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AN ARTERIAL-BASED TRANSIT SIGNAL PRIORITY CONTROL SYSTEM

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Motivation

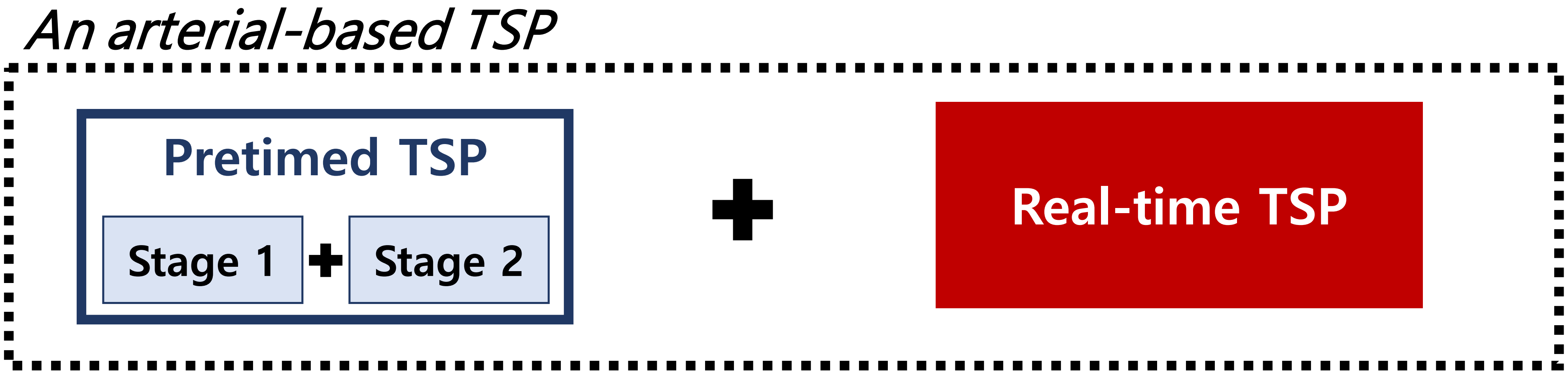
- **Transit Signal Priority (TSP):** one effective strategy to reduce transit delays at urban intersections.
- However, **implementing TSP** along **an arterial under heavy transit flows** remains **quite limited** in state of the practices.
  - **Negative impacts** on the **side-street traffic**
  - Potential **excessive delays** to the **downstream** intersection
  - Operating **costs** and the long-lasting maintenance issues

Objective

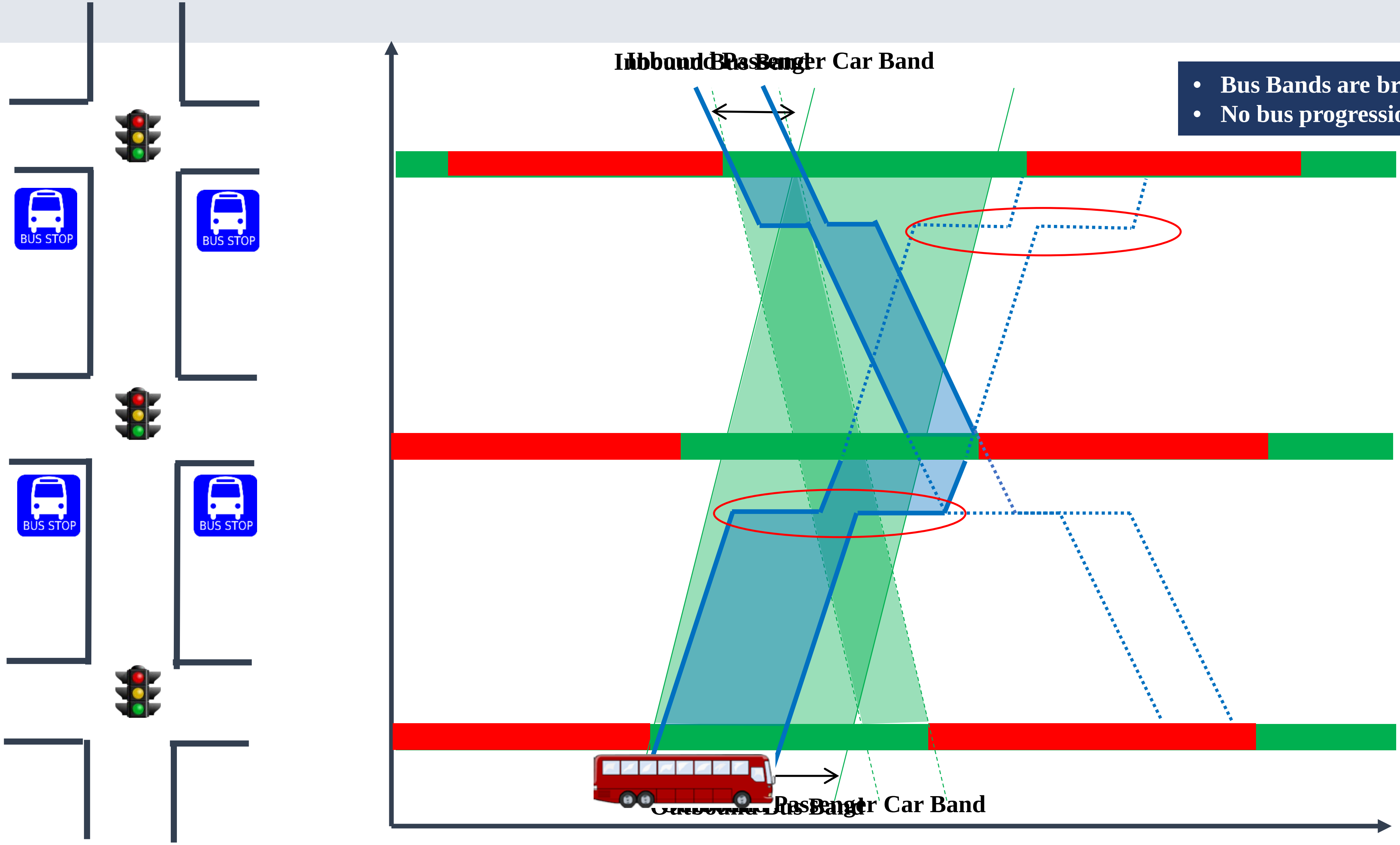
Develop an integrated arterial-based transit signal priority control system for an arterial experiencing heavy transit flows

System Structure

- **System components**
  1. **A pretimed bus-based progression model:** produce a base signal plan for an arterial to minimize real-time TSP activations
  2. **The real-time TSP model:** supplement the arterial-based bus progression at the critical intersections



