CONCURRENT PROGRESSION OF THROUGH AND TURNING MOVEMENTS FOR ARTERIALS EXPERIENCING HEAVY TURNING FLOWS AND BAY-LENGTH CONSTRAINTS

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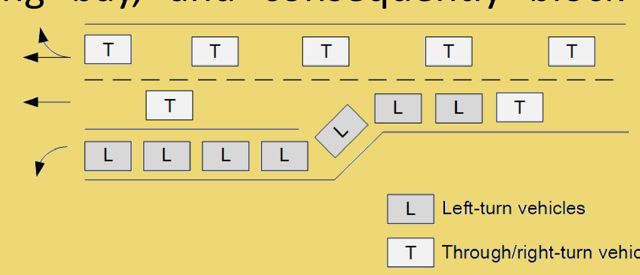
Abstract

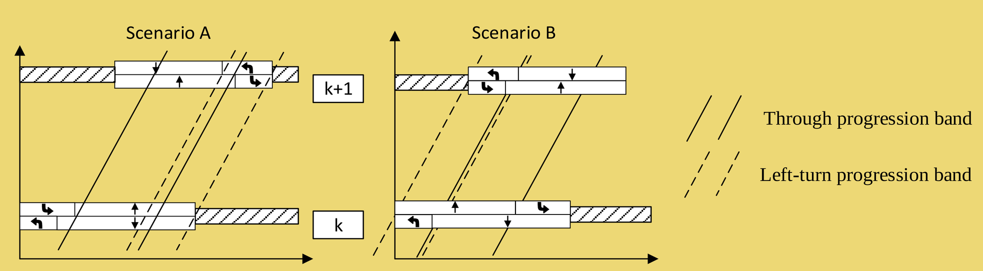
- On an arterial experiencing heavy left-turn volumes at major intersections, the left-turn queue may spill back rapidly and further degrade the effectiveness of the through progression band if the left-turn volume and the limited bay length have not been accounted for in the optimization of signal coordination plan.
- Such a negative impact from left-turn queues also justifies the need to take into account the concurrent progression of through and left-turn flows.
- This paper presents a three-stage signal optimization model that can circumvent or minimize the impact of left-turn spillback on the through movements and concurrently minimize the delay of left-turn flows.
- The results from the numerical analyses have confirmed the benefits and need of including the left-turn volume and its bay length in the design of dual progression. The simulation experiments further show a reduction in the average delay and the number of stops, respectively by 6.4% and 5.5%, compared with MULTIBAND

Critical Issues

- In optimizing the offsets for the through progression, not adequately accounting for the left-turn volume and the available bay length at some major intersections may result in rapid queue formation and even the spillback over the turning bay, and consequently block some through lanes.



- The delay experienced by left-turn vehicles even under the same progression band may still vary with its relationship with where the through band locates within the green phases in the same link. (Scenarios A and B yield different left-turn delays)



Model Formulation

Cycle length, green ratios, travel times, through volumes

Stage 1

Purpose: Obtain the initial bandwidths by a mature two-way progression method (such as MAXBAND (13))

- Initial through bandwidths
- Offsets
- Phase sequences

Through volumes, left-turn volumes, left-turn bay lengths

Stage 2

Purpose: Provide through progression realistically which takes into account the impact of limited bay length and high left-turn volume

Objective Function: Maximizing effective through bands not blocked by left-turn queue spillback

Constraints:
- Two-way through bands
- Formulating effective through bands not impacted by left-turn queue spillback

- Initial through bandwidths
- Maximized effective through bandwidths
- Offsets
- Phase sequences

