CONCURRENT OPTIMIZATION OF SIGNAL PROGRESSION AND CROSSOVER SPACING FOR DIVERGING DIAMOND INTERCHANGES

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Evolution of DDI

- Proposed early 2000's
- First DDI open on 2009
- Currently more than 80 locations around the country.
- Able to reduce conflict points for turning movements from and onto the freeway ramps by reversing the through movements at the crossovers

I-44 & Kansas Expressway in Springfield, MO
Source: http://www.divergingdiamond.com/index.html

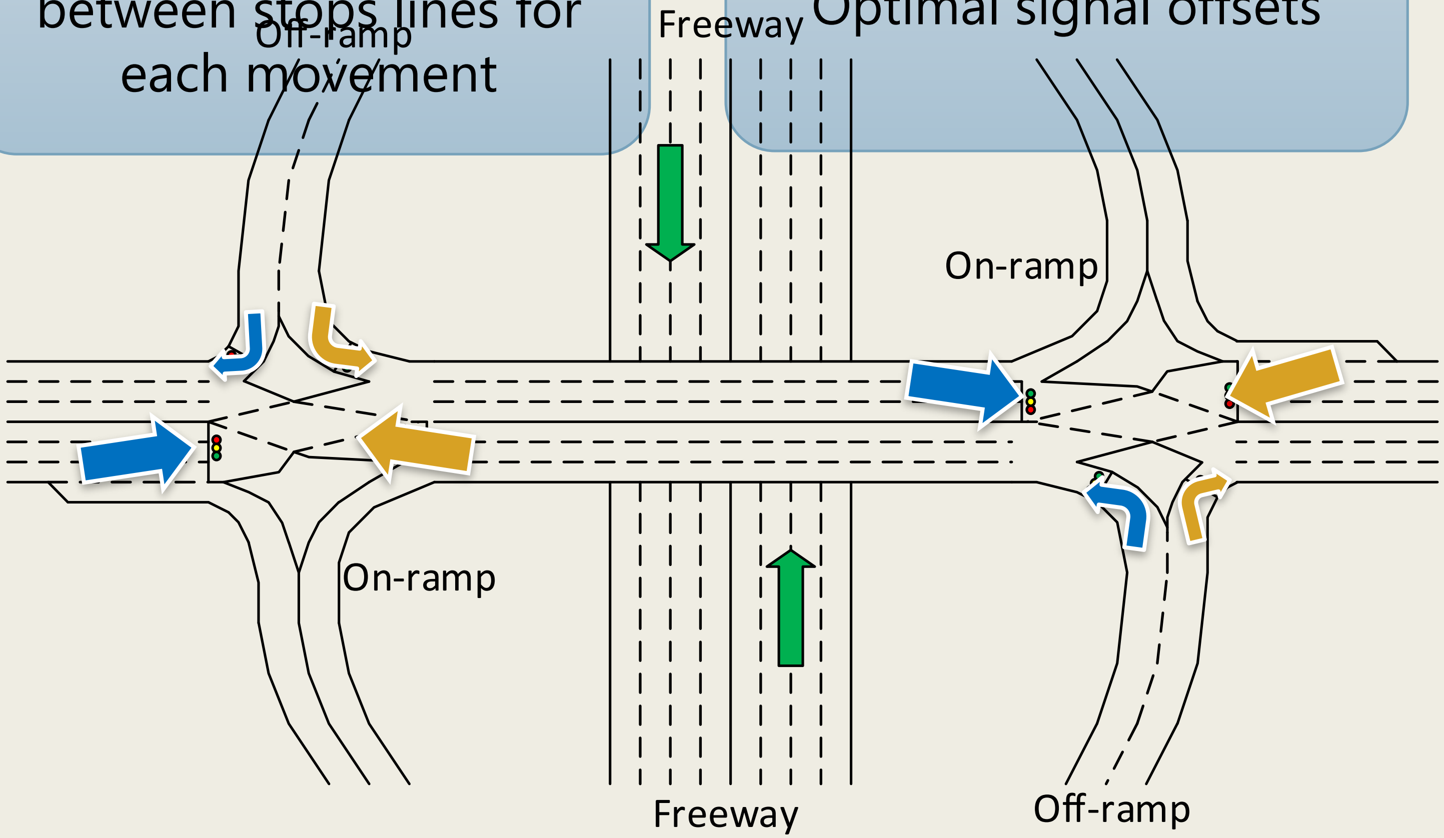
Research Issues

Optimal cycle length and signal timing plan for sub-intersections

Optimal distance between stops lines for each movement