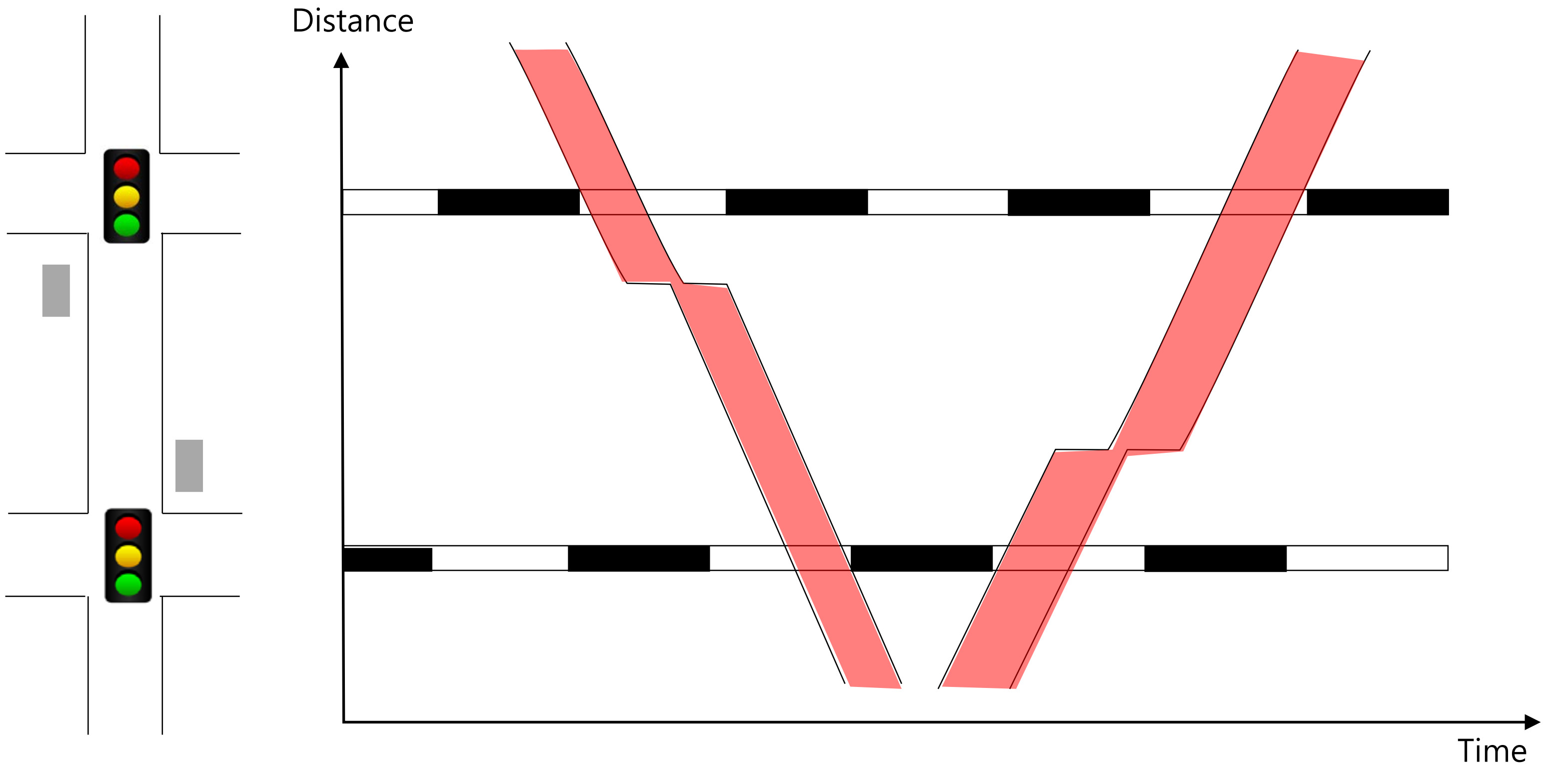
Conventional Two-way Progression



- Bus Bands are broken
- No bus progression over an arterial

Pretimed TSP Module

Stage-1: Design a Set of Bus-based Progression Bands along an Arterial



Critical Issues in Design of Bus-based Progression

Bus
Dwell Time
at Bus Stops

Bus Stop
Location

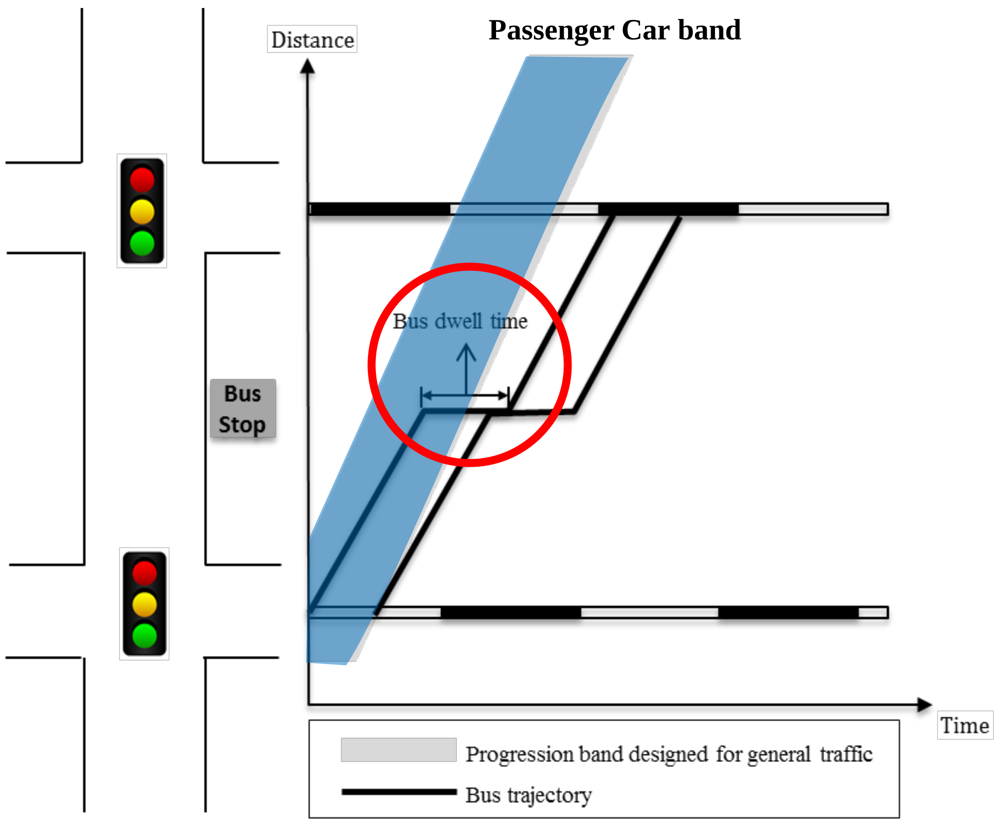
Intersection
Traffic
Queue

Modeling Methodology

Bus Dwell Time at Bus Stops

Bus Stop Location

Intersection Traffic Queue



In design of bus progression, travel times between intersections include bus dwell times at bus stops

