DESIGN OF MULTI-MODAL SIGNAL PROGRESSION ALONG AN ARTERIAL WITH BUS DEDICATED LANES

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Abstract

- In response to the increasing deployment of bus dedicated lanes in practice, this study presents a bandwidth maximization model that designs both phase sequences and offsets over a series of intersections along an arterial with bus dedicated lanes to provide concurrent progression for bus and general traffic flows.
- The proposed model takes into account the following factors that may affect the progression effectiveness:
  - *bus dwelling time at bus stops*
  - *location of bus dedicated lanes*
  - *traffic queues; and*
  - *conflicts between through bus movements and left-turning traffic.*
- The results from numerical analysis with two planned BRT sites have confirmed the effectiveness of the proposed model and the evaluation with extensive simulation experiments has verified the benefits from concurrent progression.

Modelling Methodology

Travel Time Difference between Buses and PCs

- A bus may take a longer travel time than a passenger car over the same arterial link due to the larger size and the lower cruising speed.
- Such differences may be more pronounced if a bus dwells at a bus stop → deviates away from the progression band designed for passenger cars → encounters a red phase at the downstream intersection.

Conflicts between Buses on Dedicated Bus Lanes and Turning PCs

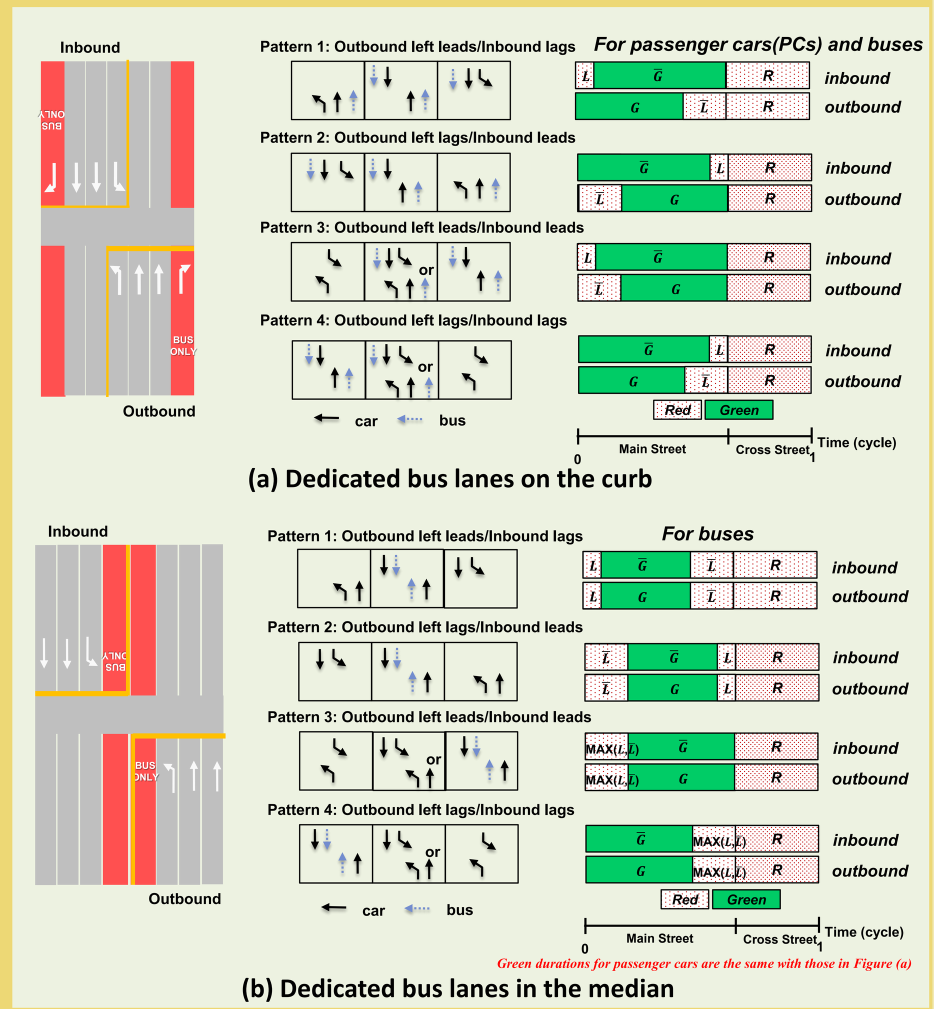
- Dedicated bus lanes are used to reduce interactions between bus and passenger cars and improve bus operations.
- If median dedicated bus lanes, there exist conflicts between buses on the dedicated bus lanes and left-turning passenger cars in the same direction, which in turn impact the effectiveness of signal phases allocated for both modes.