Optimal signal offsets

- Two phases
  - Eastbound through, southbound right, and northbound left
  - Westbound through, southbound left, and northbound right
- Cycle length and splits can be determined easily with existing methods.



Research Issues

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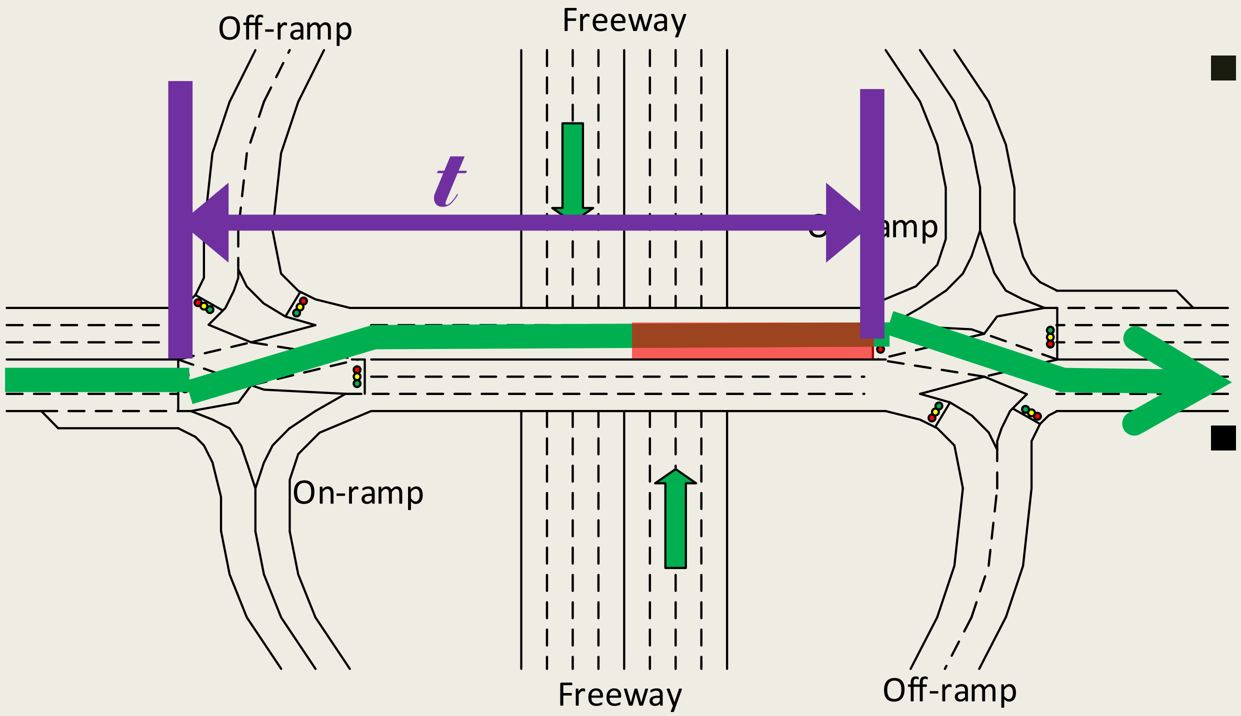

- Crossover spacing should be determined
  - *to accommodate queue consisting of vehicles that cannot experience signal progression*
  - *based on actual* ***signal offsets***
- Signal offsets should be optimized
  - *With a known travel time between the crossovers, calculated with the* ***distance between stops lines*** *for each movement*