Modeling Methodology

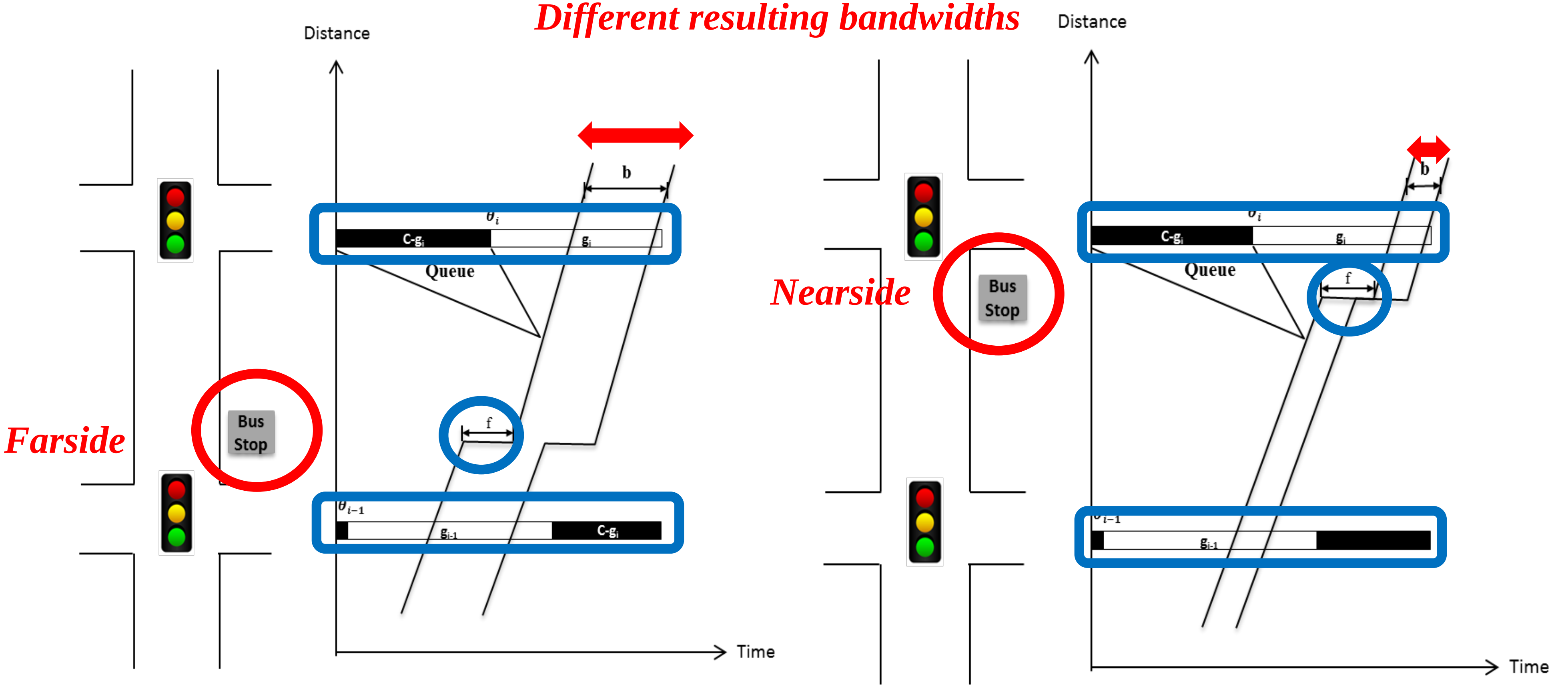
Bus Dwell Time at Bus Stops

Bus Stop Location

Intersection Traffic Queue

The same signal plans and dwell times

Different resulting bandwidths



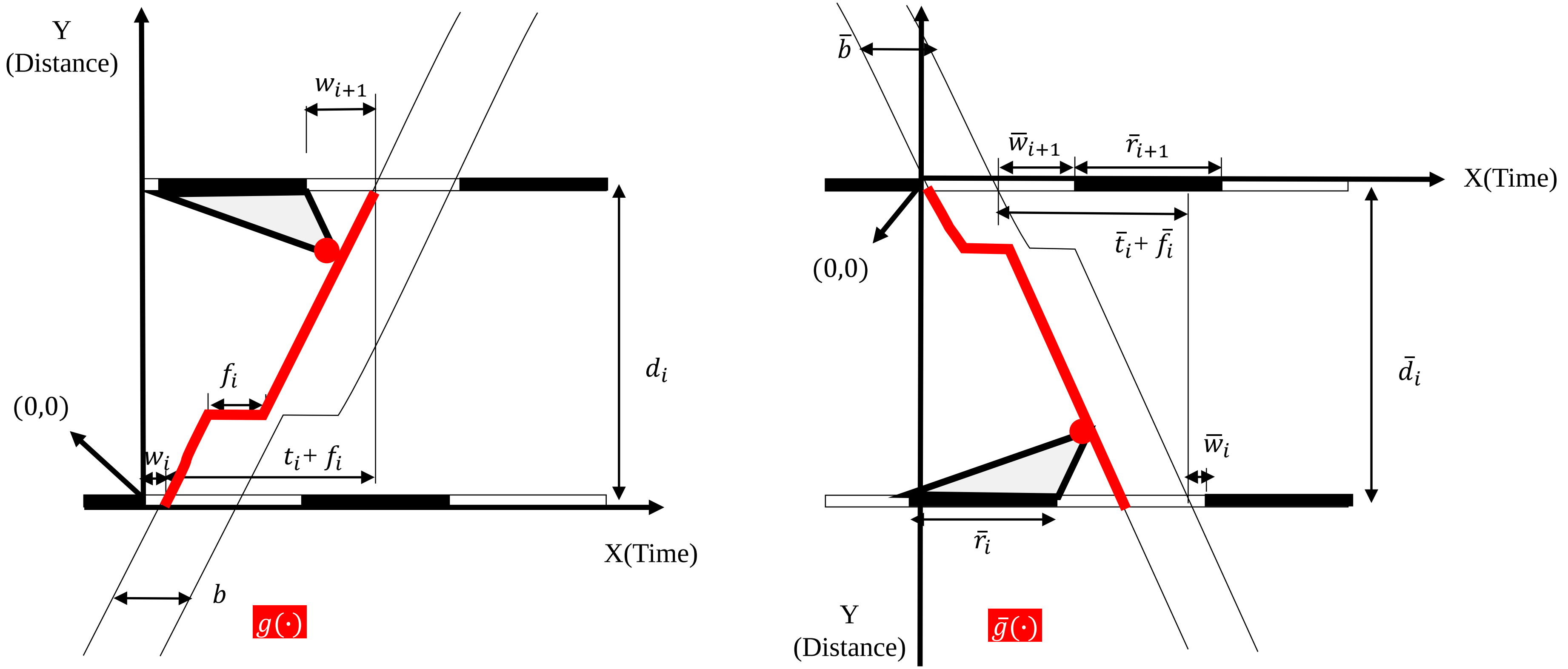
Given signal plans, traffic conditions and dwell times, the optimal bus bandwidths vary with the bus stop location