Traffic Queues on Bus Dedicated Lanes

- To prevent an interruption on buses travelling in the progression band, traffic queues at downstream intersections on the bus dedicated lanes need to be discharged before the following buses arrive.
- Depending on the position of bus dedicated lanes, those traffic queues may compose of different sets of vehicles
  - Bus dedicated lanes in the median: with the unsynchronized buses
  - Bus dedicated lanes on the curb: with both the unsynchronized buses and right-turning vehicles sharing the right-of-way

Selecting the Mode and Direction for Progression Design

- One needs to select the mode and direction to receive the progression bands, based on traffic volumes and loading factors of passenger cars and buses, as well as the design of bus dedicated lanes.



(a) Dedicated bus lanes on the curb

(b) Dedicated bus lanes in the median

<Four Possible Patterns of Left-turn Phase for Buses and PCs>

Model Formulation

Objective Function

$$\text{Max} \sum_{i=1+1}^{N} b_c V_{c,i} k_c + \sum_{i=1}^{N-1} \bar{b}_c \bar{V}_{c,i} k_c + (N-1) b_b V_b k_b + (N-1) \bar{b}_b \bar{V}_b k_b$$

Constraints for Progression Bands for Passenger Cars

$$0 \le w_{c,i} + b_c \le g_{c,i} \qquad 0 \le \bar{w}_{c,i} + \bar{b}_c \le \bar{g}_{c,i}$$
$$\theta_i + w_{c,i} + t_{c,i} + n_{c,i} \ge \theta_{i+1} + w_{c,i+1} + n_{c,i+1} - M(1 - x_c)$$
$$\theta_i + w_{c,i} + t_{c,i} + n_{c,i} \le \theta_{i+1} + w_{c,i+1} + n_{c,i+1} + M(1 - x_c)$$
$$-\theta_i + r_{c,i} + \bar{R}_{c,i} + \bar{w}_{c,i} + \bar{t}_{c,i} + \bar{n}_{c,i} \ge -\theta_{i+1} + r_{c,i+1} + \bar{R}_{c,i+1} + \bar{w}_{c,i+1} + \bar{n}_{c,i+1} - M(1 - \bar{x}_c)$$
$$-\theta_i + r_{c,i} + \bar{R}_{c,i} + \bar{w}_{c,i} + \bar{t}_{c,i} + \bar{n}_{c,i} \le -\theta_{i+1} + r_{c,i+1} + \bar{R}_{c,i+1} + \bar{w}_{c,i+1} + \bar{n}_{c,i+1} + M(1 - \bar{x}_c)$$
$$b_c \le x_c \qquad \bar{b}_c \le \bar{x}_c$$

