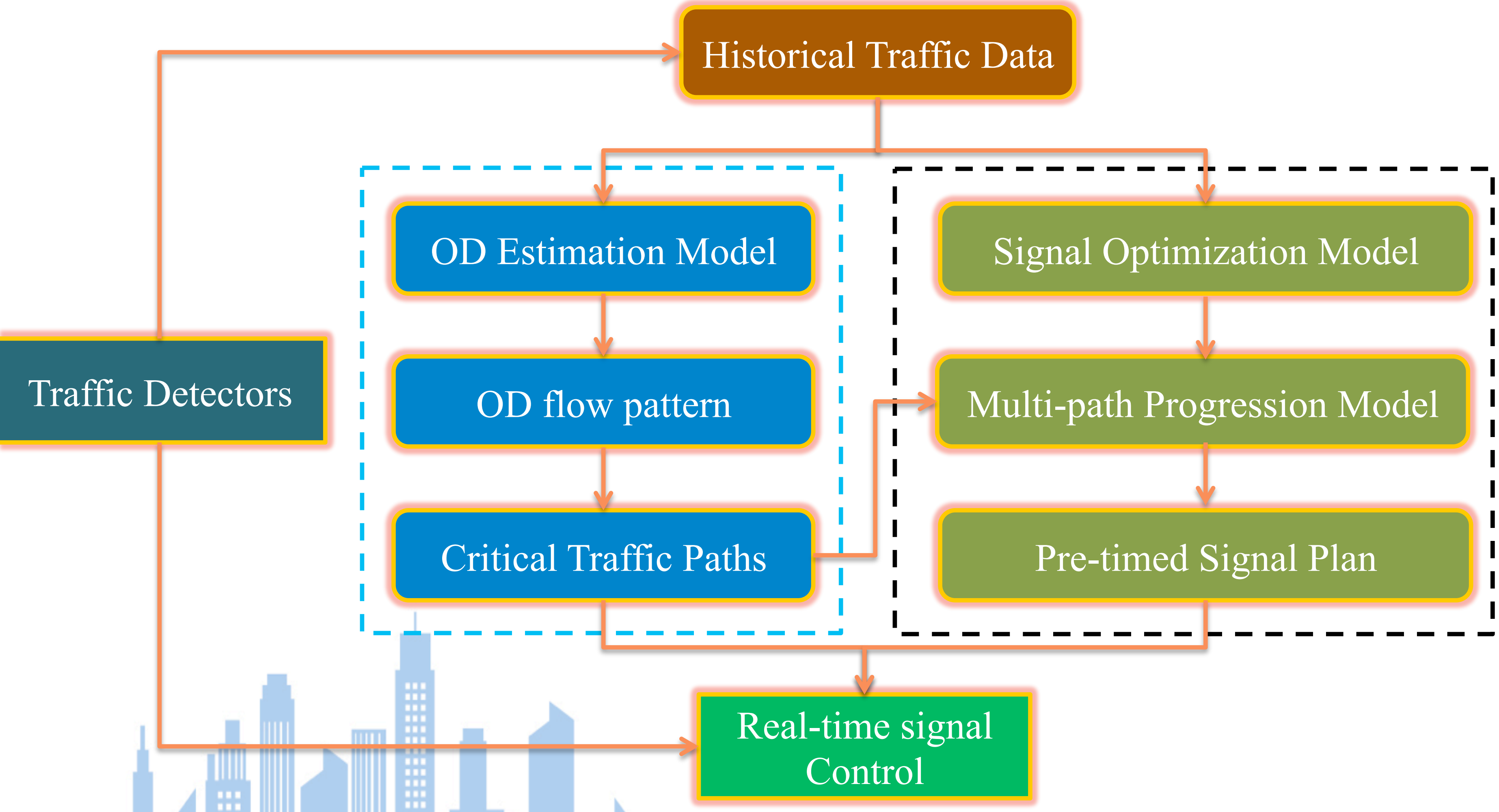
MOEs	Model 1 TRANSYT 7-F	Model 2 MAXBAND	Model 3 Proposed
Average Delay	54.3 secs	55.4 secs	47.6 secs
Average # of Stops	0.972	1.047	0.884
Average Speed	34.7 km/h	31.3 km/h	40.5 km/h

Numerical Test

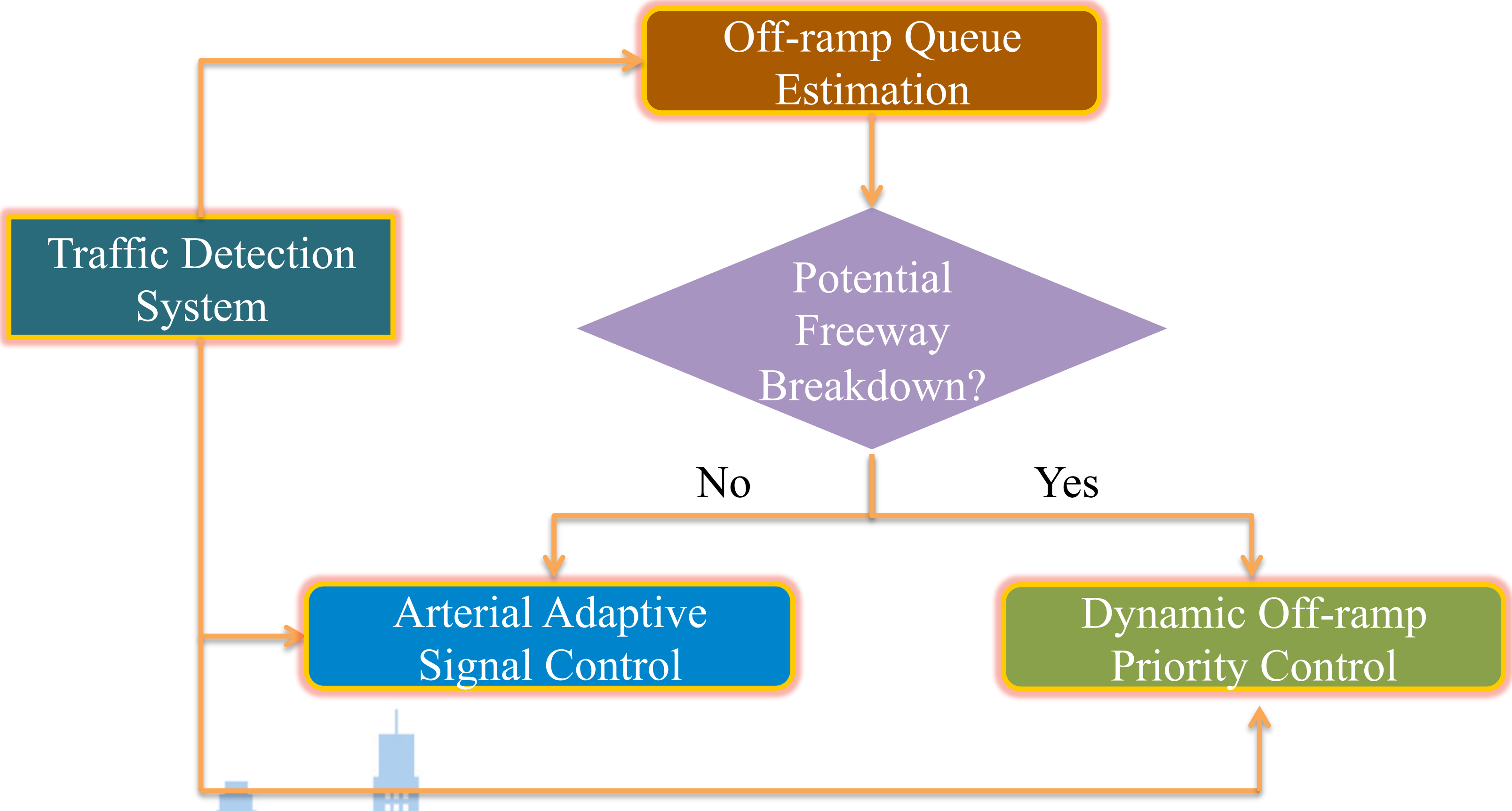
The time-dependent travel time on freeway mainline