Research Issues

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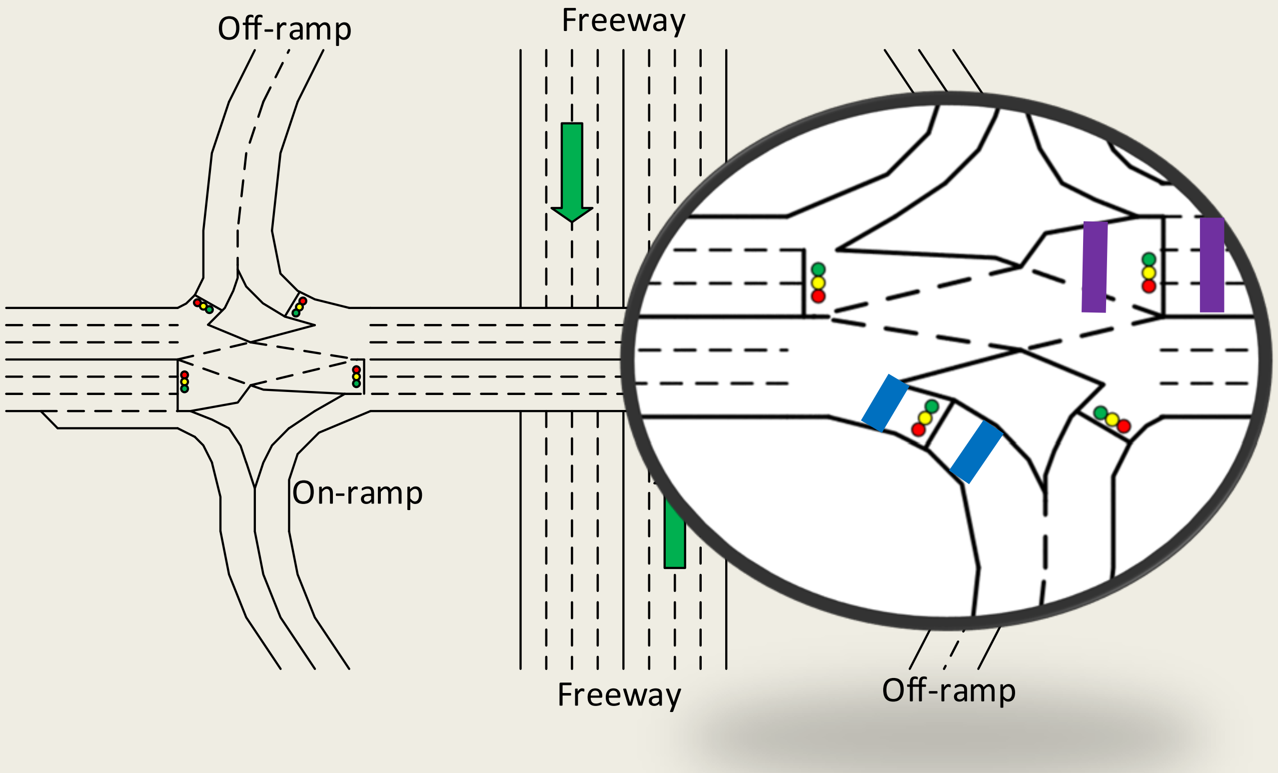


- The distances between the stop lines for through and left turn movements are significantly different.
- The positions of the stop lines can be determined with actual traffic conditions.

- A set of adjustment terms should be set to determine the actual positions of stop lines based on the crossover spacings

Model Development

Offset optimization

- Input: cycle length, green split, cruising speed, crossover spacing

Crossover spacing optimization

- Input: cycle length, green split, traffic volume, saturation flow rate, offset

Concurrent optimization of offset and crossover spacing

- Input: cycle length, green split, cruising speed, traffic volume, saturation flow rate

Model Development

Offset optimization

$$Max: \sum_j b_j$$

b_j: the progression bandwidth for critical movement j

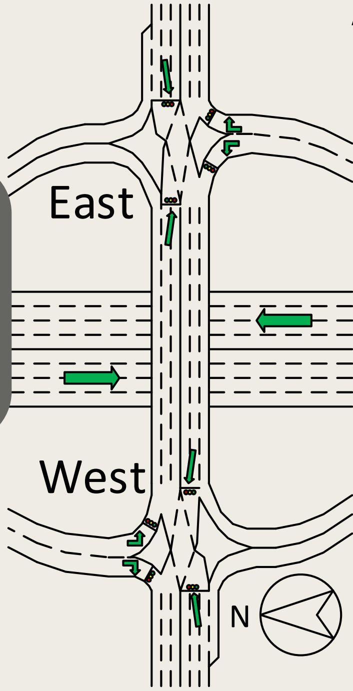
To make sure that each band only uses its corresponding green phase