Modeling Methodology

Dwell Time at Bus stops

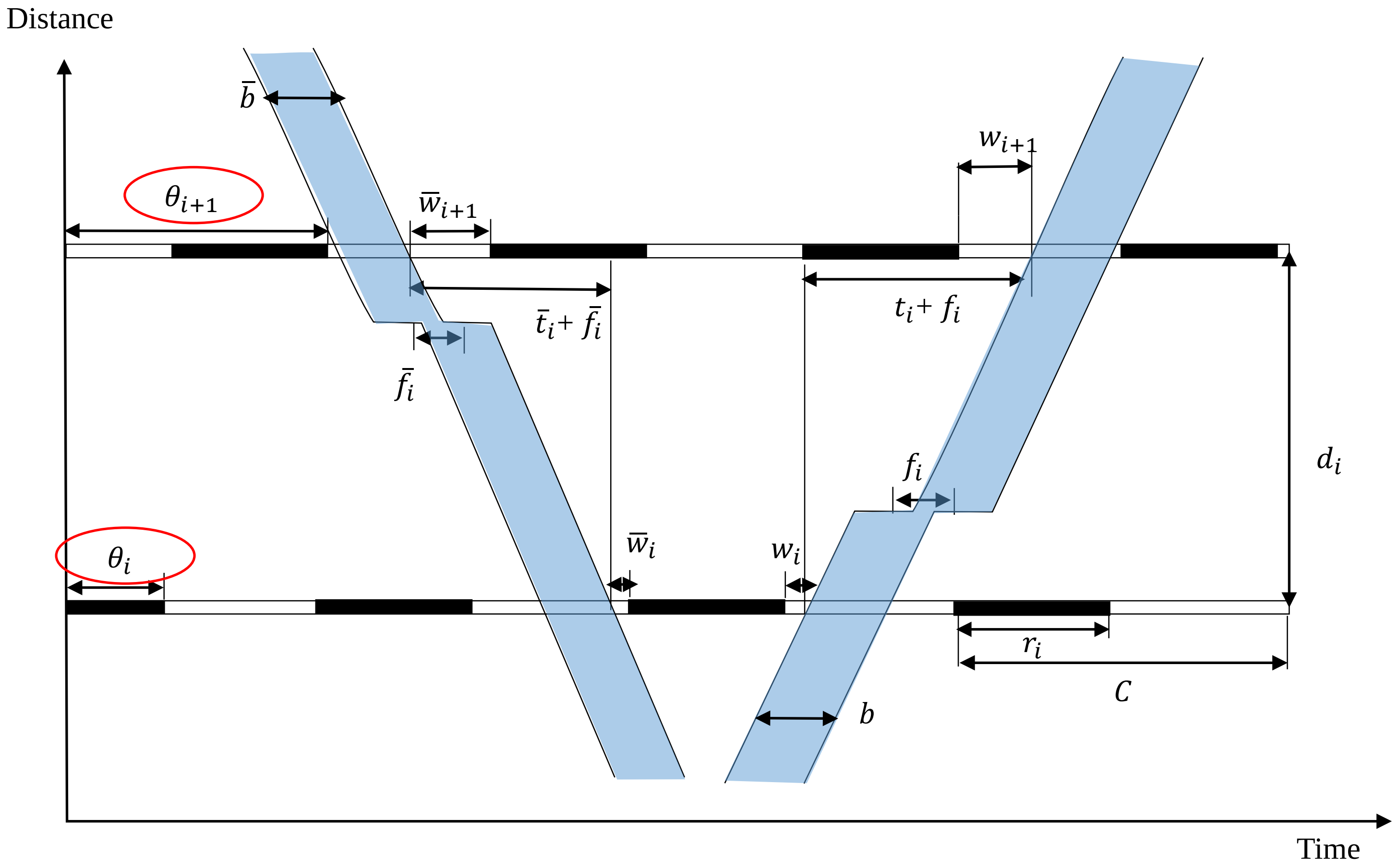
Bus Stop Location

Intersection Traffic Queue



The queue vanish point needs to be located ahead of the left boundary of the bus progression band to avoid interrupting the bus progression.

Pretimed TSP Module, Stage-1



Parameters	
	Number of intersection
	Outbound (inbound) red time at intersection i (cycles)
(	Lower and upper limits on outbound(inbound) speed (feet/second)
(	Lower and upper limits on change in outbound(inbound) speed (feet/second)
()	Average bus running speed between intersection i (i+1) and intersection i+1 (i) (feet/cycles)
()	Average bus dwell time between intersections i (i+1) and i+1 (i) (cycles)
	Distance between intersections i (i+1) and i+1 (i) (feet)
()	Distance from intersection i (i+1) to a bus stop between intersections i (i+1) and i+1 (i) (feet)
()	Queue clearance time at intersection i (cycles)
()	Maximum queue length at intersection i (feet)
(	The distance from intersections i-1(i+1) to the end of maximum queue at intersection i (feet)
z	Inverse of cycle length (1/second)
	Weight factor
M	Large number
Variables	
()	Outbound (inbound) bus bandwidth (cycles)
()	Maximized outbound (inbound) bus bandwidth from Stage-1 (cycles)
	Offset of intersection i (cycles)
()	Interference variables, equals to the time period from right(left) side of red at intersection i to left (right) edge of outbound(inbound) bus band(cycles)
	Loop integer variable for intersection i for the outbound (inbound) of bus band
()	Average bus running time from intersection i (i+1) to intersection i+1 (i) (cycles)
()	A function of left boundary of an outbound(inbound) bus band
(	The time when the queue vanishes at intersection i (cycles)

Pretimed TSP Module, Stage-1

- **Control Objective**

$$Max\ b + k\bar{b}$$

$$(1-k)\bar{b} \geq (1-k)kb$$

- **Constraints**

Interference

$$w_i + b \leq (1 - r_i) \qquad \bar{w}_i + \bar{b} \leq (1 - \bar{r}_i)$$

Loop Integer

$$(w_i + \bar{w}_i) - (w_{i+1} + \bar{w}_{i+1}) + (t_i + f_i + \bar{t}_i + \bar{f}_i) - m_i = (r_{i+1} - r_i)$$

Bus dwell tine

Intersection Queue

$$\varsigma = \left(V \times r + \frac{V \times r}{s} \times V\right) \times L \qquad \tau = \left(V \times r + \frac{V \times r}{s} \times V\right) / s$$

