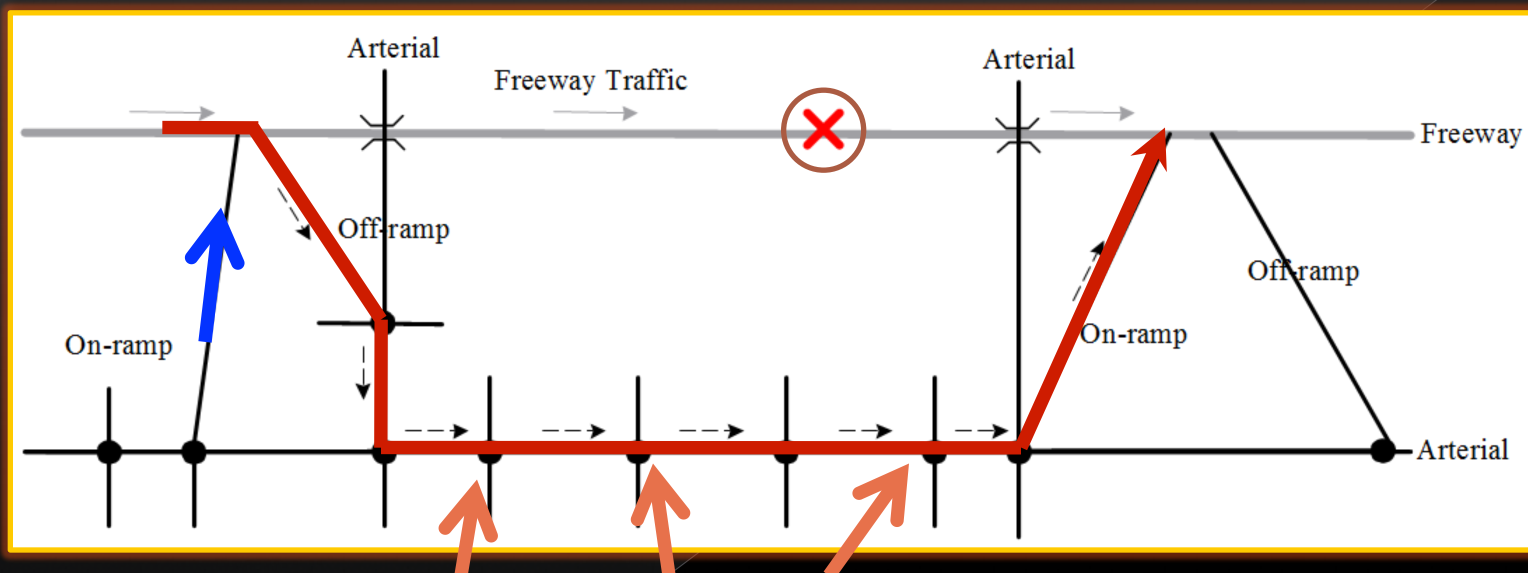
An Integrated Traffic Control System for Urban Freeway Corridors under Non-recurrent Congestion

Non-recurrent Congestion & Potential Solutions

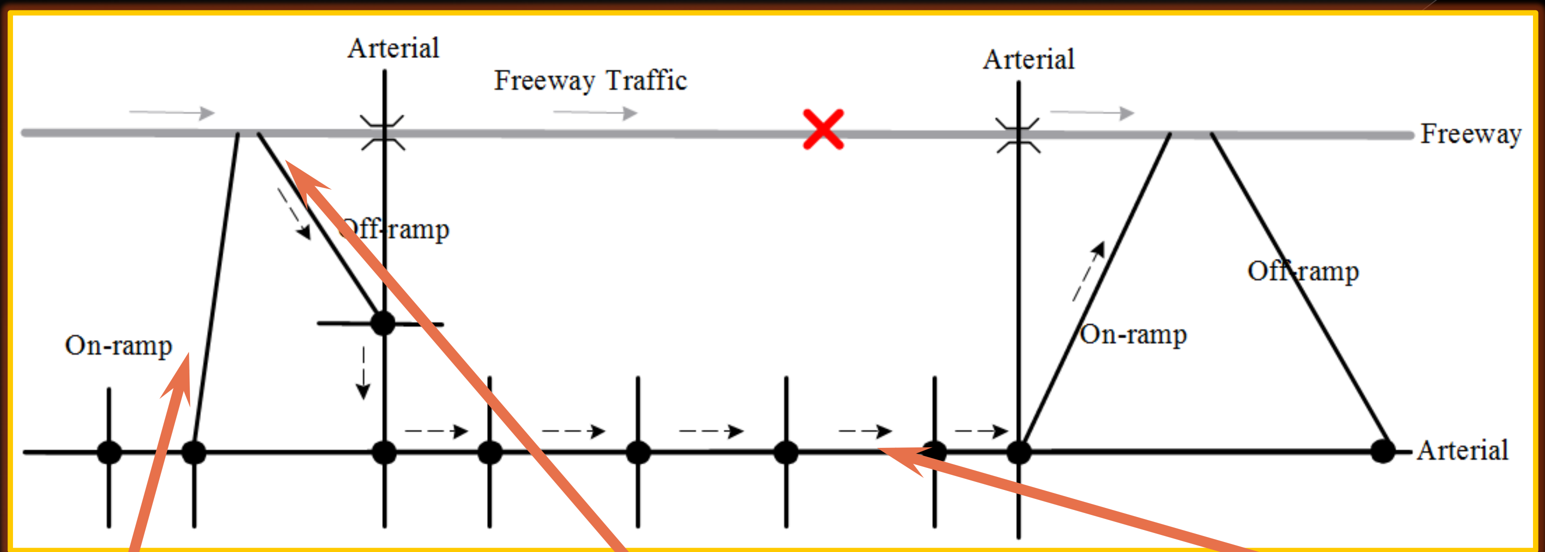
A Urban Freeway Corridor System



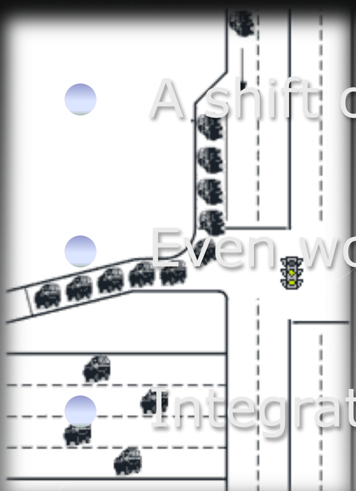
Potential Solutions III – Arterial Signal Optimization

- -Reduce stops, delays, and queuing
- -Improve Level of Service at Intersections

New Problems Arising !

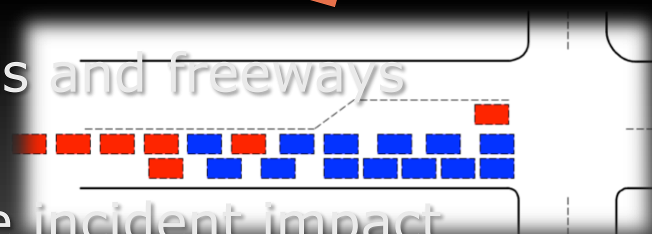


- A shift of congestion between arterials and freeways
- Even worse traffic conditions than the incident impact
- Integrated control strategies need to be developed



A. On-ramp Spillback

B. Off-ramp Congestion



C. Arterial Spillback and Blockages

Outline

- Critical issues in developing an integrated traffic control system for non-recurrent congestion management
- Findings of Literature Review
- Primary Research Tasks and Modelling Framework
- Model Development
- Summary and Future Research

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Critical Issues of the Integrated Control

I – How to choose proper control boundaries?

II – How to model dynamic traffic flow evolutions along the corridor network?

III – How to capture the interaction between freeway and arterial?

IV – How to design diversion control strategies in response to time-varying traffic conditions?

V – How to update ramp metering and signal timing plans to prevent the formation of local bottlenecks?

VI – How to solve the optimization model efficiently for real-time operations?

Critical Issues of the Integrated Control

I – How to choose proper control boundaries?

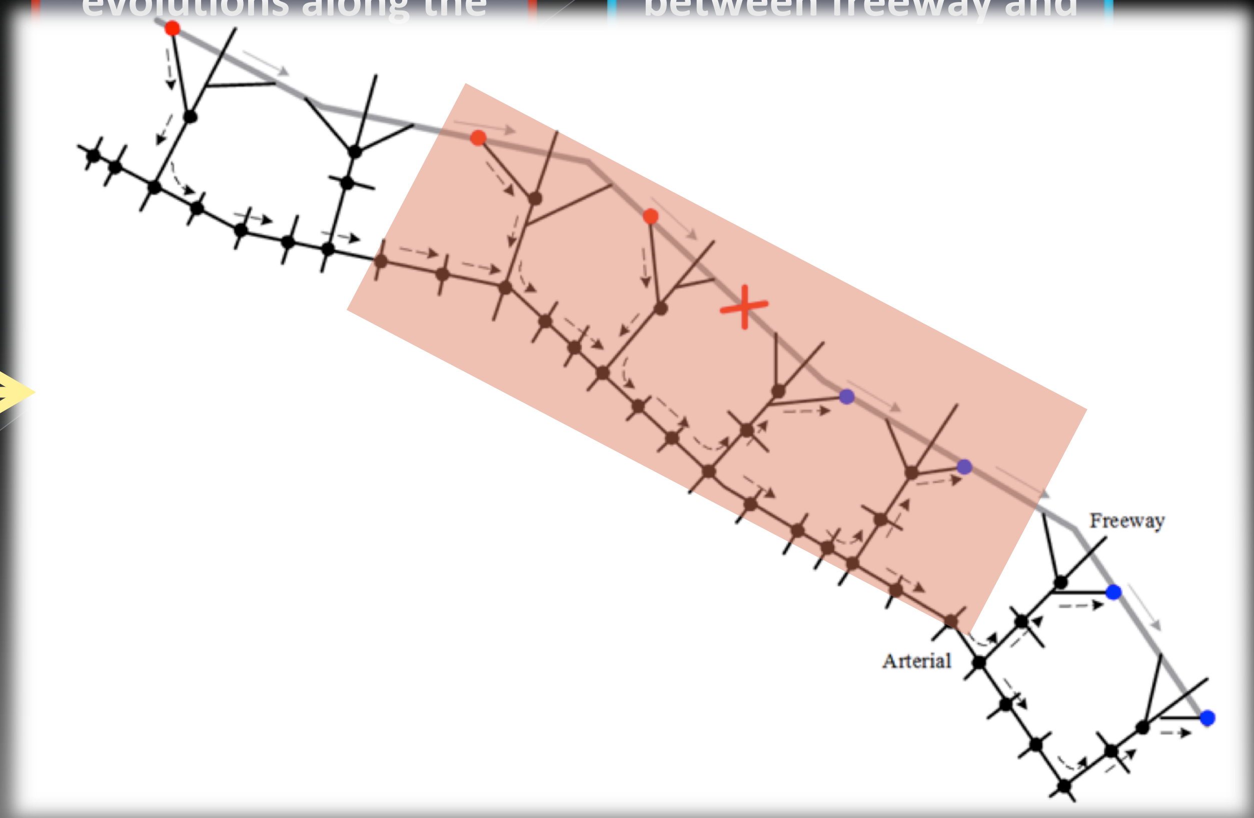
-Incident nature, available corridor capacity

-Trade-off between freeway and arterial system

II – How to model dynamic traffic flow evolutions along the

III – How to capture the interaction between freeway and

IV – How to design diversion control strategies in response to time-varying traffic conditions?



Critical Issues of the Integrated Control

-Interaction with Control Variables

-Traffic State Prediction and Estimation (constraints)

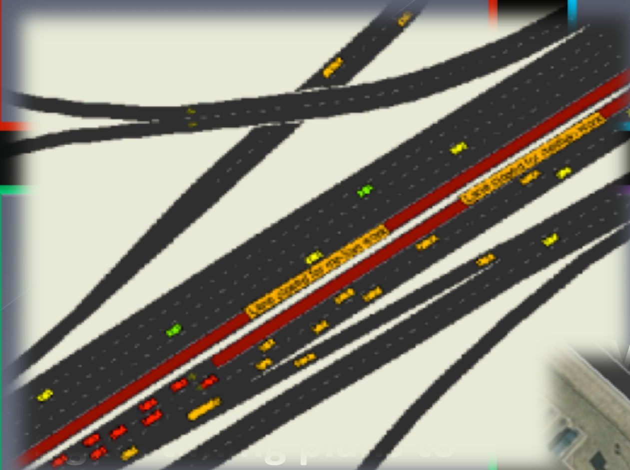
-System Performance (objective function)

I – How to choose proper control boundaries?

II – How to model dynamic traffic flow evolutions along the corridor network?

III – How to capture the interaction between freeway and arterial?

IV – How to design diversion control strategies in response to time-varying traffic conditions?



prevent the formation of local bottlenecks?

VI – How to solve the

Critical Issues of the Integrated Control

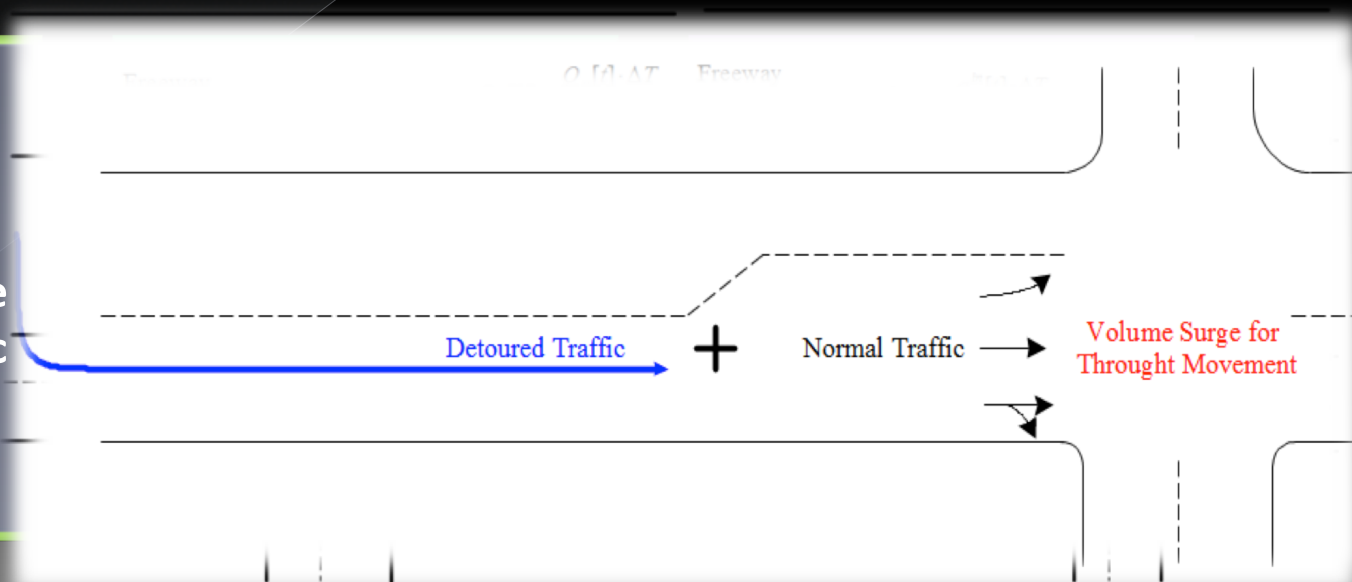
I – How to choose proper control boundaries?

II – How to capture dynamic traffic flow evolutions along the corridor network?

Project the time-varying impact of detoured traffic on existing traffic patterns

the interaction between freeway and arterial?

IV – How to design diversion control strategies in response to time-varying traffic conditions?



Critical Issues of the Integrated Control

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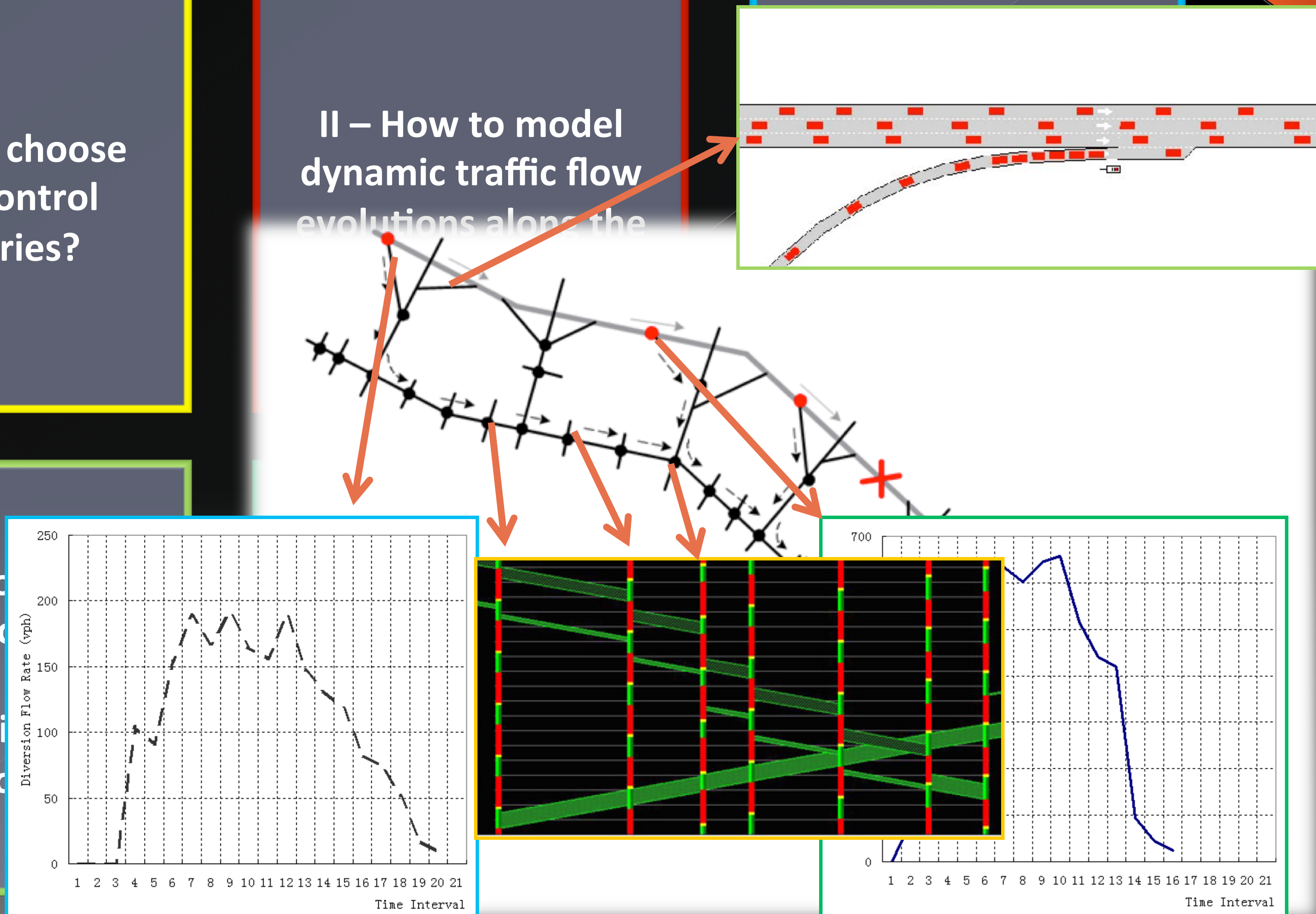

Critical Issues of the Integrated Control

I – How to choose proper control boundaries?

II – How to model dynamic traffic flow evolutions along the corridor network?

III – How to capture the interaction between freeway and arterial?

IV – How to design diversion control strategies in response to time-varying traffic conditions?

Outline

- Critical issues in developing an integrated traffic control system for non-recurrent congestion management
- Findings of Literature Review
- Primary Research Tasks and Modelling Framework
- Model Development
- Summary and Future Research

Findings of Literature Review

- Limited research has been done regarding determining the control boundaries for integrated corridor control
- Simplified network flow formulations
  - Queue arrival and departure with respect to different types of intersection lane channelization
  - Intersection signal timing – oversimplified, multiple phases, synchronization
- Interactions between the freeway and arterial
  - Flow exchanges at on-off ramps
  - The dynamic impact of detoured traffic on existing demand patterns
- Lack of consideration on local bottlenecks during severe congestion (e.g. turning bay spillback and blockages)
- The multi-objective nature of the integrated control has not been fully addressed

Outline

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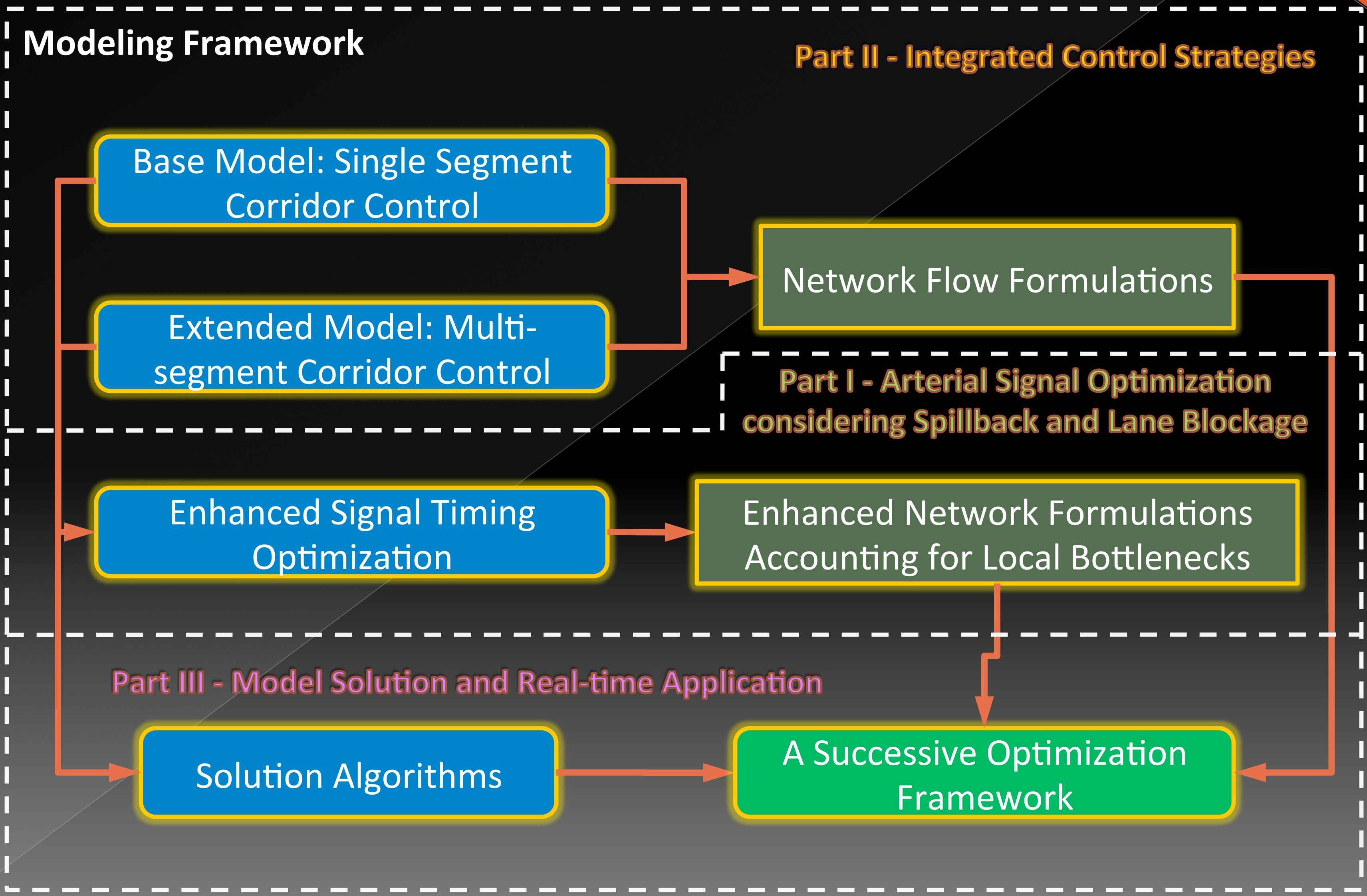
Primary Research Tasks and Modeling Framework