Constraints for Progression Bands for Buses

$$0 \le w_{b,i} + b_b \le g_{b,i} \qquad 0 \le \bar{w}_{b,i} + \bar{b}_b \le \bar{g}_{b,i}$$
$$\theta_i + w_{b,i} + t_{b,i} + n_{b,i} \ge \theta_{i+1} + w_{b,i+1} + n_{b,i+1} - M(1 - x_b)$$
$$\theta_i + w_{b,i} + t_{b,i} + n_{b,i} \le \theta_{i+1} + w_{b,i+1} + n_{b,i+1} + M(1 - x_b)$$
$$-\theta_i + r_{b,i} + \bar{R}_{b,i} + \bar{w}_{b,i} + \bar{t}_{b,i} + \bar{n}_{b,i} \ge -\theta_{i+1} + r_{b,i} + \bar{R}_{b,i} + \bar{w}_{b,i+1} + \bar{n}_{b,i+1} - M(1 - \bar{x}_b)$$
$$-\theta_i + r_{b,i} + \bar{R}_{b,i} + \bar{w}_{b,i} + \bar{t}_{b,i} + \bar{n}_{b,i} \le -\theta_{i+1} + r_{b,i} + \bar{R}_{b,i} + \bar{w}_{b,i+1} + \bar{n}_{b,i+1} + M(1 - \bar{x}_b)$$
$$b_b \le x_b \qquad \bar{b}_b \le \bar{x}_b$$

Difference in the Starting Times of Green Phases between Inbound and Outbound Through Movements

$$r_{c,i} = (\delta_i - 1)L_i - (\bar{\delta}_i - 1)\bar{L}_i$$
$$r_{b,i} = (\delta_i - 1)L_i - (\bar{\delta}_i - 1)\bar{L}_i + (\bar{\delta}_i - 1)\bar{L}_i y - (\delta_i - 1)L_i y$$

Green Time for Passenger Cars and Buses

$$g_{c,i} = 1 - (R_i + \bar{L}_i)$$
$$\bar{g}_{c,i} = 1 - (R_i + L_i)$$
$$g_{b,i} = \begin{cases} 1 - (R_i + \bar{L}_i + L_i * y) & \text{if } \delta_i + \bar{\delta}_i = 1 \\ 1 - (R_i + \max(\bar{L}_i, L_i * y)) & \text{if } \delta_i + \bar{\delta}_i \ne 1 \end{cases}$$
$$\bar{g}_{b,i} = \begin{cases} 1 - (R_i + L_i + \bar{L}_i * y) & \text{if } \delta_i + \bar{\delta}_i = 1 \\ 1 - (R_i + \max(L_i, \bar{L}_i * y)) & \text{if } \delta_i + \bar{\delta}_i \ne 1 \end{cases}$$

Traffic Queue and Bay Length Constraints

$$l_i^b = V_b\left(g_{b,i-1} - \min\left(\theta_{i-1} + g_{b,i-1} + t_{b,i-1} - \theta_i, \theta_i + g_{b,i} - t_{b,i-1} - \theta_{i-1}\right)\right)$$
$$\bar{l}_i^b = \bar{V}_b\left(\bar{g}_{b,i+1} - \min\left(\theta_{i+1} + \bar{g}_{b,i+1} + \bar{t}_{b,i} - \theta_i, \theta_i + \bar{g}_{b,i+1} - \bar{t}_{b,i} - \theta_{i+1}\right)\right)$$
$$\frac{l_i^b}{s}\left(1 + \frac{V_b}{s}\right) \le w_{b,i} + M(1 - x_b)$$
$$\frac{\bar{l}_i^b}{s}\left(1 + \frac{\bar{V}_b}{s}\right) \le \bar{g}_{b,i} - \bar{b}_b - \bar{w}_{b,i} + M(1 - \bar{x}_b)$$
$$l_i^r = f_i^r(1 - g_{c,i}) \qquad \bar{l}_i^r = \bar{f}_i^r(1 - \bar{g}_{c,i})$$
$$\frac{l_i^b + l_i^r}{s}\left(1 + \frac{V_b + f_i^r}{s}\right) \le w_{b,i} + M(1 - x_b) + My$$
$$\frac{\bar{l}_i^b + \bar{l}_i^r}{s}\left(1 + \frac{\bar{V}_b + \bar{f}_i^r}{s}\right) \le \bar{g}_{b,i} - \bar{b}_b - \bar{w}_{b,i} + M(1 - \bar{x}_b) + My$$

* OB: outbound, IB: inbound. Each pattern is shown in the figure left.