Progression Speed and the Changes in the Speeds

$$\left(\frac{d_i}{u_i}\right) \times z \leq t_i \leq \left(\frac{d_i}{e_i}\right) \times z \qquad \left(\frac{\bar{d}_i}{\bar{u}_i}\right) \times z \leq \bar{t}_i \leq \left(\frac{\bar{d}_i}{\bar{e}_i}\right) \times z$$

$$\left(\frac{d_i}{h_i}\right) \times z \leq \left(\frac{d_i}{d_{i+1}}\right) t_{i+1} - t_i \leq \left(\frac{d_i}{g_i}\right) \times z \qquad \left(\frac{\bar{d}_i}{\bar{h}_i}\right) \times z \leq \left(\frac{\bar{d}_i}{\bar{d}_{i+1}}\right) \bar{t}_{i+1} - \bar{t}_i \leq \left(\frac{\bar{d}_i}{\bar{g}_i}\right) \times z$$

Intersection Queue and Bus Band

$$a_{i+1} = (w_i - w_{i+1}) + t_i + f_i + \tau_{i+1}$$

$$\bar{a}_i = ((1 - r_{i+1}) - \bar{w}_{i+1}) + \bar{t}_i + \bar{f}_i - ((1 - r_i) - \bar{w}_i) + \bar{\tau}_i$$

$$S_{i+1} = d_i - \varsigma_{i+1} \qquad \bar{S}_i = \bar{d}_i - \bar{\varsigma}_i$$

$$g(a_{i+1}) \leq S_{i+1} \qquad -\bar{g}(\bar{a}_i) \leq \bar{S}_i$$

Bus Stop Location and Intersection Traffic Queue

$$g(z_{i+1}) = \begin{cases} v_i \times (z_{i+1} - (w_i)), & w_i \leq z_{i+1} \leq w_i + t_i \times l_i/d_i \\ v_i \times t_i \times l_i/d_i, & w_i + t_i \times l_i/d_i \leq z_{i+1} \leq w_i + t_i \times l_i/d_i + f_i \\ v_i \times (z_{i+1} - (w_{i1} + f_i)), & w_i + t_i \times l_i/d_i + f_i \leq z_{i+1} \end{cases}$$

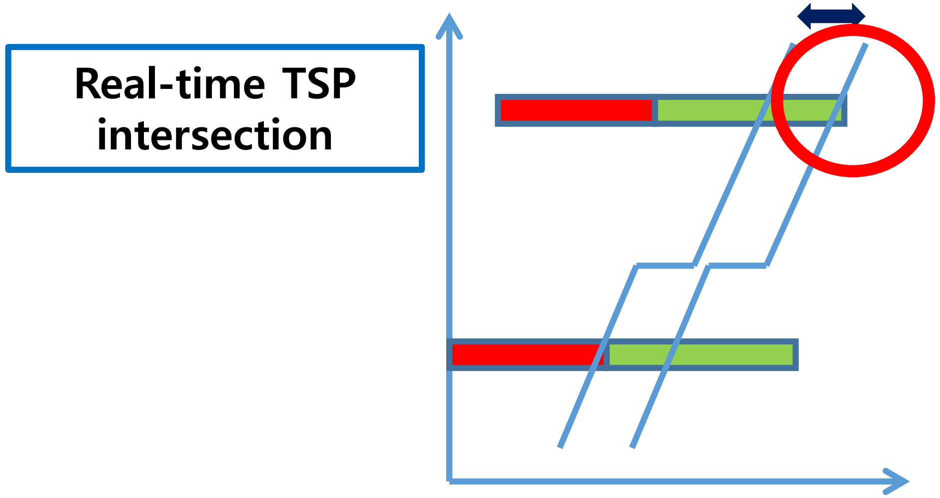
$$\bar{g}(z_i) = \begin{cases} -\bar{v}_i \times (z_i - (1 - \bar{r}_{i+1} - \bar{w}_{i+1})), & 1 - \bar{r}_{i+1} - \bar{w}_{i+1} \leq z_i \leq 1 - \bar{r}_{i+1} - \bar{w}_{i+1} + \bar{t}_i \times \bar{l}_i/\bar{d}_i \\ -\bar{v}_i \times \bar{t}_i \times \bar{l}_i/\bar{d}_i, & 1 - \bar{r}_{i+1} - \bar{w}_{i+1} + \bar{t}_i \times \bar{l}_i/\bar{d}_i \leq z_i \leq 1 - \bar{r}_{i+1} - \bar{w}_{i+1} + \bar{t}_i \times \bar{l}_i/\bar{d}_i + \bar{f} \\ -\bar{v}_i \times (z_i - (1 - \bar{r}_{i+1} - \bar{w}_{i+1} + \bar{f}_i)), & 1 - \bar{r}_{i+1} - \bar{w}_{i+1} + \bar{t}_i \times \bar{l}_i/\bar{d}_i + \bar{f}_i \leq z_i \end{cases}$$

The Boundary of the Bus Progression Band

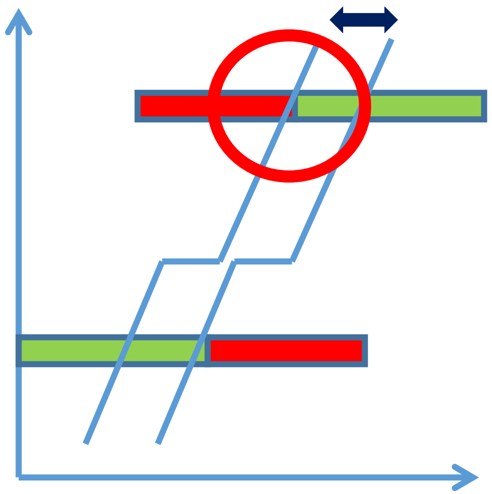
Pretimed TSP Module, Stage-2

Multiple optimal solutions from the model in stage-1

Different impacts of green extension and red truncation on non-priority movements.



Likelihood of having more green extensions



Likelihood of having more red truncations

Pretimed TSP Module, Stage-2 ➡ *BUSBAND*

Multiple optimal solutions from the model in stage-1

Different impacts of green extension and red truncation on non-priority movements.