Outline

- Critical issues in developing an integrated traffic control system for non-recurrent congestion management
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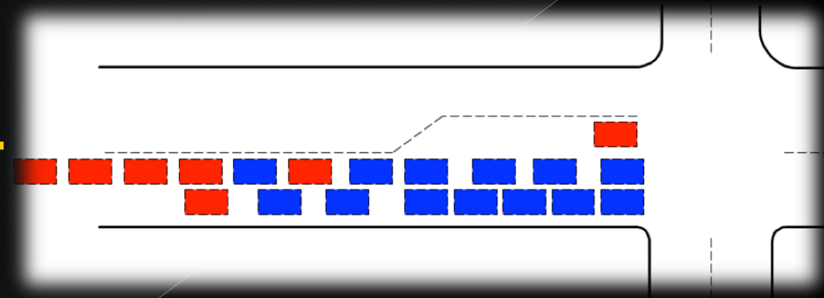
Part I - An Enhanced Arterial Signal Optimization Model

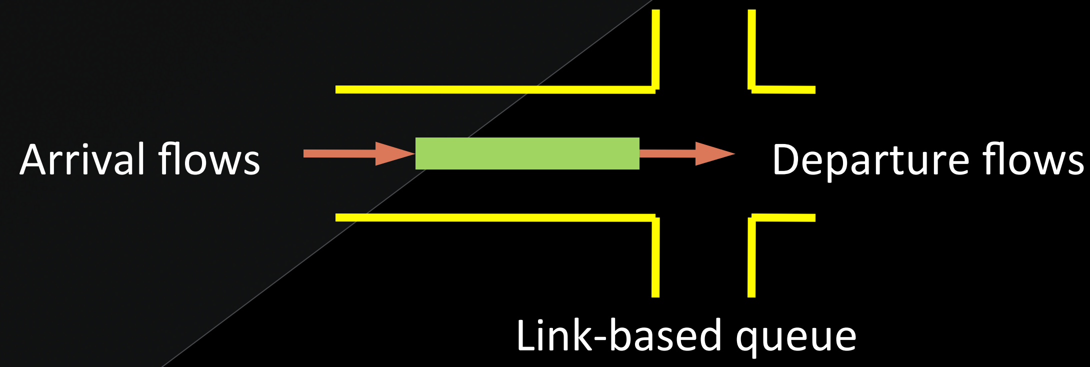
Task 1
An Arterial Network Flow Model to account for Local Bottlenecks (Spillback and Lane Blockage)



Task 2
Traffic Signal Timing Enhancement for Local Bottleneck Management

Task 1: Arterial Network Flow Formulations

A link-based model



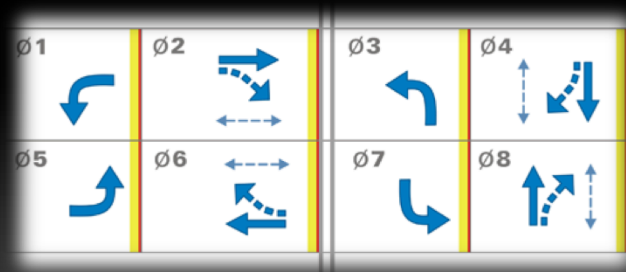
Basic Concept

-Discrete Time Steps

-Dynamic State Equations

-Queue Evolution

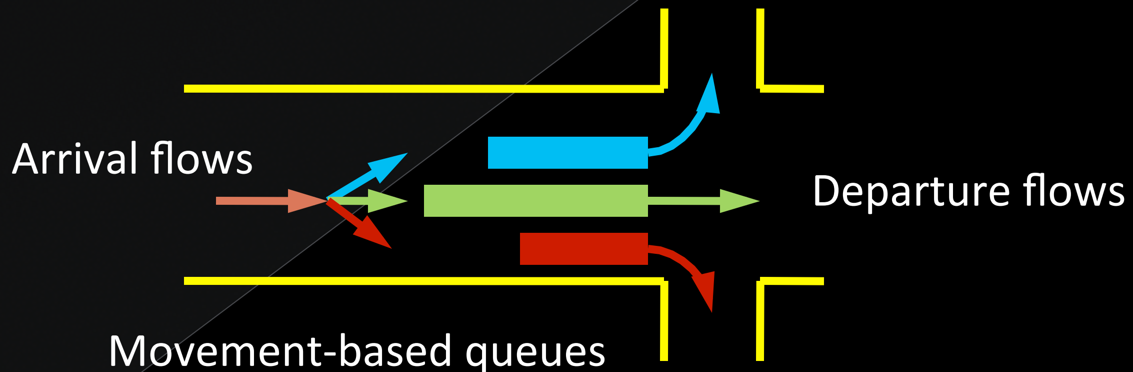
?

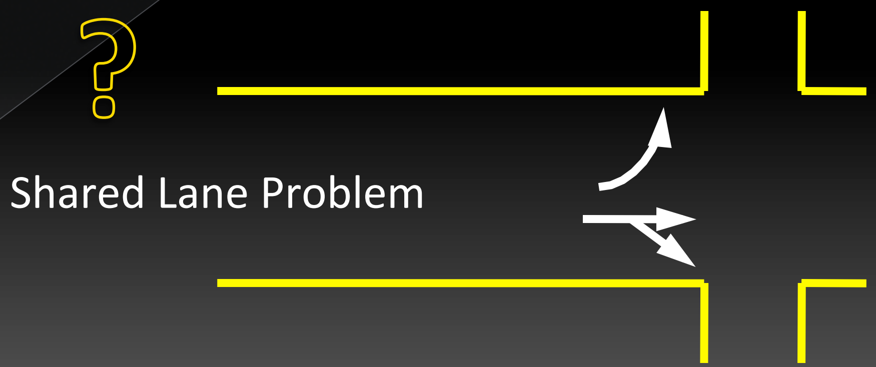


Limitation: Not compatible with multiple phase

Task 1: Arterial Network Flow Formulations

A movement-based model





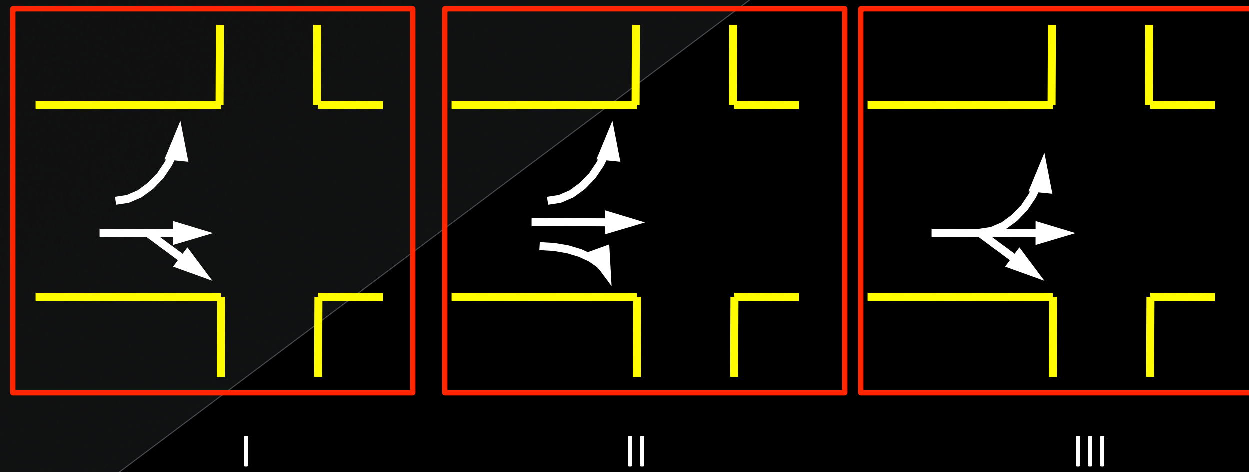
Limitation: Inaccurate modeling of traffic flow discharge process at shared lanes

Task 1: Arterial Network Flow Formulations

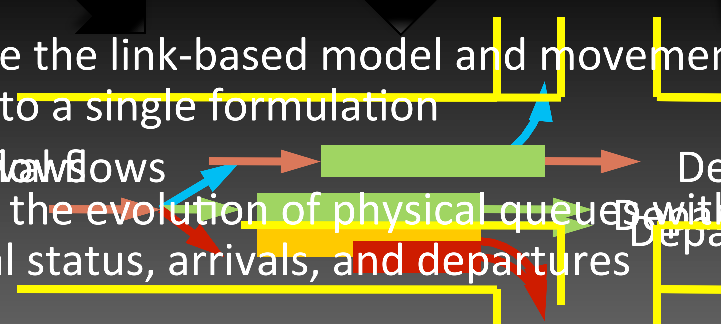
Is it possible to use a single formulation to address all above issues?

Task 1: Arterial Network Flow Formulations

The proposed solution:
A lane-group-based model



Key Features



-Integrate the link-based model and movement-based model into a single formulation

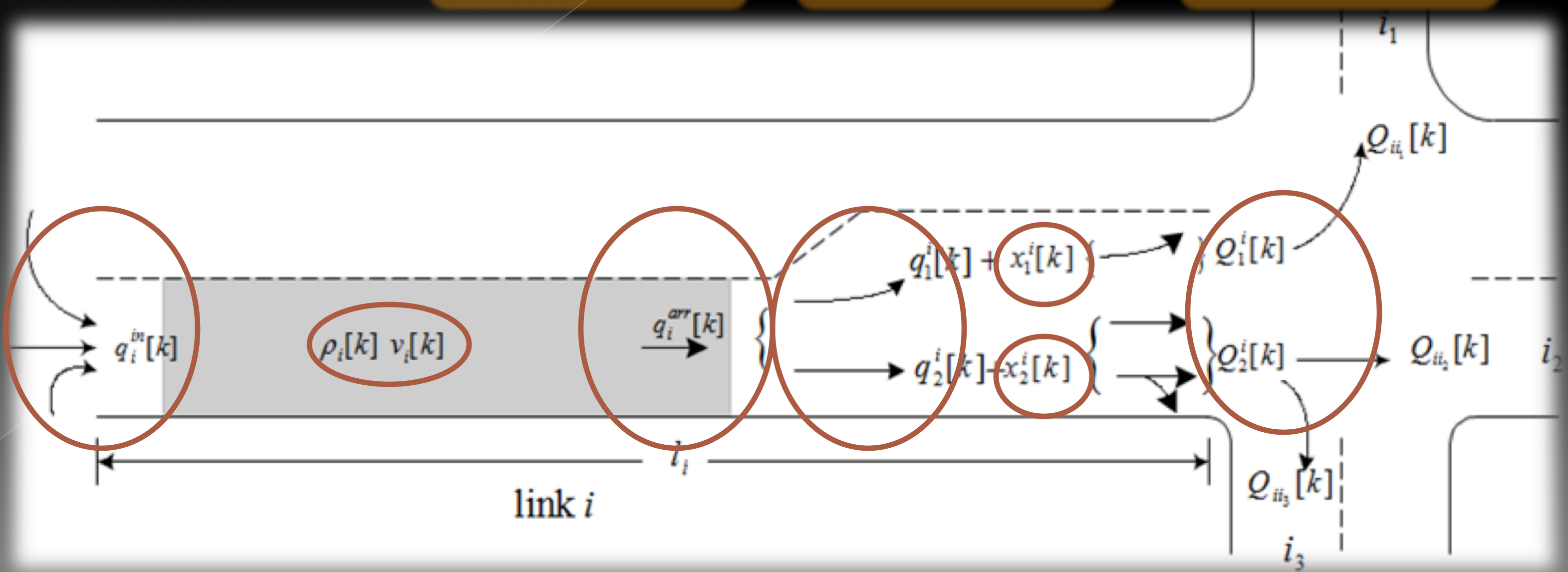
-Capture the evolution of physical queues with respect to the signal status, arrivals, and departures

-Provide better accuracy for modeling arrival and departure process at shared approach lanes

Task 1: Arterial Network Flow Formulations

Model Development

Demand Origins	Upstream Arrivals	Approach the End of Queue
Merge into Lane Groups	Departure	Flow Conservation



Task 1: Arterial Network Flow Formulations

Key Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum\nolimits_{j\in\Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k]\cdot\Delta t$$

Approach the End of Queue

$$v_i[k] = v^{\min} + (v_i^{free} - v^{\min})\cdot\left[1 - \left(\frac{\rho_i[k]}{\rho^{jam}}\right)^{\alpha}\right]^{\beta}$$

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i(l_i - \frac{x_i[k]}{n_i\rho^{jam}})}$$

$$q_i^{arr}[k] = \min\{\rho_i[k]\cdot v_i[k]\cdot n_i\cdot\Delta t, N_i[k] - x_i[k]\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} q_i^{arr}[k]\cdot\gamma_{ij}[k]\cdot\delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m\in S_i^M} \min\{q_m^i[k] + x_m^i[k], Q_m^i\cdot g_n^p[k]\}\cdot\lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij}\cdot\gamma_{ij}[k]}{\sum_{j\in\Gamma^{-1}(i)}\delta_m^{ij}\cdot\gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i\in\Gamma(j)} Q_{ij}^{pot}[k]}\cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]\cdot\delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m\in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j\in\Gamma(i)} Q_{ji}[k] - \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Task 1: Arterial Network Flow Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t} \right]$$

Flow rate entering downstream link i from demand entry r

Demand flow rate at entry r

Existing queued vehicles (in the unit of veh/h) at entry r

Discharge capacity of link i

Available space of link i (in the unit of veh/h)

Task 1: Arterial Network Flow Formulations

Demand Origins

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

- $w_r[k+1]$: Queue waiting at entry r at step k+1 (vehs)
- $w_r[k]$: Queue waiting at entry r at step k (vehs)
- $d_r[k]$: Demand flow rate at entry r at step k (veh/h)
- $q_r[k]$: Flow rate entering downstream link i from demand entry r (veh/h)

Task 1: Arterial Network Flow Formulations

Key Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j\in\Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k]\cdot\Delta t$$

Approach the End of Queue

$$v_i[k] = v^{\min} + (v_i^{free} - v^{\min})\cdot\left[1 - \left(\frac{\rho_i[k]}{\rho^{jam}}\right)^{\alpha}\right]^{\beta}$$

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i(l_i - \frac{x_i[k]}{n_i\rho^{jam}})}$$

$$q_i^{arr}[k] = \min\{\rho_i[k]\cdot v_i[k]\cdot n_i\cdot\Delta t, N_i[k] - x_i[k]\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} q_i^{arr}[k]\cdot\gamma_{ij}[k]\cdot\delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m\in S_i^M}\min\{q_m^i[k] + x_m^i[k], Q_m^i\cdot g_n^p[k]\}\cdot\lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij}\cdot\gamma_{ij}[k]}{\sum_{j\in\Gamma^{-1}(i)}\delta_m^{ij}\cdot\gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i\in\Gamma(j)} Q_{ij}^{pot}[k]}\cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]\cdot\delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m\in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j\in\Gamma(i)} Q_{ji}[k] - \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Task 1: Arterial Network Flow Formulations

Upstream Arrivals

For Internal Links

$$q_i^{in}[k] = \sum_{j \in \Gamma(i)} Q_{ji}[k]$$

Upstream inflow of link i at step k (vehs)

Set of upstream links of link i

Flow actually depart from link j to link i at step k (vehs)

Task 1: Arterial Network Flow Formulations

Upstream Arrivals

For source Links

$$q_i^{in}[k] = q_r[k] \cdot \Delta t$$

Upstream inflow of link i at step k (vehs)

Flow rate entering downstream link i from demand entry r at step k (veh/h)

Task 1: Arterial Network Flow Formulations

Key Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j \in \Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k] \cdot \Delta t$$

Approach the End of Queue

$$v_i[k] = v^{\min} + (v_i^{free} - v^{\min}) \cdot \left[1 - \left(\frac{\rho_i[k]}{\rho^{jam}}\right)^{\alpha}\right]^{\beta}$$

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i\left(l_i - \frac{x_i[k]}{n_i \rho^{jam}}\right)}$$

$$q_i^{arr}[k] = \min\left\{\rho_i[k] \cdot v_i[k] \cdot n_i \cdot \Delta t, N_i[k] - x_i[k]\right\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} q_i^{arr}[k] \cdot \gamma_{ij}[k] \cdot \delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m \in S_i^M} \min\left\{q_m^i[k] + x_m^i[k], Q_m^i \cdot g_n^p[k]\right\} \cdot \lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij} \cdot \gamma_{ij}[k]}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i \in \Gamma(j)} Q_{ij}^{pot}[k]} \cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k] \cdot \delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m \in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j \in \Gamma(i)} Q_{ji}[k] - \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Task 1: Arterial Network Flow Formulations

Approach the End of Queue

Approaching speed from upstream to the end of queue at link i at step k

Free-flow speed of link i

Density from upstream to the end of queue at link i at step k

Minimum density

$$v_i[k] = \begin{cases} v_i^{free}, & if \quad \rho_i[k] < \rho^{\min} \\ v^{\min} + (v_i^{free} - v^{\min}) \cdot \left[1 - \left(\dfrac{\rho_i[k] - \rho^{\min}}{\rho^{jam} - \rho^{\min}} \right)^{\alpha} \right]^{\beta}, & \rho_i[k] \in [\rho^{\min}, \rho^{jam}] \\ v^{\min}, & if \quad \rho_i[k] > \rho^{jam} \end{cases}$$

Minimum speed

Jam density

Task 1: Arterial Network Flow Formulations

Approach the End of Queue

Density from upstream to the end of queue at link i at step k (veh/mile/lane)

Number of vehicles at link i at step k

Total number of vehicles in queue of link i at step k

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i\left(l_i - \frac{x_i[k]}{n_i \rho^{jam}}\right)}$$

Number of lanes of link i

Length of link i

Task 1: Arterial Network Flow Formulations

Approach the End of Queue

$$q_i^{arr}[k] = \min\{\underline{\rho_i[k] \cdot v_i[k] \cdot n_i \cdot \Delta t, N_i[k] - x_i[k]}\}$$

Flows arriving at the end of queue of link i at step k (vehs)

Flows potentially arriving at the end of queue at step k (vehs)

Maximum number of vehicles that can arrive at the end of queue at step k (vehs)

Task 1: Arterial Network Flow Formulations

Key Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j\in\Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k]\cdot\Delta t$$

Approach the End of Queue

$$v_i[k] = v^{\min} + (v_i^{free} - v^{\min})\cdot\left[1-\left(\frac{\rho_i[k]}{\rho^{jam}}\right)^{\alpha}\right]^{\beta}$$

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i\left(l_i - \frac{x_i[k]}{n_i\rho^{jam}}\right)}$$

$$q_i^{arr}[k] = \min\{\rho_i[k]\cdot v_i[k]\cdot n_i\cdot\Delta t, N_i[k] - x_i[k]\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} q_i^{arr}[k]\cdot\gamma_{ij}[k]\cdot\delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m\in S_i^M}\min\{q_m^i[k] + x_m^i[k], Q_m^i\cdot g_n^p[k]\}\cdot\lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij}\cdot\gamma_{ij}[k]}{\sum_{j\in\Gamma^{-1}(i)}\delta_m^{ij}\cdot\gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i\in\Gamma(j)} Q_{ij}^{pot}[k]}\cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]\cdot\delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m\in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j\in\Gamma(i)} Q_{ji}[k] - \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Task 1: Arterial Network Flow Formulations

Merge into Lane Groups

$$q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} q_i^{arr}[k] \cdot \gamma_{ij}[k] \cdot \delta_m^{ij}$$

Flows joining lane group m of link i at step k (vehs)

Set of downstream links of link i

Flows arriving at the end of queue of link i at step k (vehs)

Turning proportion from link i to j

Binary variable indicating whether movement from link i to j uses lane group m

Task 1: Arterial Network Flow Formulations

Key Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j \in \Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k] \cdot \Delta t$$

Approach the End of Queue

$$v_i[k] = v^{\min} + (v_i^{free} - v^{\min}) \cdot \left[1 - \left(\frac{\rho_i[k]}{\rho^{jam}}\right)^{\alpha}\right]^{\beta}$$

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i(l_i - \frac{x_i[k]}{n_i \rho^{jam}})}$$

$$q_i^{arr}[k] = \min\{\rho_i[k] \cdot v_i[k] \cdot n_i \cdot \Delta t, N_i[k] - x_i[k]\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} q_i^{arr}[k] \cdot \gamma_{ij}[k] \cdot \delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m \in S_i^M} \min\{q_m^i[k] + x_m^i[k], Q_m^i \cdot g_n^p[k]\} \cdot \lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij} \cdot \gamma_{ij}[k]}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i \in \Gamma(j)} Q_{ij}^{pot}[k]} \cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k] \cdot \delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m \in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j \in \Gamma(i)} Q_{ji}[k] - \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Task 1: Arterial Network Flow Formulations

Departure Process

Flows potentially depart from link i to j at step k (vehs)

Flows joining the queue of lane group m of link i at step k (vehs)

Queues of lane group m of link i at step k (vehs)

$$Q_{ij}^{pot}[k] = \sum_{m \in S_i^M} \min\left\{ q_m^i[k] + x_m^i[k], Q_m^i \cdot g_n^p[k] \right\} \cdot \lambda_m^{ij}[k]$$

Discharging capacity of lane group m at link i (vehs)

Binary value indicating whether signal phase p of intersection n is set to green at step k

Percentage of traffic in lane group m going from link i to j

Task 1: Arterial Network Flow Formulations

Departure Process

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij} \cdot \gamma_{ij}[k]}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \gamma_{ij}[k]}$$

Percentage of traffic in lane group m going from link i to j

Binary variable indicating whether movement from link i to j uses lane group m

Turning proportion from link i to j at step k

Task 1: Arterial Network Flow Formulations

Departure Process

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i\in\Gamma(j)} Q_{ij}^{pot}[k]} \cdot s_j[k]\right\}\right\}$$

Flows actually depart from link i to j at step k (vehs)

Flows potentially depart from link i to j at step k (vehs)

Available downstream capacity allocated for flows from link i

Task 1: Arterial Network Flow Formulations

Departure Process

$$Q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k] \cdot \delta_m^{ij}$$

Flows actually depart from lane group m of link i at step k (vehs)

Flows actually depart from link i to j at step k (vehs)

Binary variable indicating whether movement from link i to j uses lane group m

Task 1: Arterial Network Flow Formulations

Key Formulations

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j\in\Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k]\cdot\Delta t$$

Approach the End of Queue

$$v_i[k] = v^{\min} + (v_i^{free} - v^{\min})\cdot\left[1-\left(\frac{\rho_i[k]}{\rho^{jam}}\right)^{\alpha}\right]^{\beta}$$

$$\rho_i[k] = \frac{N_i[k] - x_i[k]}{n_i\left(l_i - \frac{x_i[k]}{n_i\rho^{jam}}\right)}$$

$$q_i^{arr}[k] = \min\{\rho_i[k]\cdot v_i[k]\cdot n_i\cdot\Delta t, N_i[k] - x_i[k]\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} q_i^{arr}[k]\cdot\gamma_{ij}[k]\cdot\delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m\in S_i^M}\min\{q_m^i[k] + x_m^i[k], Q_m^i\cdot g_n^p[k]\}\cdot\lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij}\cdot\gamma_{ij}[k]}{\sum_{j\in\Gamma^{-1}(i)}\delta_m^{ij}\cdot\gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i\in\Gamma(j)} Q_{ij}^{pot}[k]}\cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]\cdot\delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m\in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j\in\Gamma(i)} Q_{ji}[k] - \sum_{j\in\Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Task 1: Arterial Network Flow Formulations

