Design of a Dual-Modal Signal Progression Model for Urban Arterials Accommodating Heavy Transit and Passenger-car Flows

by Yao Cheng, Hyeonmi Kim, and Gang-Len Chang

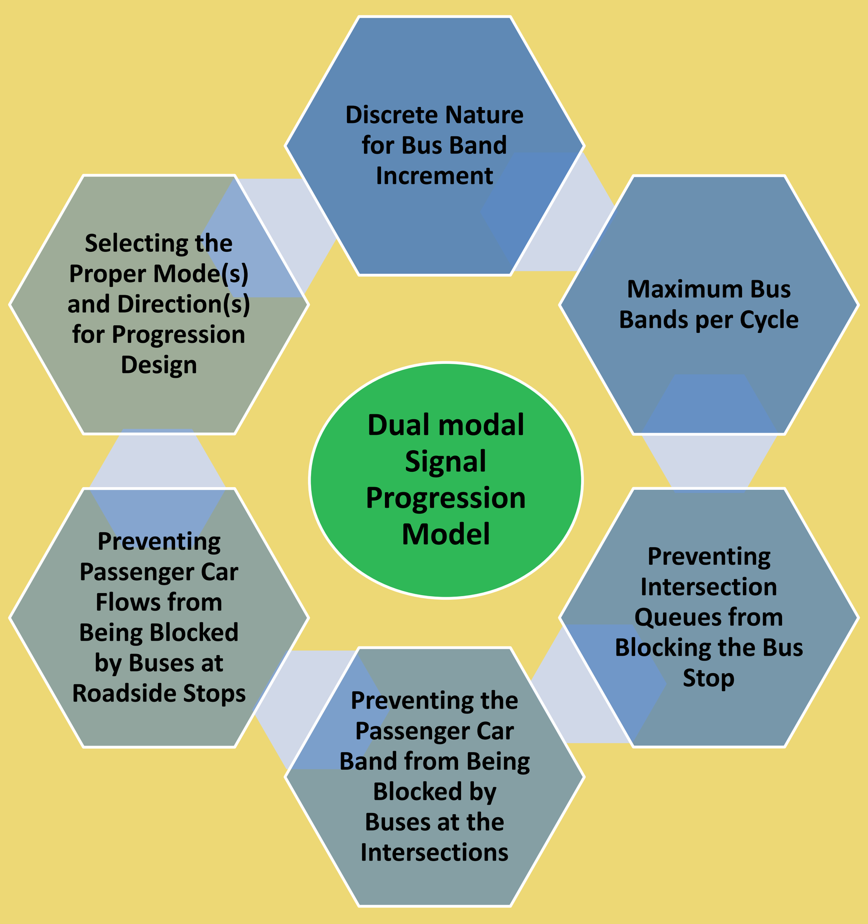
The University of Maryland, College Park