Enhance the model to reduce the potential TSP activations having worse impacts on non-priority movements

Estimate the negative impact of the green extension or red truncation on the non-priority movements

Identify the transit priority type with the larger negative impact

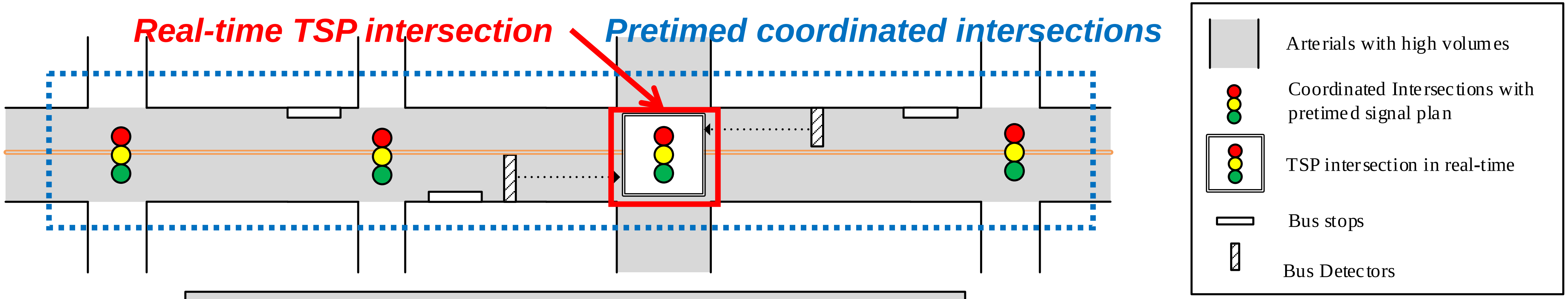
Adjust the model from Stage-1 to minimize the activation of the less favorable type

If red truncation is less favorable, max $\theta_{k-1}-\theta_k+(\theta_{k+1}-\theta_k)$

If green extension is less favorable, min $\theta_{k-1}-\theta_k+(\theta_{k+1}-\theta_k)$

$$b \geq b_m, \bar{b} \geq \bar{b}_m$$

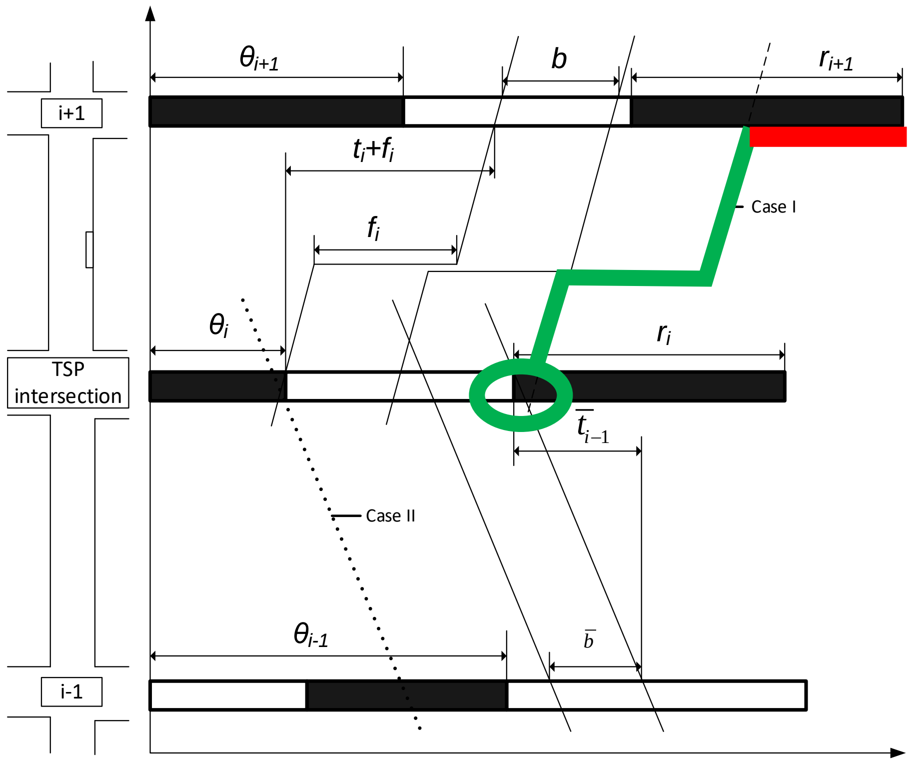
System Structure



An arterial-based TSP	
Pretimed TSP	**Real-time TSP**
Stage 1 Facilitate bus progression • Bus dwell time • Initial traffic queue • Bus stop location Stage 2 Avoiding activations of the less favorable priority type by adjusting offsets	Active rule-based TSP • Green extension and red truncation • Effectiveness of activations based on offsets • Activations in the previous cycle • Number of buses arriving in the red phase

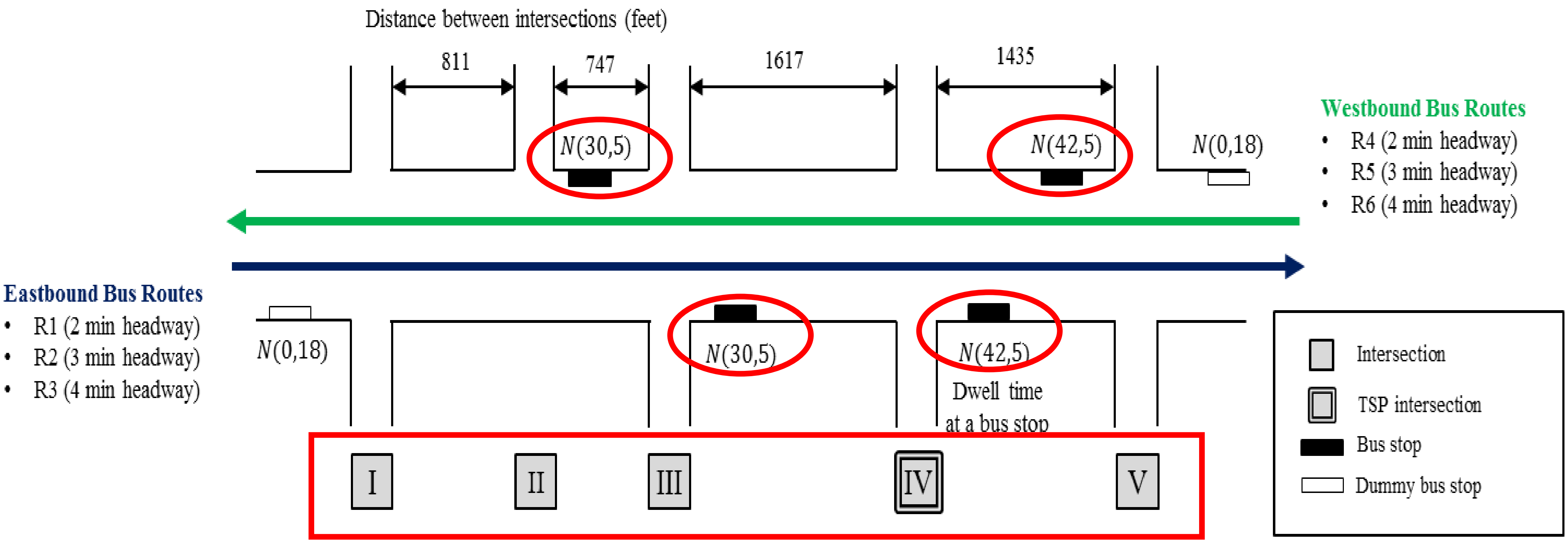
Real-Time TSP Module (Rule-based Strategy)