Real-Time Signal Control

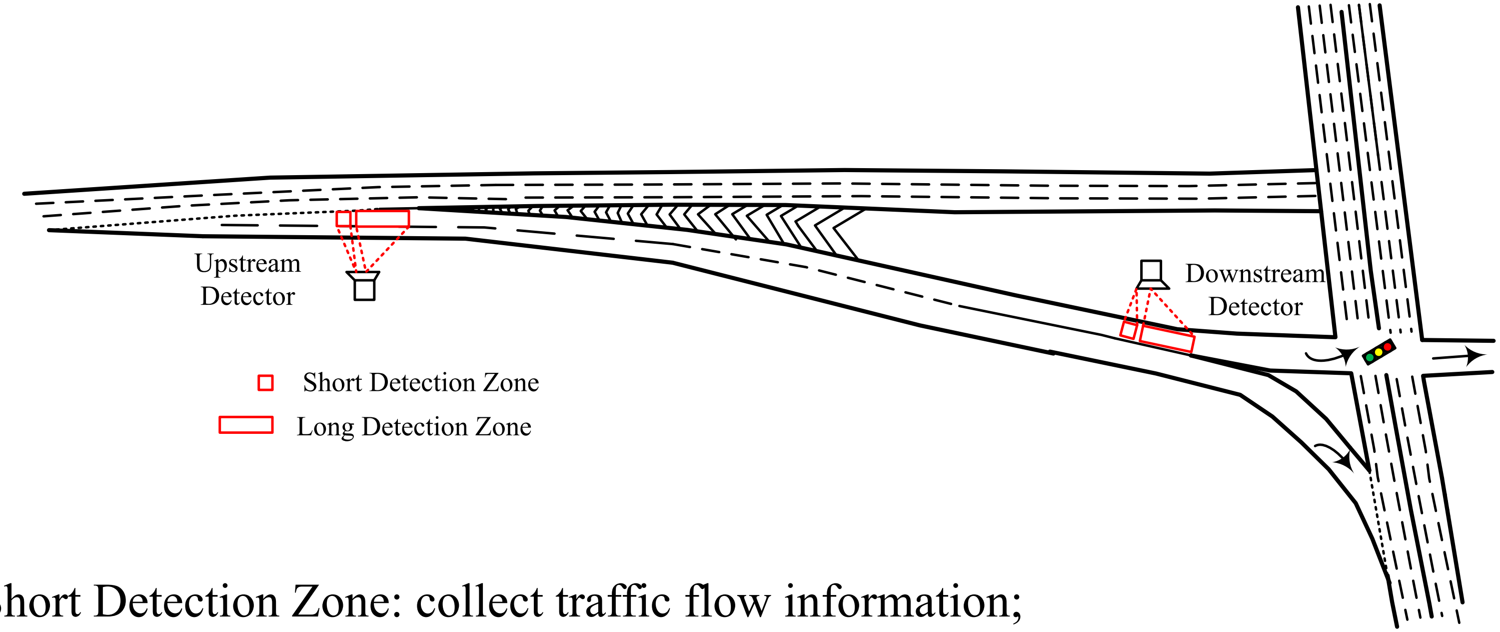


Real-Time Signal Control



Off-ramp Queue Estimation Model

Location of dual-zone detectors on the target off-ramp



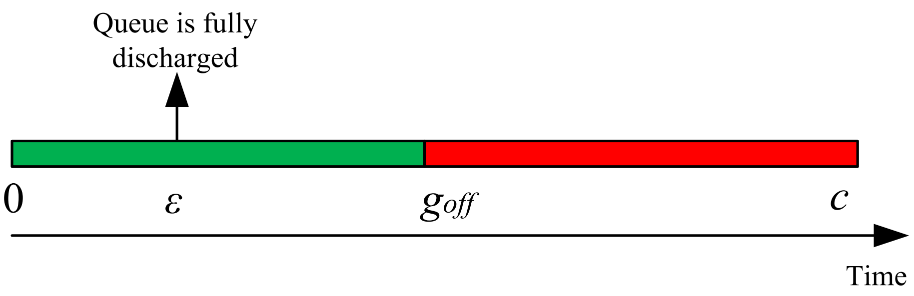
Short Detection Zone: collect traffic flow information;
Long Detection Zone: identify the presence of queue

Off-ramp Queue Estimation Model

This study proposed two models in response to different congestion levels at the off-ramp:

- Model I: off-ramp queue **can** be cleared during the green phase;
- Model II: off-ramp queue **cannot** be cleared during the green phase.

Model I



At time ε: $\delta(\varepsilon,k) = \sum_{t=\varepsilon - t_{off}}^{\varepsilon} q_{up}(t,k)$ equals the number of vehicles passed the upstream detector during time period $[\varepsilon - t_{off}, \varepsilon]$

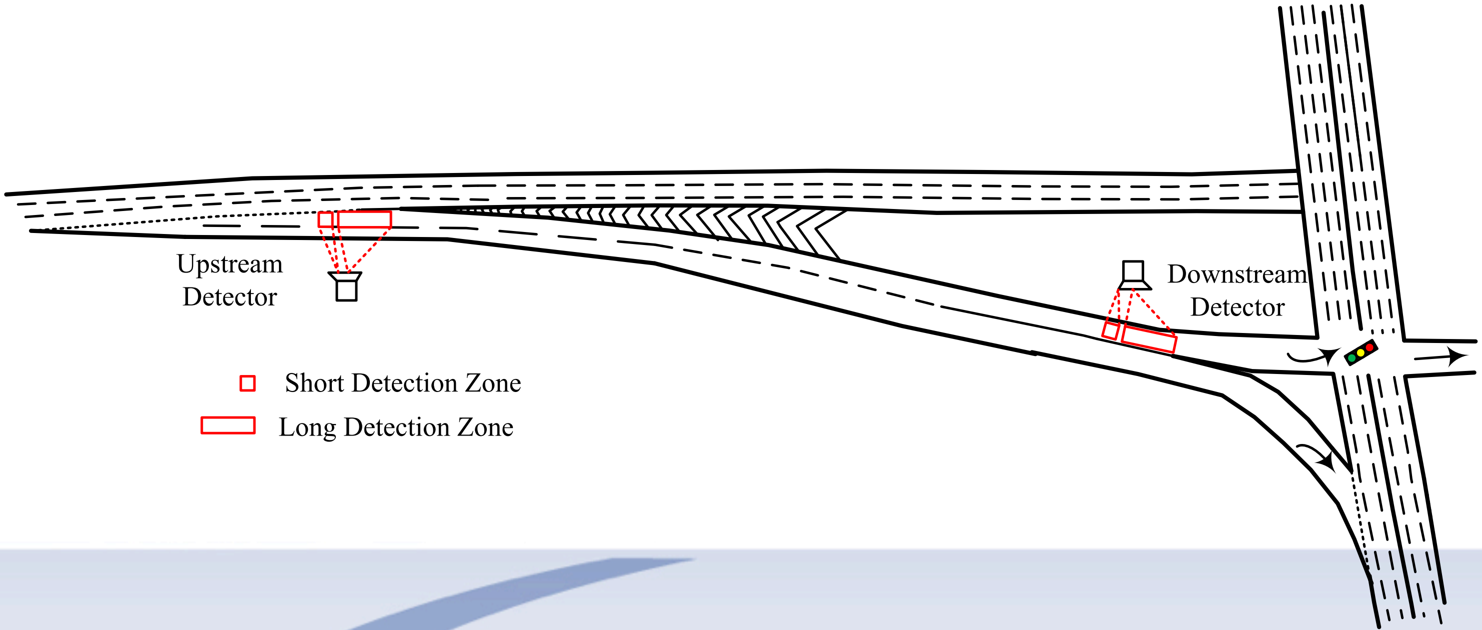
At time g_{off}: $\delta(g_{off},k) = \delta(\varepsilon,k) + \sum_{t=\varepsilon}^{g_{off}} q_{up}(t,k) - \sum_{t=\varepsilon}^{g_{off}} q_{down}(t,k)$ plus # of arrivals and minus # of departures