Abstract

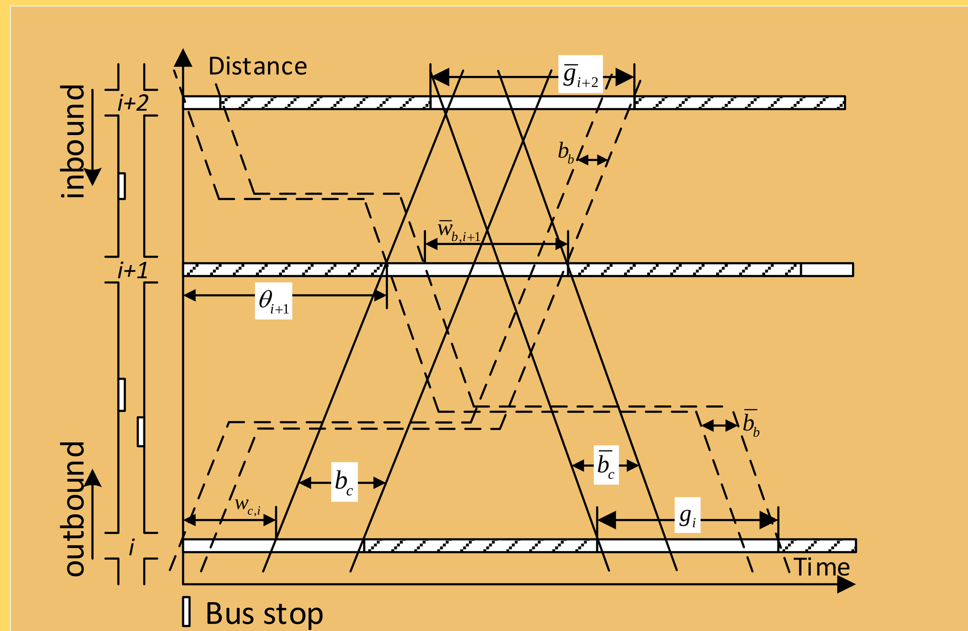
- For an arterial experiencing **both heavy bus and passenger car flows**, this study has presented **a signal optimization model** that can offer **concurrent progression to both modes** or **to a selected mode(s) in a selected direction(s)**, based on traffic volume, bus ratio, and geometric conditions.
- To capture **operational features of both modes**, the proposed model has taken into account **critical issues that result in mutual impedance between two modes.**
- By **weighting** bandwidths with **passenger volumes** by mode and by direction, the proposed model offers the progression only to the selected mode(s) and the direction(s) to **maximize the benefits for all roadway users**.
- Numerical analysis results have confirmed the flexibility of the proposed model in producing proper progression bands for both modes under various realistic constraints and volume levels, as well as the effectiveness of the developed constraints.
- Extensive simulation experiments have also demonstrated that the proposed model yields lower bus delays than with MULTIBAND; lower car delay than with MULTIBAND-B; and lower average person delay under different traffic conditions.

Model Methodology

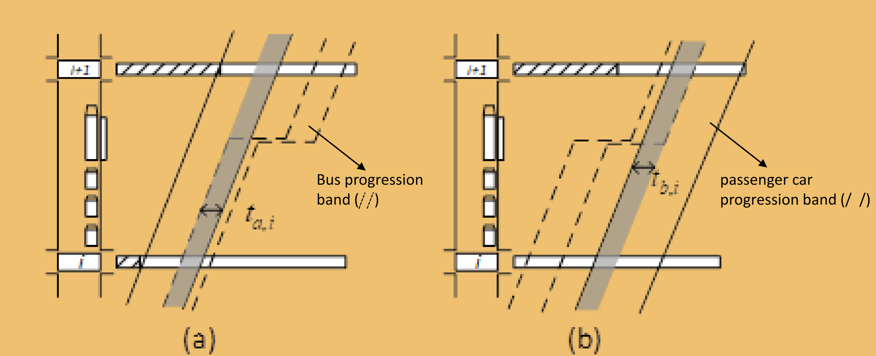
- To **progress both modes (passenger car and bus)** over an arterial segment, one shall take into account the **differences of their operational features** and **their interactions in the evolution of arterial traffic flows** including:



Model Formulation



<Figure 1 Key notations used in the proposed model. >



- $t_{a,i}$: The portion of passenger car band after bus band starts
- $t_{b,i}$: The portion of passenger car band before bus band ends

<Figure 2 Interruption to passenger cars due to buses at bus stops.>

Generating the Progression Band for Passenger Cars

$$w_{c,i} \ge 0, w_{c,i} + b_c \le g_i \qquad \bar{w}_{c,i} \ge 0, \bar{w}_{c,i} + \bar{b}_c \le \bar{g}_i$$

$$\theta_i + w_{c,i} + t_i + n_{c,i} \ge \theta_{i+1} + w_{c,i+1} + n_{c,i+1} - M(1 - x_c)$$

$$\theta_i + w_{c,i} + t_i + n_{c,i} \le \theta_{i+1} + w_{c,i+1} + n_{c,i+1} + M(1 - x_c)$$

$$-\theta_i - r_i + \bar{w}_{c,i} + \bar{t}_i + \bar{n}_{c,i} \ge -\theta_{i+1} - r_{i+1} + \bar{w}_{c,i+1} + \bar{n}_{c,i+1} - M(1 - \bar{x}_c)$$

$$-\theta_i - r_i + \bar{w}_{c,i} + \bar{t}_i + \bar{n}_{c,i} \le -\theta_{i+1} - r_{i+1} + \bar{w}_{c,i+1} + \bar{n}_{c,i+1} + M(1 - \bar{x}_c)$$

$$b_c \ge \beta - M(1 - x_c) \qquad \bar{b}_c \ge \beta - M(1 - \bar{x}_c) \qquad b_c \le x_c \qquad \bar{b}_c \le \bar{x}_c$$