Stage 3

Purpose: Provide left-turn movements with minimized delay

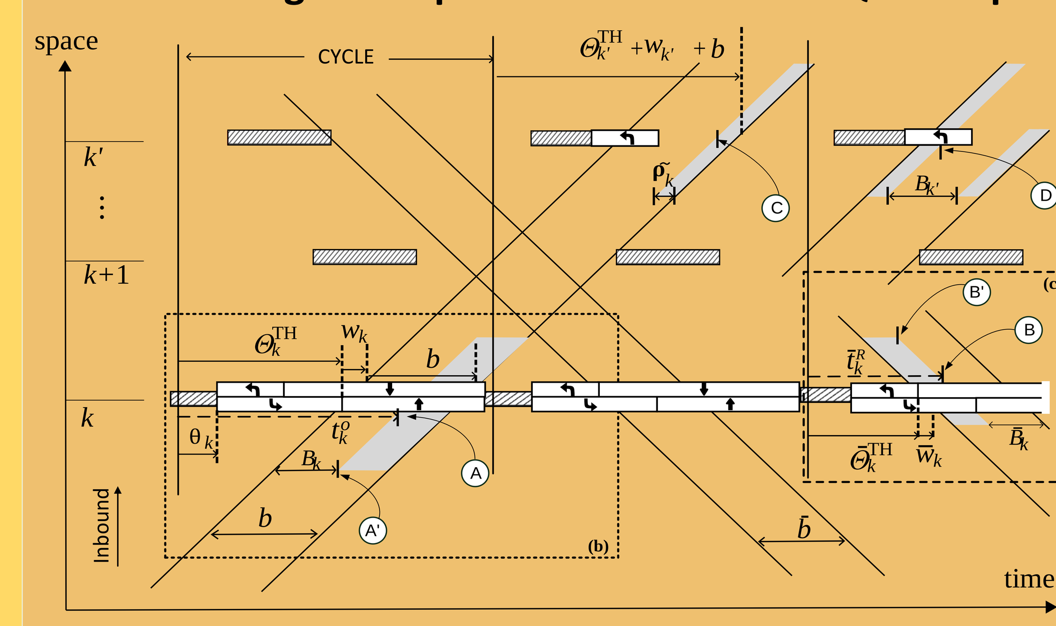
Objective Function: Maximizing left-turn efficiency index

Constraints:
- Two-way through bands
- Formulating effective through bands not impacted by left-turn queue spillback
- Formulating left-turn efficiency index

Objective Values
- Maximized initial through bandwidths
- Maximized effective through bandwidths
- Maximized left-turn efficiency index

Optimal Signal Settings
- Optimal offsets
- Optimal phase sequences

❖ Formulating the Impacts of the Left-Turn Queue Spillback on Through Progression Bands



(a) Graphical interruptions of left-turn queue spillback on the through bands

Starting Time of the Spillback

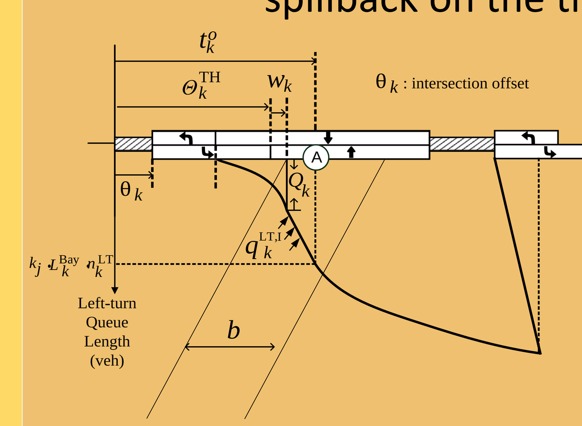
$$t_k^O = \frac{k_j n_k^{\mathrm{LT}} L_k^{\mathrm{Bay}} - Q_k}{q_k^{\mathrm{LT,I}}} + \Theta_k^{\mathrm{TH}} + w_k$$

Vanishing Time of Left-Turning Queues

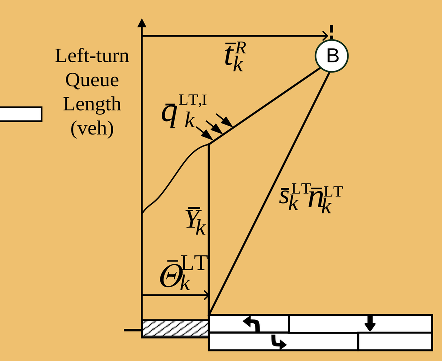
$$t_k^R = \Theta_k^{\mathrm{LT}} + \frac{Y_k}{s^{\mathrm{LT}} n_k^{\mathrm{LT}} - q_k^{\mathrm{LT,I}}}$$

