Integrating off-ramp spillback control with a decomposed arterial signal optimization model

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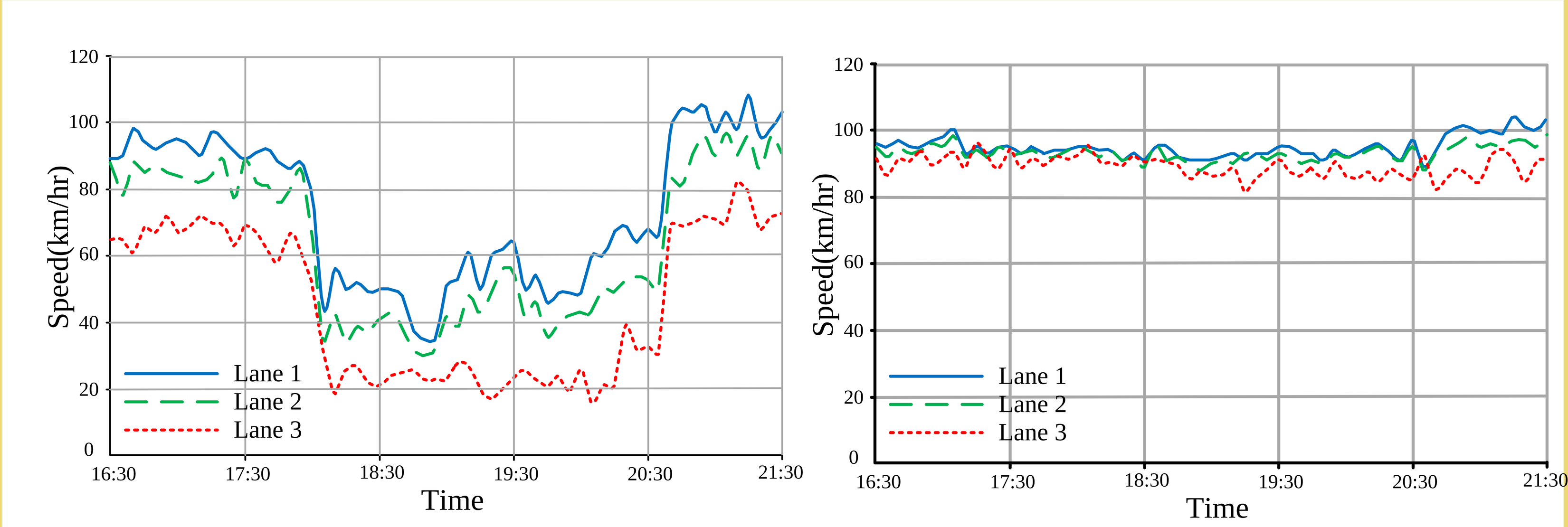
Abstract

- Congestion at the downstream of a freeway off-ramp often propagates the traffic queue to the mainline, and thus reduces the freeway capacity at the interchange area.
- To prevent the potential queue spillback, this study proposes a two-stage control model to optimize the signal plans on an off-ramp connected arterial.
- The first-stage of the model aims to optimize the green splits with a specified off-ramp queue length constraint.
- The second stage of this model is focused on the coordination of both off-ramp flows and local through traffic.

Problem Nature

Field Observation

- This study has collected the field speed data from one freeway segment in Chupei, Taiwan.
- During the period of 18:00 – 20:30, one can observe significant speed drops on all three freeway lanes. Lane 3, nearest to the spillback lane, has dropped its speed to 20 km/h. However, after the traffic passes the off-ramp entry, the speeds on all three lanes can quickly recover to 90 km/h.



Upstream Detector Data   Downstream Detector Data

Stage-1: Signal Optimization

Objective:

Maximizing intersection capacity & preventing off-ramp queue spillover.

Control Variables:

Green splits, common cycle length

$$M1: Maxmize \sum_i \mu_i$$

$$s.t.$$

$$\mu_i \alpha_{k,i} q_{k,i} \le s_{k,i} \sum_m \beta_{k,m,i} \Phi_{m,i} - \delta \times \xi \quad \forall i,k$$

$$\sum_m \Phi_{m,i} = 1 \quad \forall i$$

$$(1 - \sum_m \beta_{o,m,i} \Phi_{m,i} + \delta \times \xi) \cdot q_{o,i} \cdot s_{o,i} \le \tau_{o,i}^{\max} (s_{o,i} - q_{o,i}) \xi$$

$$\frac{1}{C_{\max}} \le \xi \le \frac{1}{C_{\min}}$$

$$\xi \times g_{\min} \le \Phi_{m,i} \le \xi \times g_{\max} \qquad \forall m,i$$