At time c: $\delta(c,k) = \delta(g_{off},k) + \sum_{t=g_{off}}^{c(k)} q_{up}(t,k)$ plus # of arrivals

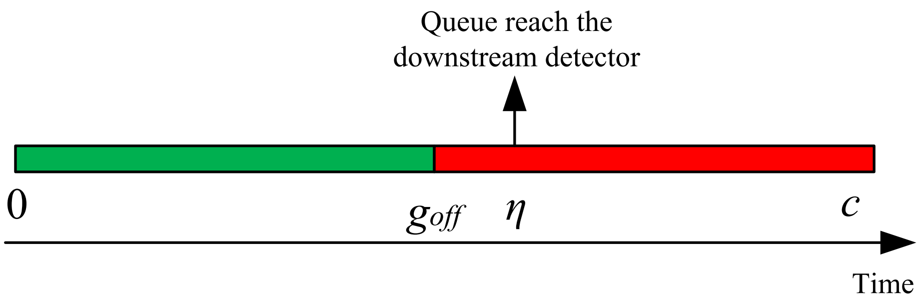
Model II

Two additional scenarios might be encountered:

- ❑ Scenario 1: residual queue **cannot** reach the downstream detector;
- ❑ Scenario 2: residual queue **can** reach the downstream detector;



Scenario 1



At time c:

$$\delta(c,k) = \sum_{t=\eta-t_{off}}^{c(\mathrm{k})} q_{up}(t,k)$$

equals the number of vehicles passed the upstream detector during time period $[\eta - t_{off}, c]$

Scenario 2

If the residual queues have exceeded the downstream detector, the queue length at the end of a cycle can be approximated with :

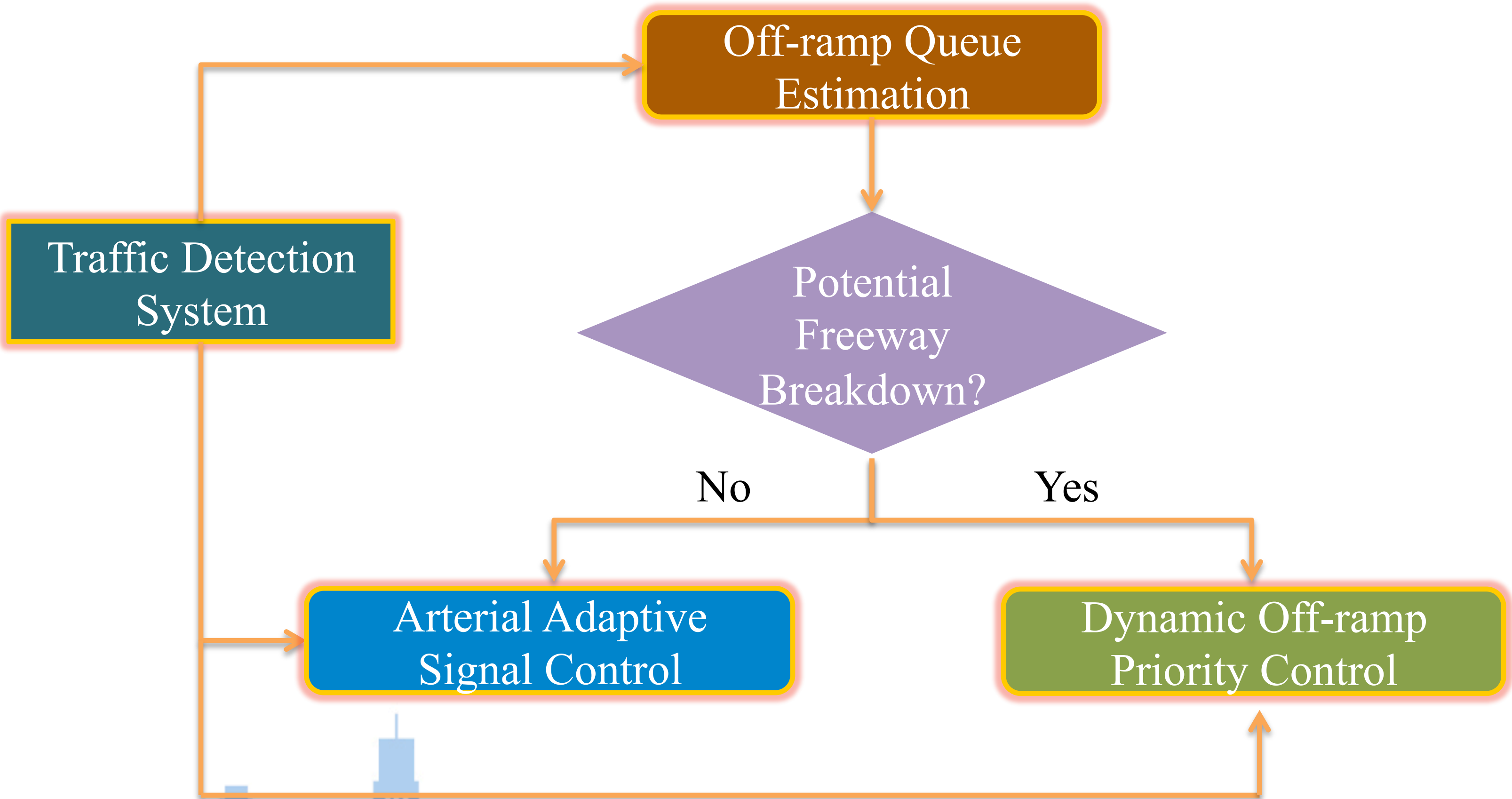
$$\tau_{off}(c,k) = \tau_{off}(c,k-1) + \sum_{t=1}^{c(k)} q_{up}(t,k) - \sum_{t=1}^{c(k)} q_{down}(t,k)$$

Last cycle queue

Total Arrivals

Total Departures

Real-Time Signal Control



Arterial Adaptive Signal Control

Intersection Signal Timing Adjustment

Objective
Minimization of intersection Delays

Solution Algorithm
Gradient Search

Adaptive Signal Progression Design

Objective
Maximization of Progression Efficiency

Solution Algorithm
Dynamic Programming

Intersection Signal Timing Adjustment

$M1: \ Min \ \ d_i(k)$ → Minimization of intersection total delay

s.t.

$$d_i(k)=\sum_{j=1}^{N_j}\sum_{t=1}^{c}\tau_{i,j}(t,k)\Delta t$$ → Total delay estimation with queue

$$\mu_{i,j}(t,k)=\frac{1}{c}q_{i,j}(k) \quad \forall j,t$$ → Arrival rate calculation

$$r_{i,j}(t,k)=\begin{cases} s_{i,j}\Delta t & if \ \ green \\ 0 & if \ \ red \end{cases} \quad \forall j,t$$ → Departure rate estimation

$$\tau_{i,j}(0,k)=\tau_{i,j}(c,k-1) \quad \forall j$$

$$\tau_{i,j}(t,k)=Max[\tau_{i,j}(t-1,k)+\mu_{i,j}(t,k)-r_{i,j}(t,k),0] \quad \forall j,t$$ → Queue Estimation

$$\sum_{p=1}^{N_p}(g_{i,p}(k)+l_{i,p}(k))=c(k)$$ → Common cycle length constraint

$$g_{i,p,\min}\le g_{i,p}(k)\le g_{i,p,\max}$$ → Min & Max green time constraint

$$g_{i,p}(k-1)-\Delta g_i\le g_{i,p}(k)\le g_{i,p}(k-1)+\Delta g_i$$ → Max green time adjustment constraint

Solution Algorithm

Gradient Search Algorithm:

Step 1: Initialization. Let p = 1 and get the green time of each phase at the previous signal cycle;