Temporal Relation Between the Spillback Duration and Through Bands

$$B_k = b - \left(\max\{0, \min\{t_k^R, \Theta_k^{\mathrm{TH}} + w_k + b\}\right)$$



(b) Calculating the starting time of left-turn spillback



(c) Calculating the vanishing time of left-turn queues

Q_k :number of vehicles in the left-turn queue when the through band begins

Y_k :number of left-turn vehicles in the queue at the onset of a left-turn green phase for inbound direction

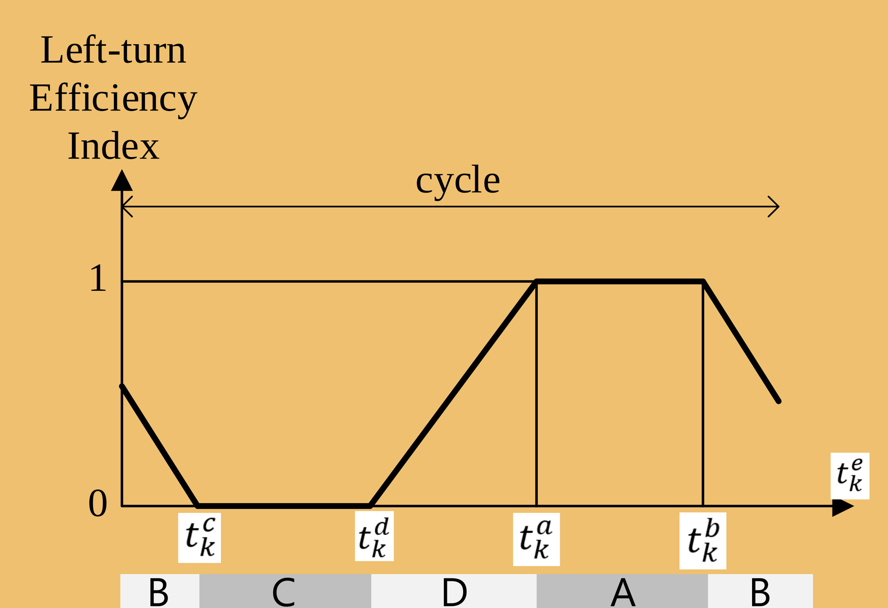
❖ Four Types of Scenarios for Computing Left-turn Queue Length

	Scenario type			
	A	B	C	D
Condition	$t_k^a \le t_k^e + N'_k \le t_k^b + N_{k-1}$	$t_k^b + N_{k-1} \le t_k^e + N'_k \le t_k^c + N_{k-1}$	$t_k^c + N_{k-1} \le t_k^e + N'_k \le t_k^d$	$t_k^d \le t_k^e + N'_k \le t_k^a$
Q_k	$q_k^{\mathrm{LT,II}}(t_k^b - t_k^e + w_{k-1})$	$q_k^{\mathrm{LT,II}} \cdot w_{k-1}$	$q_k^{\mathrm{LT,II}} \cdot [t_k^d - (t_k^e + N'_k)]$	$q_k^{\mathrm{LT,II}}(\Phi_{k-1}^{\mathrm{TH}} - b) + q_k^{\mathrm{LT,I}}[t_k^a - (t_k^e + N'_k)]$
Y_k	$q_k^{\mathrm{LT,II}}(t_k^b + N_{k-1} - (t_k^e + N'_k) + w_{k-1}) - q_k^{\mathrm{LT,I}}(\Theta_k^{\mathrm{LT}} - t_k^d)$	$q_k^{\mathrm{LT,II}}(w_{k-1}) + q_k^{\mathrm{LT,I}}(\Theta_k^{\mathrm{LT}} - t_k^d)$	Large number†	$q_k^{\mathrm{LT,II}}(\Phi_{k-1}^{\mathrm{TH}} - b) + q_k^{\mathrm{LT,I}}(b - \Phi_k^{\mathrm{LT}})$