	Left Turn Phase Patterns*	$r_{c,i}$	$r_{b,i}$ ($y = 0$)	$r_{b,i}$ ($y = 1$)
1	OB Left Leads, IB Lags	$-L_i$	$-L_i$	0
2	OB Left Lags, IB Leads	$\bar{L}_i$	$\bar{L}_i$	0
3	OB and IB Left Leads	$-L_i + \bar{L}_i$	$-L_i + \bar{L}_i$	0
4	OB and IB Left Lags	0	0	0

Case Study

Experimental Design

Case 1: Dedicated Bus Lane on the curb

- Bus Schedule: SB- 1 bus/1min, NB- 1 bus/2min
- Dwell Time: SB-15sec, NB-21sec

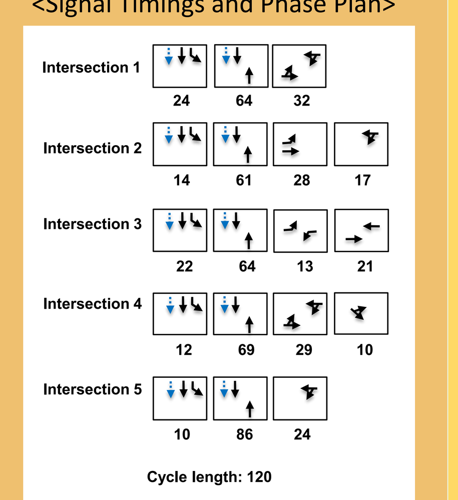
<Demand Patterns>

(in veh/hr)

Intersection	US29 NB L	US29 NB T	US29 NB R	US29 SB L	US29 SB T	US29 SB R	WB L	WB T	WB R	EB L	EB T	EB R	SEB L	SEB T	SEB R
1	17	882	101	184	1808	55	0	209	101	101	404	0	na	na	na
2	5	1052	26	121	1821	335	117	183	100	207	144	109	na	na	na
3	0	1348	12	229	2247	274	20	220	175	135	125	10	na	na	na
4	51	1578	28	84	2255	117	65	265	105	145	265	430	35	35	5
5	na	1751	77	44	1956	na	500	na	85	na	na	na	na	na	na

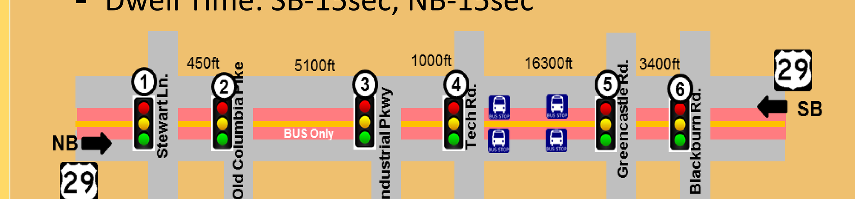
* Note: L=left, T=through, R=right; NB: northbound, SB: southbound, WB: westbound, EB: eastbound, SEB: south-eastbound; na=not applicable

<Signal Timings and Phase Plan>



Case 2: Dedicated Median BUS Lanes

- Bus Schedule SB: 2 bus/1min, NB: 2 bus/1min
- Dwell Time: SB-15sec, NB-15sec



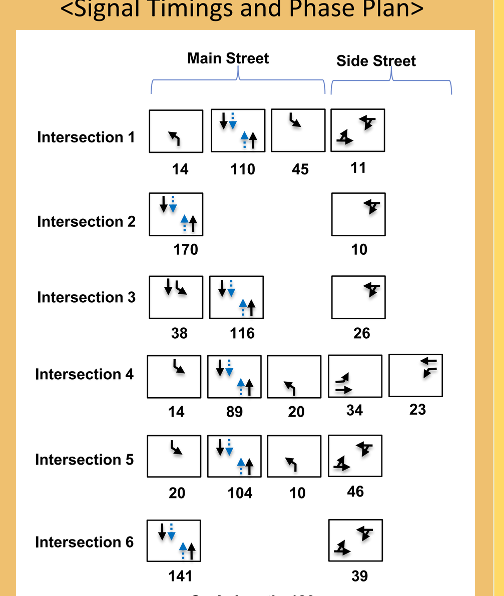
<Demand Patterns>

(in veh/hr)