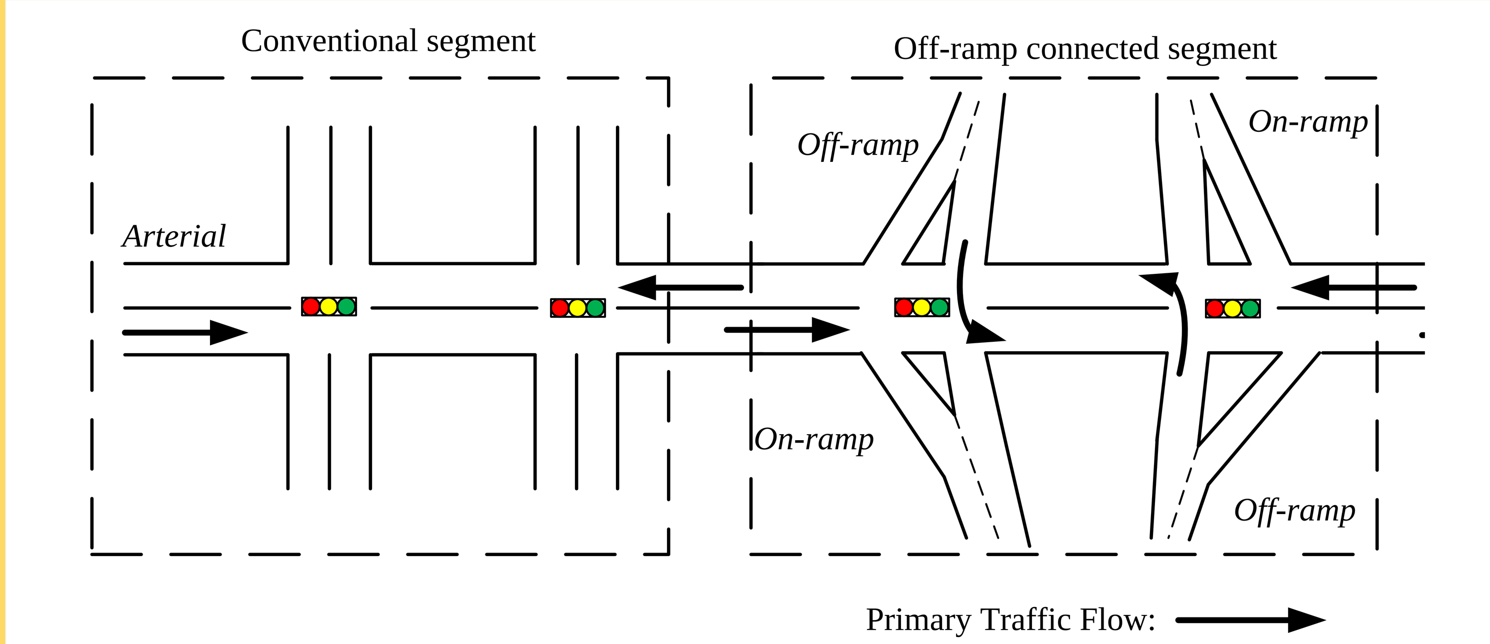
Stage-2: Signal Progression

Arterial Decomposition:

At the interchanged area, one can identify two types of segments:

1) the conventional segment with heavy through traffic along the arterial;

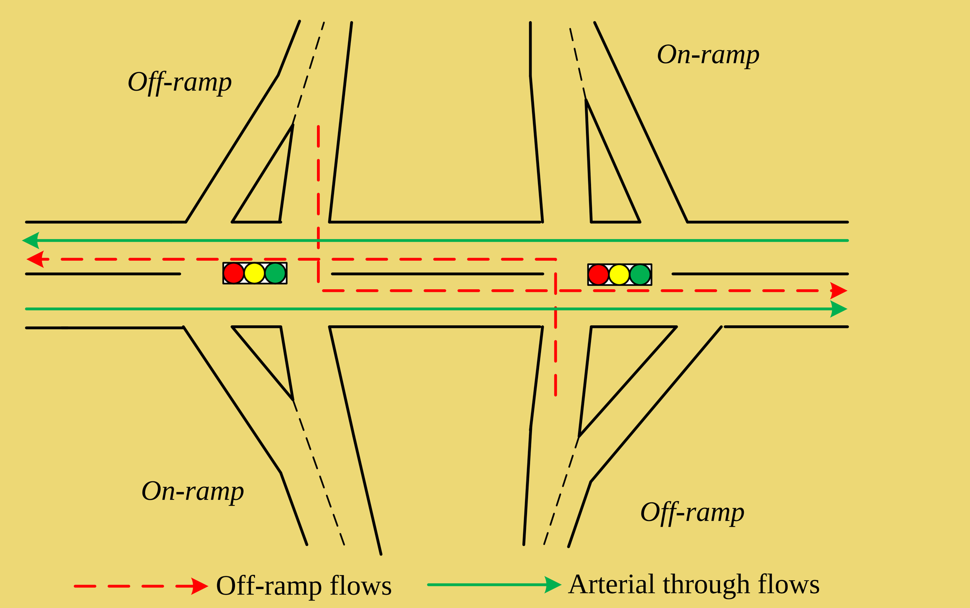
2) the off-ramp connected segment with both heavy off-ramp and arterial through flows.