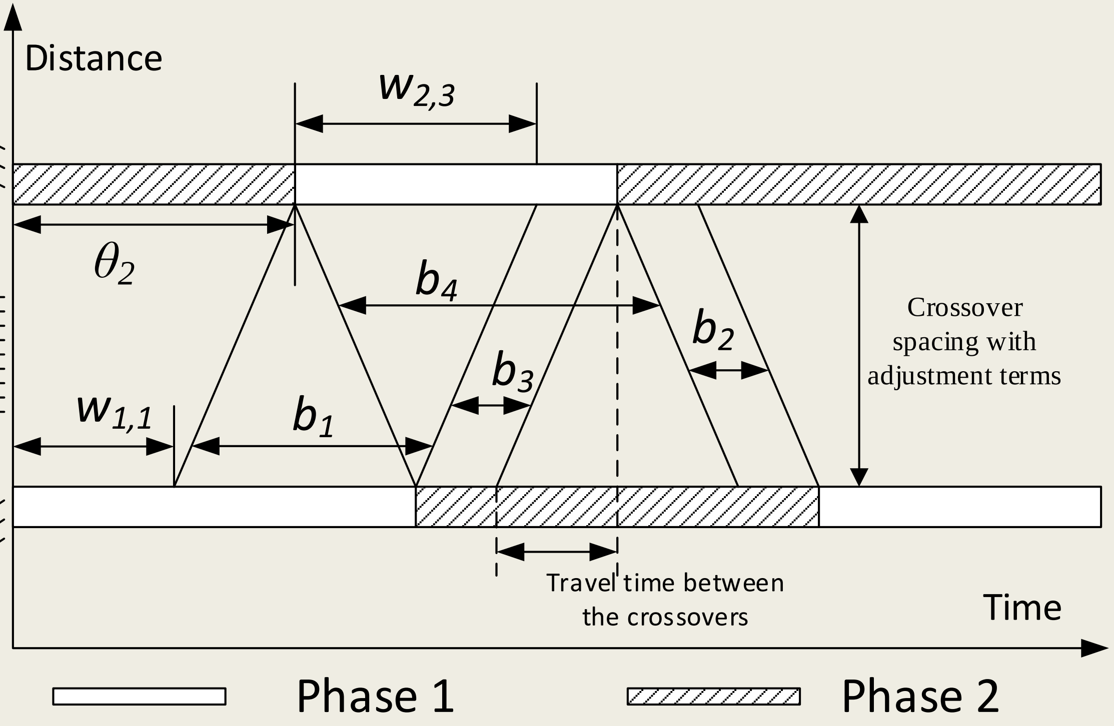
$$w_{i,j} + b_j \le g_{i,j}$$

$$w_{i,j} \ge 0$$

$w_{i,j}$: the part of green time before the specified band used by flows on movement j at intersection i;

$g_{i,j}$: the duration of the phase for movement j at intersection i.





1: eastbound through
2: westbound through
3: southbound left
4: northbound left

Model Development

Offset optimization

$$\theta_1 + w_{1,1} + \frac{l + l'_1}{v_1 C} + n_{1,1} = \theta_2 + w_{2,1} + n_{2,1}$$

To determine the proper offsets based on travel time.