Intersection	US29 NB L	US29 NB T	US29 NB R	US29 SB L	US29 SB T	US29 SB R	WB L	WB T	WB R	EB L	EB T	EB R
1	5	2155	95	192	2588	38	55	5	15	50	25	20
2	na	2220	0	na	2733	na	85	na	215	na	na	na
3	na	2164	271	234	2588	na	145	na	345	na	na	na
4	164	1909	436	171	2467	71	240	130	130	20	275	115
5	35	2449	20	77	2303	30	180	110	115	45	90	80
6	na	2543	92	na	2255	na	150	55	105	5	70	5

* Note: L=left, T=through, R=right; NB: northbound, SB: southbound, WB: westbound, EB: eastbound; na=not applicable

<Signal Timings and Phase Plan>



Optimization Results

❖ Resulting Signal Plans with Different Models

Case 1: Dedicated Bus Lane on the Southbound Curb Only

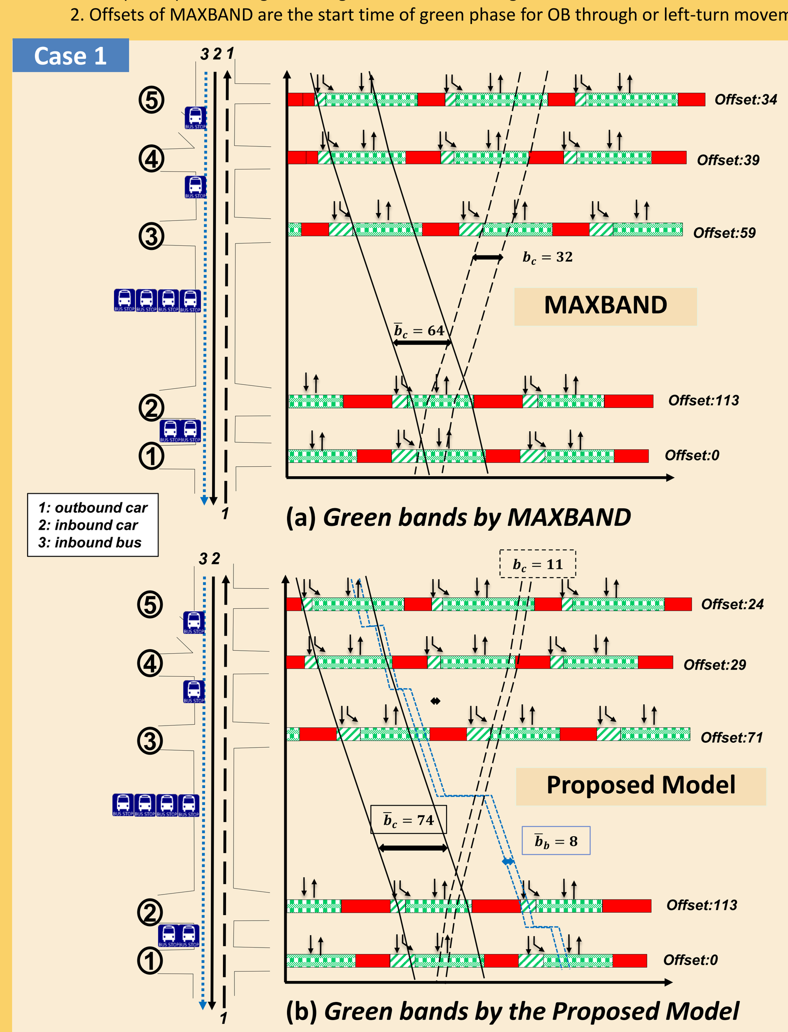
Intersection	T7F Left-Turn Phase Patterns	T7F Offset (s)	MAXBAND Left-Turn Phase Patterns	MAXBAND Offset (s)	The Proposed Model Left-Turn Phase Patterns	The Proposed Model Offset (s)
1	IB Left leading	0	IB Left leading	0	IB Left leading	0
2		25		113		113
3		113		59		71
4		104		39		29
5		109		34		24