Step 2: For phase p, change the green time by α seconds (could be negative or positive) by solving the following sub-problem:

$$
\begin{aligned}
&\alpha = \arg\min\{d_i(k);\ m \in N_p,\ m \neq p\} \\
&s.t.\quad g_{i,p}(k) = g_{i,p}(k-1) + \alpha \\
&\qquad g_{i,m}(k) = g_{i,m}(k-1) - \alpha \\
&\qquad -\Delta g_i \le \alpha \le \Delta g_i \\
&\qquad g_{i,p,\min} \le g_{i,p}(k) \le g_{i,p,\max} \\
&\qquad g_{i,m,\min} \le g_{i,m}(k) \le g_{i,m,\max}
\end{aligned}
$$

Step 3: Let $p = p + 1$. If $p > |N_{pi}|$, stop; otherwise go back to Step 2.

applied;

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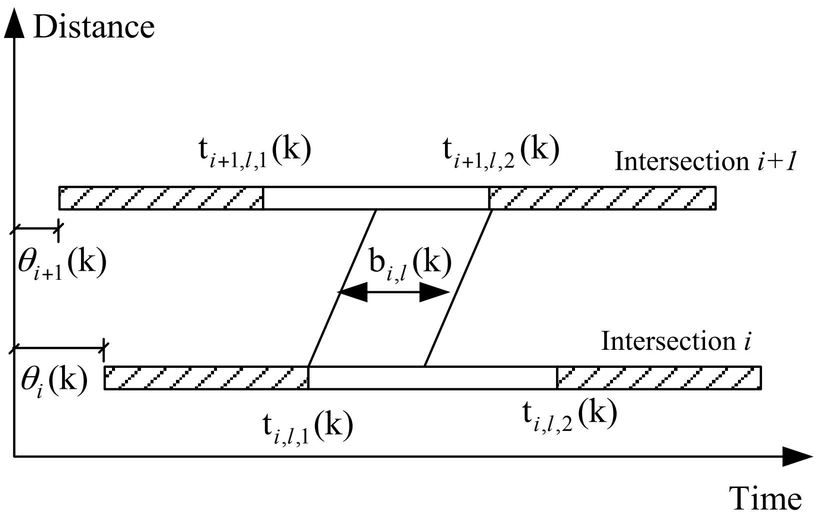
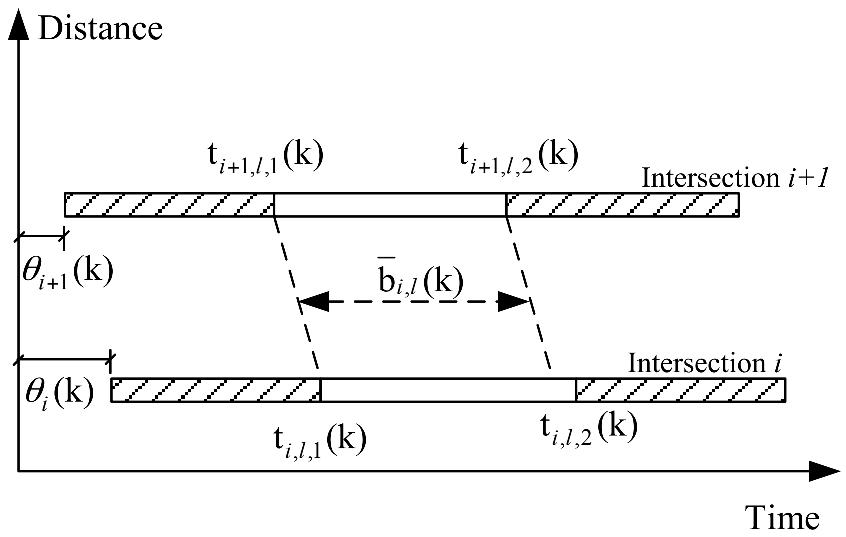
rom Step 0;

improvement

Adaptive Signal Progression Control



Green band of an outbound path between two intersections



Green band of an inbound path between two intersections

Adaptive Signal Progression Control

$$M2:\ Max \sum_i \sum_l \phi_l(\mathrm{k})\mathrm{b}_{i,1}(\mathrm{k}) + \sum_i \sum_l \bar{\phi}_l(\mathrm{k})\bar{\mathrm{b}}_{i,1}(\mathrm{k})$$

→ Maximization of total green bandwidths

s.t.

$$b_{i,1}(\mathrm{k}) = Max[Min(\mathrm{t}_{i+1,j,2}(\mathrm{k}), \mathrm{t}_{i,j,2}(\mathrm{k}) + \mathrm{t}_{i,i+1}(\mathrm{k})) - Max(\mathrm{t}_{i,j,1}(\mathrm{k}) + \mathrm{t}_{i,i+1}(\mathrm{k}), \mathrm{t}_{i,j,1}(\mathrm{k})), 0]$$

→ Estimation of green bandwidth for an outbound path

$$\bar{b}_{i,j}(\mathrm{k}) = Max[Min(\mathrm{t}_{i,j,2}(\mathrm{k}), \mathrm{t}_{i+1,j,2}(\mathrm{k}) + \mathrm{t}_{i+1,i}(\mathrm{k})) - Max(\mathrm{t}_{i,j,1}(\mathrm{k}), \mathrm{t}_{i,j,1}(\mathrm{k}) + \mathrm{t}_{i+1,i}(\mathrm{k})), 0]$$

→ Estimation of green bandwidth for an inbound path

$$\mathrm{t}_{i,l,1}(\mathrm{k}) = \sum_q \sum_p \zeta_{i,l,p}\varphi_{p,q}g_{i,p}(\mathrm{k}) + \theta_i(\mathrm{k})$$

→ Identification of start of green for path *i*

$$\mathrm{t}_{i,l,2}(\mathrm{k}) = \sum_q \sum_p \zeta_{i,l,p}\varphi_{p,q}g_{i,p}(\mathrm{k}) + \sum_p \zeta_{i,j,p}\varphi_{p,q}g_{i,p}(\mathrm{k}) + \theta_i(\mathrm{k})$$

→ Identification of end of green for path *i*

$$\theta_i(\mathrm{k}-1) - \Delta\theta_i \le \theta_i(\mathrm{k}) \le \theta_i(\mathrm{k}-1) + \Delta\theta_i$$

→ Max allowed offset adjustment constraint

Solution Algorithm

Dynamic Programming:

Let $f_i(.)$ denote the accumulated performance measure, the algorithm consists of the following steps:

Step 1: set $i = 1$, $\theta_1(\mathrm{k}) = 0$, and $f_i(0) = 0$;

$$\Theta_i(\mathrm{k}) = \{\theta_i(\mathrm{k}-1) - \Delta\theta_i, \theta_i(\mathrm{k}-1) - \Delta\theta_i + 1, \cdots, \theta_i(\mathrm{k}-1) + \Delta\theta_i\}$$

Step 2: $i = i + 1$;

$$f_i(\theta_i^*(k)) = \min_{\theta_i(k)} \{ f_{i-1}(\theta_{i-1}^*(k)) + B_i(\theta_i(k)) \,|\, \theta_i \in \Theta_i(\mathrm{k}) \}$$