Travel time

θ_i: the offset at inter

C: the predetermine

l: the variable for c

l'_i : the distance adjustment term defined by the position of the stop;

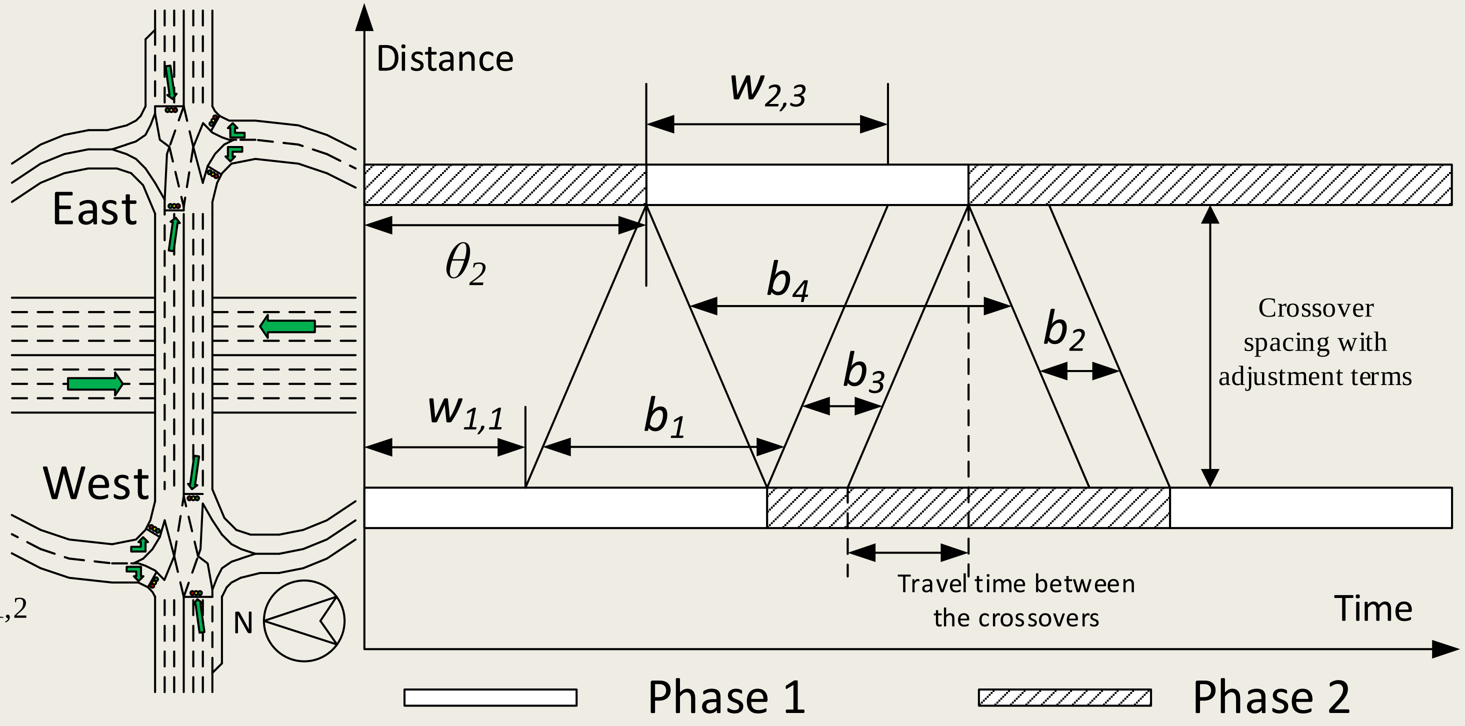
v_j: the progression speed defined for critical movement j;

$n_{i,j}$: integer variables

$$\theta_2 + g_2 + w_{2,2} + \frac{l + l'_2}{v_2 C} + n_{2,2} = \theta_1 + g_1 + w_{1,2} + n_{1,2}$$

$$\theta_1 + g_1 + w_{1,3} + \frac{l + l'_3}{v_3 C} + n_{1,3} = \theta_2 + w_{2,3} + n_{2,3}$$

$$\theta_2 + w_{2,4} + \frac{l + l'_4}{v_4 C} + n_{2,4} = \theta_1 + g_1 + w_{1,4} + n_{1,4}$$