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

Queues of lane group m of link i at step k+1 (vehs)

Queues of lane group m of link i at step k (vehs)

Flows joining the queue of lane group m of link i at step k (vehs)

Flows actually depart from lane group m of link i at step k (vehs)

Task 1: Arterial Network Flow Formulations

Flow Conservation

$$x_i[k+1] = \sum_{m \in S_i^M} x_m^i[k+1]$$

Total number of vehicles queued at link i at step k+1 (vehs)

Queues of lane group m of link i at step k+1 (vehs)

Task 1: Arterial Network Flow Formulations

Flow Conservation

$$N_i[k+1] = N_i[k] + \sum_{j \in \Gamma(i)} Q_{ji}[k] - \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k]$$

- Total number of vehicles at link i at step k+1 (vehs)
- Total number of vehicles at link i at step k (vehs)
- Flows actually depart from upstream to link i at step k (vehs)
- Flows actually depart from link i to downstream at step k (vehs)

Task 1: Arterial Network Flow Formulations

Flow Conservation

$$s_i[k+1] = N_i - N_i[k+1]$$

Available space of link i at step k+1 (vehs)

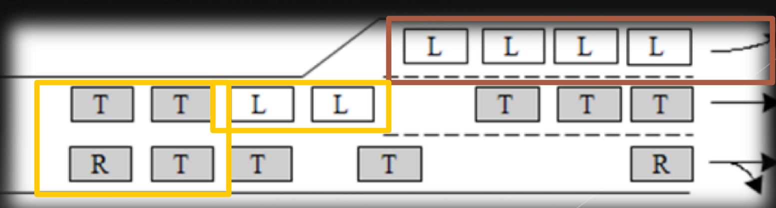
Storage space of link i (vehs)

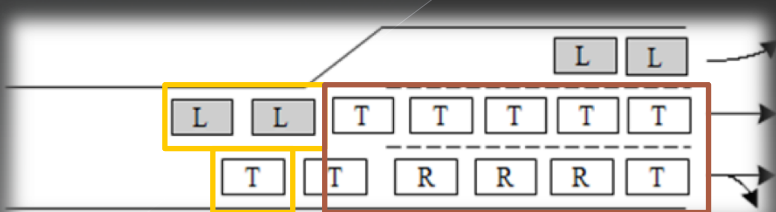
Total number of vehicles at link i at step k+1 (vehs)

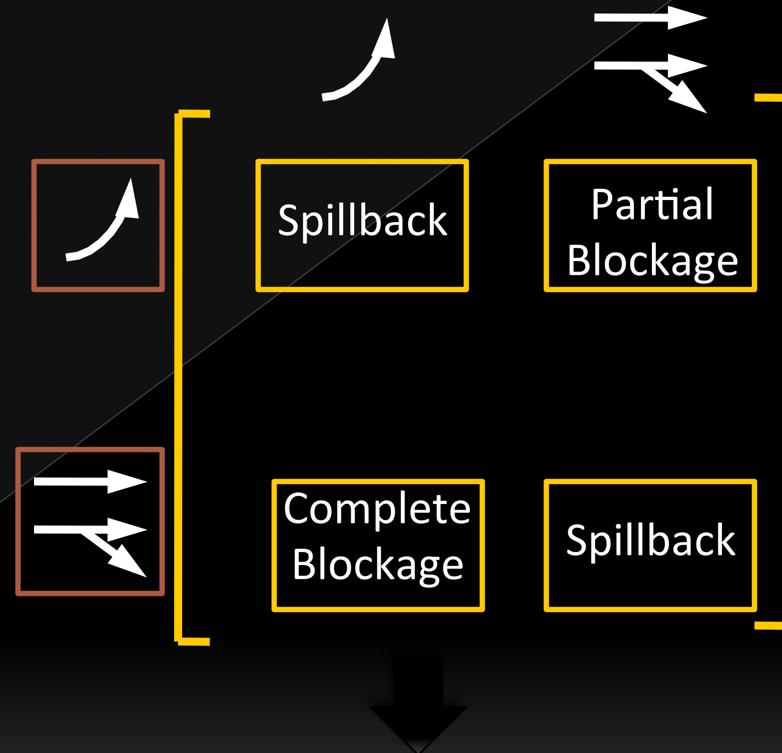
Capturing Local Bottlenecks

**Further Enhancement
to account for queue interaction**

Capturing Local Bottlenecks

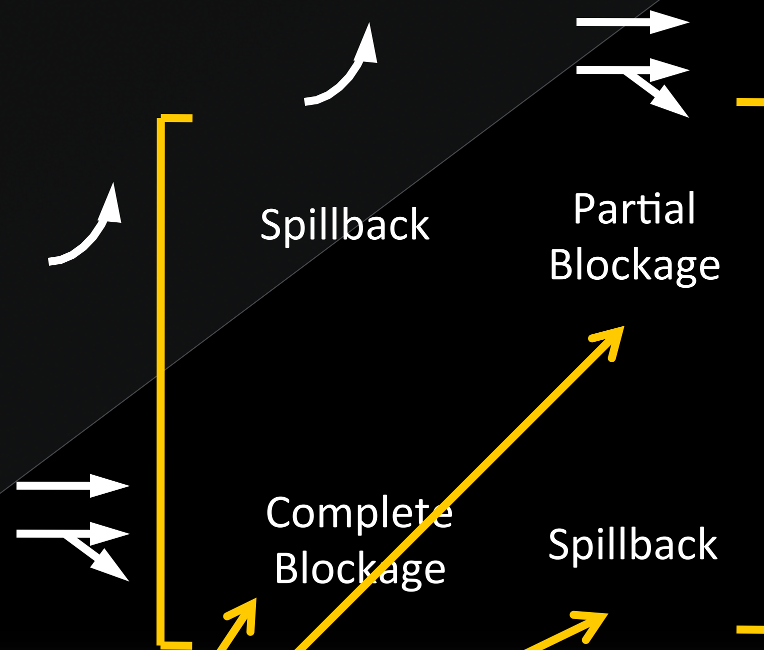






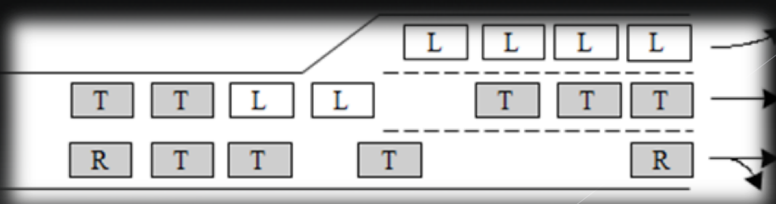
Propose the concept of "Blocking Matrix" to model the dynamic interaction between various lane group queues

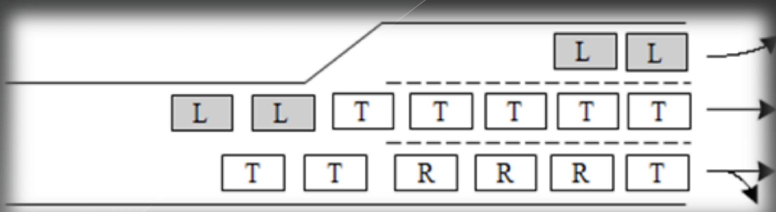
Capturing Local Bottlenecks



$$\omega^{i}_{m'm}[k] = \begin{cases} 1 & x^{i}_{m'}[k] > N^{i}_{m'}, \textit{complete blockage} \\ \phi_{m'm} \cdot \dfrac{q^{i,pot}_{m'}[k]}{\sum_{m \in S_i^M} q^{i,pot}_{m}[k]} & x^{i}_{m'}[k] > N^{i}_{m'}, \textit{partial blockage} \\ 0 & \textit{no blockage or } x^{i}_{m'}[k] \le N^{i}_{m'} \end{cases}$$

A value between 0 and 1





Capturing Local Bottlenecks

$$\omega^{i}_{m'm}[k] = \begin{cases} 1 & x^{i}_{m'}[k] > N^{i}_{m'}, \textit{complete blockage} \\ \phi_{m'm} \dfrac{q^{i,pot}_{m'}[k]}{\sum_{m \in S_i^M} q^{i,pot}_{m}[k]} & x^{i}_{m'}[k] > N^{i}_{m'}, \textit{partial blockage} \\ 0 & \textit{no blockage or } x^{i}_{m'}[k] \le N^{i}_{m'} \end{cases}$$

The percentage of merging capacity reduction for lane group m due to the queue spillback at lane group m’ at step k

Constant parameter related to driver’s response to lane blockage and geometry features

Potential flows may merge into group m at link i at step k (vehs)

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Capturing Local Bottlenecks

$$q_m^{i,pot}[k] = \widetilde{x}_m^{i}[k] + \sum_{j\in\Gamma^{-1}(i)} q_i^{arr}[k]\cdot\gamma_{ij}[k]\cdot\delta_m^{ij}$$

- Potential flows may merge into group m at link i at step k (vehs)
- Number of vehicles bound to lane group m but queued outside at link i due to blockage at step k
- Flows arriving at the end of queue of link i at step k (vehs)
- Turning proportion from link i to j
- Binary variable indicating whether movement from link i to j uses lane group m

Capturing Local Bottlenecks

Key Enhancement

Demand Origins

$$q_r[k] = \min\left[d_r[k] + \frac{w_r[k]}{\Delta t}, Q_i, \frac{s_i[k]}{\Delta t}\right]$$

$$w_r[k+1] = w_r[k] + \Delta t[d_r[k] - q_r[k]]$$

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j \in \Gamma(i)} Q_{ji}[k]$$

$$q_i^{in}[k] = q_r[k] \cdot \Delta t$$

Enhanced Formulations

$$q_m^i[k] = \min\left\{\max\left\{N_m^i - x_m^i[k], 0\right\}, q_m^{i,pot}[k] \cdot \left[1 - \sum_{m' \in S_i^M \wedge m' \neq m} \omega_{m'm}^i[k]\right]\right\}$$

$$\rho_i[k] = \frac{\cdots}{n_i\left(l_i - \frac{x_i[k]}{n_i \rho^{jam}}\right)}$$

$$q_i^{arr}[k] = \min\left\{\rho_i[k] \cdot v_i[k] \cdot n_i \cdot \Delta t, N_i[k] - x_i[k]\right\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} q_i^{arr}[k] \cdot \gamma_{ij}[k] \cdot \delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m \in S_i^M} \min\left\{q_m^i[k] + x_m^i[k], Q_m^i \cdot g_n^p[k]\right\} \cdot \lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij} \cdot \gamma_{ij}[k]}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \gamma_{ij}[k]}$$

$$Q_{ij}[k] = \max\left\{0, \min\left\{Q_{ij}^{pot}[k], \frac{Q_{ij}^{pot}[k]}{\sum_{i \in \Gamma(j)} Q_{ij}^{pot}[k]} \cdot s_j[k]\right\}\right\}$$

$$Q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k] \cdot \delta_m^{ij}$$

Flow Conservation

$$x_m^i[k+1] = x_m^i[k] + q_m^i[k] - Q_m^i[k]$$

$$x_i[k+1] = \sum_{m \in S_i^M} x_m^i[k+1]$$

$$N_i[k+1] = N_i[k] + \sum_{j \in \Gamma(i)} Q_{ji}[k] - \sum_{j \in \Gamma^{-1}(i)} Q_{ij}[k]$$

$$s_i[k+1] = N_i - N_i[k+1]$$

Capturing Local Bottlenecks

Key Enhancement

$$q_m^i[k] = \min\left\{ \max\left\{ N_m^i - x_m^i[k], 0 \right\}, q_m^{i,pot}[k] \cdot \left[1 - \sum_{m' \in S_i^M \wedge m' \neq m} \omega_{m'm}^i[k] \right] \right\}$$

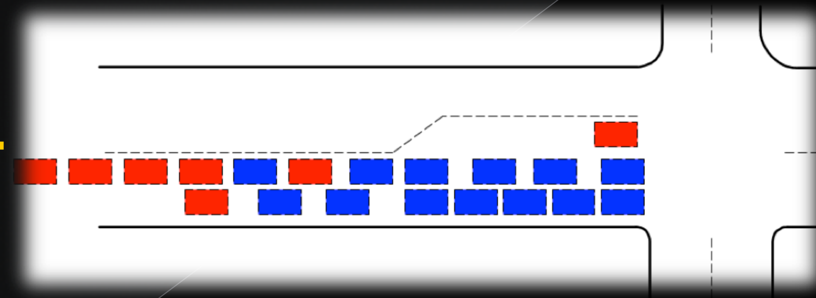
Number of vehicles allowed to merge into group m at link i at step k (vehs)

Available storage capacity of lane group m at step k

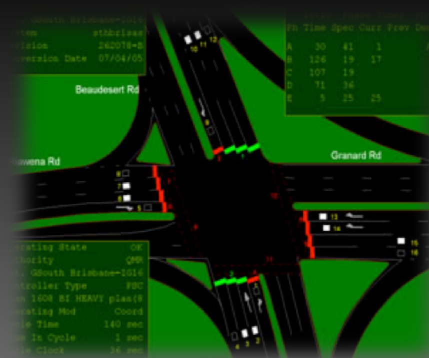
Number of vehicles allowed to merge into group m at link i at step k considering the blockage effect (vehs)

Part I - An Enhanced Arterial Signal Optimization Model

Task 1
Network Enhancement Approach to account for Local Bottlenecks (Queue Interactions and Blockages)



Task 2
Traffic Signal Timing Enhancement for Local Bottleneck Management



Task 2: An Enhanced Signal Optimization Model

Task 2
Traffic Signal Timing Enhancement for Local Bottleneck Management

Control Objectives

$$\min \sum_{k=1}^{T} \left[\sum_{i \in S^U} N_i[k] + \sum_{r \in S_r} w_r[k] \right] \cdot \Delta t$$

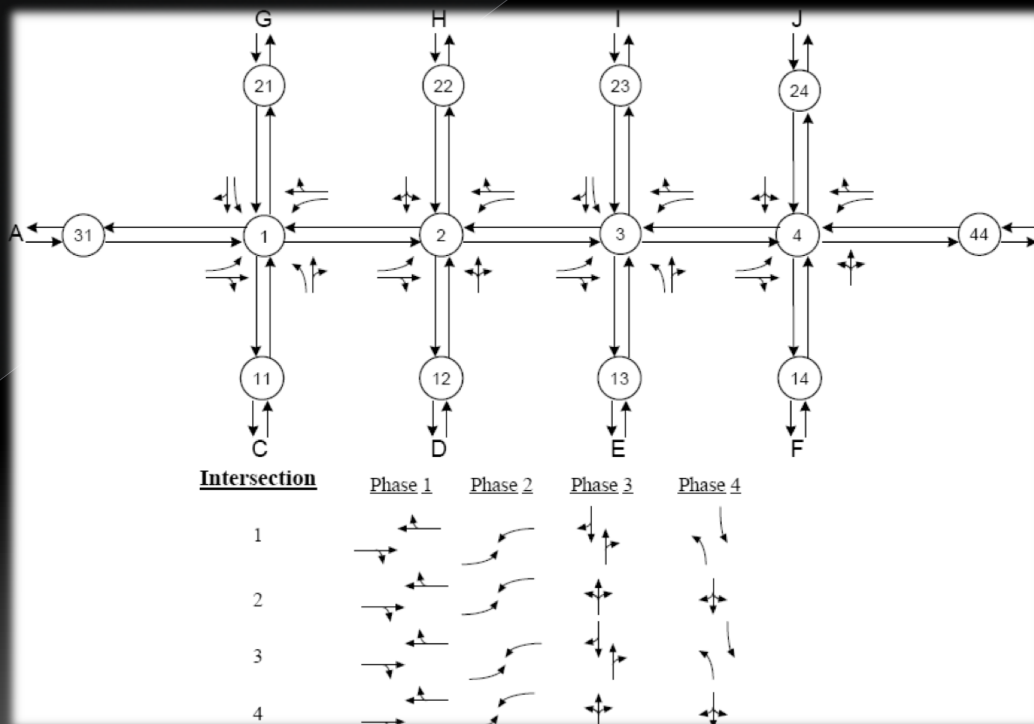
$$\max \sum_{k=1}^{T} \sum_{i \in S^{OUT}} q_i^{in}[k]$$

1. Minimize total travel time and queue time – under saturated conditions

2. Maximize total throughput – oversaturated conditions

Task 2: An Enhanced Signal Optimization Model

Task 2
Traffic Signal Timing Enhancement for Local Bottleneck Management



Experimental Design

1. A hypothetical arterial
2. Three traffic demand levels
3. Comparison with TRANSYT-7F with the turning bay spillover factor set

Task 2: An Enhanced Signal Optimization Model

Task 2
Traffic Signal Timing Enhancement for Local Bottleneck Management

Control Plans

The proposed model tends to select shorter cycle length to reduce the chance of blockages

The proposed model

TRANSYT-7F

Demand Scenarios	Intersection	Cycle Length (s) I	Cycle Length (s) II	Offset (s) I	Offset (s) II	Start of Green (s) Phase I I	Phase I II	Phase II I	Phase II II	Phase III I	Phase III II	Phase IV I	Phase IV II
Low	1	52	65	17	7	0	0	16	22	28	35	40	53
	2			11	8	0	0	13	21	27	33	39	49
	3			18	3	0	0	13	23	25	35	39	53
	4			9	2	0	0	15	21	27	33	39	49
Medium	1	70	80	10	6	0	0	21	30	33	44	58	67
	2			5	6	0	0	24	27	36	40	53	60
	3			9	3	0	0	22	29	34	43	55	66
	4			4	0	0	0	21	25	34	40	53	60
High	1	93	111	7	25	0	0	24	42	45	61	77	94
	2			2	0	0	0	26	38	43	55	72	83
	3			6	24	0	0	26	40	45	58	77	93
	4			1	1	0	0	29	36	45	55	72	83

Task 2: An Enhanced Signal Optimization Model

Task 2
Traffic Signal Timing Enhancement for Local Bottleneck Management

Control Performance

1. Low- and medium demand scenario: less total delay and total queue time but less total throughput
2. High-demand scenario: less total queue time and more total throughput

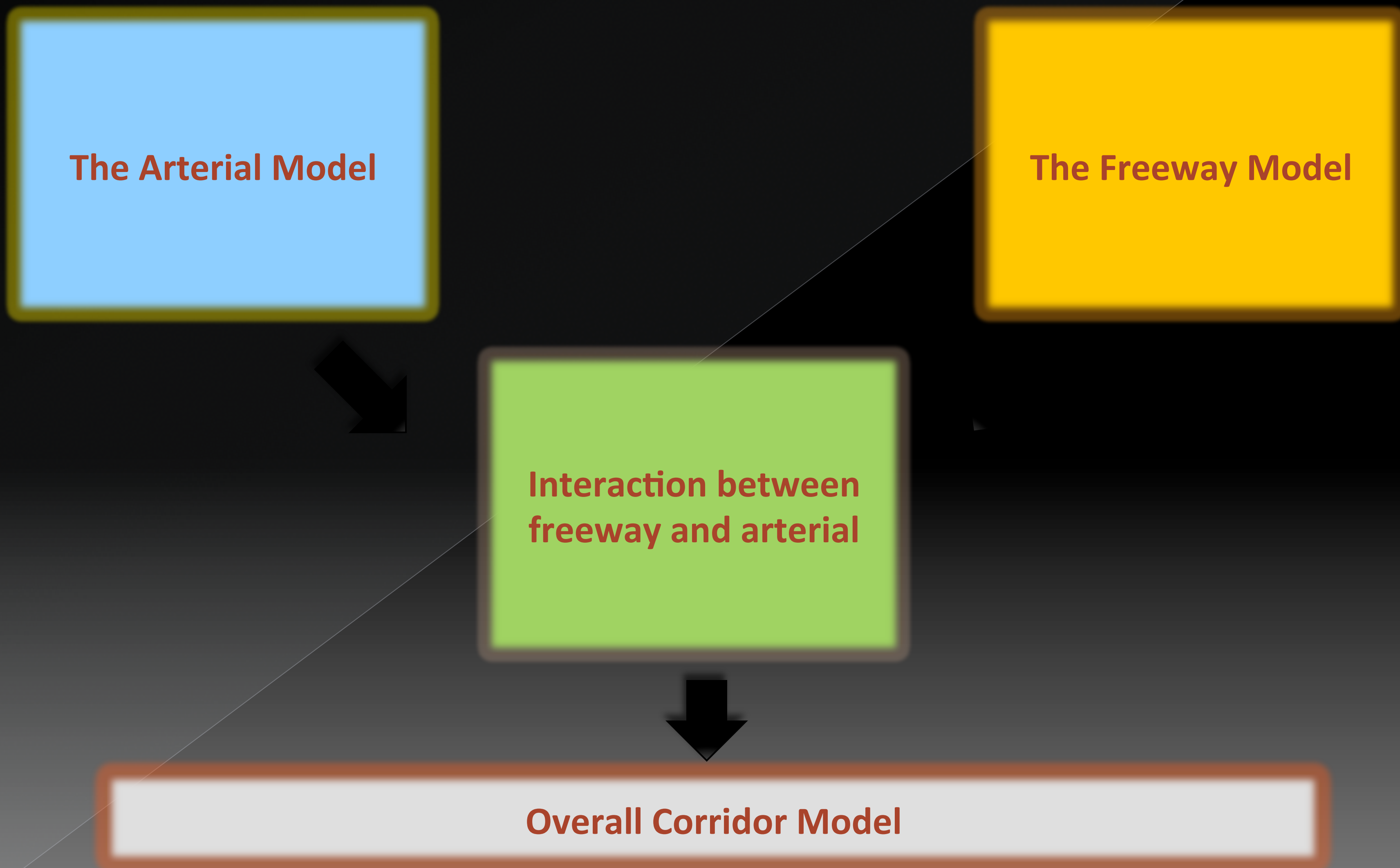
Scenarios	MOEs	Simulation Results from CORSIM (1 hour)		
		Proposed Model	TRANSYT-7F	Improvement* (%)
Low-demand	Total Delay (veh-min)	1728.6	1794.6	-3.7
	Total Queue Time (veh-min)	1327	1410.4	-5.9
	Total Throughput (veh)	2798	2807	-0.3
Medium-demand	Total Delay (veh-min)	3307.2	3358.2	-1.5
	Total Queue Time (veh-min)	2607.8	2680.7	-2.7
	Total Throughput (veh)	4206	4219	-0.3
High-demand	Total Queue Time (veh-min)	10625.9	13089.6	-18.8
	Total Throughput (veh)	5737	5574	+2.9

Summary

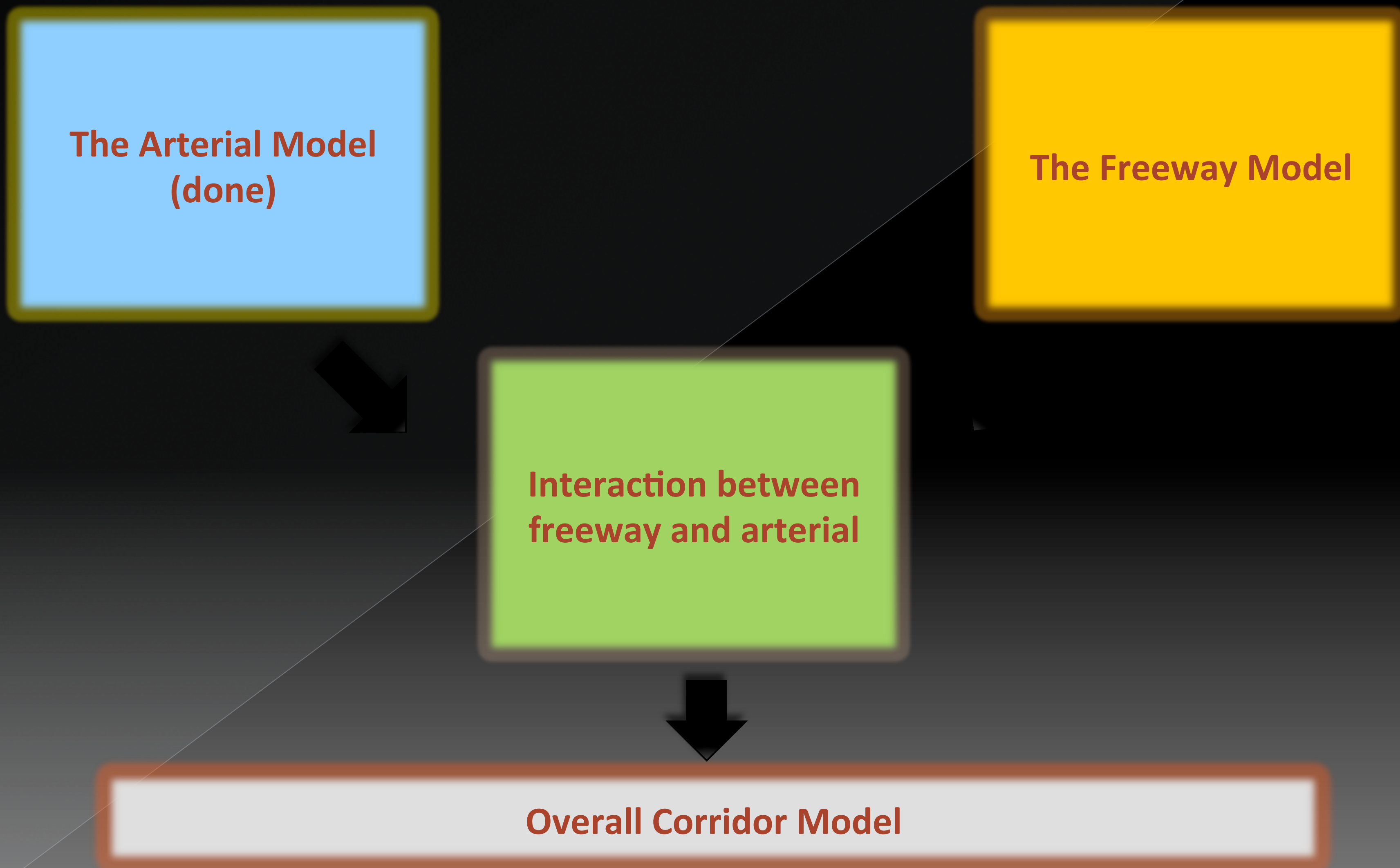
1. The proposed model outperforms TRANSYT-7F in terms of total system queue time for all experimental demand scenarios

2. For oversaturated traffic conditions, in terms of the total system queue time and total system throughput, the proposed model can mitigate the congestion and blockage more effectively than TRANSYT-7F due to the use of enhanced network flow formulations.