Case 2: Dedicated Bus Lane in the Median

Intersection	T7F Left-Turn Phase Patterns	T7F Offset (s)	MAXBAND Left-Turn Phase Patterns	MAXBAND Offset (s)	The Proposed Model Left-Turn Phase Patterns	The Proposed Model Offset (s)
1	OB Left Lead /IB Left Lag	0	OB Left Lead /IB Left Lag	0	OB/IB Left Lead	0
2	N/A	15	N/A	145	N/A	0
3	IB Left leading	42	IB Left leading	119	IB Left leading	93
4	OB Left Lag /IB Left Lead	52	OB Left Lag /IB Left Lead	124	OB/IB Left Lead	93
5	OB Left Lag /IB Left Lead	116	OB Left Lag /IB Left Lead	38	OB/IB Left Lag	9
6	N/A	93	N/A	104	N/A	0

Note: 1. The phase plan and signal timings are shown in the Figure left
2. Offsets of MAXBAND are the start time of green phase for OB through or left-turn movement; offsets of the propose model are based on start time of green phase for OB through movement.

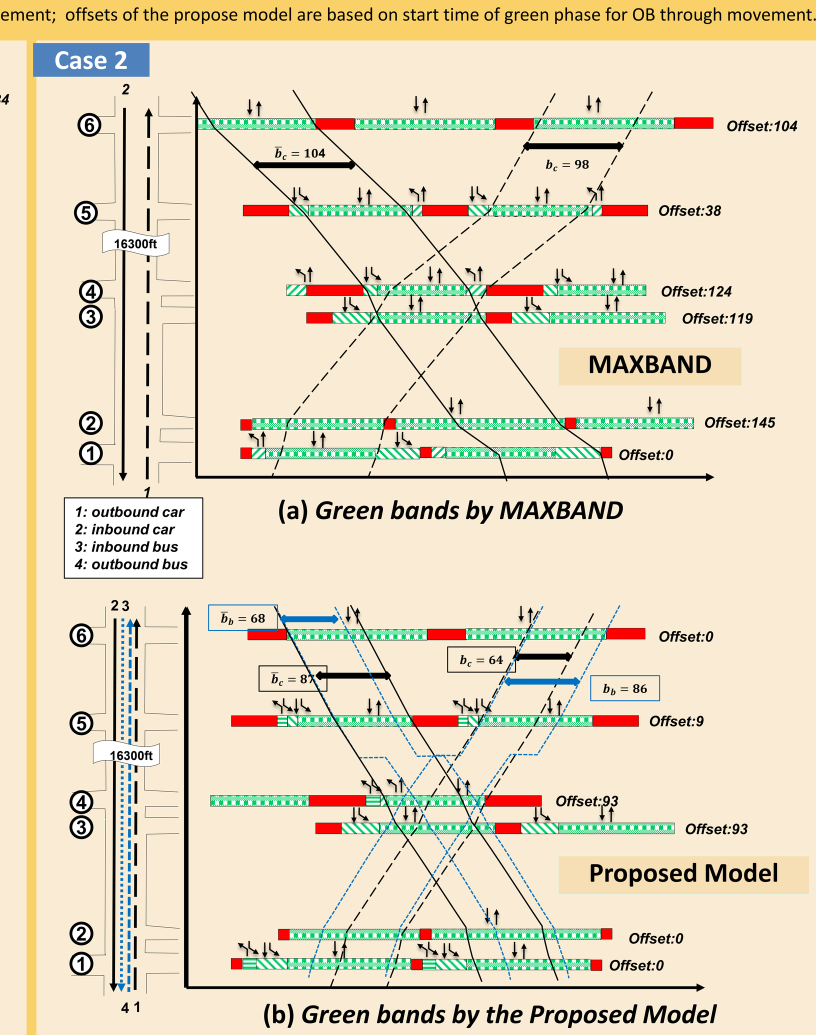
Case 1



(a) Green bands by MAXBAND

(b) Green bands by the Proposed Model

Case 2



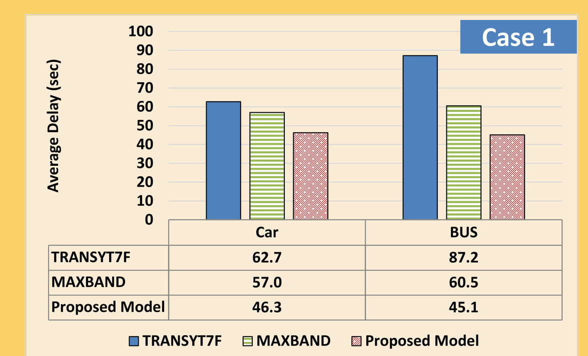
(a) Green bands by MAXBAND

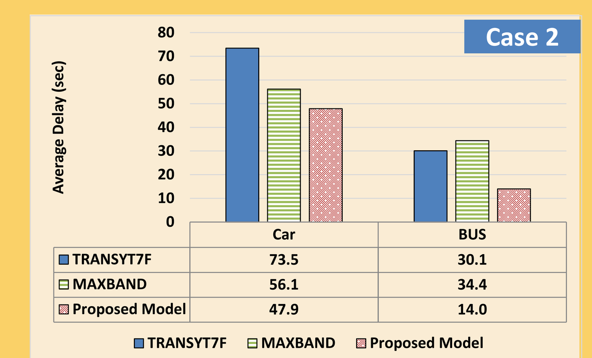
(b) Green bands by the Proposed Model

<Signal progression plan generated with MAXBAND and the proposed model>

Simulation Results

❖ Control delay for passenger car and bus flows





❖ Average Person Delay (in seconds/person)

	Case 1	Case 2
TRANSYT 7F	69.3	54.3
MAXBAND	57.9	46.5
The proposed Model	46.0	33.2

* Loading factors: passenger car (1.2) and buses (35)

❖ Percent Change in Average Person Delay compared to MAXBAND

Loading Factor		Case 1 Passenger Car 1.2	Case 1 Passenger Car 1.5	Case 2 Passenger Car 1.2	Case 2 Passenger Car 1.5