1: eastbound through

2: westbound through

3: southbound left

4: northbound left

Model Development

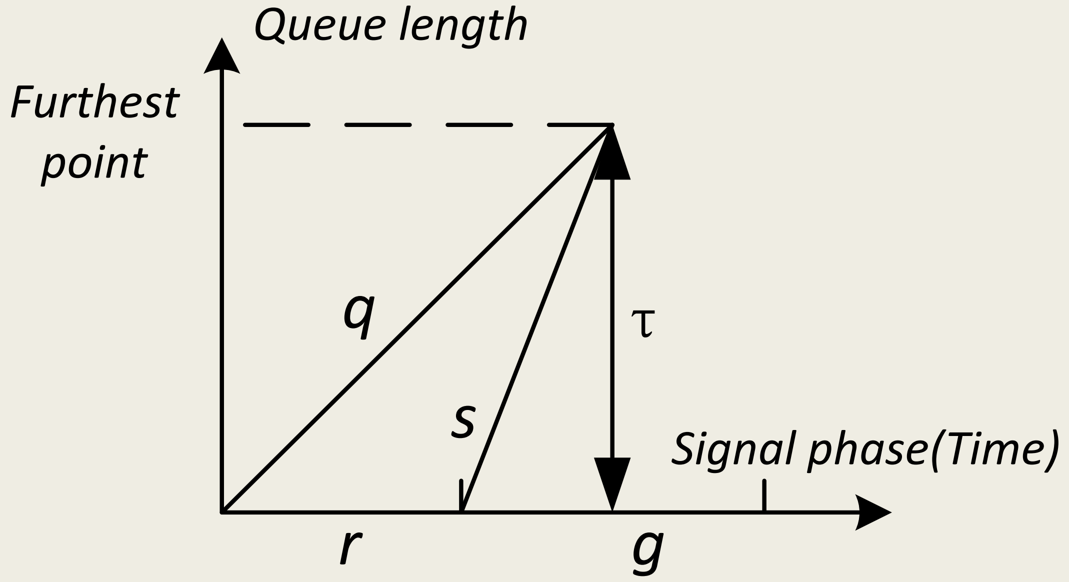
Crossover spacing optimization

Queue length calculation:

$$\tau = \frac{(Cr+\delta)\alpha q \, s}{s-\alpha q}$$

The queue length at the end of the red phase

τ: the distance between the stop bar and the end of queue before it is fully discharged;
r: the fraction of red phase;
δ: the lost time in seconds;
q: the volume;
α: the corresponding lane use factor;
s: the saturation flow rate.



Model Development

Crossover spacing optimization

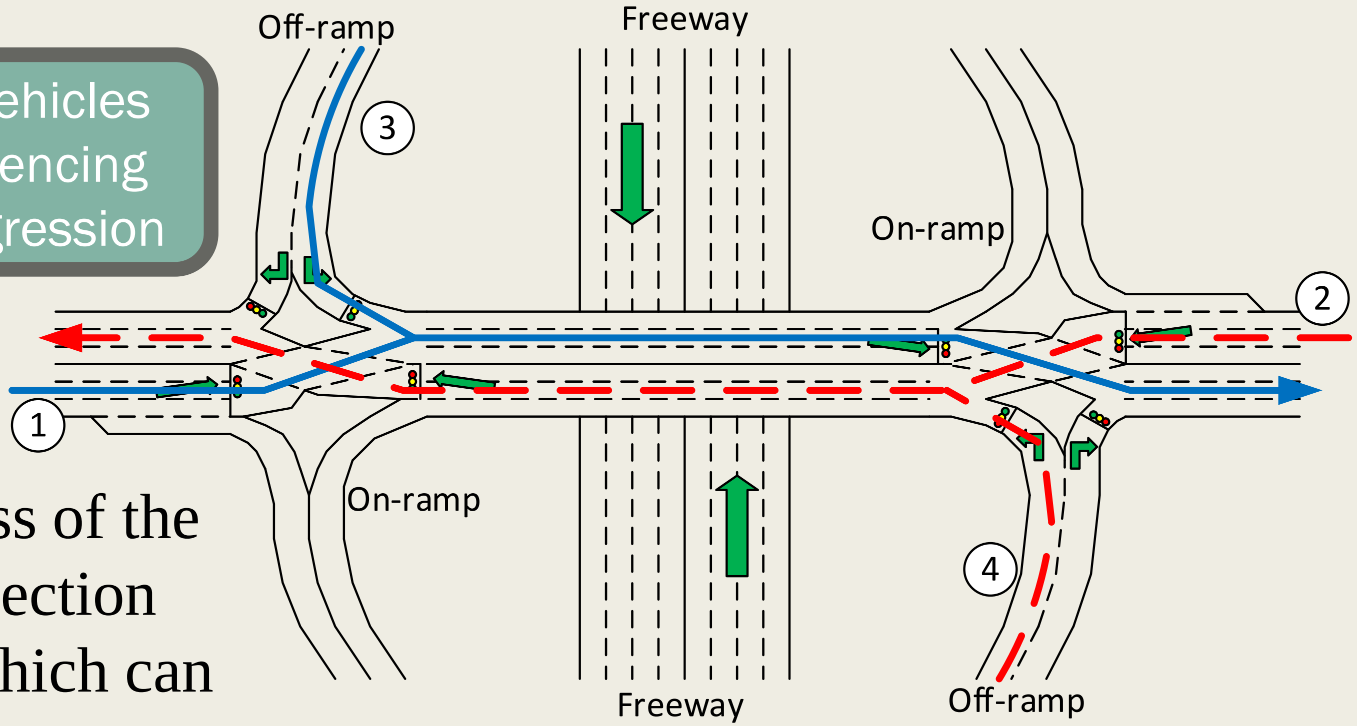
$$\frac{s}{s-\alpha q_j}\left[\alpha q_2(1-g_2-b_2)C/g_2+\alpha q_4(g_2-b_4)C/g_2\right]\le(l+l'_4)/h, \qquad j=2,4$$