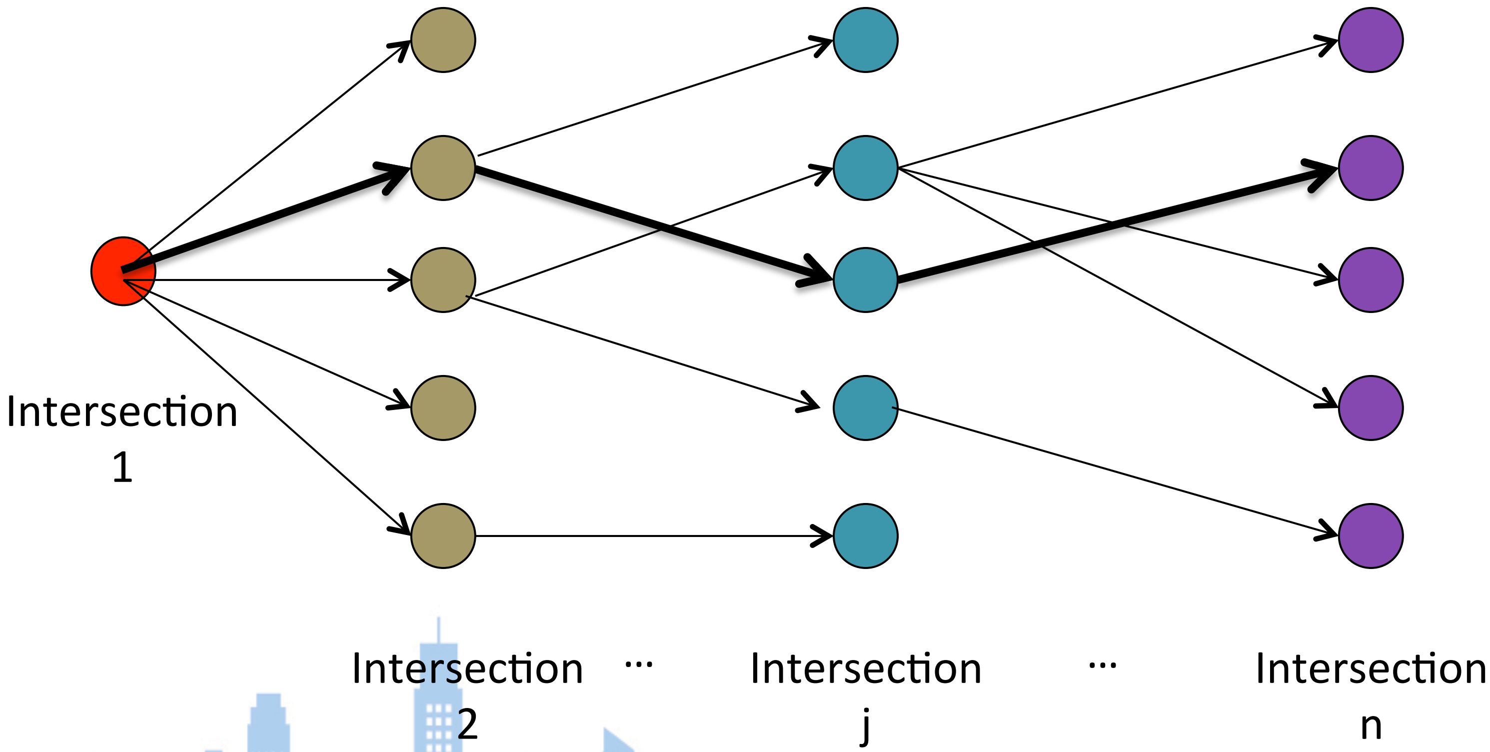
Record $\theta_i^*(k)$ as the optimal solution in Step 2.

Step 3: if $i < N_i$, go to Step 2.

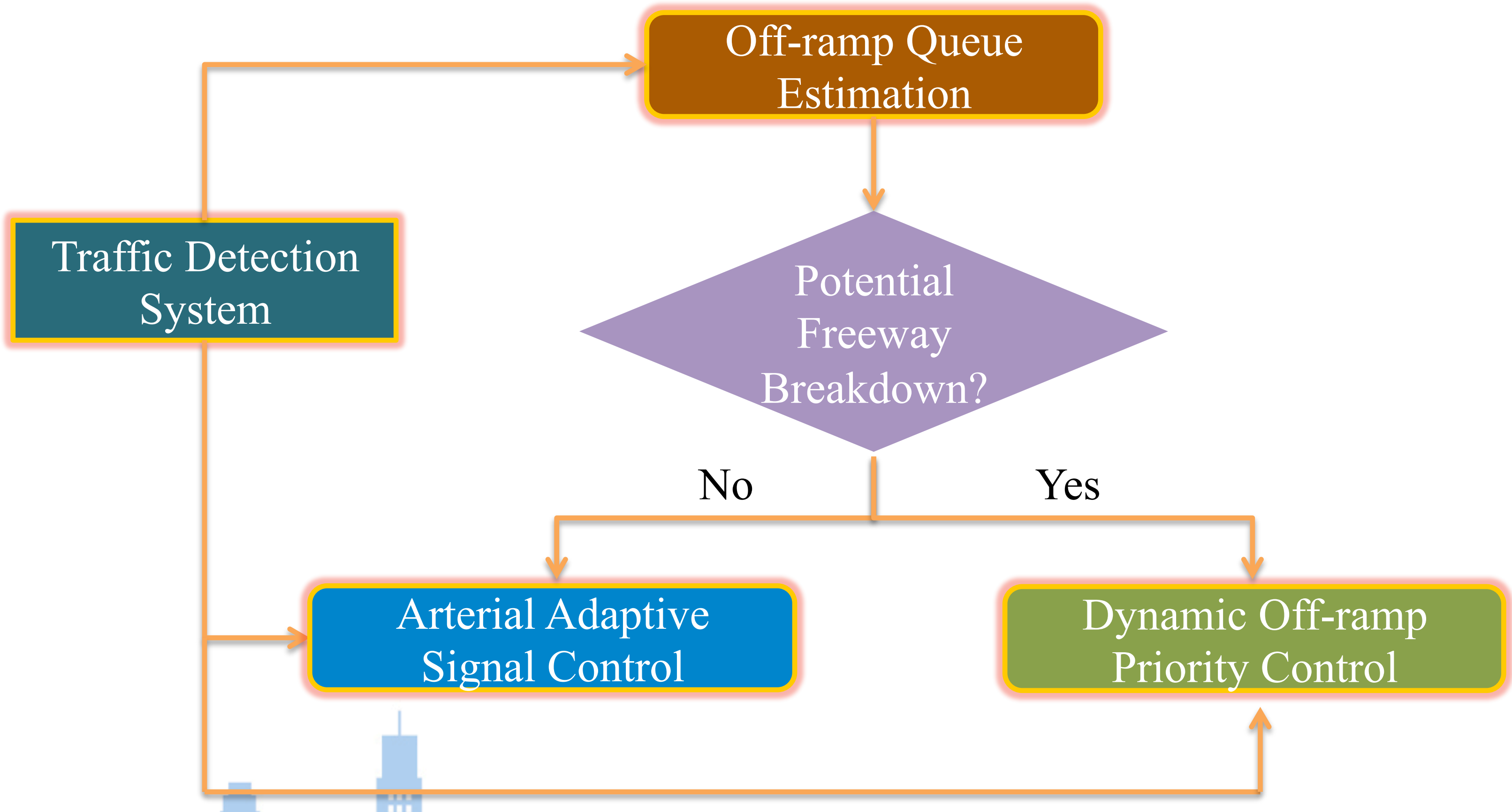
Else, Stop.

Solution Algorithm

Dynamic Programming:



Real-Time Signal Control



Dynamic Off-ramp Priority Control

Intersection Signal Timing Adjustment

Objective

Minimization of intersection Delays

Solution Algorithm

gradient search

Adaptive Signal Progression Design

Objective

Maximization of Coordination Efficiency

Solution Algorithm

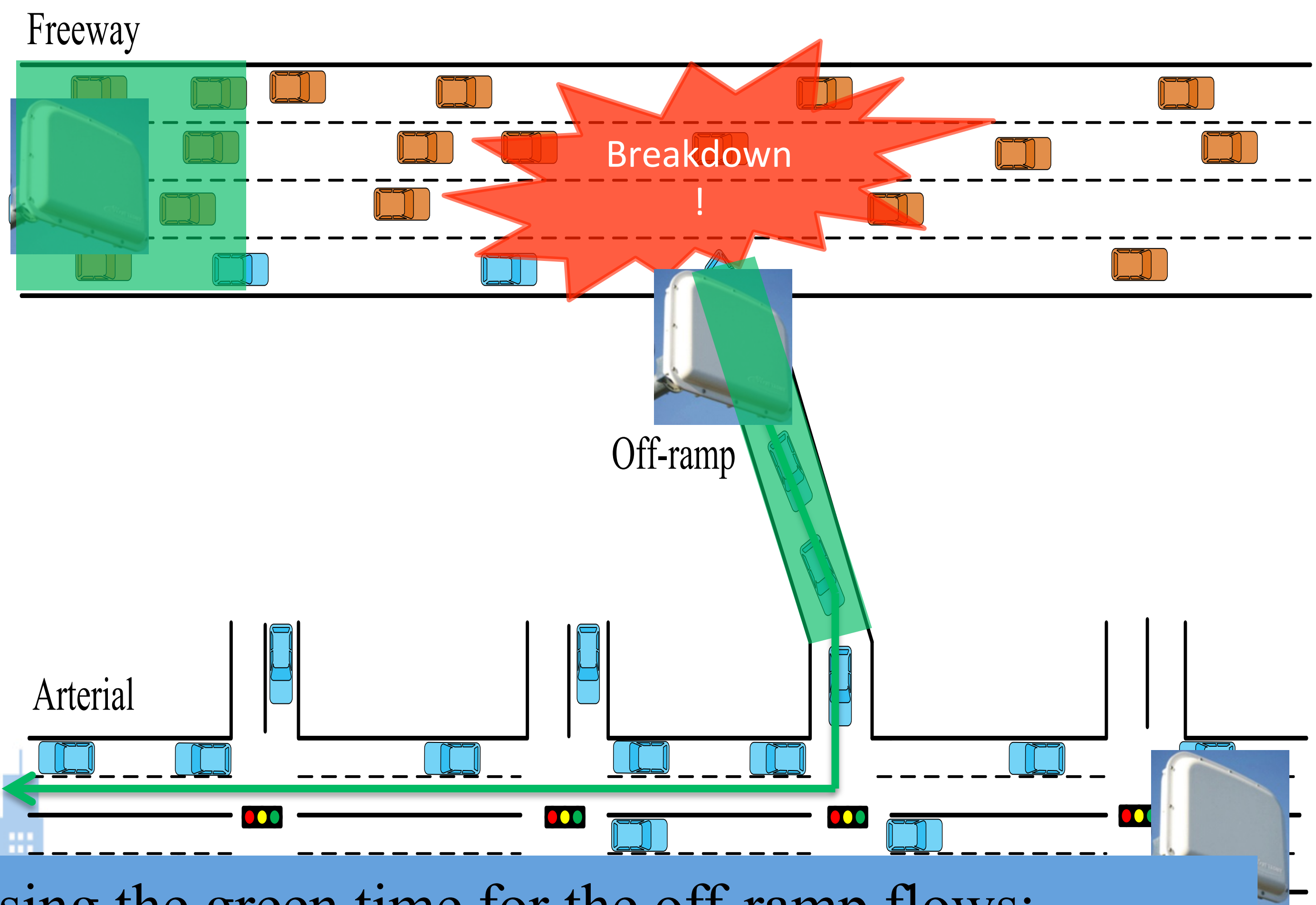
Dynamic programming

Control Logic

Data Collection

Data Analysis

Priority Control



1) increasing the green time for the off-ramp flows;

2) providing signal progression priority to those path-flows from the target off-ramp.

Intersection Signal Timing Adjustment with Off-ramp Priority

Step 1: computation of the minimum green extension to off-ramp flows

$$e_{off}^{\min}(k)=\frac{L_{off}-\tau_{off}(c,k-1)+Max[s_{off}g_{off}(k)-q_{off}(k),\sum_{m=k}^{k+1}(s_{off}g_{off}(m)-q_{off}(m))]}{s_{off}}$$

The minimal green extension will ensure the prevention of queue spillover until the end of the following signal cycle.

Intersection Signal Timing Adjustment with Off-ramp Priority

Step 2: adaptive signal control with off-ramp priority

$$M3: \ Min \ \ d_i(k)$$

s.t.

$$d_i(k) = \sum_{j=1}^{N_j} \sum_{t=1}^{c} \tau_{i,j}(t,k)\Delta t$$

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

$$r_{i,j}(t,k) = \begin{cases} s_{i,j}\Delta t & if \ \ green \\ 0 & if \ \ red \end{cases} \quad \forall j,t$$

$$\tau_{i,j}(0,k) = \tau_{i,j}(c,k-1) \quad \forall j$$

$$\tau_{i,j}(t,k) = Max[\tau_{i,j}(t-1,k) + \mu_{i,j}(t,k) - r_{i,j}(t,k), 0] \quad \forall j,t$$

$$\sum_{p=1}^{N_p} (g_{i,p}(k) + l_{i,p}(k)) = c(k)$$

$$g_{i,p,\min} \le g_{i,p}(k) \le g_{i,p,\max}$$

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

$$g_{off}(k) - g_{off}(k-1) \ge e_{off}^{\min}(k)$$

Green extension constraint

Adaptive Signal Progression Control with Off-ramp Priority

$$M4: \ Max \sum_i \sum_l \phi_l(\mathrm{k}) \mathrm{b}_{i,1}(\mathrm{k}) + \sum_i \sum_l \bar{\phi}_l(\mathrm{k}) \bar{\mathrm{b}}_{i,1}(\mathrm{k})$$

s.t.

$$b_{i,1}(\mathrm{k}) = Max[Min(\mathrm{t}_{i+1,j,2}(\mathrm{k}), \mathrm{t}_{i,j,2}(\mathrm{k}) + \mathrm{t}_{i,i+1}(\mathrm{k})) - Max(\mathrm{t}_{i,j,1}(\mathrm{k}) + \mathrm{t}_{i,i+1}(\mathrm{k}), \mathrm{t}_{i,j,1}(\mathrm{k})), 0]$$

$$\bar{b}_{i,j}(\mathrm{k}) = Max[Min(\mathrm{t}_{i,j,2}(\mathrm{k}), \mathrm{t}_{i+1,j,2}(\mathrm{k}) + \mathrm{t}_{i+1,i}(\mathrm{k})) - Max(\mathrm{t}_{i,j,1}(\mathrm{k}), \mathrm{t}_{i,j,1}(\mathrm{k}) + \mathrm{t}_{i+1,i}(\mathrm{k})), 0]$$

$$\mathrm{t}_{i,l,1}(\mathrm{k}) = \sum_q \sum_p \zeta_{i,l,p} \varphi_{p,q} g_{i,p}(\mathrm{k}) + \theta_i(\mathrm{k})$$

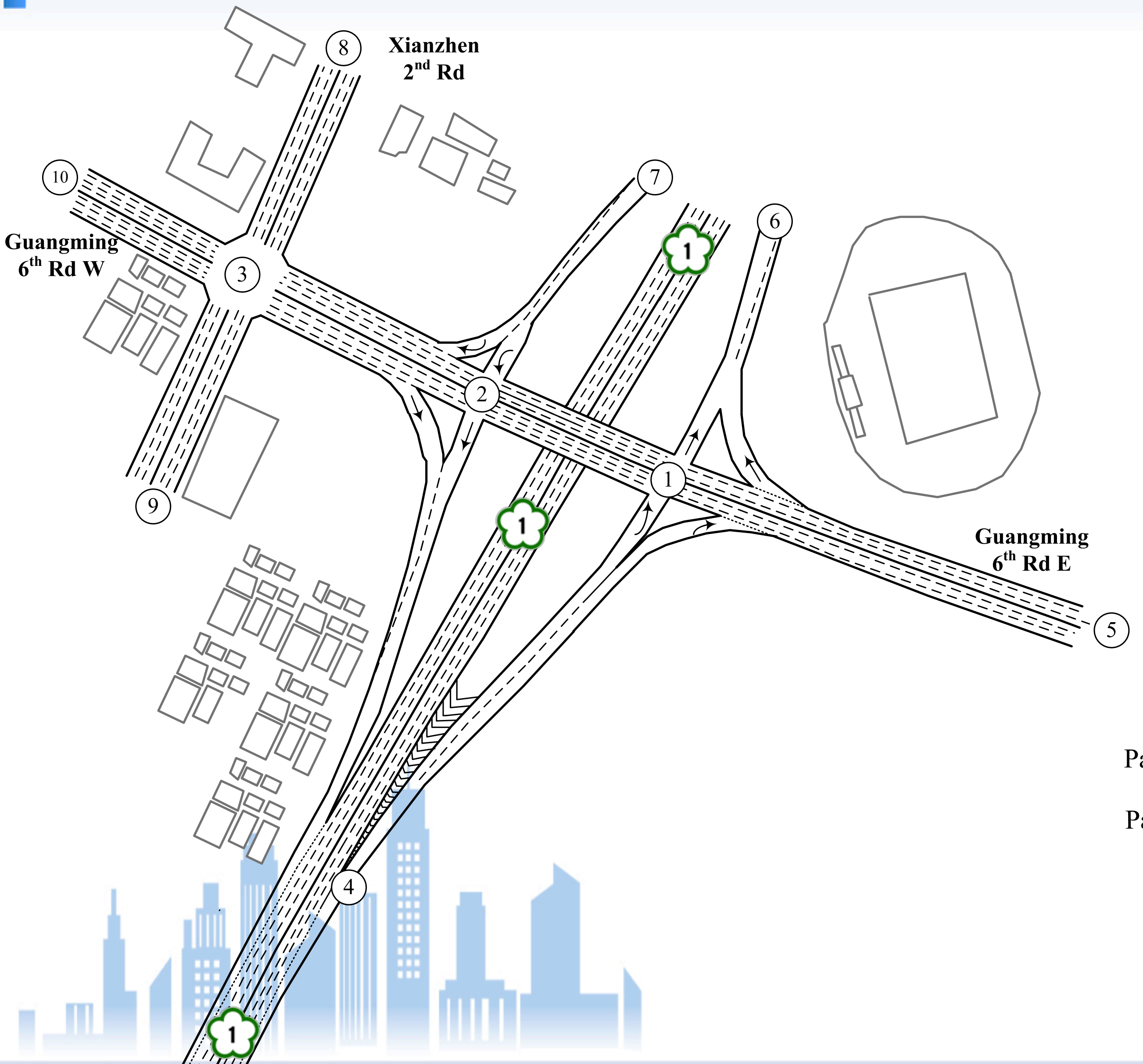
$$\mathrm{t}_{i,l,2}(\mathrm{k}) = \sum_q \sum_p \zeta_{i,l,p} \varphi_{p,q} g_{i,p}(\mathrm{k}) + \sum_p \zeta_{i,j,p} \varphi_{p,q} g_{i,p}(\mathrm{k}) + \theta_i(\mathrm{k})$$