Multi-flow Progression at the Freeway Connected Segment

Control Objective:

Providing signal progression for both off-ramp flows and local through traffic.



$$M2: Maxmize \sum_j (\varphi_j b_j) + \sum_j (\bar{\varphi}_j \bar{b}_j)$$

$$s.t. \quad (1-p)\sum_{j \in \bar{\Omega}} \bar{b}_j \ge (1-p) p \sum_{j \in \Omega} b_j$$

$$0 \le w_{j,i} + b_j \le \sum_m \beta_{k,m,i} \Phi_{m,i} \quad \forall j \in \Omega; \forall i \in \sigma_j$$

$$0 \le \bar{w}_{j,i} + \bar{b}_j \le \sum_m \beta_{k,m,i} \Phi_{m,i} \quad \forall j \in \bar{\Omega}; \forall i \in \sigma_j$$

$$\theta_i + r_{j,i} + w_{j,i} + t_i + n_{j,i} = \theta_{i+1} + r_{j,i+1} + w_{j,i+1} + \tau_{j,i+1} + n_{j,i+1} \quad \forall j \in \Omega; \forall i \in \sigma_j$$

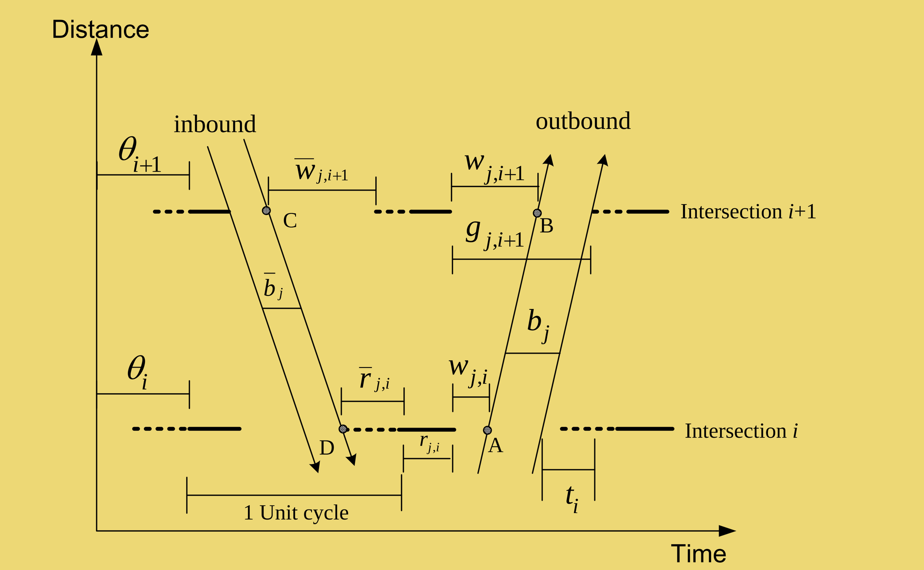
$$-\theta_i + \bar{r}_{j,i} + \bar{w}_{j,i} - \bar{\tau}_{j,i} + \bar{t}_i + \bar{n}_{j,i} = -\theta_{i+1} + \bar{r}_{j,i+1} + \bar{w}_{j,i+1} + \bar{n}_{j,i+1} \quad \forall j \in \bar{\Omega}; \forall i \in \sigma_j$$

$$w_{j,i}, b_j \ge 0 \quad 0 \le \theta_i \le 1 \quad \forall j \in \Omega; \forall i \in \sigma_j \qquad \bar{w}_{j,i}, \bar{b}_j \ge 0 \quad \forall j \in \bar{\Omega}; \forall i \in \sigma_j$$

Two-way Progression at Conventional Segments

Control Objective:

Providing signal progression for local through traffic.