- ***R1: Execute the TSP only if the reduced delay would not be transferred into extra waiting time at the downstream intersection***
- ***R2: Do not execute the same type of TSP in consecutive cycles***
- ***R3: Activate the red truncation only if at least two buses are detected to have the benefits from the execution***



Case Study

❑ An arterial segment on Dongzhimenwai Road in Beijing, CHINA



< Geometry and bus operations >

Experimental Analyses

❑ Model Comparison

1. **MULTIBAND - TSP 1: Conditional TSP on MULTIBAND signal plan**
2. **MULTIBAND - TSP 2: Unconditional TSP on MULTIBAND signal plan**
3. **BUSBAND: The proposed bus-based progression model without real-time TSP**
4. **BUSBAND with TSP: The proposed real-time TSP on BUSBAND signal plan**

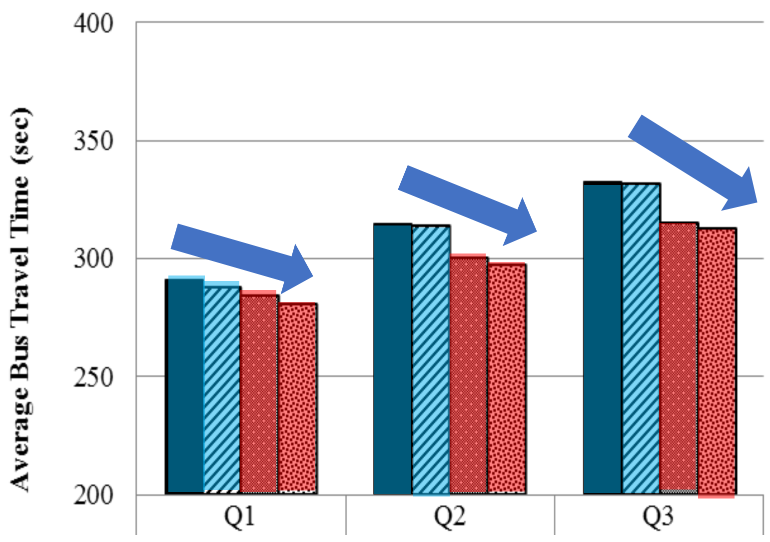
❑MOEs

- **Average and variance of bus travel times along the arterial**
- **Delays at the TSP intersection and along the entire arterial**
- **Total person delay along the arterial**

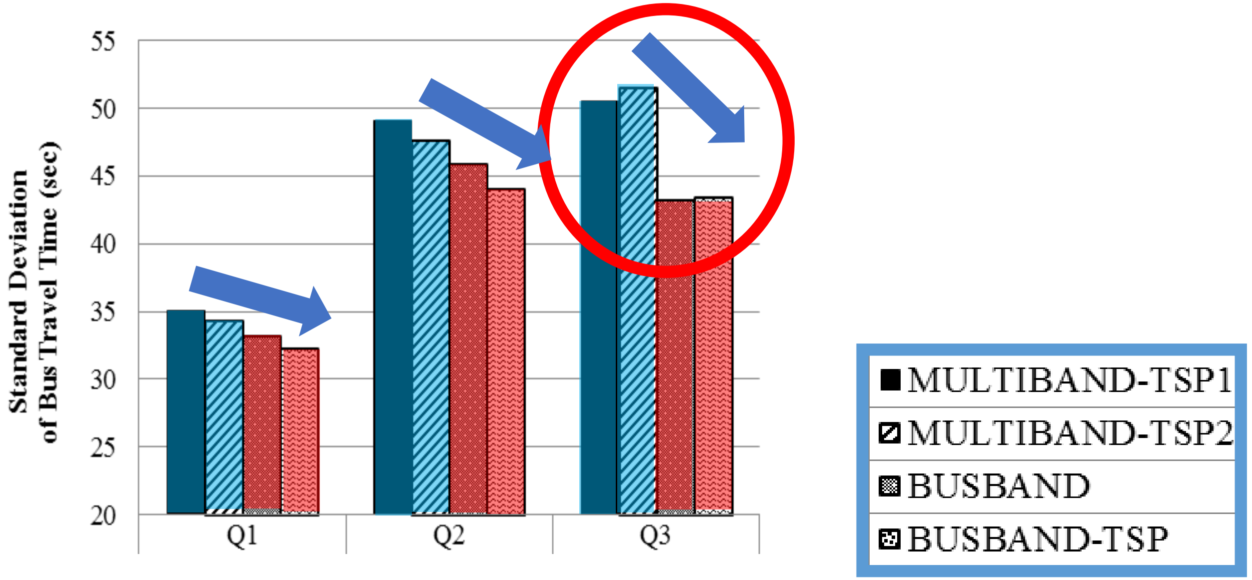
** This study adopts VISSIM as an unbiased traffic simulation tool, and the active TSP are implemented with COM interface and Visual Basic code.*

Experimental Analyses

❑Average bus travel times and standard deviations along the arterial



< Average Bus Travel Time >

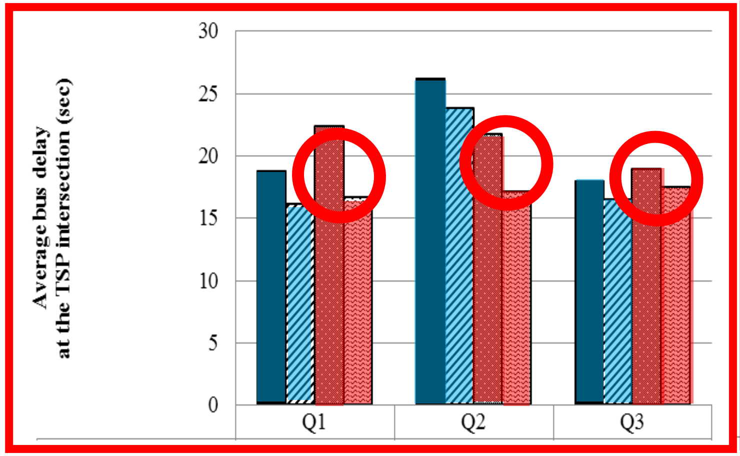


< Standard Deviations of Bus Travel Time >

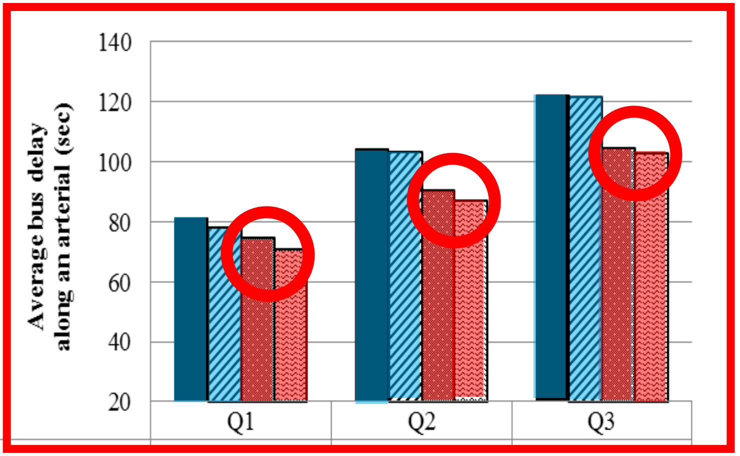
- **BUSBAND and BUSBAND+TSP** outperform **MULTIBAND + TSP** on
  - reducing travel times
  - lowering travel time standard deviations (results in a lower headway variation of buses along the arterial)