Defining the Progression Band for Buses

$$w_{b,i} \ge 0, w_{b,i} + b_b \le g_i \qquad \bar{w}_{b,i} \ge 0, \bar{w}_{b,i} + \bar{b}_b \le \bar{g}_i$$

$$\theta_i + w_{b,i} + t_i + t_{d,i} + n_{b,i} \ge \theta_{i+1} + w_{b,i+1} + n_{b,i+1} - M(1 - x_b)$$

$$\theta_i + w_{b,i} + t_i + t_{d,i} + n_{b,i} \le \theta_{i+1} + w_{b,i+1} + n_{b,i+1} + M(1 - x_b)$$

$$-\theta_i - r_i + \bar{w}_{b,i} + \bar{t}_i + \bar{t}_{d,i} + \bar{n}_{b,i} \ge -\theta_{i+1} - r_{i+1} + \bar{w}_{b,i+1} + \bar{n}_{b,i+1} - M(1 - \bar{x}_b)$$

$$-\theta_i - r_i + \bar{w}_{b,i} + \bar{t}_i + \bar{t}_{d,i} + \bar{n}_{b,i} \le -\theta_{i+1} - r_{i+1} + \bar{w}_{b,i+1} + \bar{n}_{b,i+1} + M(1 - \bar{x}_b)$$

$$m_b u_b \xi \le b_b \qquad \bar{m}_b u_b \xi \le \bar{b}_b \qquad m_b \le q_i \qquad m_b \le \frac{V_b}{3600\xi} \qquad \bar{m}_b \le \frac{\bar{V}_b}{3600\xi}$$

$$b_b \le x_b \qquad \bar{b}_b \le \bar{x}_b \qquad \bar{m}_b \le \bar{q}_i$$

Passenger Car Queue Blocking Bus Stop

$$l_{i+1} = \left(f_i^t \left(g_i - \min\left(\theta_i + g_i + t_i - \theta_{i+1}, \theta_{i+1} + g_{i+1} - \theta_i - t_i\right)\right) + f_i^c \right) \frac{h}{3600\xi}$$

$$y_i = \begin{cases} 1, & l_i s/(s - f_i) \ge d_i^s \\ 0, & \text{otherwise} \end{cases}$$

$$w_{b,i+1} - t_i \frac{l_{i+1} s/(s - f_{i+1})}{d_i} - t_{d,i} \ge \frac{l_{i+1}}{s - f_{i+1}} \xi - (1 - y_i) \times M$$

Intersection Bus Queues Blocking the Passenger Car Progression

$$\gamma_i = \frac{V_b}{3600\xi} \left(g_i - \min\left(\theta_i + g_i + t_i + t_{d,i} - \theta_{i+1}, \theta_{i+1} + g_{i+1} - \theta_i - t_i - t_{d,i}\right)\right) / g_i$$

$$b'_{c,i} = b_c - \max\left(\gamma_i u_b \xi - w_i, 0\right) / z_i$$

Buses at Bus Stops Blocking Passenger Cars

$$t_{a,i} = \max\left(0, \min\left(b_c, w_{c,i} + b_c - w_{b,i}\right)\right)$$

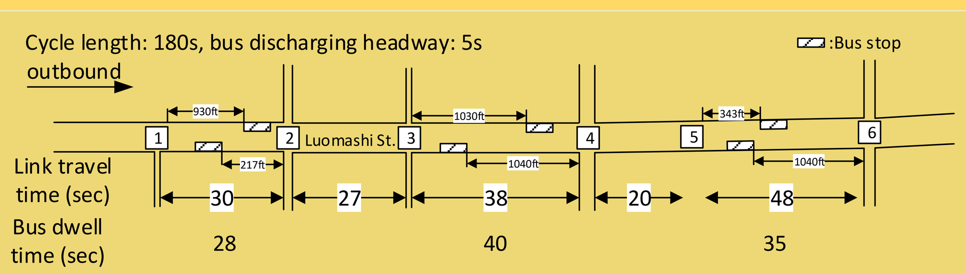
$$t_{b,i} = \max\left(0, \min\left(b_c, w_{b,i+1} + b_b - w_{c,i+1}\right)\right)$$