$$M3: Maxmize\ (b + \bar{b})$$

$$s.t. \quad (1-p)\bar{b} \ge (1-p) p b$$

$$w_i + b \le 1 - r_i \quad \forall i$$

$$\bar{w}_i + \bar{b} \le 1 - \bar{r}_i \quad \forall i$$

$$\theta_i + r_i + w_i + t_i + n_i = \theta_{i+1} + r_{i+1} + w_{i+1} + \tau_{i+1} + n_{i+1} \quad \forall i \in \sigma$$

$$-\theta_i + \bar{r}_i + \bar{w}_i - \bar{\tau}_i + \bar{t}_i + \bar{n}_i = -\theta_{i+1} + \bar{r}_{i+1} + \bar{w}_{i+1} + \bar{n}_{i+1} \quad \forall i \in \sigma$$

$$w_e < w'_{j,e} + b' - b_{\min} \quad \forall j$$

$$w_e + b > w'_{j,e} + b_{\min} \quad \forall j$$

$$\bar{w}_e < \bar{w}'_{j,e} + \bar{b}' - b_{\min} \quad \forall j$$

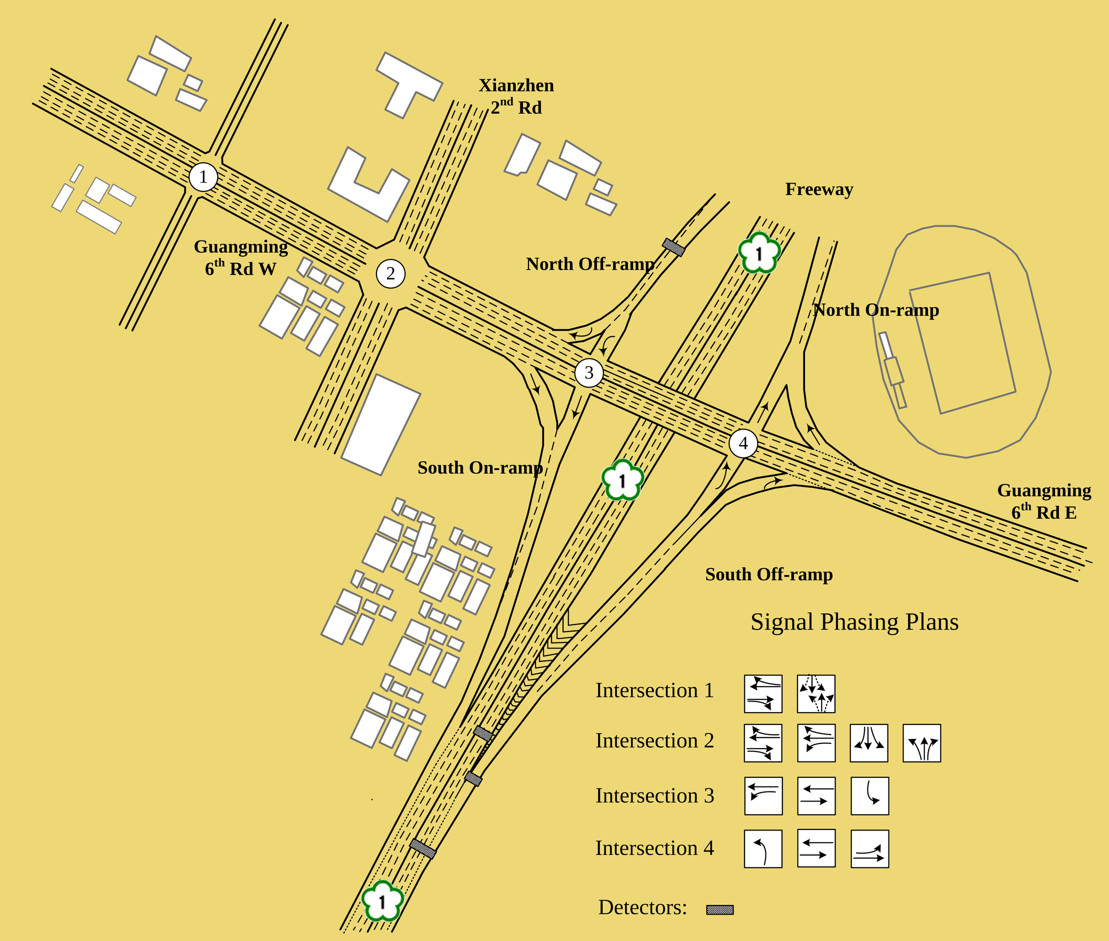
$$\bar{w}_e + \bar{b} > \bar{w}'_{j,e} + b_{\min} \quad \forall j$$

$$w_i, b, \bar{w}_i, \bar{b} \ge 0 \quad 0 \le \theta_i \le 1 \quad \forall i \in \sigma$$