Part II – The Integrated Corridor Control Model



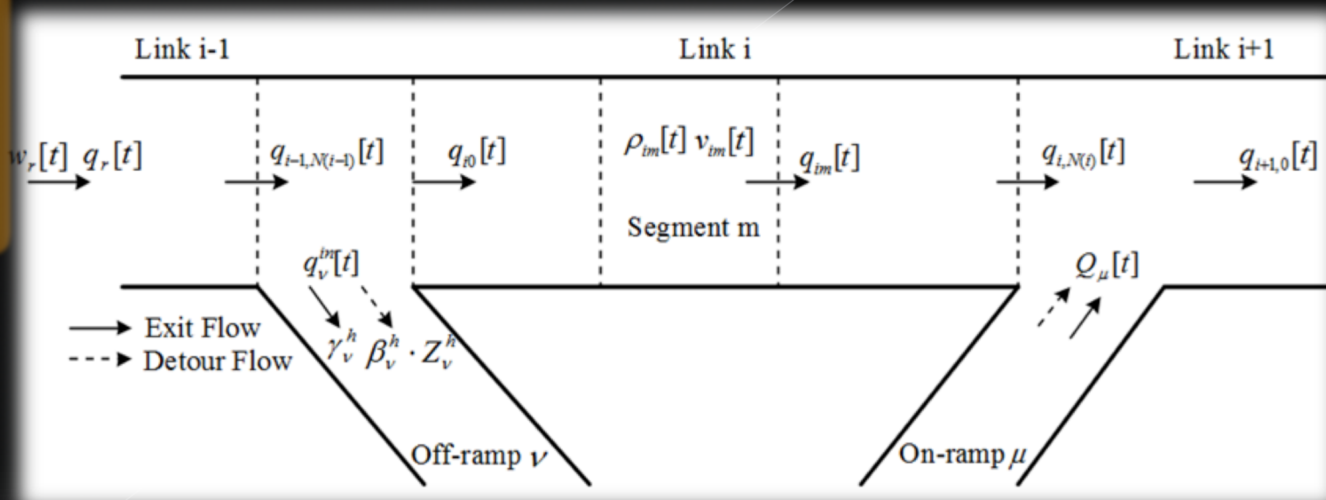
Part II – The Integrated Corridor Control Model



The Freeway Model

The Freeway Model

METANET Model
(Messmer and Papageorgiou, 1990)



Basic Concept

-Discrete Time Steps

-Dynamic State Equations

-Sub-sections of freeway mainline

Extension

Sections near the off-ramp and on-ramp

$$q_{i-1,N(i-1)}[t] = \rho_{i-1,N(i-1)}[t] \cdot v_{i-1,N(i-1)}[t] \cdot n_{i-1,N(i-1)} \cdot [1 - \gamma_v^h - \beta_v^h \cdot Z_v^h] + q_v^{in}[t]$$

$$q_{i0}[t] = q_{i-1,N(i-1)}[t] - q_v^{in}[t]$$

$$q_{i+1,0}[t] = q_{i,N(i)}[t] + Q_\mu[t]$$

The Freeway Model

Sections near the off-ramp and on-ramp

Density at time t

Speed at time t

Number of lanes

Actual entering flow rate into off-ramp at time *t*

$$q_{i-1,N(i-1)}[t] = \rho_{i-1,N(i-1)}[t] \cdot v_{i-1,N(i-1)}[t] \cdot n_{i-1,N(i-1)} \cdot [1 - \gamma_v^h - \beta_v^h \cdot Z_v^h] + q_v^{in}[t]$$

Actual flow rate leaving from the freeway link right before the off-ramp at time *t*

Normal exit rate for off-ramp during interval *h*

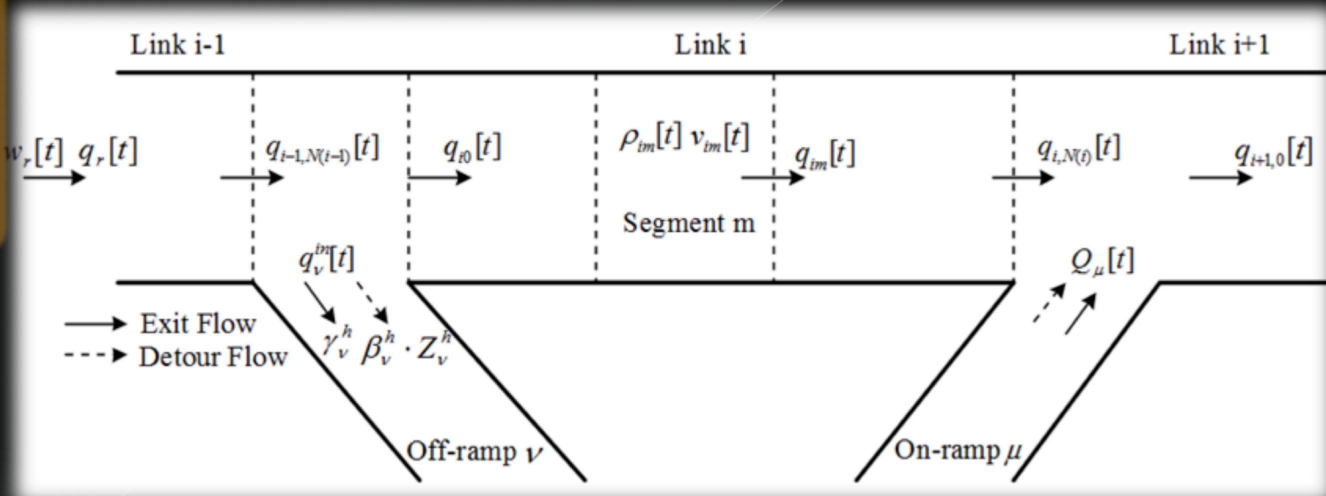
Driver compliance rate to the detour operation

Diversion rate for off-ramp during interval *h*

The Freeway Model

The Freeway Model

METANET Model
(Messmer and Papageorgiou, 1990)



Basic Concept

-Discrete Time Steps

-Dynamic State Equations

-Sub-sections of freeway mainline

Extension

Sections near the off-ramp and on-ramp

$$q_{i-1,N(i-1)}[t] = \rho_{i-1,N(i-1)}[t]\cdot v_{i-1,N(i-1)}[t]\cdot n_{i-1,N(i-1)}\cdot[1-\gamma_\nu^h - \beta_\nu^h\cdot Z_\nu^h] + q_\nu^{in}[t]$$

$$q_{i0}[t] = q_{i-1,N(i-1)}[t] - q_\nu^{in}[t]$$

$$q_{i+1,0}[t] = q_{i,N(i)}[t] + Q_\mu[t]$$

The Freeway Model

Sections near the off-ramp and on-ramp

$$q_{i0}[t] = q_{i-1,N(i-1)}[t] - q_{v}^{in}[t]$$

Actual flow rate entering the freeway link right after the off-ramp at time *t*

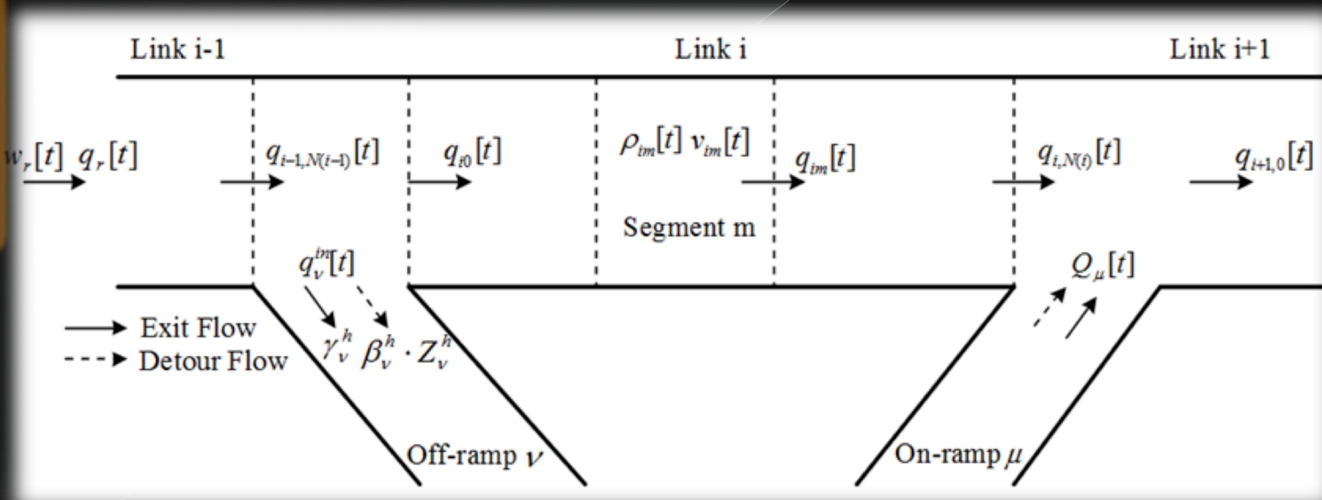
Actual flow rate leaving from the freeway link right before the off-ramp at time *t*

Actual entering flow rate into off-ramp at time *t*

The Freeway Model

The Freeway Model

METANET Model
(Messmer and Papageorgiou, 1990)



Basic Concept

-Discrete Time Steps

-Dynamic State Equations

-Sub-sections of freeway mainline

Extension

Sections near the off-ramp and on-ramp

$$q_{i-1,N(i-1)}[t] = \rho_{i-1,N(i-1)}[t] \cdot v_{i-1,N(i-1)}[t] \cdot n_{i-1,N(i-1)} \cdot [1 - \gamma_{\nu}^{h} - \beta_{\nu}^{h} \cdot Z_{\nu}^{h}] + q_{\nu}^{in}[t]$$

$$q_{i0}[t] = q_{i-1,N(i-1)}[t] - q_{\nu}^{in}[t]$$

$$q_{i+1,0}[t] = q_{i,N(i)}[t] + Q_{\mu}[t]$$

The Freeway Model

Sections near the off-ramp and on-ramp

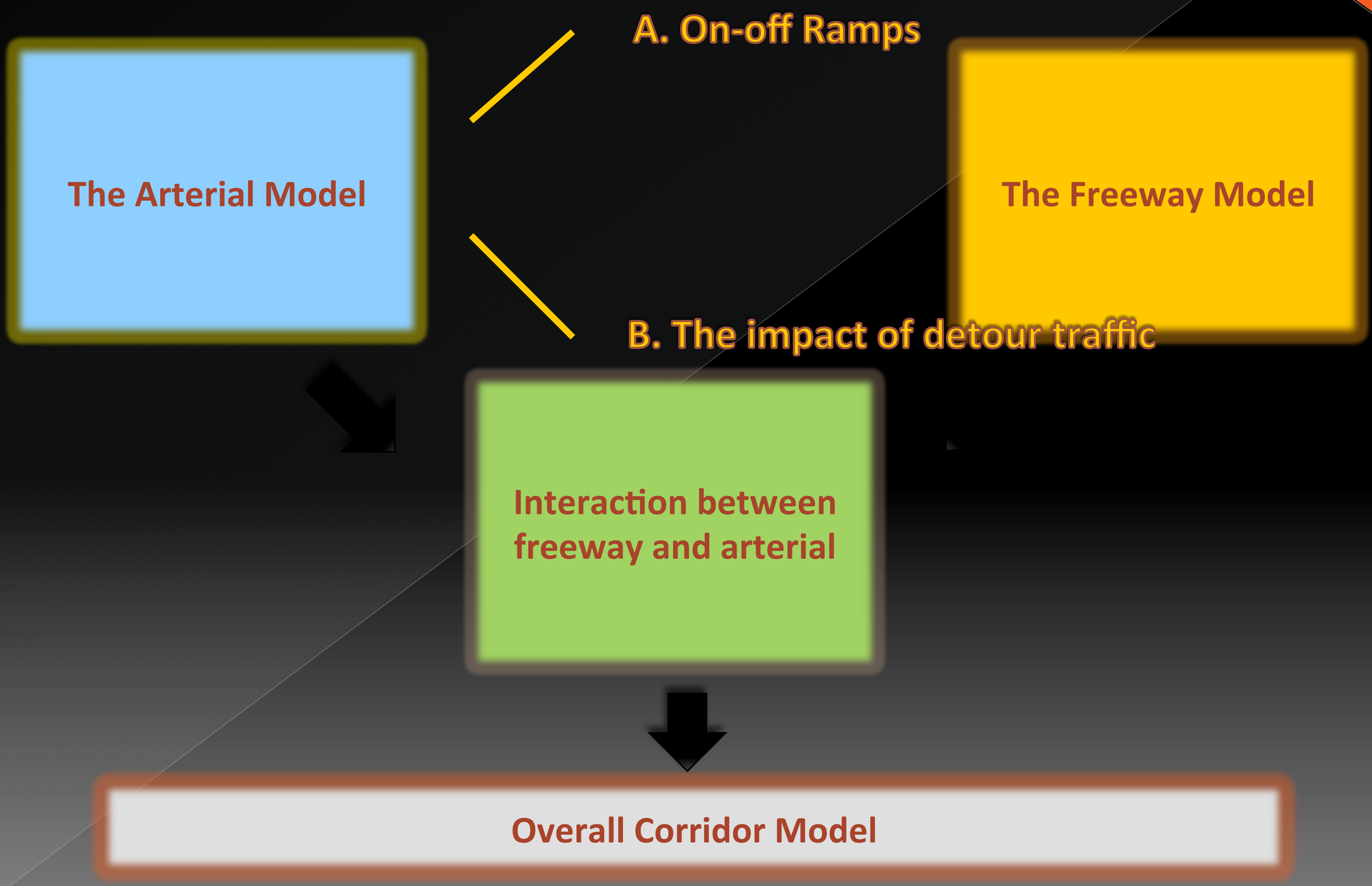
$$q_{i+1,0}[t] = q_{i,N(i)}[t] + Q_{\mu}[t]$$

Actual flow rate entering the freeway link right after the on-ramp at time *t*

Actual flow rate leaving from the freeway link right before the on-ramp at time *t*

Actual merging flow rate into freeway from on-ramp at time *t*

Part II – The Integrated Corridor Control Model



The On-ramp Model

Interaction between freeway and arterial

A. On-off Ramps (On-ramp)

Revised departure process

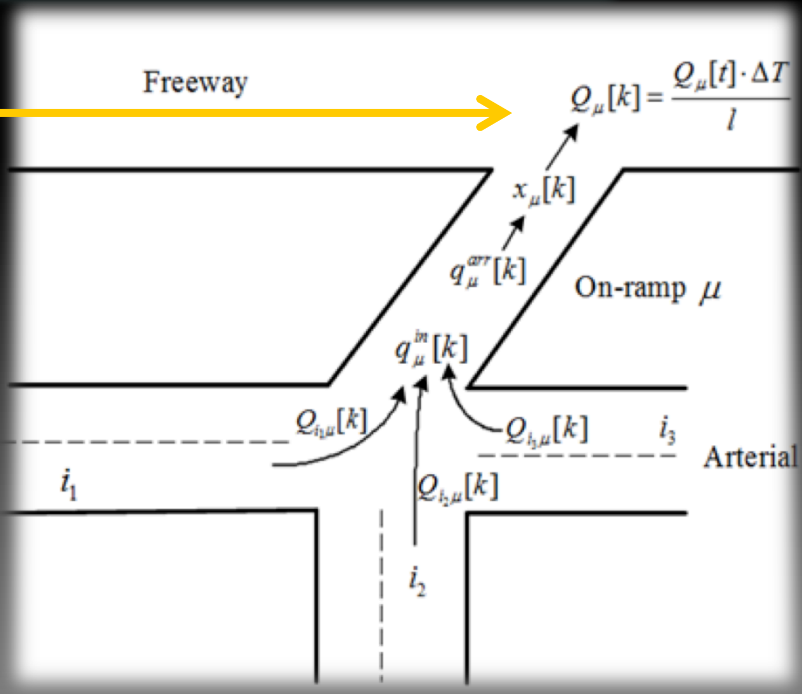
$$Q_\mu[t] = \min\left(\frac{x_\mu[l \cdot t] + \sum_{k=lt}^{l(t+1)-1} q_\mu^{arr}[k]}{\Delta T}, Q_\mu \cdot R_\mu^h, Q_\mu \cdot \min[1, \frac{\rho^{jam} - \rho_{i+1,0}[t]}{\rho^{jam} - \rho_i^{crit}}] \right)$$

Basic Concept

-Model ramps as simplified arterial links with the lane-group concept

-Modify departure process for on-ramp

-Modify arrival process for off-ramp



The On-ramp Model

A. On-off Ramps (On-ramp)

$$Q_{\mu}[t] = \min\left(\frac{x_{\mu}[l \cdot t] + \sum_{k=lt}^{l(t+1)-1} q_{\mu}^{arr}[k]}{\Delta T}, Q_{\mu} \cdot R_{\mu}^{h}, Q_{\mu} \cdot \min[1, \frac{\rho^{jam} - \rho_{i+1,0}[t]}{\rho^{jam} - \rho_{i}^{crit}}] \right)$$

Actual flow rate allowed to merge into freeway from on-ramp

Potential number of vehicles to merge into freeways (waiting +arrival)

Discharging capacity under the ramp metering

Available downstream freeway capacity (veh/h)

The Off-ramp Model

Interaction between freeway and arterial

A. On-off Ramps (Off-ramp)

Revised arrival process

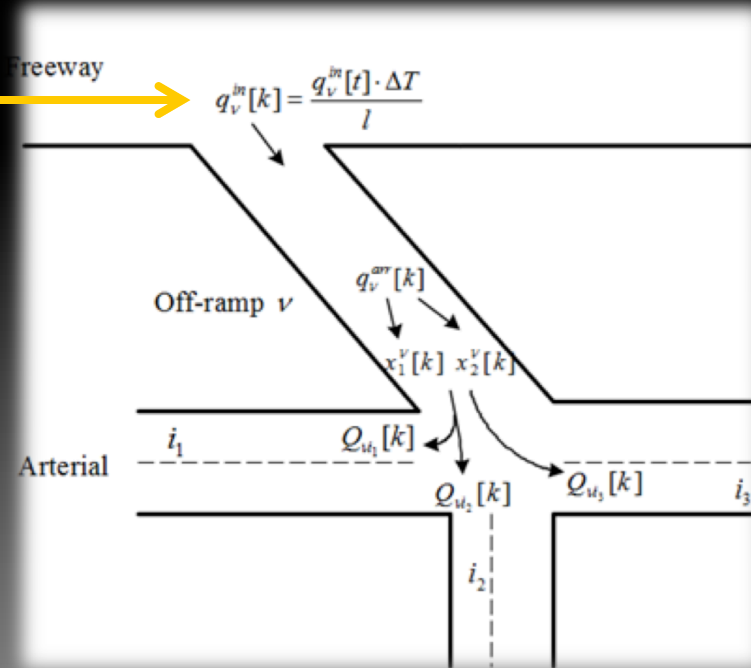
$$q_v^{in}[t] = \min\{\rho_{i-1,N(i-1)}[t] \cdot v_{i-1,N(i-1)}[t] \cdot n_{i-1,N(i-1)} \cdot (\gamma_v^h + \beta_v^h \cdot Z_v^h), Q_v, \frac{s_v[l \cdot t] + \sum_{k=lt}^{l(t+1)-1} \sum_{j \in \Gamma^{-1}(v)} Q_{vj}[k]}{\Delta T}\}$$

Basic Concept

-Model ramps as simplified arterial links with the lane-group concept

-Modify departure process for on-ramp

-Modify arrival process for off-ramp



The Off-ramp Model

A. On-off Ramps (Off-ramp)

$$q_v^{in}[t] = \min\{\rho_{i-1,N(i-1)}[t]\cdot v_{i-1,N(i-1)}[t]\cdot n_{i-1,N(i-1)}\cdot(\gamma_v^h+\beta_v^h\cdot Z_v^h),\ Q_v,\ \frac{s_v[l\cdot t]+\sum_{k=lt}^{l(t+1)-1}\sum_{j\in\Gamma^{-1}(v)}Q_{vj}[k]}{\Delta T}\}$$

Actual flow rate entered the off-ramp

Potential flow rate to enter the off-ramp (normal+detour)