$$b''_{c,i} = b'_{c,i} - \left(t_{a,i} + t_{b,i} - b_c \times p_i\right) / z_i$$

Objective Function

$$\max \sum_i^{N-1} b''_{c,i} V_c k_c + \sum_i^{N-1} \bar{b}''_{c,i} \bar{V}_c \bar{k}_c + (N-1) m_b u_b \xi V_b k_b + (N-1) \bar{m}_b u_b \xi \bar{V}_b \bar{k}_b$$

Numerical Example



*Signal 5 is a pedestrian signal

The arterial of six intersections on Luomashi St. in Beijing, China

Scenario	Bus stop capacity	Green split (in cycle) for the through movements at each intersection					
		1	2	3	4	5	6
1-4	2	0.63	0.50	0.57	0.50	0.84	0.56
5	2	0.63	0.50	0.57	0.45	0.84	0.69
6	3	0.63	0.50	0.57	0.45	0.84	0.69
7	3	0.63	0.35	0.57	0.35	0.84	0.46

<Figure 3 The key geometric, bus operational, and signal timing information of study site >

<Table 1 Traffic Volumes and Loading Factors Adopted in the Numerical Experiments>

Scenario	Car volume (vehicle per hour)		Bus volume (vehicle per hour)		Bus loading factors (person per vehicle)	
	Outbound	Inbound	Outbound	Inbound	Outbound	Inbound
1	2000	1800	48	48	50	50
2	2000	1800	3	3	20	20
3	2000	1800	30	30	30	30
4	2000	2200	30	60	30	40
5	2000	2200	60	60	50	50
6	2000	2200	60	30	20	20
7	2000	1800	100	100	80	80

Numerical Analysis

- To evaluate a unique function for offering the progression bands for a mode(s) and a direction(s) and to assess the effectiveness of the model formulations, especially on:
  - The impact of bus stop capacity on bus band width;
  - Formulations of bus stops blocked by passenger car queues;
  - The potential interruption of bus queues at the intersection's stop line on the passenger car bands; and
  - The potential interruption of buses dwelling at bus stops on the progression band designed for passenger cars

❖ **Selecting the directions and modes to offer the progression <Table 2>**

- Type-1: concurrent progression for both bus and passenger car
  Scenarios 1, 5 and 6; their demand levels justify such design.
- Type-2: two-way progression for a single mode
  Scenarios 2 and 7; demand of one mode far exceeds the other.
- Type-3: one-way progression for both modes
  Scenarios 3 and 4; demand of one direction is higher than the other.

<Table 2 Summary of the Produced Progression Strategies and the Resulting Bands>

Scenario	Bus bands (seconds)[a]		PC bands (seconds)[b]		Produced bands
	Outbound	Inbound	Outbound	Inbound	
1	10 (2)	5 (1)	90	0	Two-way bus bands+one-way car band
2	0 (0)	0 (0)	35	31	Two-way car bands
3	0 (0)	5 (1)	90	0	One-way car band+one-way bus band
4	0 (0)	10 (2)	0	90	One-way car band+bus band
5	10(2)	10 (2)	37	41	Two-way car bands+bus bands
6	15(3)	0	37	41	Two-way car bands+one-way bus band
7	15(3)	15 (3)	0	0	Two-way bus bands

a Numbers in parenthesis represent the number of accommodated buses in the bus band; b PC: passenger cars