Bus	30	-20.5%	-20.2%	-27.7%	-25.8%
	35	-20.7%*	-20.4%	-29.2%*	-27.1%
	40	-20.8%	-20.5%	-30.5%	-28.3%

* Base scenario of loading factors: passenger car(1.2) and bus(35)

❖ Number of stops for passenger car and bus flows

	Case 1 PC	Case 1 Bus	Case 2 PC	Case 2 Bus
TRANSYT7F	3.7	4.1	2.2	1.9
MAXBAND	3.6	3.7	1.9	2.7
The proposed Model	2.5	2.7	1.5	1.1

Conclusions

- This study has developed **a signal optimization model to provide concurrent progression** to passenger cars and buses along an arterial with dedicated bus lanes.
- The proposed model computes **the optimal phase sequences and offsets** that maximize the **total benefit of all arterial users** under various geometric conditions and left-turn phase patterns.
- The model takes into account **the difference in travel times between passenger cars and buses, conflicts between buses on dedicated bus lanes and turning vehicles, and relations between bus stop locations and traffic queues**.
- The comparison results from the extensive simulation experiments show that **the proposed model can outperform other arterial signal design models** in terms of control delays for buses, the number of stops for buses, and average person delay, compared to MAXBAND and TRANSYT7F.
- With such a signal system, **responsible traffic agencies can minimize the resistance from passenger car users** when promoting and facilitating the use of transit system.
- **Further research:** incorporating an active TSP in the design, developing a rigorous yet robust model for the selection of its deployment location and accounting for potential variance in the available input data.