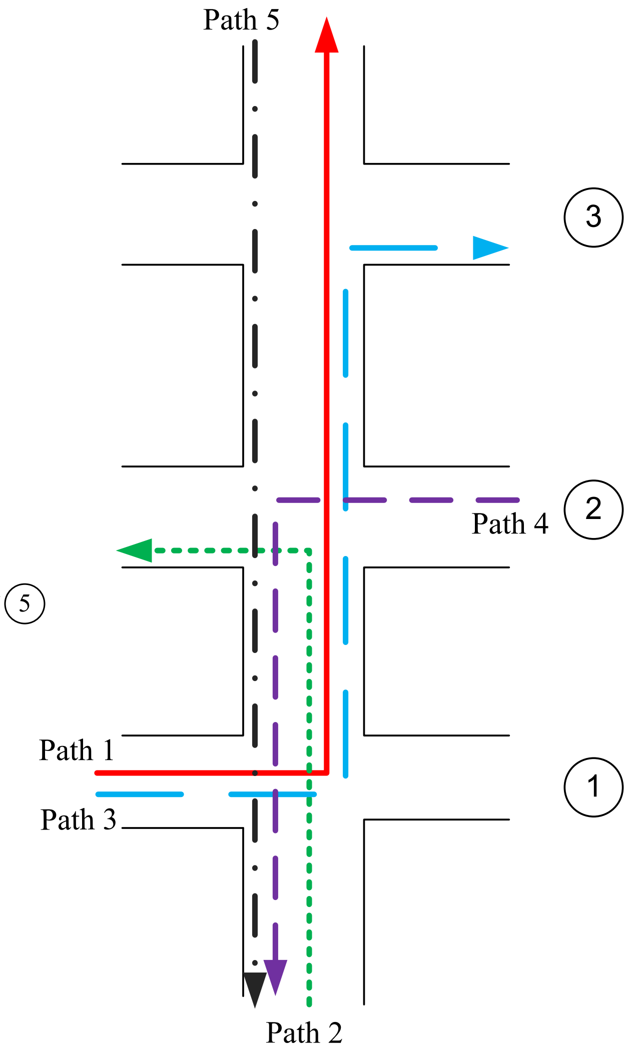
$$\sum_{l \in \Gamma_{off}} b_{i,l}(k) > B_{off}^{\min}$$