Experimental Analyses

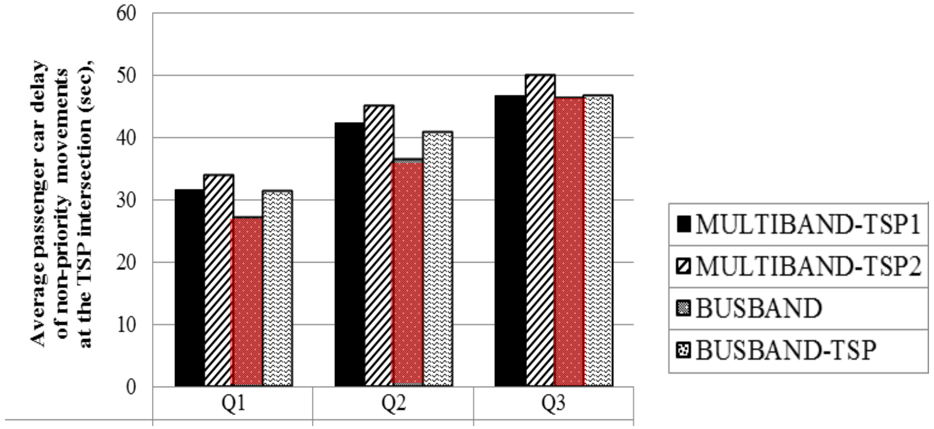
❑Delays at the TSP intersection and along the arterial



< Bus delays
at the active TSP intersection >



< Bus delay along an arterial>

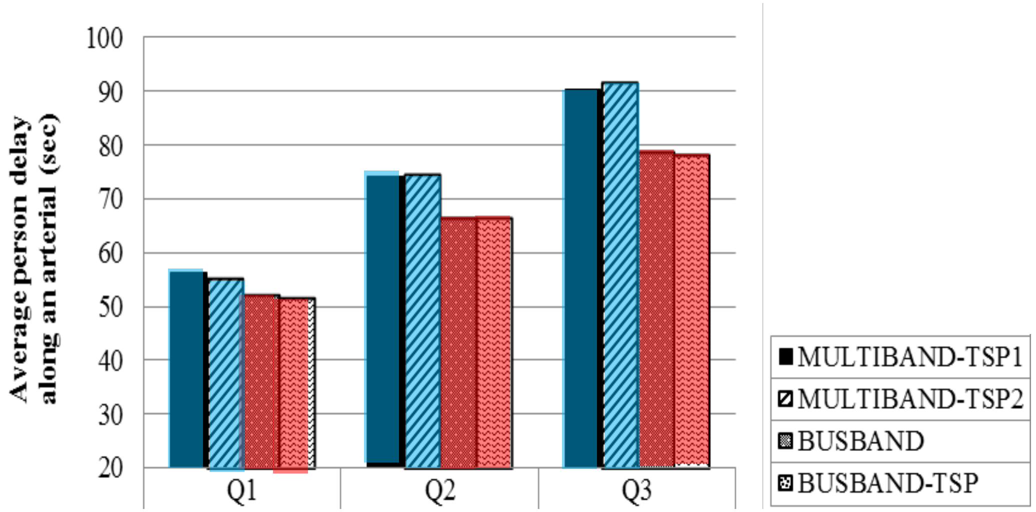


< Passenger car delay
of non-priority movements
at the active TSP intersection >

- **BUSBAND** outperforms **MULTIBAND+TSPs** with respect to **bus delays along the arterial**. **BUSBAND+TSP** yields even lower bus delays.
- BUSBAND-only shows the lowest average delay on non-priority movements at the TSP intersection.

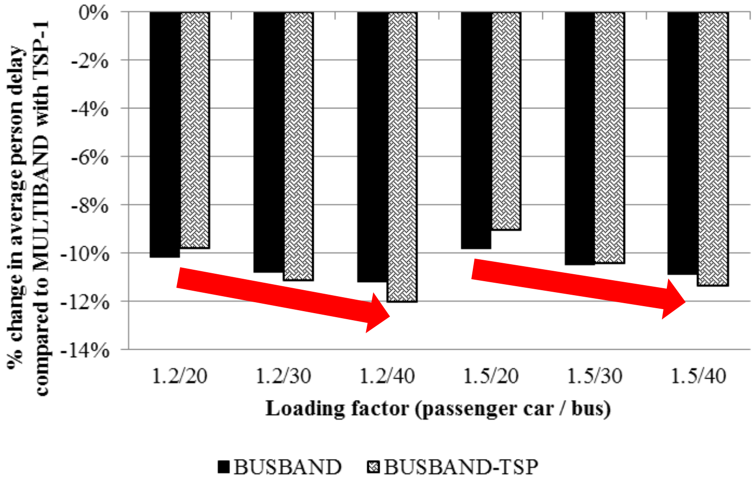
Experimental Analyses

❑Total person delay along the arterial



** loading factor of passenger cars and buses: 1.5 and 30*

< Average person delays along an arterial >



< Sensitivity of average person delays along an arterial on loading factors >

- **BUSBAND and BUSBAND+TSP outperform MULTIBAND+TSPs on reducing the average person delay.**
- **BUSBAND and BUSBAND+TSP can contribute more to the reduction of average person delay under higher bus loading factors.**

Conclusions

- This study has proposed **a TSP system for an arterial with heavy transit flows**
  - **The base signal plan for bus progression**
    - Stage-1 is to **maximize the two-way bus bandwidth** considering the bus stop location and the initial traffic queues at intersections;
    - Stage-2 designs to **identify the most favorable local TSP strategy at critical intersections from the multiple sets of non-inferior bus progression offsets**.
  - **Rule-based TSP control for buses at critical intersections in real time**
    - **Based on the effectiveness of activations**, the state of activation in the previous cycle, and the number of arriving buses during the red phase.

Conclusions

- The results of case study show that the proposed system is able to
  - **improve the bus performance** with lower and more stable travel times **along an arterial**
  - **cause less negative impacts** on traffic in the non-priority movements at TSP intersections.

Conclusions

- Further research
  - A guideline to select the control objective in design of signal progression for a given set of geometric and traffic conditions
    - Bus-based progression, passenger car progression, and concurrent progression
  - A reliable method to determine the optimal locations to implement active TSP

THANK YOU

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