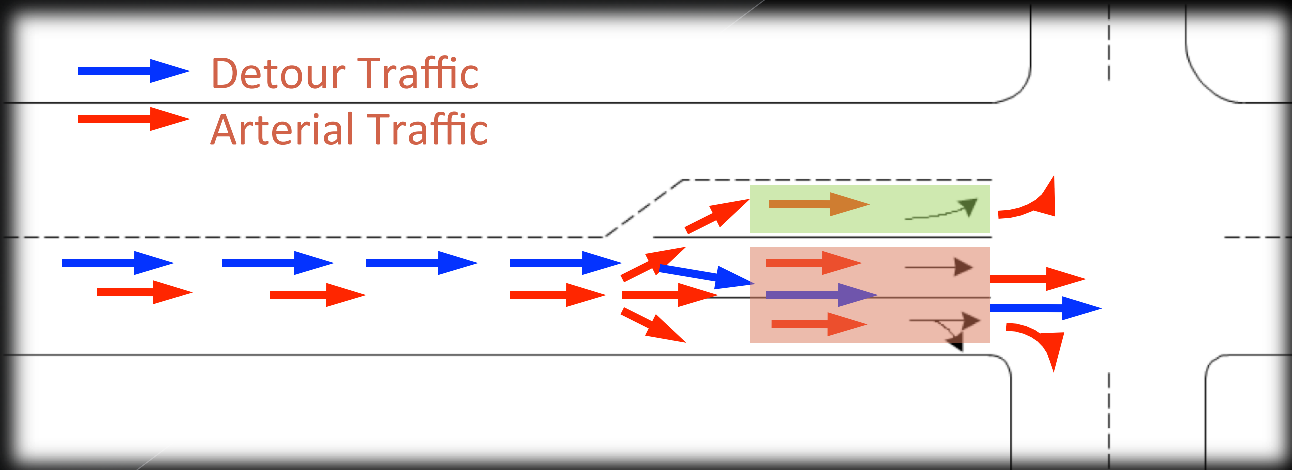
Off-ramp capacity (veh/h)

Available space at the off-ramp (veh/h)

The Impact of Detour Traffic

Interaction between freeway and arterial

B. The impact of detour traffic



Basic Concept

-Integrate the “sub-flow” concept with the lane-group-based arterial model

The Impact of Detour Traffic

Interaction be
freeway and a

B. The impact of detour traffic

Model Extensions

Upstream Arrivals

$$q_i^{in}[k] = \sum_{j\in\Gamma(i)} \overline{Q}_{ji}[k] + \sum_{j\in\Gamma(i)} Q_{ji}^{\mu^-}[k]$$

Approach the End of Queue

$$\rho_i[k] = \frac{\overline{N}_i[k] + N_i^{\mu^-}[k] - x_i[k]}{n_i\left(l_i - \frac{x_i[k]}{n_i \cdot \rho^{jam}}\right)}$$

$$q_i^{arr}[k] = \min\left\{\rho_i[k]\cdot v_i[k]\cdot n_i \cdot \Delta t, \overline{N}_i[k] + N_i^{\mu^-}[k] - x_i[k]\right\}$$

Merge into Lane Groups

$$q_m^i[k] = \sum_{j\in\Gamma^{-1}(i)} q_i^{arr}[k]\cdot[\eta_i[k]\cdot\overline{\gamma}_{ij}[k] + (1-\eta_i[k])\cdot\gamma_{ij}^{\mu^-}]\cdot\delta_m^{ij}$$

Departure Process

$$Q_{ij}^{pot}[k] = \sum_{m\in S_i^M} \min\left\{q_m^i[k] + x_m^i[k], Q_m^i \cdot g_n^p[k]\right\}\cdot\lambda_m^{ij}[k]$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij}\cdot[\eta_i[k]\overline{\gamma}_{ij}[k] + (1-\eta_i[k])\gamma_{ij}^{\mu^-}]}{\sum_{j\in\Gamma^{-1}(i)}\delta_m^{ij}\cdot[\eta_i[k]\overline{\gamma}_{ij}[k] + (1-\eta_i[k])\gamma_{ij}^{\mu^-}]}$$

$$\overline{\lambda}_m^{ij}[k] = \frac{\delta_m^{ij}\cdot\eta_i[k]\cdot\overline{\gamma}_{ij}[k]}{\sum_{j\in\Gamma^{-1}(i)}\delta_m^{ij}\cdot[\eta_i[k]\overline{\gamma}_{ij}[k] + (1-\eta_i[k])\gamma_{ij}^{\mu^-}]}$$

$$\overline{Q}_{ij}[k] = Q_m^i[k]\cdot\overline{\lambda}_m^{ij}[k]$$

$$Q_{ij}^{\mu^-}[k] = Q_m^i[k]\cdot(\lambda_m^{ij}[k] - \overline{\lambda}_m^{ij}[k])$$

Flow Conservation

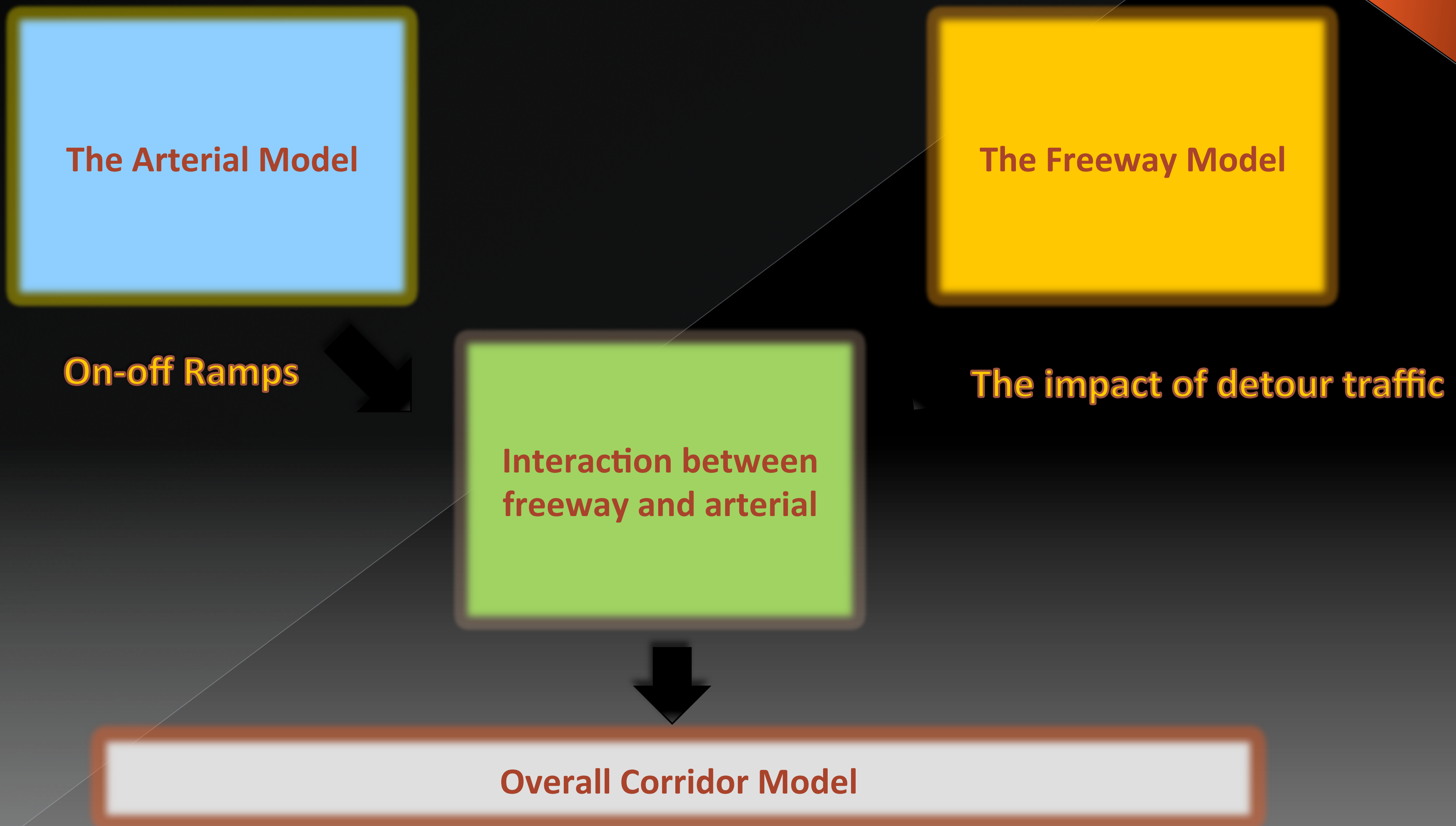
$$\overline{N}_i[k+1] = \overline{N}_i[k] + \sum_{j\in\Gamma(i)}\overline{Q}_{ji}[k] - \sum_{j\in\Gamma^{-1}(i)}\overline{Q}_{ij}[k]$$

$$N_i^{\mu^-}[k+1] = N_i^{\mu^-}[k] + \sum_{j\in\Gamma(i)} Q_{ji}^{\mu^-}[k] - \sum_{j\in\Gamma^{-1}(i)} Q_{ij}^{\mu^-}[k]$$

$$s_i[k+1] = N_i - \overline{N}_i[k+1] - N_i^{\mu^-}[k+1]$$

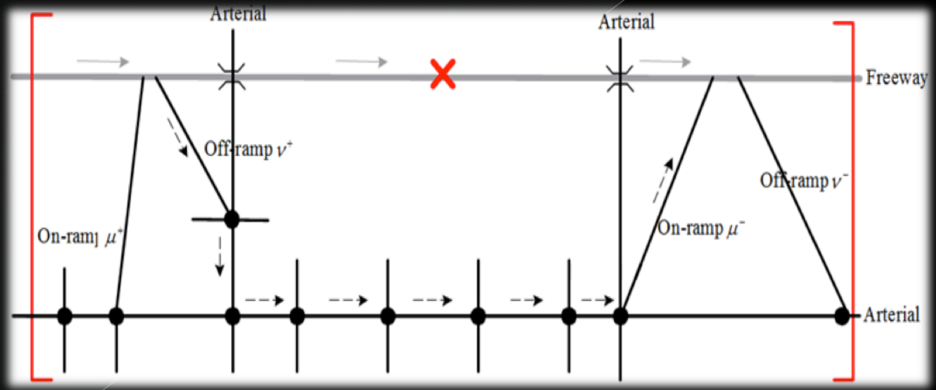
$$\eta_i[k+1] = \frac{\overline{N}_i[k+1]}{\overline{N}_i[k+1] + N_i^{\mu^-}[k+1]}$$

The Overall Corridor Model

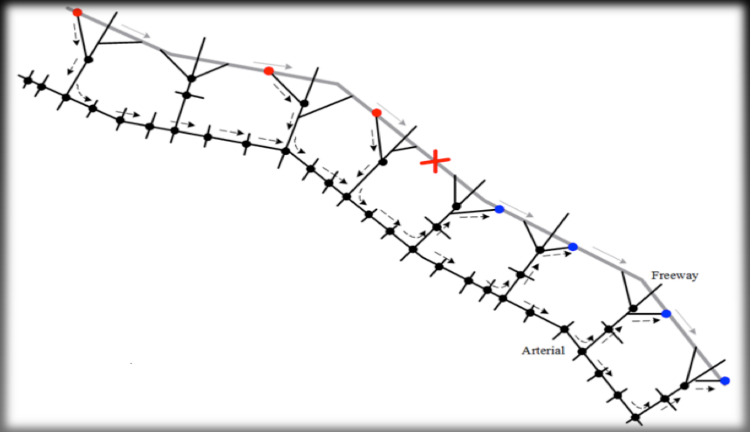


Part II – The Integrated Corridor Control Model

Step 1
Base Model - Integrated Control of a Single Corridor Segment



Step 2
Extended Model - Integrated Control of a Multi-segment Corridor

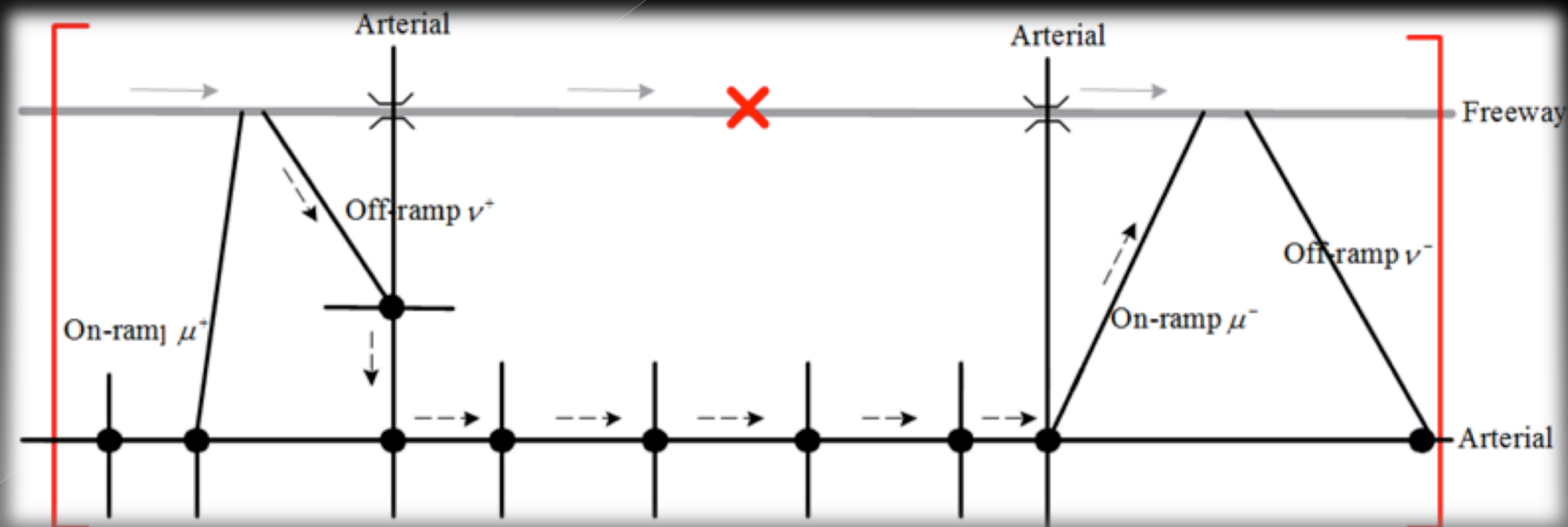


Part II – The Integrated Corridor Control Model

Step 1
Base Model - Integrated Control of a Single Corridor Segment

Expected Output:

1. Diversion rates at the off-ramp
2. Arterial signal timings: cycle length, offsets, and splits
3. Incident upstream on-ramp metering rates



Part II – The Integrated Corridor Control Model

Key Formulations

Step 1
Base Model - Integrated Control of a Single Corridor Segment

$$\min \quad \Phi(s) = \begin{bmatrix} f_1(s) \\ f_2(s) \end{bmatrix}$$

$$f_1 : -\left[\sum_{t=1}^{H} q_{i+1,0}[t] \cdot \Delta T + \sum_{k=1}^{H} \sum_{i \in S^{OUT}} q_i^{in}[k] \right]$$

$$f_2 : \sum_{k=1}^{H} \left[\sum_{i \in S^U} N_i^{\mu^-}[k] + N_{\nu^+}^{\mu^-}[k] + N_{\mu^-}^{\mu^-}[k] \right] \cdot \Delta t$$

$$s.t. \quad s : \{C^h, \Delta_n^h, G_{np}^h, R_{\mu^+}^h, Z_{\nu^+}^h, \forall h \in H\}$$

Max. Total Corridor Throughput

Min. Total Spent Time by Detour Traffic

Operational Constraints

$$C^{\min} \le C^h \le C^{\max}$$

$$G_{np}^{\min} \le G_{np}^h < C^h \quad , \forall n \in S_N, p \in P_n, h \in H$$

$$\sum_{p \in P_n} G_{np}^h + \sum_{p \in P_n} I_{np} = C^h, \forall n \in S_N, p \in P_n, h \in H$$

$$0 \le \Delta_n^h < C^h \quad , \quad \forall n \in S_N, h \in H$$

$$R^{\min} \le R_{\mu^+}^h \le R^{\max}, h \in H$$

$$\beta_{\nu^+}^h \cdot Z_{\nu^+}^h + \gamma_{\nu^+}^h \le Z^{\max}, h \in H$$

+

Network Flow Constraints

Part II – The Integrated Corridor Control Model

Operational Constraints

$C^{\min} \le C^h \le C^{\max}$ **Cycle length constraint**

$G_{np}^{\min} \le G_{np}^h < C^h \quad , \forall n \in S_N, p \in P_n, h \in H$ **Green time constraint**

$\sum_{p \in P_n} G_{np}^h + \sum_{p \in P_n} I_{np} = C^h, \forall n \in S_N, p \in P_n, h \in H$ **The sum of green times and clearance times should be equal to cycle length.**

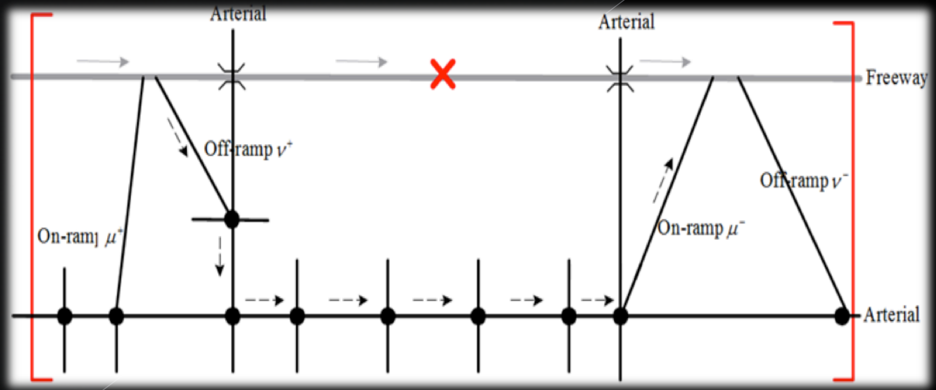
$0 \le \Delta_n^h < C^h \quad , \quad \forall n \in S_N, h \in H$ **Offset constraint**

$R^{\min} \le R_{\mu^+}^h \le R^{\max}, h \in H$ **Metering rate constraint**

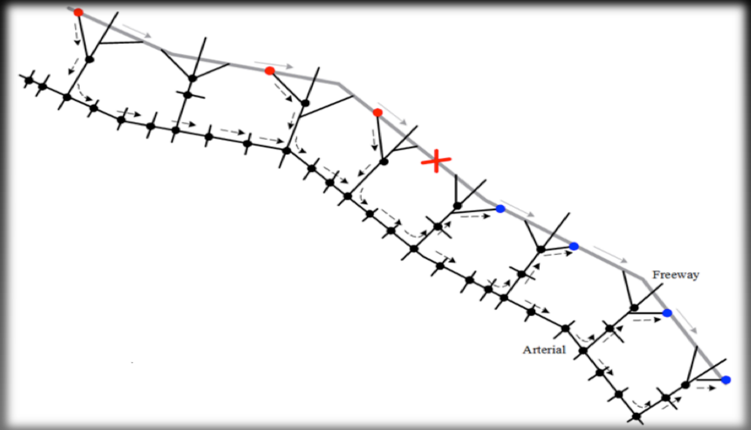
$\beta_{\nu^+}^h \cdot Z_{\nu^+}^h + \gamma_{\nu^+}^h \le Z^{\max}, h \in H$ **Diversion rate constraint**

Part II – The Integrated Corridor Control Model

Step 1
Base Model - Integrated Control of a Single Corridor Segment

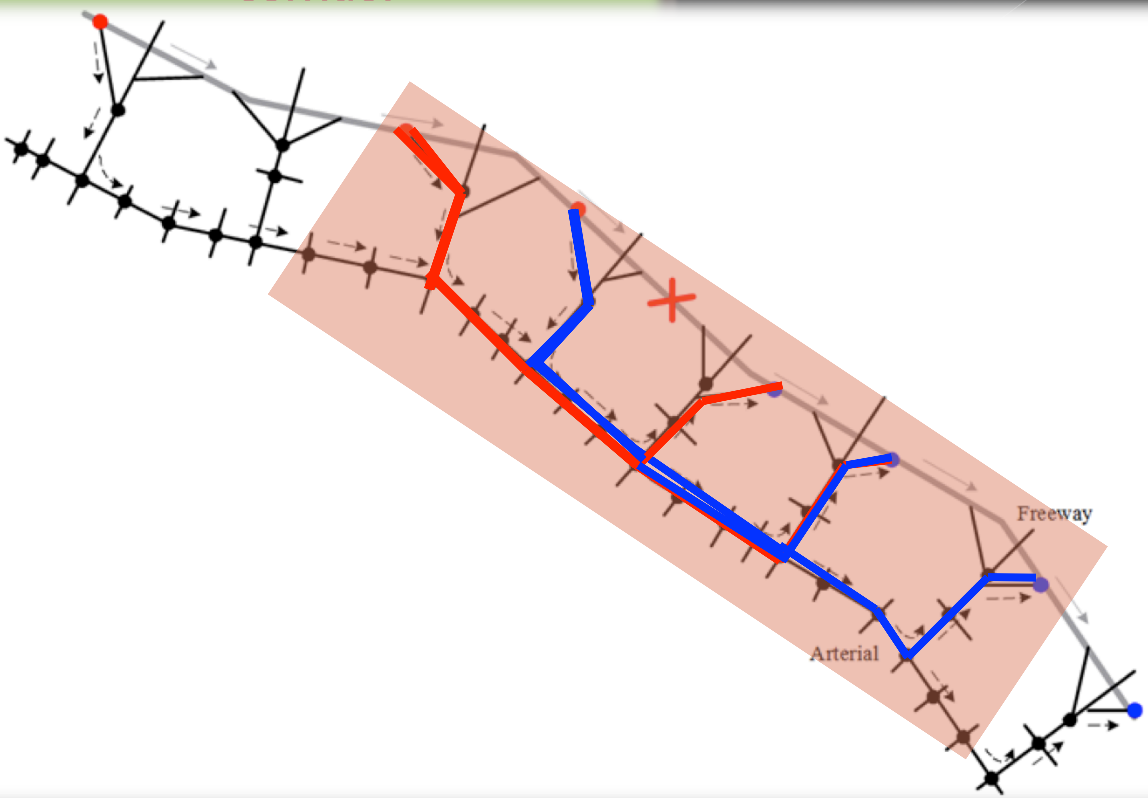


Step 2
Extended Model - Integrated Control of a Multi-segment Corridor



Part II – The Integrated Corridor Control Model

Step 2
Extended Model - Integrated Control of a Multi-segment Corridor



Expected Output:

1. Control boundaries for detour operations
2. Detour plans
3. Diversion rates at each off-ramp
4. Arterial signal timings: cycle length, offsets, and splits
5. Incident upstream on-ramp metering rates

Part II – The Integrated Corridor Control Model

Step 2
Extended Model - Integrated Control of a Multi-segment Corridor

Formulations

$$\min \qquad \Phi(s) = \begin{bmatrix} f_1(s) \\ f_2(s) \end{bmatrix}$$

$$f_1 : -\left[\sum_{t=1}^{H} q_{i+1,0}[t] \cdot \Delta T + \sum_{k=1}^{H} \sum_{i \in S^{OUT}} q_i^{in}[k] \right]$$

$$f_2 : \sum_{k=1}^{H} \left[\sum_{i \in S^U} \sum_{\mu \in S_\mu^-} N_i^\mu[k] + \sum_{v \in S_v^+} \sum_{\mu \in S_\mu^-} N_v^\mu[k] + \sum_{\mu \in S_\mu^-} N_\mu^\mu[k] \right] \cdot \Delta t$$

$$s.t. \quad s : \{C^h, \Delta_n^h, G_{np}^h, R_u^h, Z_v^h, \delta_{vu}^h, \forall h \in H\}$$

Additional set of decision variables for detour route choice (δ_{vu}^h)