Case Study

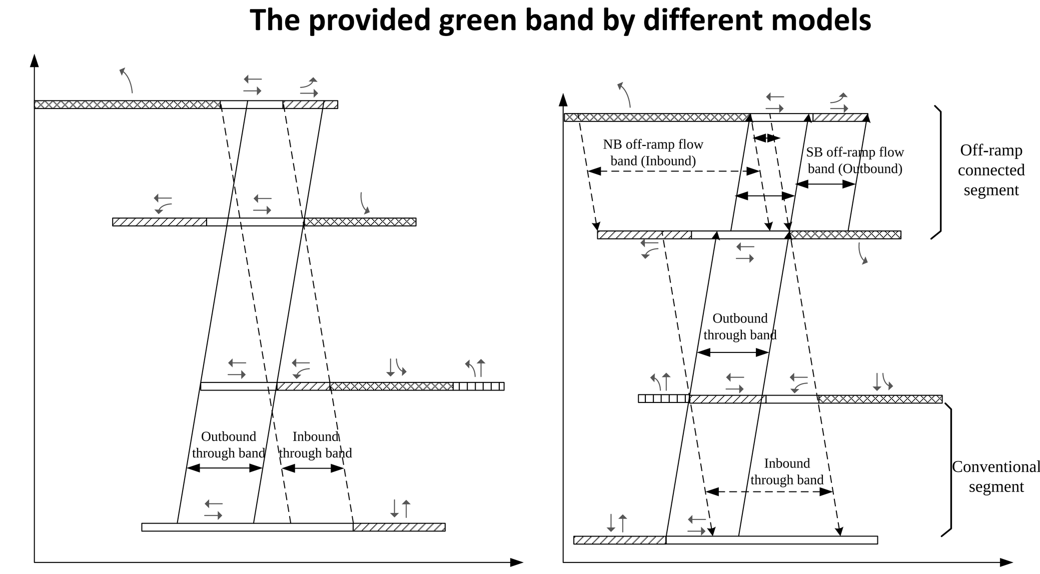
Three models are compared:

- Model-1: The TRANSYT 7-F model;
- Model-2: The proposed stage-1 model integrated with a two-way progression model;
- Model-3: The proposed two-stage model.

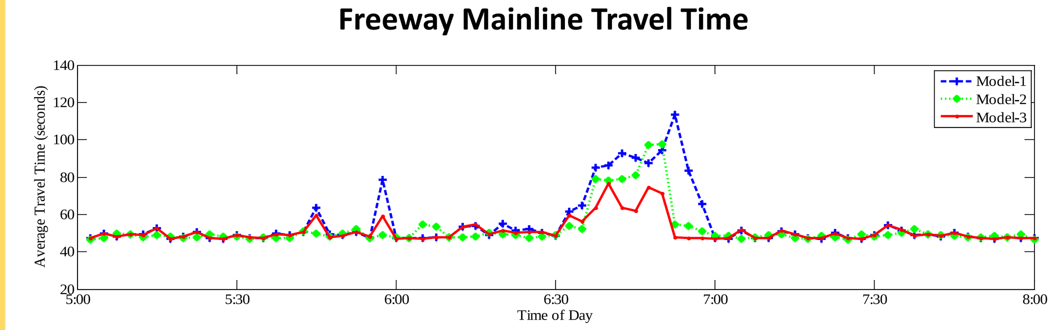


The geometric layout of the study site (Chupei, Taiwan)

The provided green band by different models



Freeway Mainline Travel Time



Network Performance

Performance Index	Model 1	Model 2	Model 3
Average freeway TT (s)	98.72	86.44 (-12.44%)	74.42 (-24.62%)
Average arterial delay (s)	87.21	81.52 (-6.52%)	78.91(-9.52%)
Average network delay (s)	62.20	54.65 (-12.14%)	49.01 (-21.21%)

Conclusions

- To mitigate the freeway congestion caused by the queue spillback at its off-ramp, this study has proposed a two-stage control model to optimize the signal plans on the off-ramp connected arterial..
- The comparisons between TRANSYT-7F and our proposed model indicate that the proposed model can successfully offer sufficient green time to the off-ramp flows and prevent the occurrence of queue spillover.
- Also, by accommodating both the off-ramp flows and arterial through flows for progression design, the proposed model can clearly improve the operational efficiency of the target arterial, evidenced by the comparison of experimental results between MAXBAND and the proposed stage-2 model.