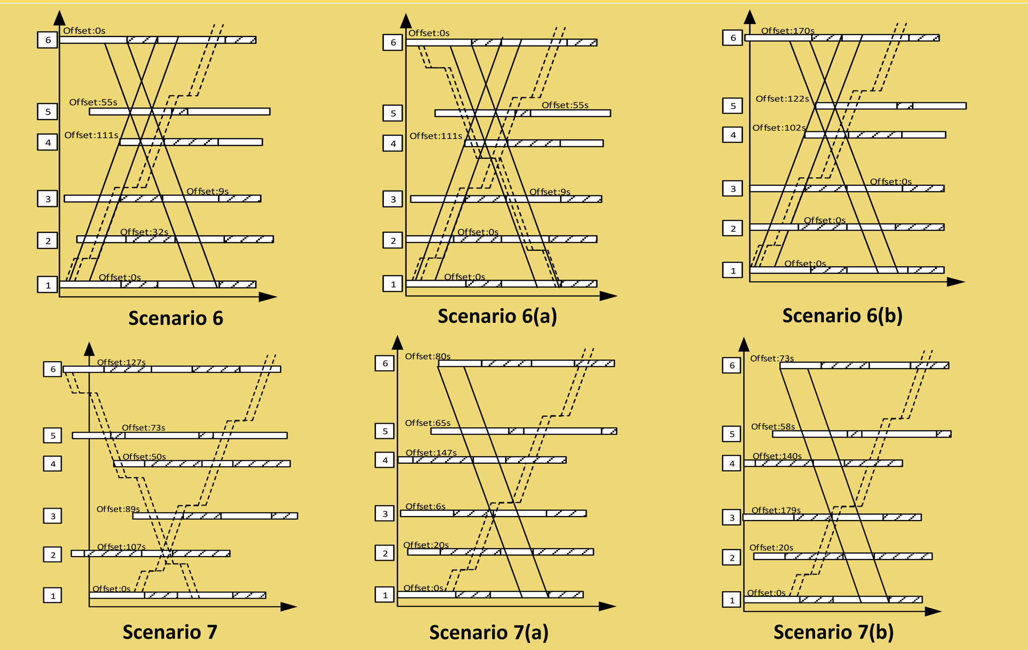
❖ **Necessity and effectiveness of developed constraints confirmed by below comparisons <Table 3, Figure 4>**

- Scenarios 7 and 7(a): Bus stop capacity
- Scenarios 7 and 7(b): Impacts of PC queue at an intersection
- Scenarios 6 and 6(a): Impacts of buses dwelling at bus stops
- Scenarios 6 and 6(b): Interruptions of buses at an intersection to passenger car bands

<Table 3 Numerical Experiment Results to Evaluate the Performance of Developed Constraints>

Scenario	Bus bands (seconds)[a]		PC bands (seconds)		Conditions
	Outbound	Inbound	Outbound	Inbound	
6	15(3)	0	37	41	
6(a)	15(3)	10(2)	37	41	A model without constraints reflecting interruptions of buses at bus stops
6(b)	15(3)	0	37	41	A model without constraints reflecting interruptions of buses at stop bars
7	15(3)	15(3)	0	0	
7(a)	15(3)	0	0	50	Reduced capacity of bus stops in IB of 2 buses
7(b)	15(3)	0	0	57	Higher turn-in volumes from side streets

[a] Numbers in parenthesis represent the number of accommodated buses in the band;



<Figure 4 Progression bands and offsets generated by the proposed model>

Simulation Evaluation

- Compared models:
  - MULTIBAND: a state-of-the-art model to design two-way progression for passenger cars
  - MULTIBAND-B: a revised MULTIBAND model for bus progression where the average dwell time at bus stops is added to link travel times
- **The proposed model** can yield **lower bus delays than with MULTIBAND**, and **lower car delay than with MULTIBAND-B**, since it concurrently considers the benefits of both modes <Table 4>.
- The same improvements by **the proposed model** also exist when evaluated with the MOE of the **number of stops**, as shown in Table 5.