Enhanced Network Flow Constraints

$$q_i^{in}[k] = \sum_{j \in \Gamma(i)} \overline{Q}_{ji}[k] + \sum_{\mu \in S_\mu^-} \sum_{j \in \Gamma(i)} Q_{ji}^\mu[k]$$

$$\rho_i[k] = \frac{\overline{N}_i[k] + \sum_{\mu \in S_\mu^-} N_i^\mu[k] - x_i[k]}{n_i \left(l_i - \frac{x_i[k]}{n_i \cdot \rho^{jam}}\right)}$$

$$q_i^{arr}[k] = \min\{\rho_i[k] \cdot v_i[k] \cdot n_i \cdot \Delta t, \overline{N}_i[k] + \sum_{\mu \in S_\mu^-} N_i^\mu[k] - x_i[k]\}$$

$$q_m^i[k] = \sum_{j \in \Gamma^{-1}(i)} q_i^{arr}[k] \cdot \left[\eta_i[k] \cdot \overline{\gamma}_{ij}[k] + \sum_{\mu \in S_\mu^-} (1 - \eta_i[k]) \cdot \theta_i^\mu[k] \cdot \gamma_{ij}^\mu \right] \cdot \delta_m^{ij}$$

$$\overline{Q}_{ij}[k] = Q_m^i[k] \cdot \overline{\lambda}_m^{ij}[k]$$

$$Q_{ij}^\mu[k] = Q_m^i[k] \cdot \lambda_m^{ij\mu}[k], \mu \in S_\mu^-$$

$$\overline{N}_i[k+1] = \overline{N}_i[k] + \sum_{j \in \Gamma(i)} \overline{Q}_{ji}[k] - \sum_{j \in \Gamma^{-1}(i)} \overline{Q}_{ij}[k]$$

$$N_i^\mu[k+1] = N_i^\mu[k] + \sum_{j \in \Gamma(i)} Q_{ji}^\mu[k] - \sum_{j \in \Gamma^{-1}(i)} Q_{ij}^\mu[k], \mu \in S_\mu^-$$

$$s_i[k+1] = N_i - \overline{N}_i[k+1] - \sum_{\mu \in S_\mu^-} N_i^\mu[k+1]$$

$$\eta_i[k+1] = \frac{\overline{N}_i[k+1]}{\overline{N}_i[k+1] + \sum_{\mu \in S_\mu^-} N_i^\mu[k+1]} \qquad \theta_i^\mu[k+1] = \frac{N_i^\mu[k+1]}{\sum_{\mu \in S_\mu^-} N_i^\mu[k+1]}, \mu \in S_\mu^-$$

$$\lambda_m^{ij}[k] = \frac{\delta_m^{ij} \cdot \left[\eta_i[k]\overline{\gamma}_{ij}[k] + \sum_{\mu \in S_\mu^-} (1 - \eta_i[k])\theta_i^\mu[k]\gamma_{ij}^\mu \right]}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \left[\eta_i[k]\overline{\gamma}_{ij}[k] + \sum_{\mu \in S_\mu^-} (1 - \eta_i[k])\theta_i^\mu[k]\gamma_{ij}^\mu \right]}$$

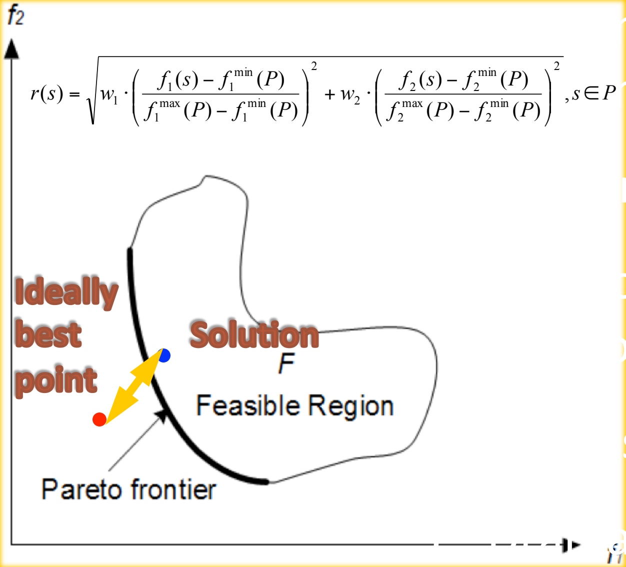
$$\overline{\lambda}_m^{ij}[k] = \frac{\delta_m^{ij} \cdot \eta_i[k]\overline{\gamma}_{ij}[k]}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \left[\eta_i[k]\overline{\gamma}_{ij}[k] + \sum_{\mu \in S_\mu^-} (1 - \eta_i[k])\theta_i^\mu[k]\gamma_{ij}^\mu \right]}$$

$$\lambda_m^{ij\mu}[k] = \frac{\delta_m^{ij} \cdot (1 - \eta_i[k])\theta_i^\mu[k]\gamma_{ij}^\mu}{\sum_{j \in \Gamma^{-1}(i)} \delta_m^{ij} \cdot \left[\eta_i[k]\overline{\gamma}_{ij}[k] + \sum_{\mu \in S_\mu^-} (1 - \eta_i[k])\theta_i^\mu[k]\gamma_{ij}^\mu \right]}$$

Part III – Solution Algorithms for Integrated Control

Module I: A compromised GA to solve the proposed bi-objective model (Gen and Cheng, 1998)

Difficulties



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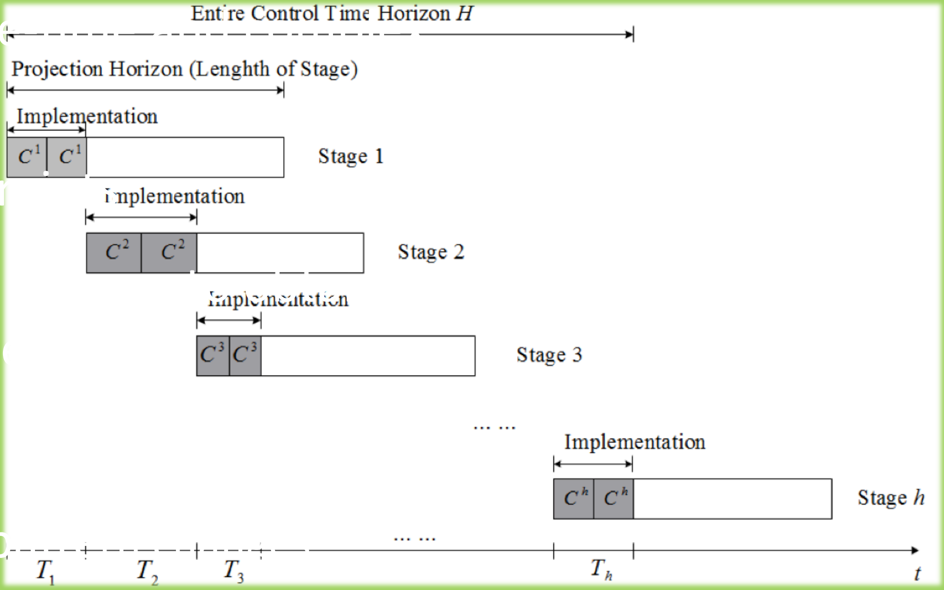
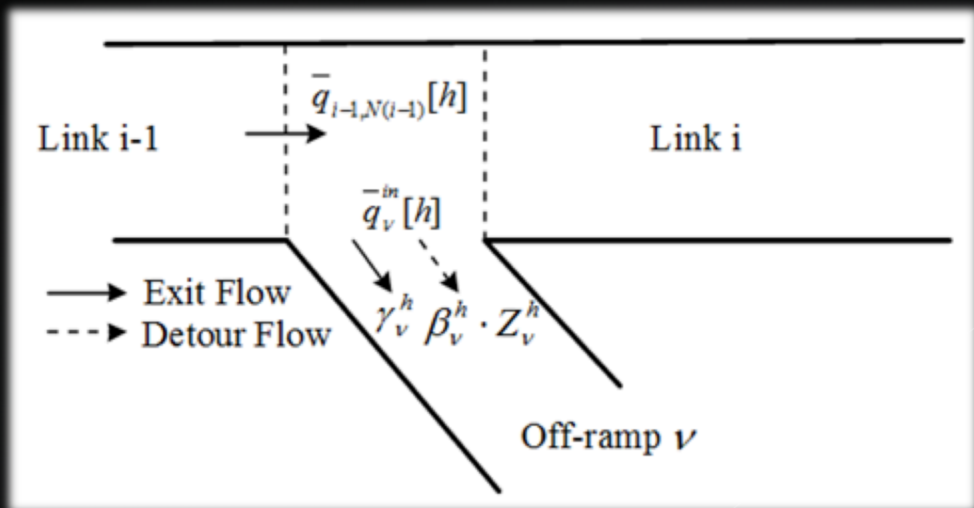
Module II: A successive optimization framework for real-time application with variable rolling time window



On-line Estimation of Diversion Compliance Rates



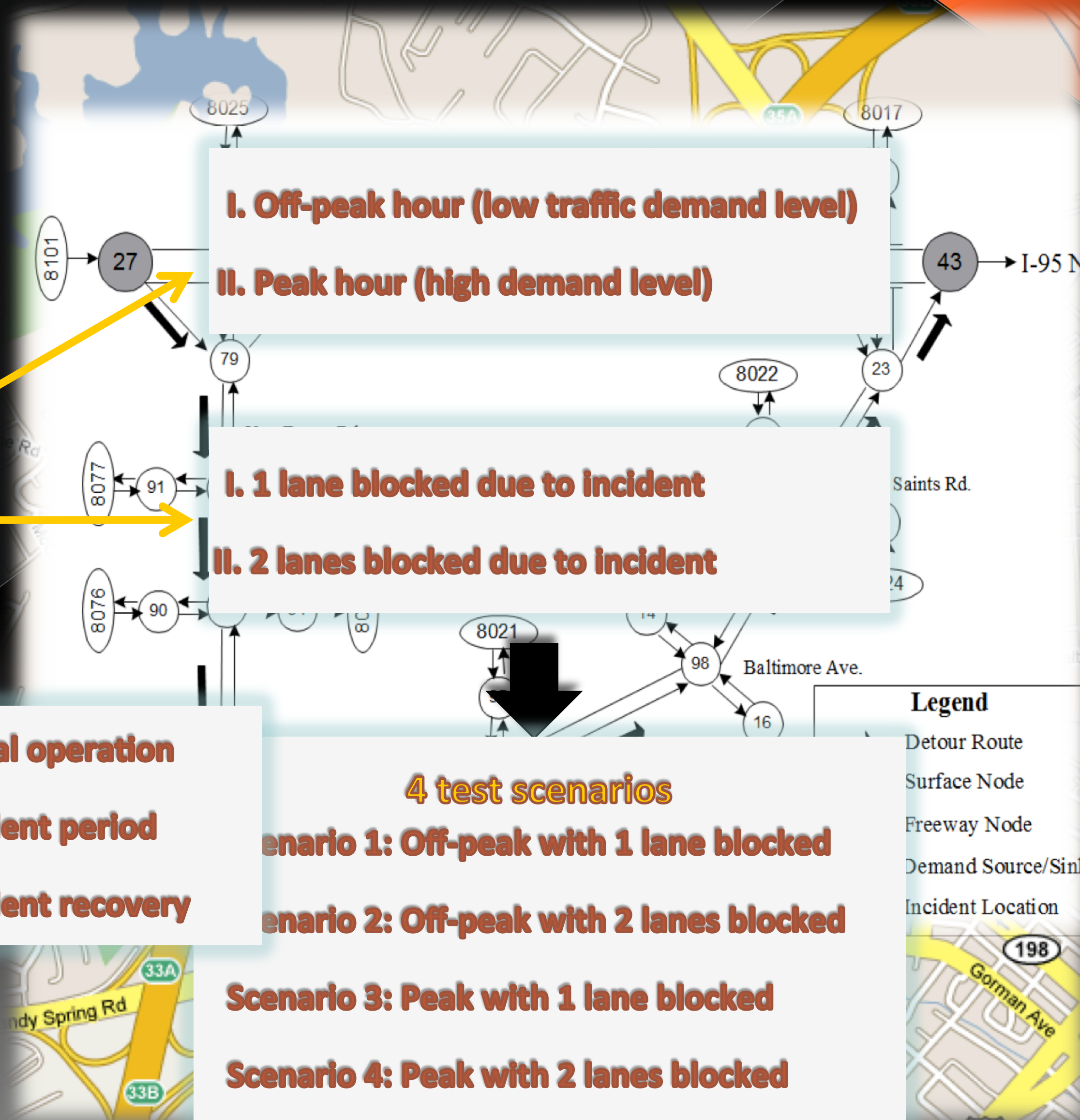
$$\hat{\beta}_v^h = [\bar{q}_v^{in}[h] / \bar{q}_{i-1,N(i-1)}[h] - \gamma_v^h] / Z_v^h$$

- Estimation of compliance rate
- Measurement of flow rate at the off-ramp
- Measurement of flow rate at the freeway upstream
- Normal exit rate
- Applied diversion rate

Case Studies – The Base Model

Experiment Design

1. I-95 corridor northbound
2. MD198 and MD216
3. 6 arterial intersections
4. 2 traffic demand levels
5. 2 levels of incident effect
6. 35-min control period



I. Off-peak hour (low traffic demand level)

II. Peak hour (high demand level)

I. 1 lane blocked due to incident

II. 2 lanes blocked due to incident

5-min normal operation

20-min incident period

10-min incident recovery

4 test scenarios

enario 1: Off-peak with 1 lane blocked

enario 2: Off-peak with 2 lanes blocked

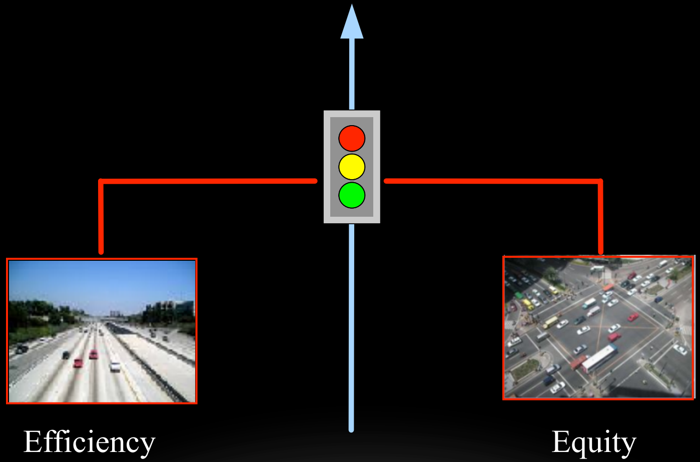
Scenario 3: Peak with 1 lane blocked

Scenario 4: Peak with 2 lanes blocked

Case Studies – The Base Model

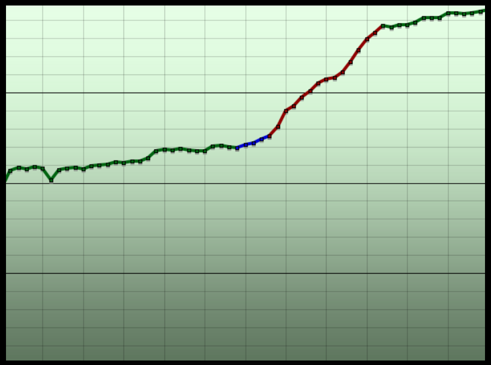
Step- 1:

Evaluate the performance of the proposed model with systematically varied weights to provide operational guidelines for decision makers in best weighting importance between both control objectives under a given scenario



Step- 2:

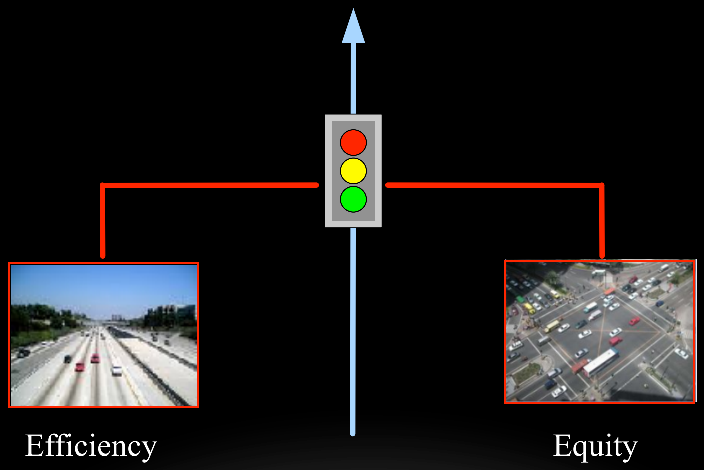
With a set of properly selected weights from Step - 1, compare the model performance with other two strategies



Case Studies – The Base Model

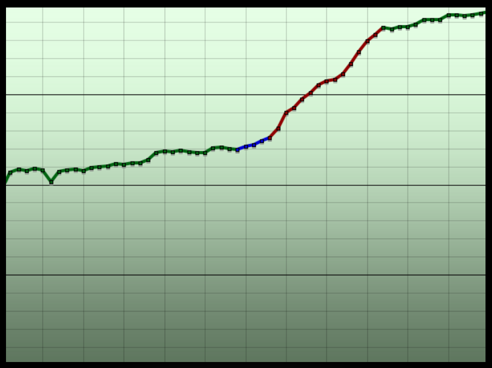
Step- 1:

Evaluate the performance of the proposed model with systematically varied weights to provide operational guidelines for decision makers in best weighting importance between both control objectives under a given scenario



Step- 2:

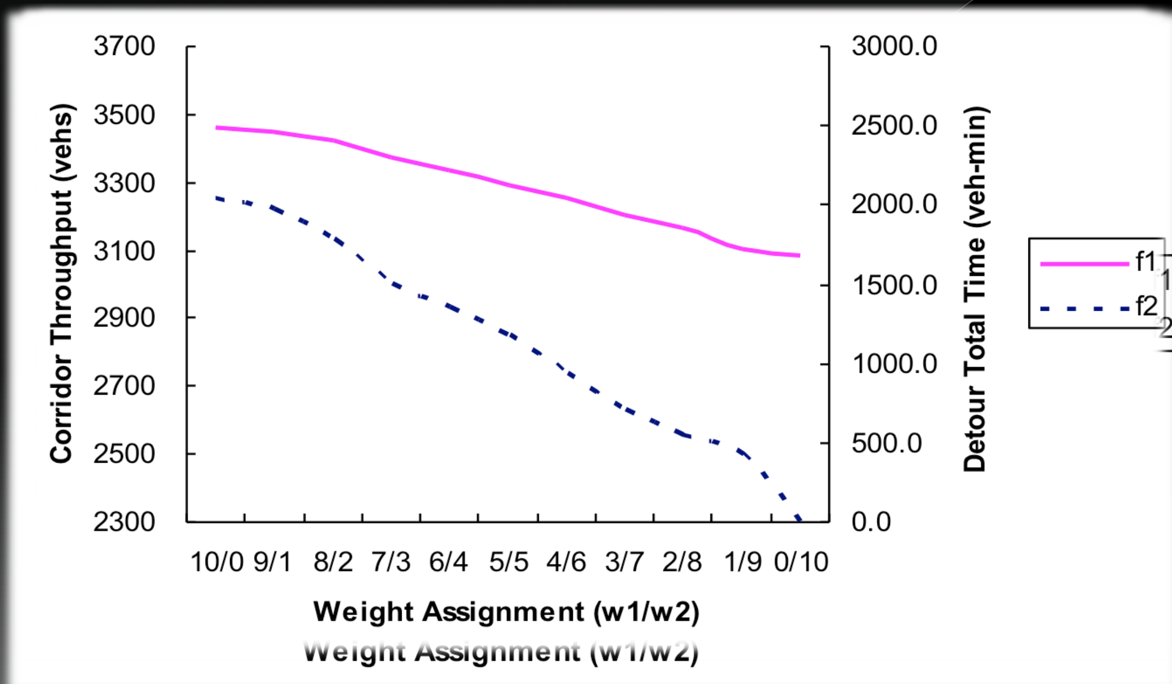
With a set of properly selected weights from Step - 1, compare the model performance with other two strategies

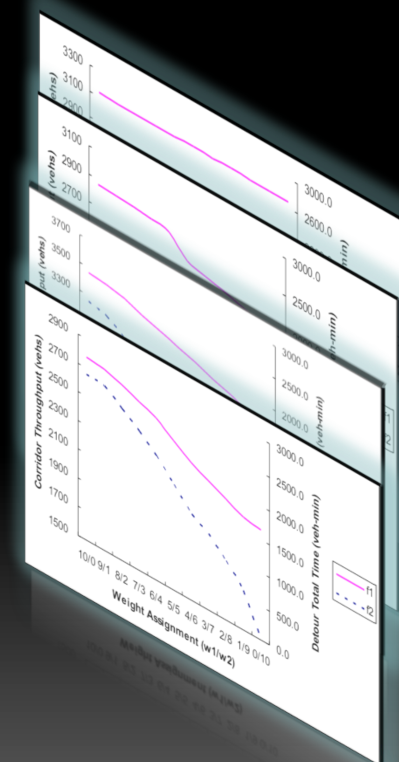


Case Studies – The Base Model

Step- 1: Objective function values under different weight assignment (w1/w2)

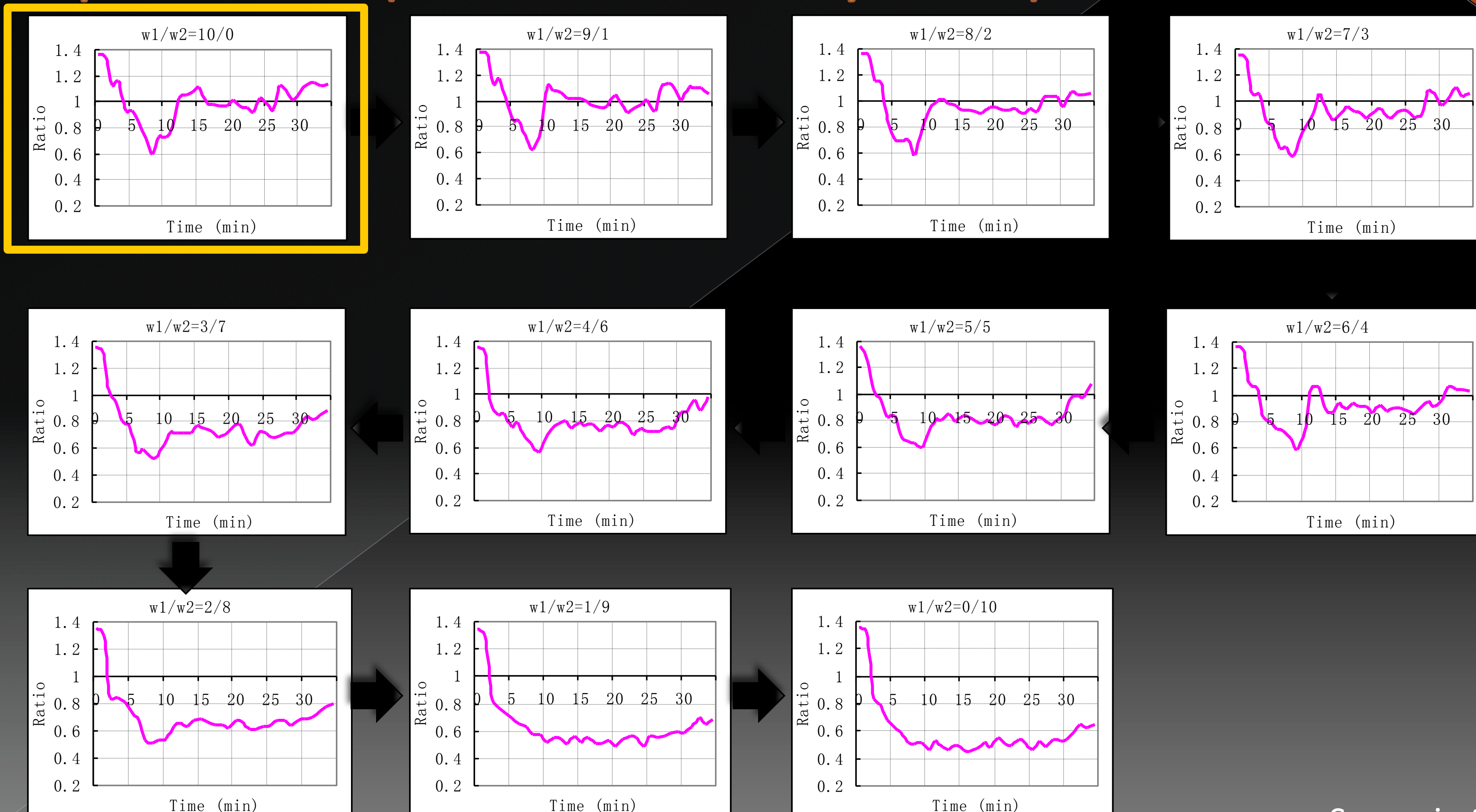
Scenario 4: Off-peak with 2 lanes blocked