❖ Approximating Left-turn Delay

To reflect the benefit of left-turn vehicles, this study introduces a left-turn efficiency index which is negatively correlated to the approximated delay.

$$e_k = \begin{cases} 1 & \text{if type A applies} \\ 1 - \dfrac{(t_k^e + N'_k) - (t_k^c + N_{k-1})}{(1 - \Phi_{k-1}^{\mathrm{TH}})} & \text{if type B applies} \\ 0 & \text{if type C applies} \\ \dfrac{(t_k^e + N'_k) - t_k^d}{b} & \text{if type D applies} \end{cases}$$



❖ Objective Functions

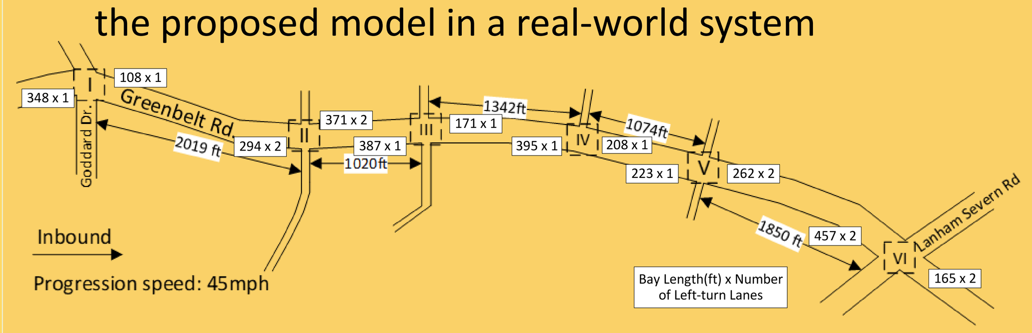
Stage 2: Maximize $B + \bar{B}$, $B \le B_k$, $\bar{B} \le \bar{B}_k$

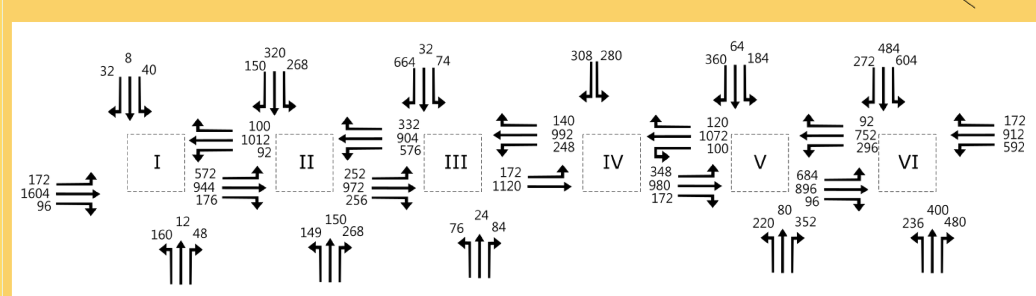
Stage 3: Maximize $\sum_k n_k^{\mathrm{LT}} e_k$

Case Study

The Case study contains two parts:

- Numerical analysis to demonstrate the effectiveness of the formulated constraints
- Simulation experiments to ensure the effectiveness of the proposed model in a real-world system