$$\sum_{l \in \Gamma_{off}} \bar{b}_{i,l}(k) > B_{off}^{\min}$$

Min bandwidth constraint for off-ramp path-flows

Numerical Test

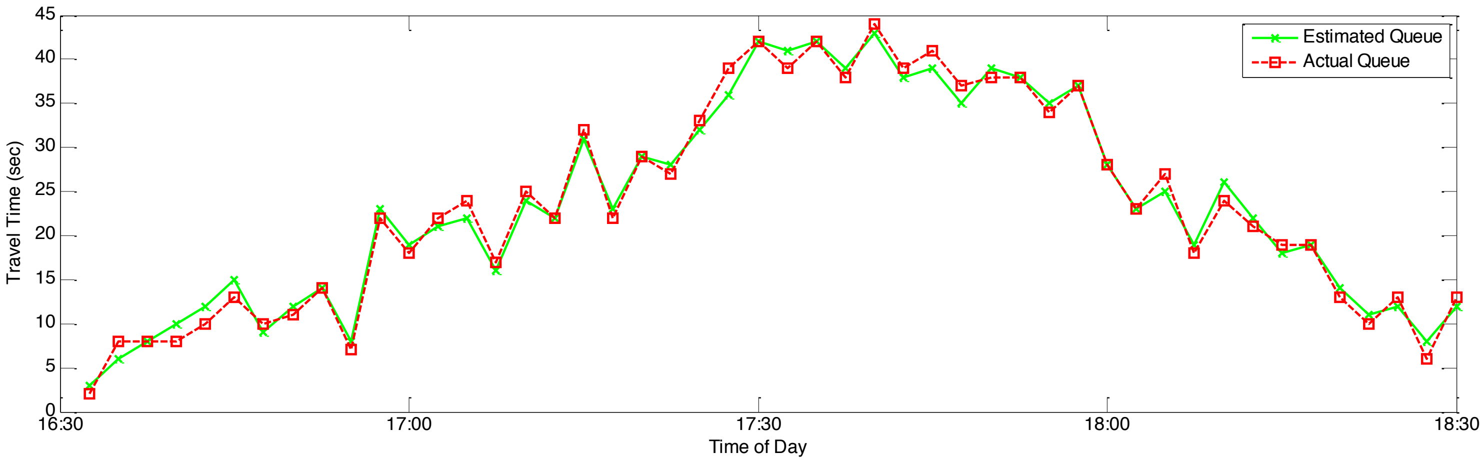




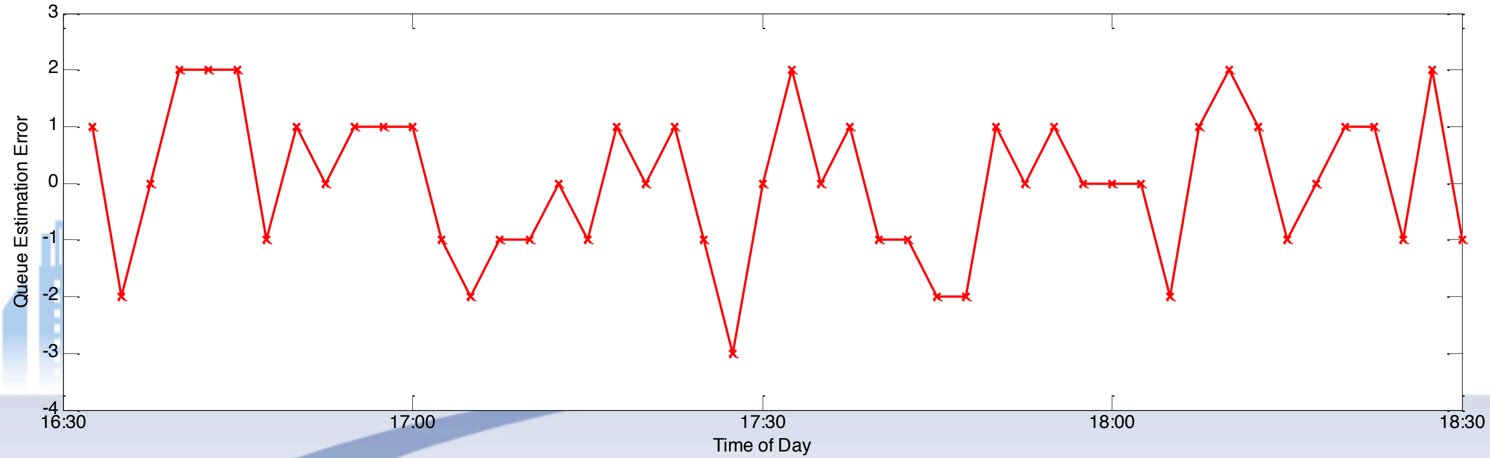
Numerical Test

Queue Estimation Accuracy

Comparison of estimated and actual queue length at the off-ramp



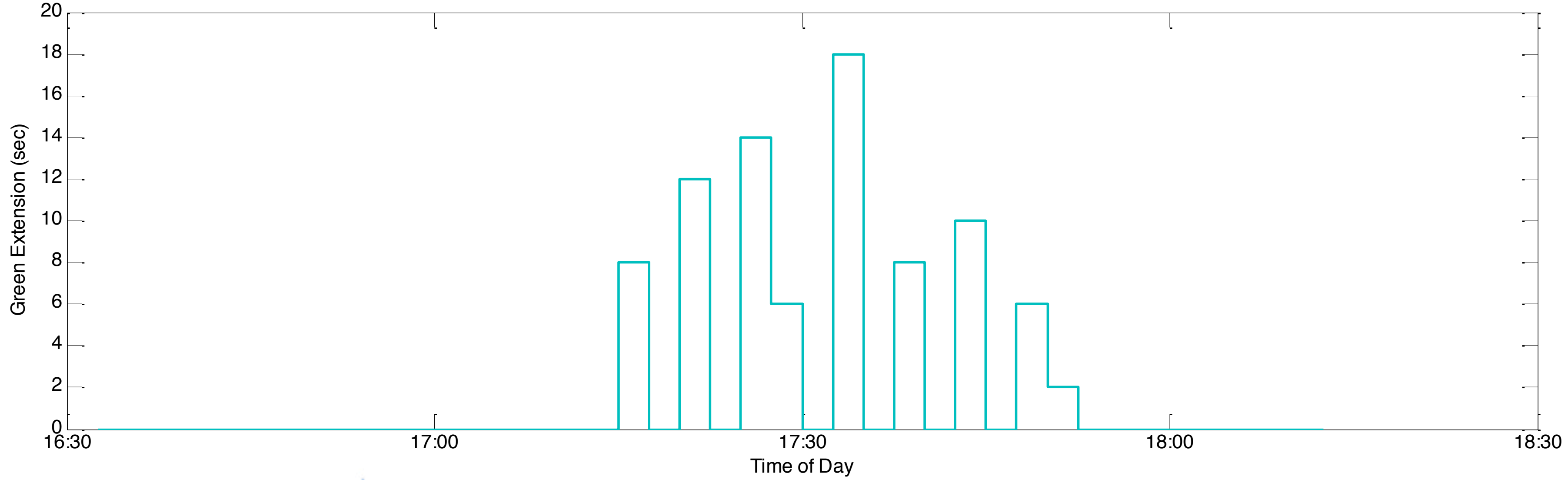
The estimation errors of the off-ramp queue estimation model



Numerical Test

Activation of off-ramp priority control function

Green extension time granted to the off-ramp flows



Numerical Test

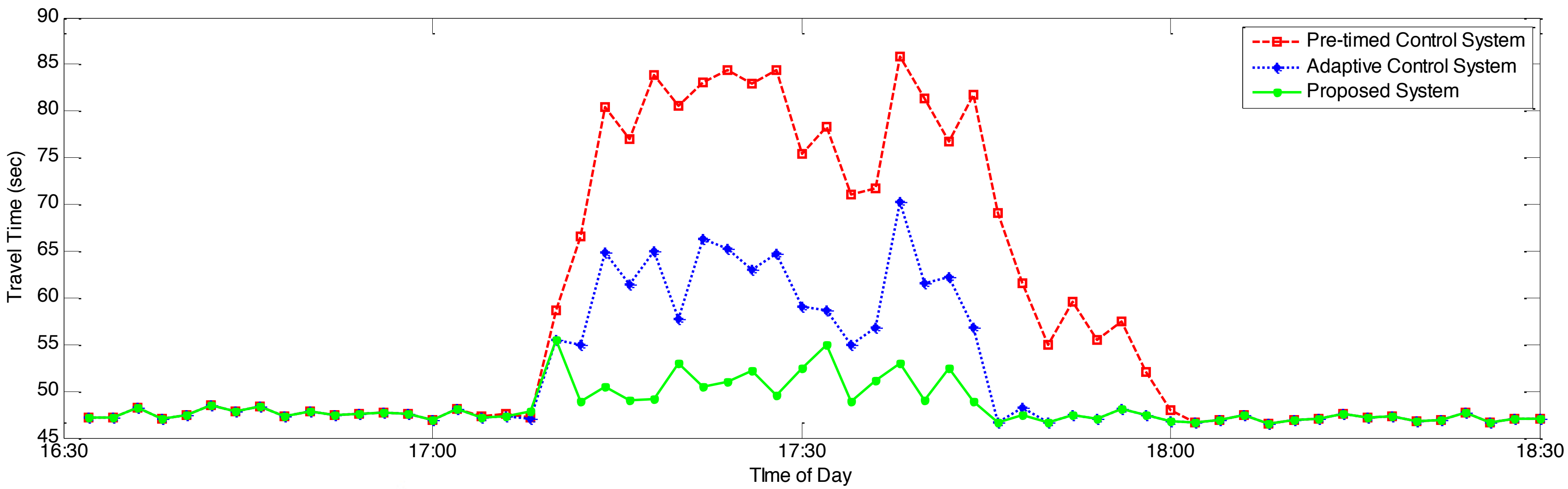
System Evaluation

The following three systems are tested for comparison:

- ❑ Pre-timed Control System: using the proposed pre-timed models to generate the signal plans;
- ❑ Adaptive Control System: only the proposed adaptive signal control model and dynamic signal progression model are implemented;
- ❑ Proposed System: including the off-ramp queue estimation, arterial signal adaptive control, and off-ramp priority control.

Numerical Test

The time-dependent travel time along the freeway mainline



Numerical Test

Network Performance

Performance Index	Pre-timed System	Adaptive System	Proposed System
Ave number of stops	2.391	1.711 (-28.4%)	1.621 (-32.2%)
Ave speed (km/h)	36.116	38.633 (+7.0%)	39.25 (+8.7%)
Ave Network delay (s)	89.065	73.77 (-13.7%)	68.209 (-19.6%)

Outline

1 • Research Background & Literature Review

2 • Primary Tasks & Modeling Framework

3 • System Framework & Model Formulations

4 • Conclusions and Future Research Directions

Conclusions

Summary of Contributions:

- Developed an effective operational framework for the integrated traffic control at the off-ramp interchanged area;
- Constructed a new O-D estimation model with real-time queue information;
- Formulated a signal optimization model to prevent the off-ramp queue spillover;
- Proposed a multi-path progression model to facilitate traffic flows to reach their destinations;
- Advanced all key control models for real-time operations, in response to traffic fluctuations in practice.

Conclusions

Future Research Directions:

- Development of an optimal traffic control model to concurrently account for the delay of traffic flows on the freeway and local arterial;

- Integration of both on-ramp and off-ramp control strategies (ramp metering, variable speed limit, off-ramp priority, local signal adaptive control) for a large-scale corridor traffic management;

- Enhancement of the current real-time signal control system with advanced information/communication technologies (e.g., connected vehicles).

THANKS & Questions?