Case Studies – The Base Model

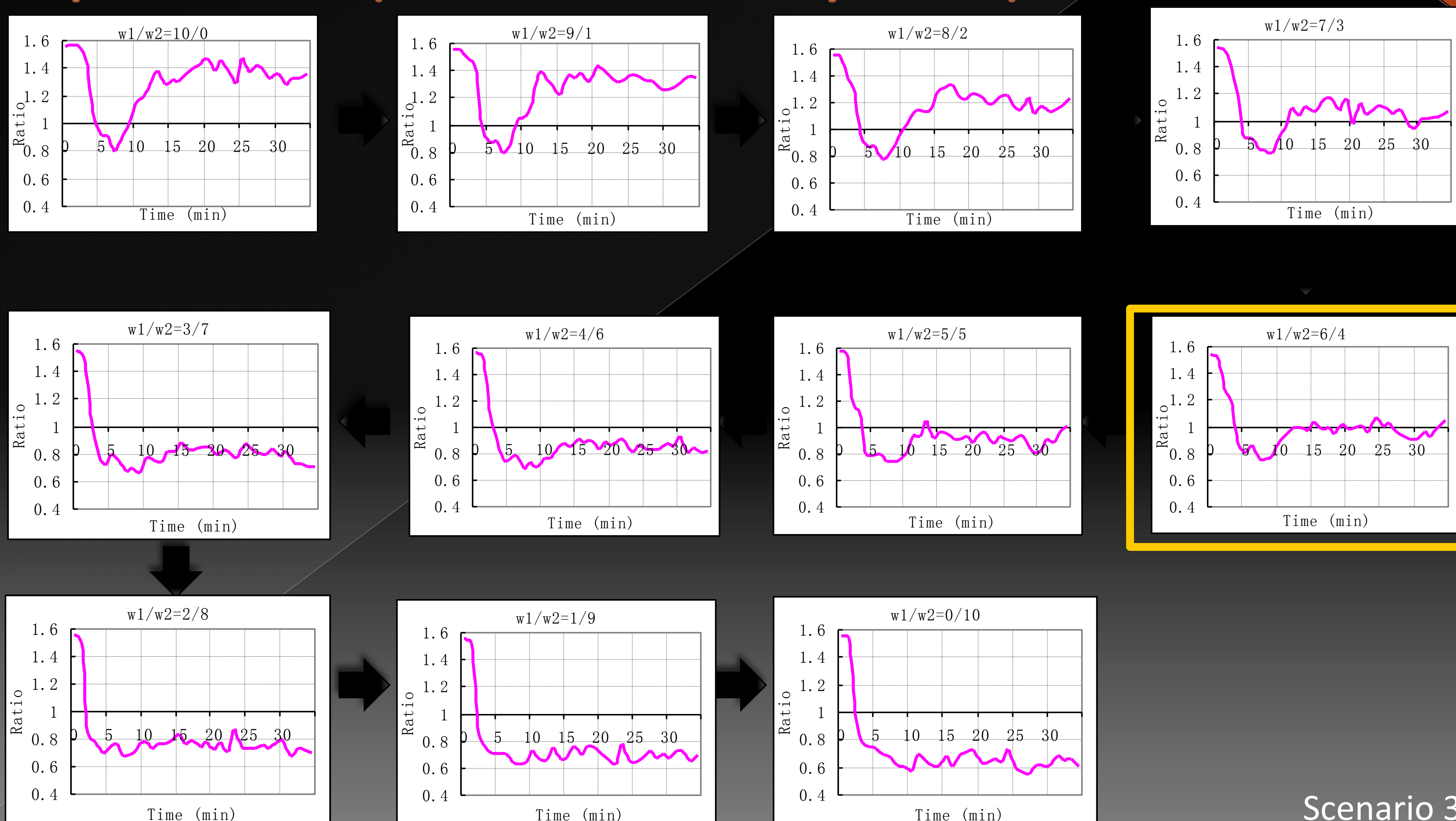
Step- 1: Travel Time (Detour Route v.s. Freeway Mainline)



Scenario 2

Case Studies – The Base Model

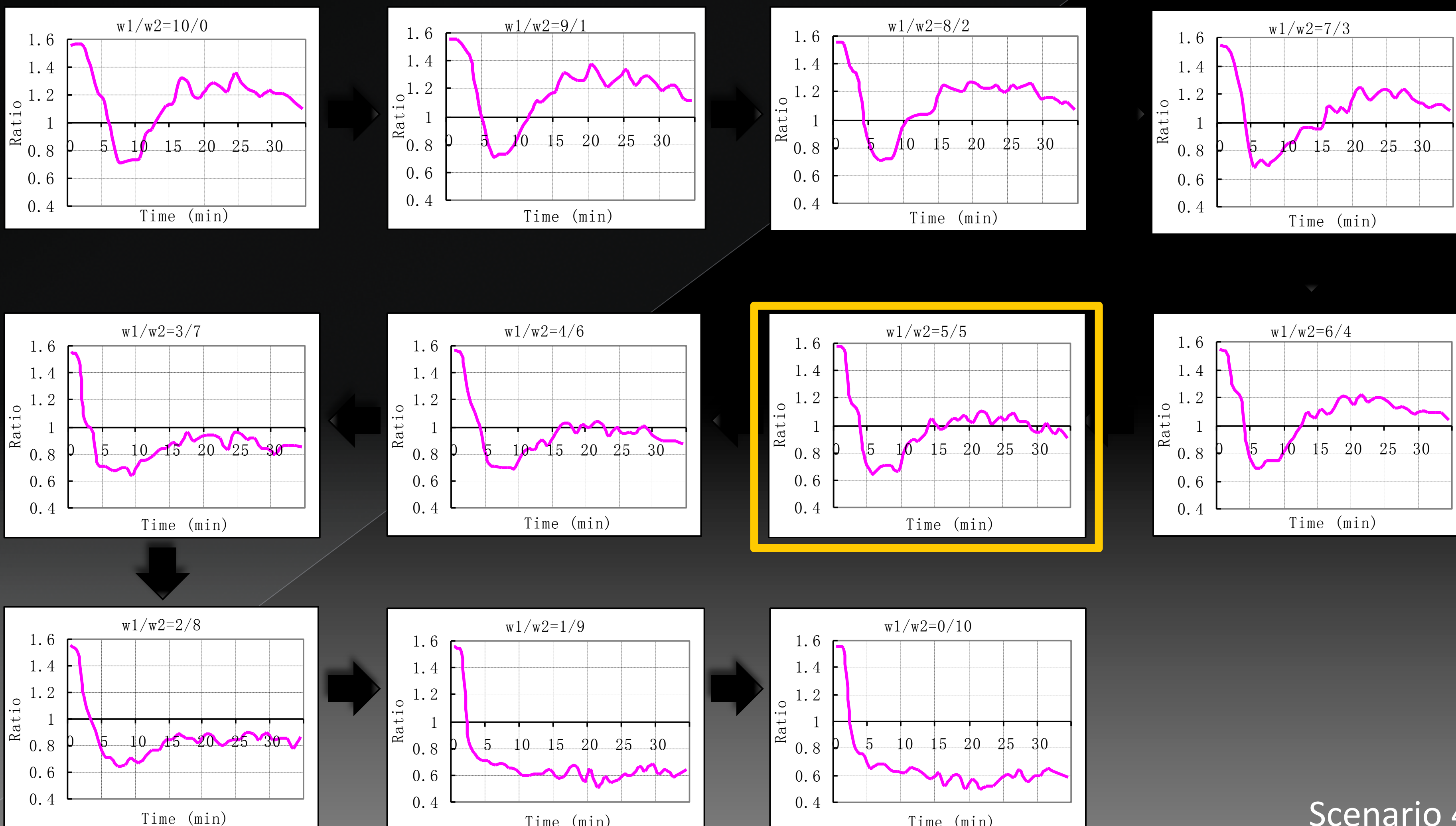
Step- 1: Travel Time (Detour Route v.s. Freeway Mainline)



Scenario 3

Case Studies – The Base Model

Step- 1: Travel Time (Detour Route v.s. Freeway Mainline)



Scenario 4

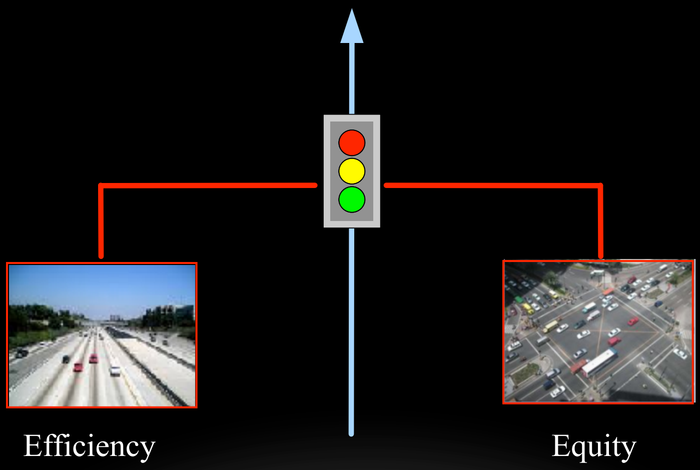
1. Single control objective may effectively maximize the utilization of corridor capacity under light traffic and incident conditions, however it may cause unbalanced traffic conditions under over-saturated conditions which will degrade the diversion compliance rates

2. Traffic operators need to properly select the weighting factors between two control objectives to achieve the best operational efficiency while balancing the traffic conditions

Case Studies – The Base Model

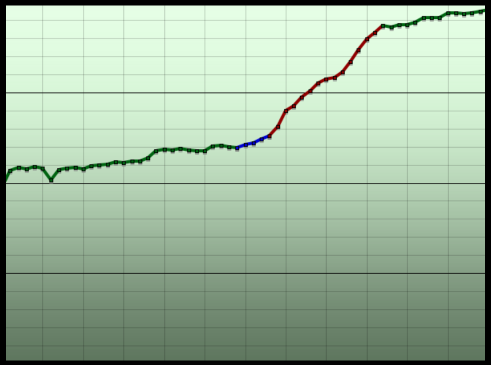
Step- 1:

Evaluate the performance of the proposed model with systematically varied weights to provide operational guidelines for decision makers in best weighting importance between both control objectives under a given scenario



Step- 2:

With a set of properly selected weights from Step - 1, compare the model performance with other two strategies



Case Studies – The Base Model

Step- 2: Comparison with other strategies

Plan A
No Control – base line

Plan B
Local Responsive Control

1. Detour – Static User Equilibrium (UE)
2. On-ramp metering – ALINEA
3. Arterial signal timing – TRANSYT-7F

Plan C
The Proposed control model

4 test scenarios

Scenario 1: Off-peak with 1 lane blocked

Scenario 2: Off-peak with 2 lanes blocked

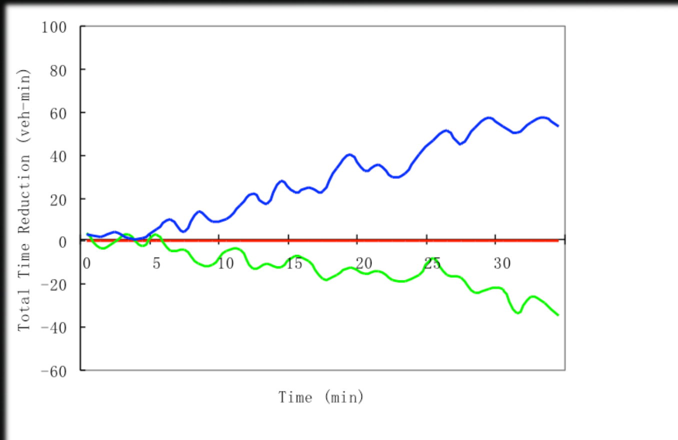
Scenario 3: Peak with 1 lane blocked

Scenario 4: Peak with 2 lanes blocked

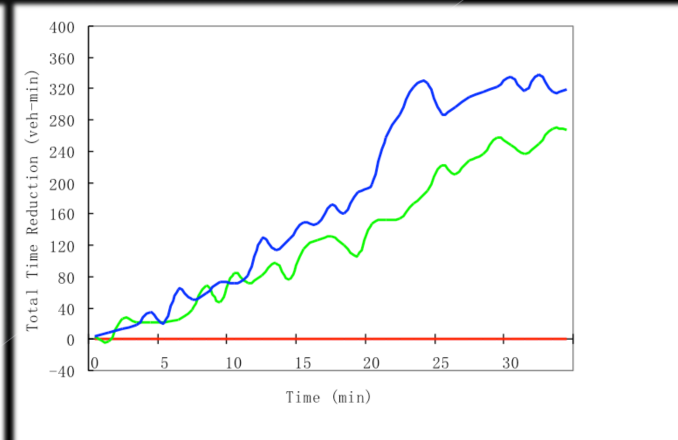
Case Studies – The Base Model

MOE -1. Accumulated Total Travel Time Savings

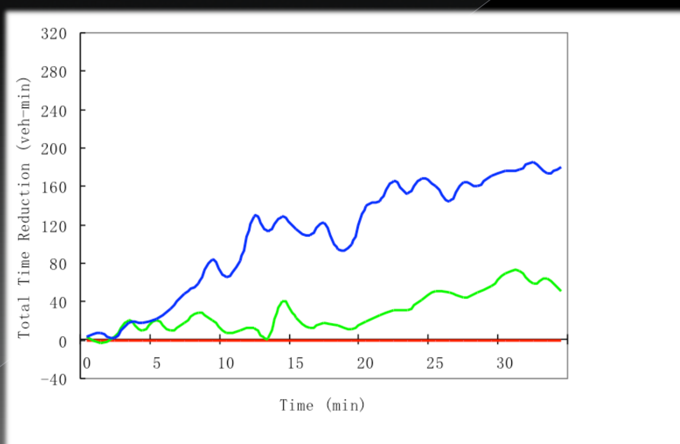
Scenario 1
w1/w2=10/0



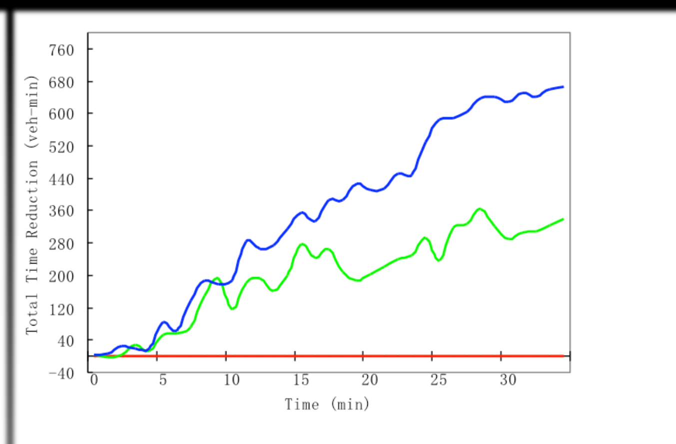
Scenario 2
w1/w2=10/0



Scenario 3
w1/w2=6/4



Scenario 4
w1/w2=5/5



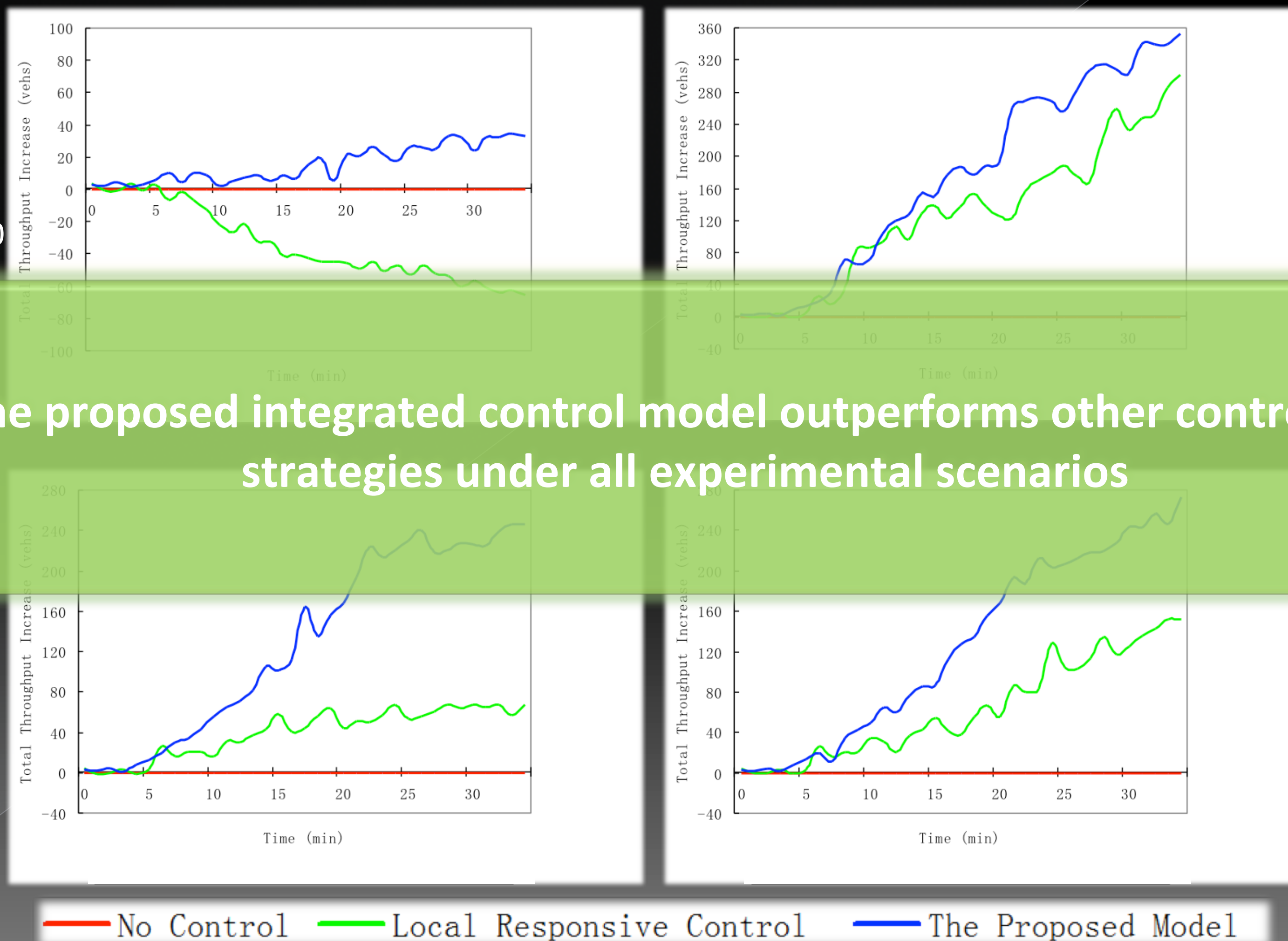
No Control Local Responsive Control The Proposed Model

Case Studies – The Base Model

MOE-2. Accumulated Total Corridor Throughput Increases

Scenario 1
w1/w2=10/0

Scenario 2
w1/w2=10/0



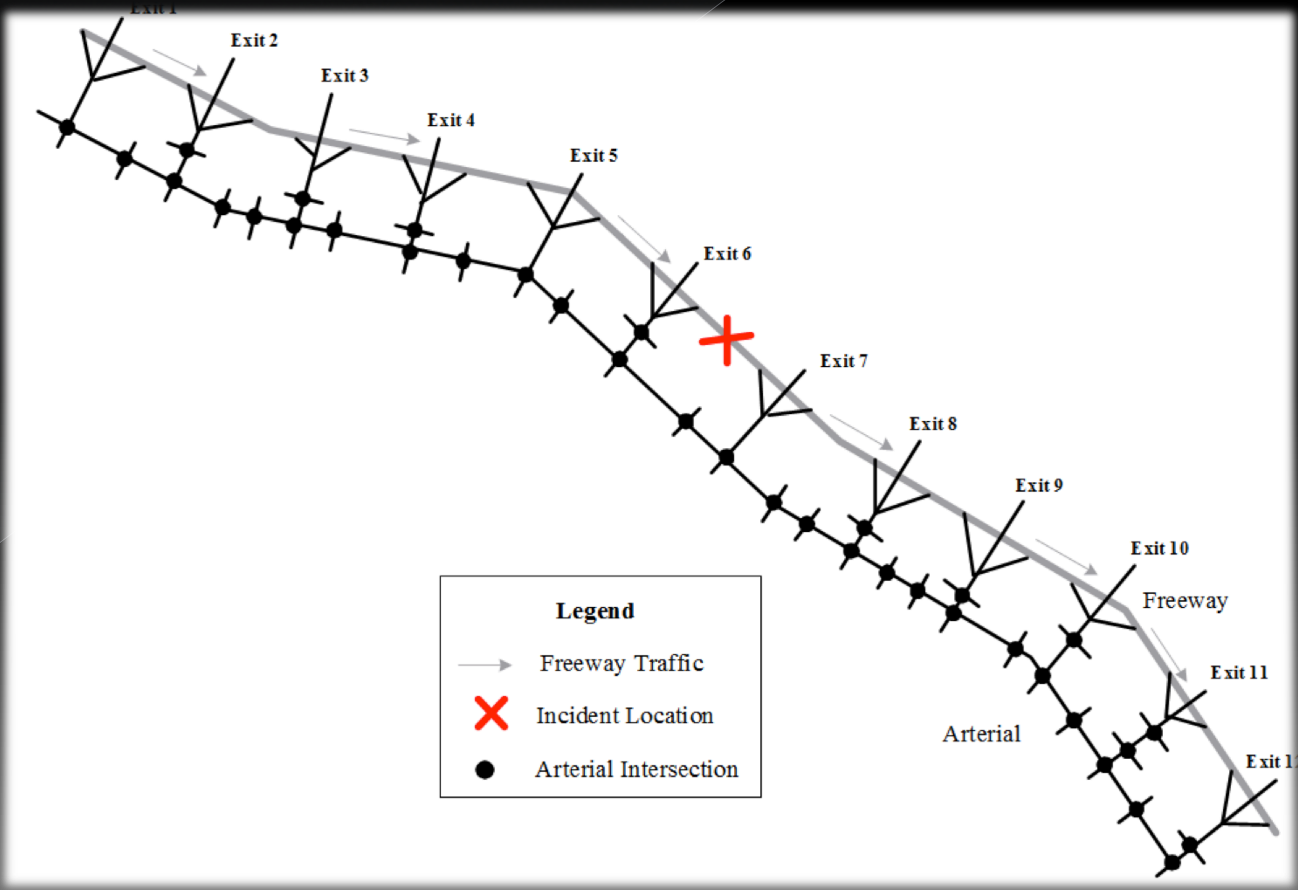
The proposed integrated control model outperforms other control strategies under all experimental scenarios