<Table 4 Average Delay along the Arterial>

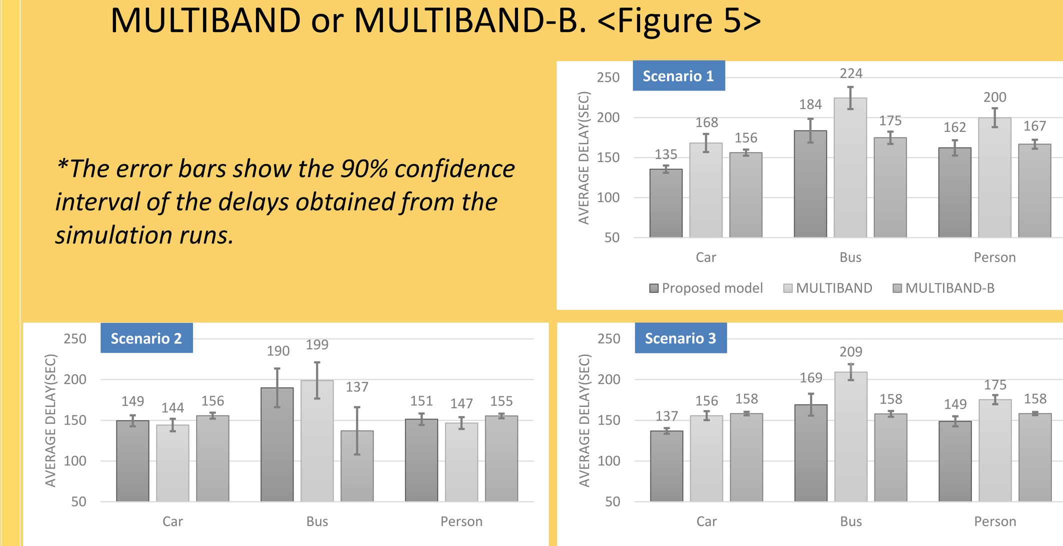
Scenario	Model	Passenger cars (secs)			Buses (secs)		
		OB	IB	Total	OB	IB	Total
1	Proposed model	85	193	135	157	213	184
	MULTIBAND	168	169	168	228	221	224
	MULTIBAND-B	150	164	156	144	208	175
2	Proposed model	137	164	149	212	172	190
	MULTIBAND	140	148	144	198	202	199
	MULTIBAND-B	148	165	156	95	184	137
3	Proposed model	90	190	137	139	201	169
	MULTIBAND	157	154	156	218	201	209
	MULTIBAND-B	150	167	158	120	199	158

<Table 5 Number of Stops along the Arterial >

Scenario	Model	Passenger cars			Buses		
		OB	IB	Total	OB	IB	Total
1	Proposed model	2.58	4.53	3.49	3.22	4.59	3.87
	MULTIBAND	3.55	4.57	4.04	4.76	4.73	4.74
	MULTIBAND-B	4.52	4.08	4.32	3.07	4.15	3.59
2	Proposed model	3.16	3.60	3.37	3.73	2.95	3.31
	MULTIBAND	2.86	4.16	3.48	2.95	3.50	3.23
	MULTIBAND-B	4.45	3.87	4.18	1.50	2.98	2.19
3	Proposed model	2.68	4.35	3.47	2.18	4.05	3.08
	MULTIBAND	3.26	4.08	3.65	3.93	3.73	3.82
	MULTIBAND-B	4.48	4.16	4.33	2.14	3.58	2.83

- **The proposed model** can **reduce person delays** along the arterial by considering traffic volumes of both modes and their loading factors, and be more efficient than either MULTIBAND or MULTIBAND-B. <Figure 5>

**The error bars show the 90% confidence interval of the delays obtained from the simulation runs.*



<Figure 5 Average delay under different volumes>

Conclusions

- **The study has developed a dual-modal progression model to offer concurrent progression for both passenger and transit flows.**
- The proposed model has tackled various issues that may prevent progression for the both flows, **including potential blockage of passenger car queues to the bus stops, excessive start-up delays caused by transit vehicles queueing at the intersections stop line, and the impedance to the travel lanes due to the buses dwelling at their roadside stations of limited storage capacity.**
- **Weighted with the passenger volumes by mode and by direction**, the proposed model can offer the progression only to the mode(s) and the direction(s) that are justified **to maximize the benefits for the entire arterial users.**
- Numerical analysis results have **confirmed the effectiveness of the proposed model in producing concurrent progression bands** under various realistic constraints and volume levels. Extensive simulation experiments has also demonstrated that **the proposed model yielded lower bus delays than with MULTIBAND; lower car delay than with MULTIBAND-B; and lower average person delay under different traffic conditions.**
- **Further research** includes 1) the consideration of **heavy turning flows** from and onto side street in design of signal progression; 2) **an arterial decomposition** to design progression boundaries for a long arterial; and 3) **a real-time adaptive control strategy** based on the detected number of vehicles and loading factors.