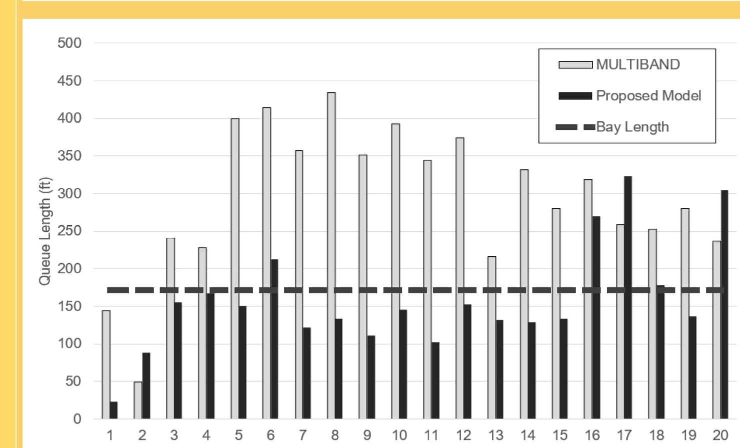


Phase sequence	Demand scenario	Initial bandwidth [a] (sec)		Effective bandwidth not impeded by spillback (sec)				Average left-turn efficiency index
				By MAXBAND		By the Proposed Model		
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound	
Fixed	Level-1 (Low)	49.6	43.3	49.6 (0%)	43.3 (0%)	49.6 (0%)	43.3 (0%)	0.568
	Level-2 (Medium)	49.5	43.6	30.2 (39.0%)	43.6 (0%)	49.5 (0%)	43.6 (0%)	0.560
	Base Case (High)	49.6	42.9	6.7 (86.5%)	42.9 (0%)	37.5 (24.4%)	42.9 (0%)	0.545
	Level-3 (High turning volume)	49.7	42.9	0 (100.0%)	42.9 (0%)	26.7 (46.3%)	42.9 (0%)	0.545
Variable	Base Case (High)	49.9	43.3	9.6 (80.8%)	31.2 (27.9%)	49.9 (0%)	43.3 (0%)	0.619
	Level-3 (High turning Volume)	50.0	43.2	15.2 (69.6%)	31.1 (28.0%)	34.9 (30.2%)	43.2 (0%)	0.617

[a] Initial bandwidths with MAXBAND, but neglecting the impacts of overflows from the left-turn volume.
* The numbers in the parenthesis indicate the reduced percentage of bandwidth.

Direction	Inter-section	MULTIBAND		Proposed Model		Percentage Change	
		Average Delay (sec/veh)	Average # of stops (-/veh)	Average Delay (sec/veh)	Average # of stops (-/veh)	Average Delay	Average # of stops
Overall arterial performance for through movements							
Overall	-	110.1	2.35	103.1	2.22	-6.4%	-5.5%
Inbound	-	83.4	2.36	82.0	2.38	-1.7 %	0.84%
Outbound	-	139.7	2.35	125.8	2.04	- 9.9 %	-13.2 %
Performance of through movements at the selected intersections							
Outbound	IV	17.9	0.45	15.7	0.38	-12.2%	-17.0%
	III	35.9	0.74	30.9	0.63	-14.0%	-14.0%
	II	38.2	0.65	37.8	0.66	-1.1%	1.4%
Performance of left-turn movements with high left-turn efficiency indices							
Inbound	IV	92.7	2.65	86.0	2.63	-7.2%	-0.75%
	V	72.6	2.16	72.1	2.19	-0.70%	1.3%
Outbound	II	140.5	2.40	126.3	2.15	-10.1%	-10.4%
	V	85.6	1.18	84.3	1.15	-1.4%	-2.2%

▲MOEs produced from the simulation experiments.



◄ Median of maximum left-turn queue lengths within the through progression bands at intersection III for the outbound direction.

- With medium demand level, about 39.0% of inbound bandwidth generated by MAXBAND will be impeded by the queue spillback, but not with our proposed model.
- The proposed model can keep substantial percentage of the through band intact.
- The signal progression plan produced by the proposed model, as expected, can produce not only the maximum effective bandwidth, but also lowest average delay and number of stops to both the through and left-turn vehicles.

Conclusions

- To contend with spillback blockages often observed between left-turn queues and through flows on major arterials with their signal plans designed mainly to facilitate through traffic movements, this study has presented a three-stage optimization model to **offer the progression for both the through and left-turning flows**.
- Depending on the initial two-way through bandwidths obtained in Stage 1, one can then proceed to Stage 2 to compute the optimal offsets that **can maximize the effective bandwidths** not impacted by such spillback under the given left-turn volumes and bay lengths. Since the arriving pattern of the left-turn flows and its queue formation pace vary with the signal phasing and timings at the upstream intersection, Stage 3 of the proposed model further offers the function to search the offsets and phase sequences that can also **yield the minimum delay for the left-turn flows without compromising** the total effective bandwidth for the entire arterial.
- Hence, this proposed model has the potential to be used in practice, especially for urban arterials consisting of some major intersections plagued by **high turning volumes and limited bay lengths**.