Scenario 3
w1/w2=6/4

Scenario 4
w1/w2=5/5

Case Studies – The Extended Model

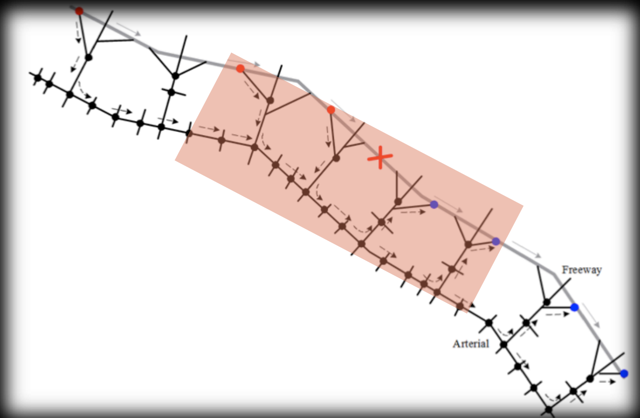
Experiment Design: A 12-mile hypothetical corridor with 12 exits and 36 arterial intersections



Case Studies – The Extended Model

Step- 1:

Investigate the control area variation with respect to different weight assignment settings, and its impact on the system MOEs



Step- 2:

Compare the performance of the extended model with the base model under the same incident scenario and the same control objective

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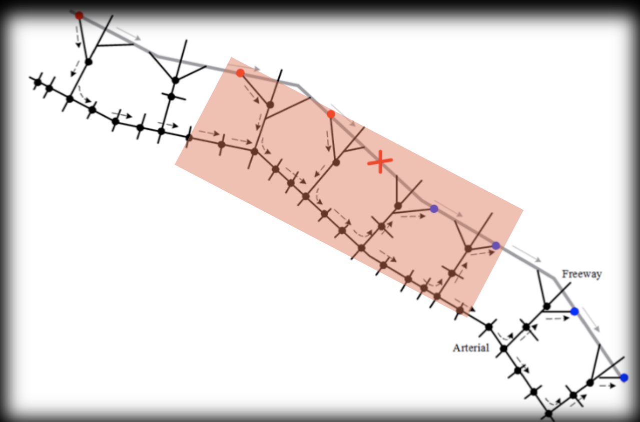

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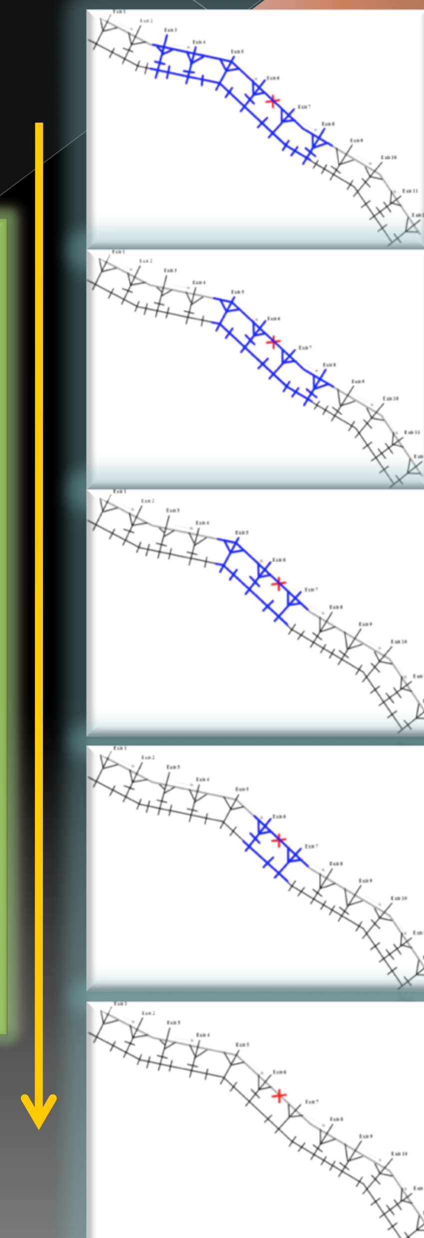
Case Studies – The Extended Model

Step- 1: The variation of control boundaries

Preliminary Findings:

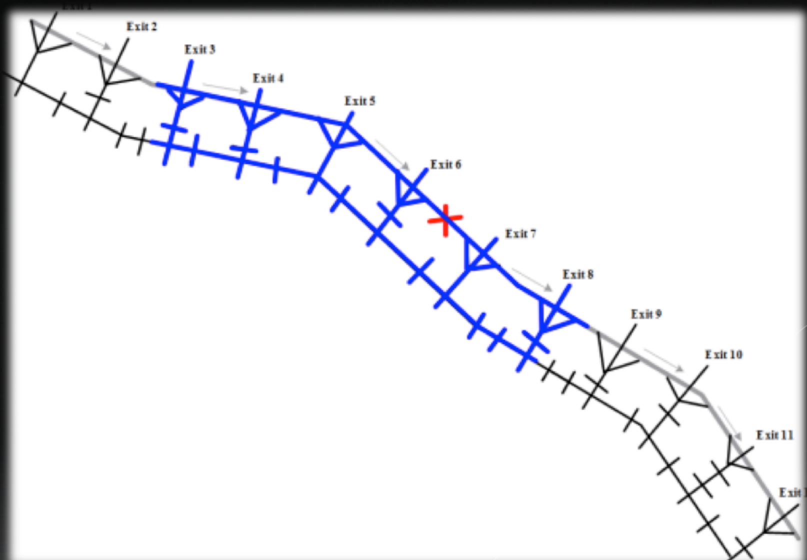
1. The control boundaries shrink with the weight assignment between two control objectives varying from 10/0 to 0/10
2. There exists a critical control area beyond which the total corridor throughput no longer increases.
3. The number of incident downstream on-ramps used to divert traffic back to the freeway is less than that of incident upstream off-ramps.



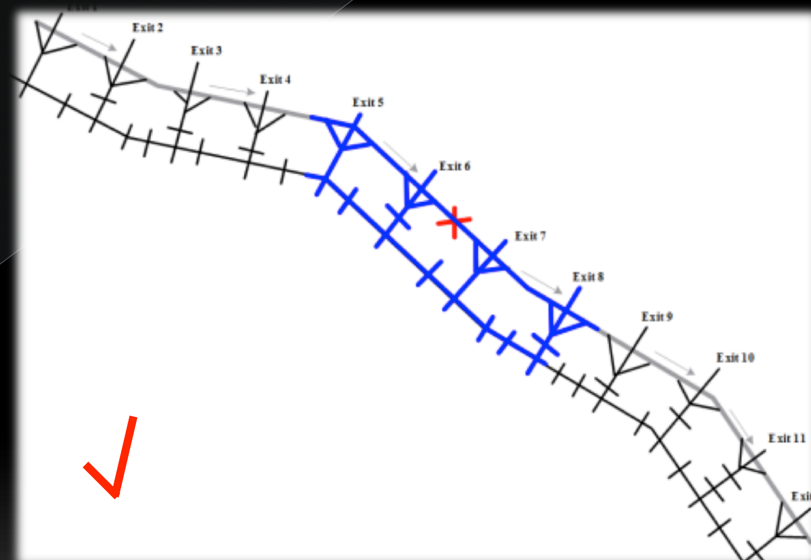
Case Studies – The Extended Model

Step- 1: Determine the proper control boundaries

w1/w2=10/0



w1/w2=8/2

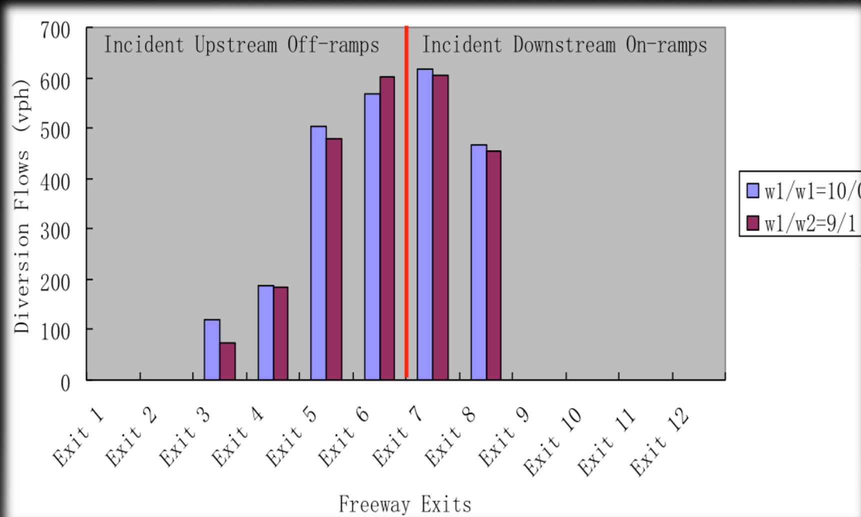


Total corridor throughput decreases only 3.2%
Total spent time by detour traffic decreases 19.8%

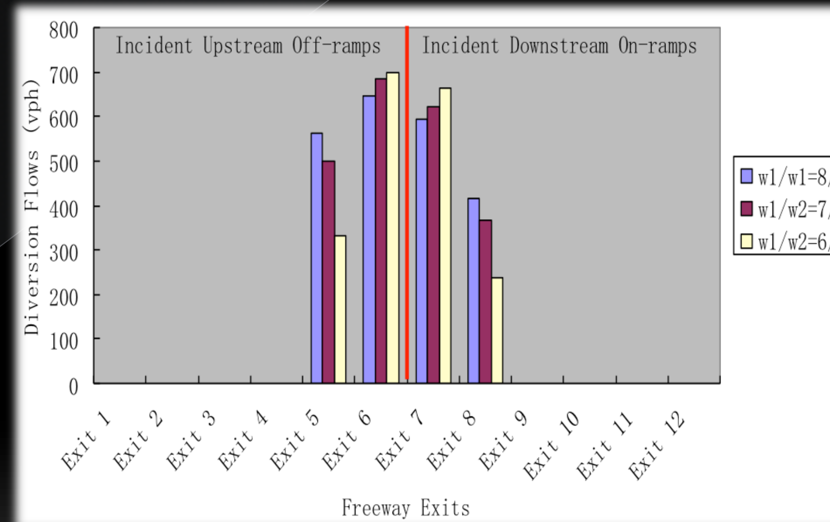
Case Studies – The Extended Model

Step- 1: Distribution of diversion flows

w1/w2=10/0 and 9/1



w1/w2=8/2, 7/3, 6/4



1. The diversion flows are not evenly distributed over the upstream off-ramps. An off-ramp closer to the incident location has carried more diversion flows
2. The most upstream off-ramps only carry a small percent of diversion traffic but significantly increase the total time spent

Case Studies – The Extended Model

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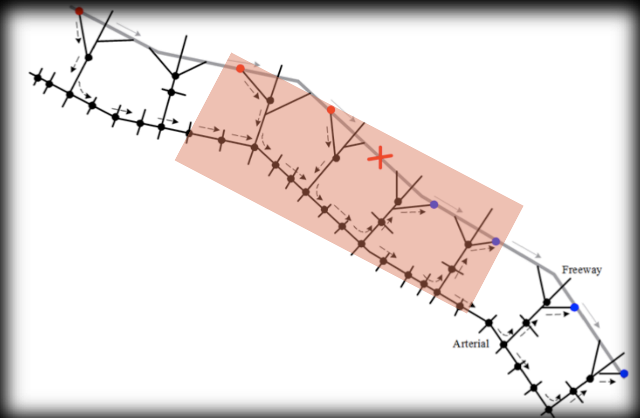
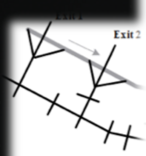


Step- 2:

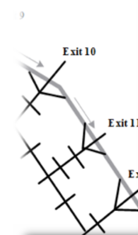
Compare the performance of the extended model with the base model under the same incident scenario and the same control objective

Case Studies – The Extended Model

Step- 2: Comparison with the base model under the same incident scenario and the same control objective



Performance Indices	Model 1	Model 2	Improvement over Model 1
Total diversion rates (vph)	984	1379	+40.1%
Total corridor throughput (vehs)	2917	3352	+14.9%
Average detour link total queue time (veh-min)	547.2	416.8	-23.8%
Average side street link total queue time (veh-min)	833.7	575.9	-30.9%



The control boundaries of the base model The control boundaries of the extended model

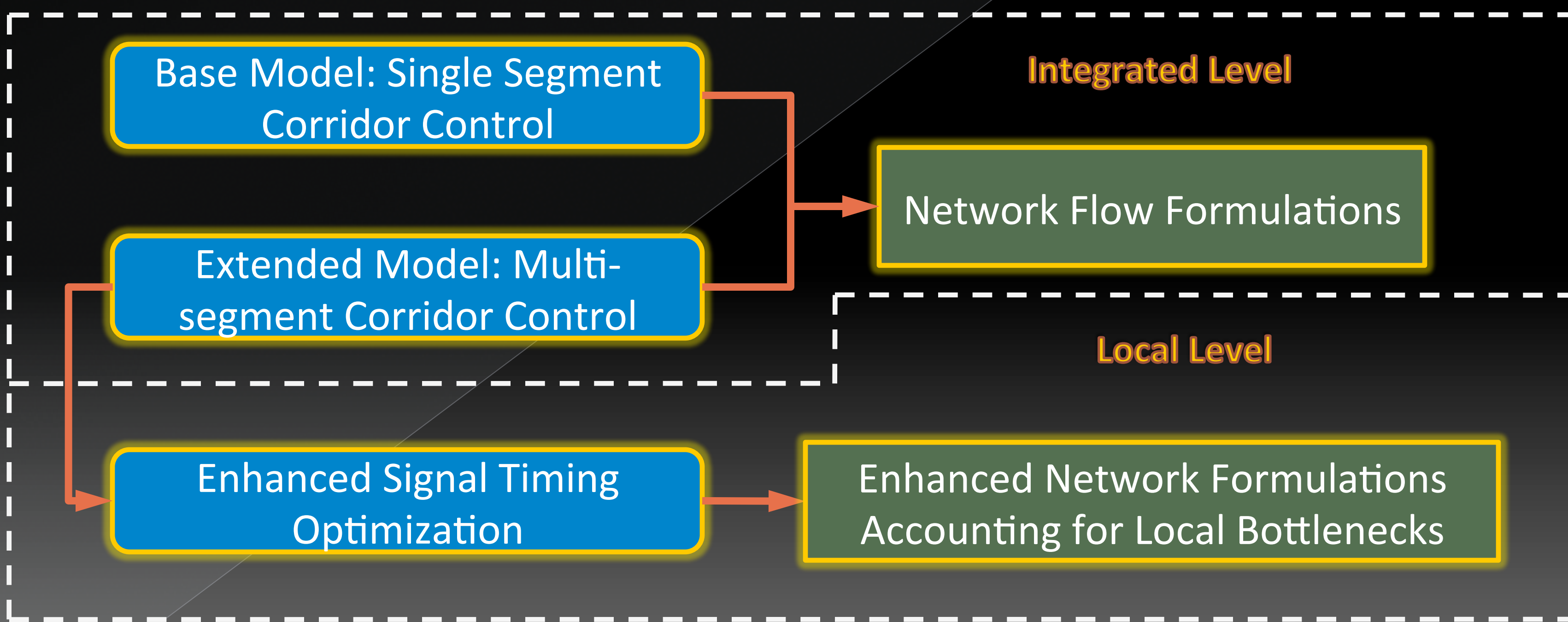
1. The extended model outperforms the base model in terms of the total corridor throughput
2. The extended model can also significantly decrease the average total queue time on detour links and at the side street links

Outline

- Critical issues in developing an integrated traffic control system for non-recurrent congestion management
- Findings of Literature Review
- Primary Research Tasks and Modelling Framework
- Model Development
- Summary and Future Research

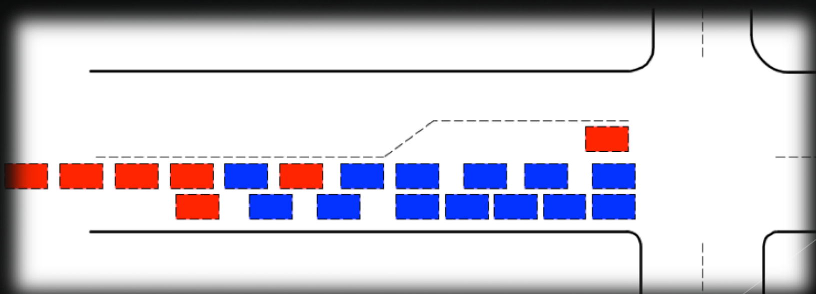
Summary of Contributions

- Develop an effective operational framework to integrate different control strategies for incident management



Summary of Contributions

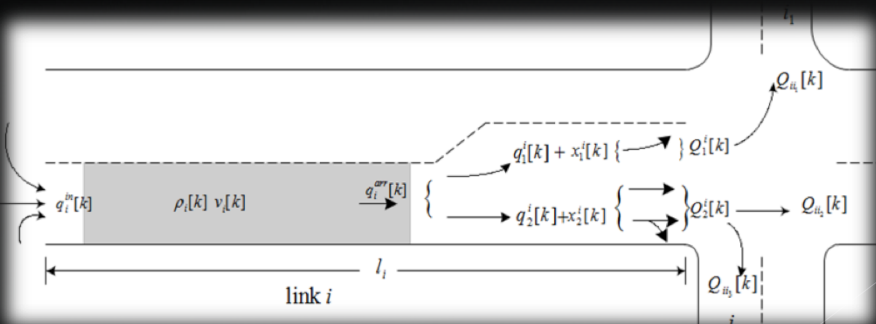
- Develop an enhanced arterial signal optimization model to produce control strategies that can effectively prevent the formation of local bottlenecks

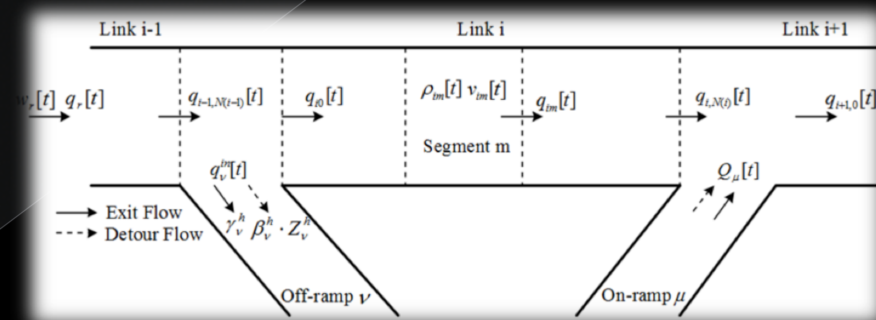


Scenarios	MOEs	Simulation Results from CORSIM (1 hour)		
		Proposed Model	TRANSYT-7F	Improvement* (%)
Low-demand	Total Delay (veh-min)	1728.6	1794.6	-3.7
	Total Queue Time (veh-min)	1327	1410.4	-5.9
	Total Throughput (veh)	2798	2807	-0.3
Medium-demand	Total Delay (veh-min)	3307.2	3358.2	-1.5
	Total Queue Time (veh-min)	2607.8	2680.7	-2.7
	Total Throughput (veh)	4206	4219	-0.3
High-demand	Total Queue Time (veh-min)	10625.9	13089.6	-18.8
	Total Throughput (veh)	5737	5574	+2.9

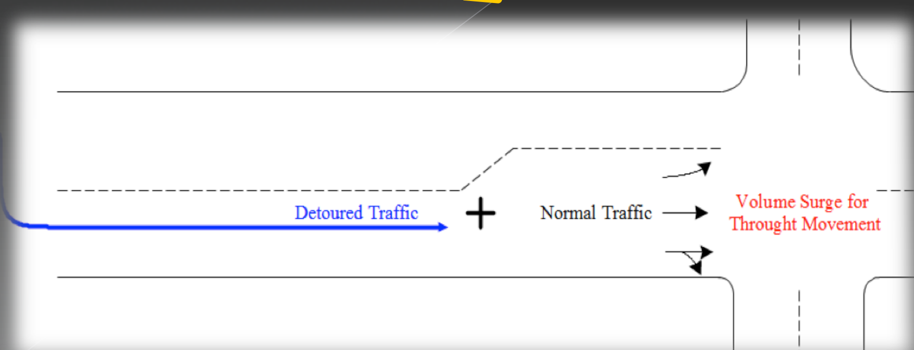
Summary of Contributions

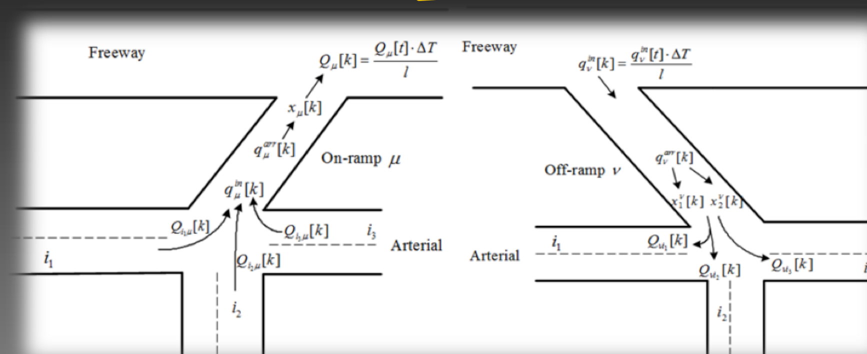
- Construct an overall corridor model that can capture network flow evolution in a dynamic control environment





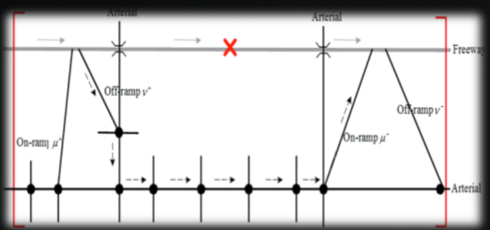
The Overall Corridor Model



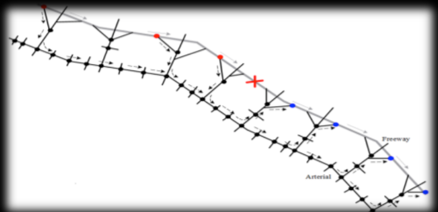


Summary of Contributions

- Formulate a set of mathematical models solved by an efficient algorithm for design of integrated corridor control strategies in real time



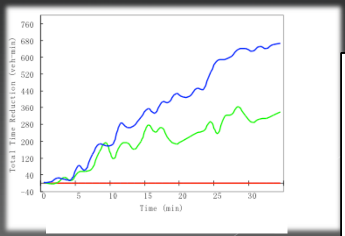
Base Model

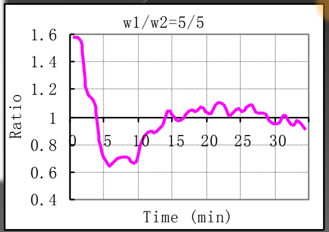


Extended Model

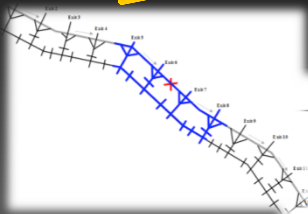
A Multi-objective Framework

GA-based Heuristic
+
A successive optimization framework





Substantially improved operational performance with balanced traffic conditions between the freeway and detour routes



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Less negative impact on the local arterial and better system performance compared with the base model

Future Research

- Development of efficient solution algorithms for large-scale network-wide control
- Development of robust solution algorithms for the proposed models when available control inputs are missing or contain some errors
- Development of an intelligent interface with advanced surveillance systems

Thanks for your attention!

Q & C?

Computational Performance

	The Base Model	The Extended Model
Projection Stage	4-min	10-min
Update Interval	1 cycle length	2 cycle length
Convergence Failure	<3%	<10%

System Application

Intelligent On-line Traffic Management System