$$\frac{s}{s-\alpha q_j}\left[\alpha q_1(g_1-b_1)C/g_1+\alpha q_3(1-g_1-b_3)C/(1-g_1)\right]\le(l+l'_3)/h, \qquad j=1,3$$

Through vehicles not experiencing signal progression

Through vehicles not experiencing signal progression

h: the spatial headway of vehicles between two sub-intersections



- ❑ To avoid queue spillback regardless of the signal phase at the upstream intersection
- ❑ Based on the given bandwidths, which can be directly computed from the offset.

Model Development

Concurrent optimization of offset and crossover spacing

$$Max : \sum_j b_j - \frac{l / vC}{M}$$

$$w_{i,j} + b_j \le g_{i,j} \qquad w_{i,j} \ge 0$$

- Both offset and crossover spacing are decision variables.
- Model is able to avoid queue spillback and generate maximum progression bands.

$$\theta_1 + w_{1,1} + \frac{l + l'_1}{v_1 C} + n_{1,1} = \theta_2 + w_{2,1} + n_{2,1} \qquad \theta_2 + g_2 + w_{2,2} + \frac{l + l'_2}{v_2 C} + n_{2,2} = \theta_1 + g_1 + w_{1,2} + n_{1,2}$$

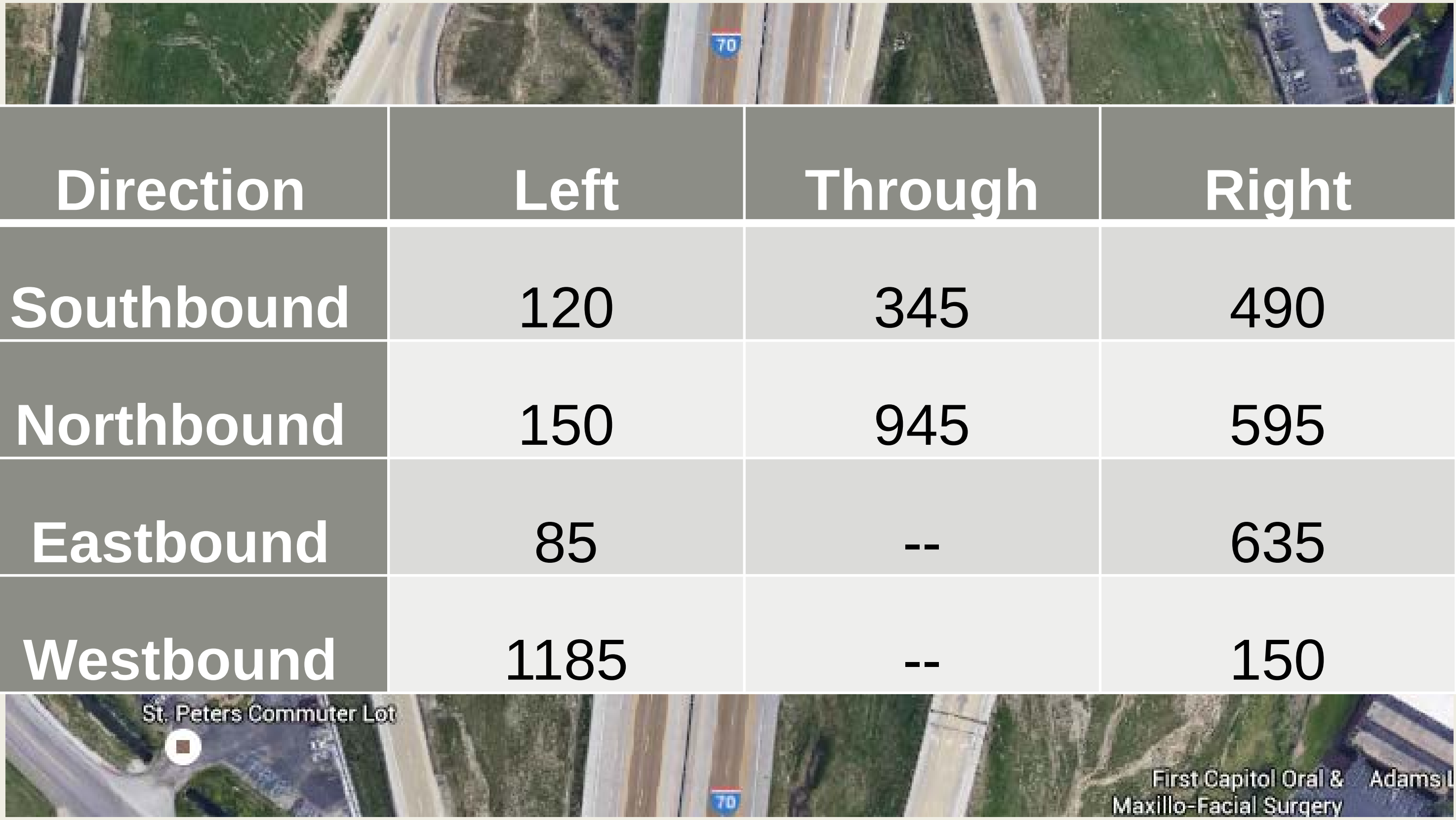
$$\theta_1 + g_1 + w_{1,3} + \frac{l + l'_3}{v_3 C} + n_{1,3} = \theta_2 + w_{2,3} + n_{2,3} \qquad \theta_2 + w_{2,4} + \frac{l + l'_4}{v_4 C} + n_{2,4} = \theta_1 + g_1 + w_{1,4} + n_{1,4}$$

$$\frac{s}{s - \alpha q_j}\left(\alpha q_2 \left(1 - g_2 - b_2\right) C / g_2 + \alpha q_4 \left(g_2 - b_4\right) C / g_2\right) \le \left(l + l'_4\right) / h, \qquad j = 2,4$$

$$\frac{s}{s - \alpha q_j}\left[\alpha q_1 \left(g_1 - b_1\right) C / g_1 + \alpha q_3 \left(1 - g_1 - b_3\right) C / \left(1 - g_1\right)\right] \le \left(l + l'_3\right) / h, \qquad j = 1,3$$

Case Study

- A DDI at I-70 & Mid Rivers Mall Dr in Saint Peters, MO
- Adopted PM peak demand data from a traffic survey in April 2016.
- Cycle length and green splits are calculated based on volumes



Direction	Left	Through	Right
Southbound	120	345	490
Northbound	150	945	595
Eastbound	85	--	635
Westbound	1185	--	150

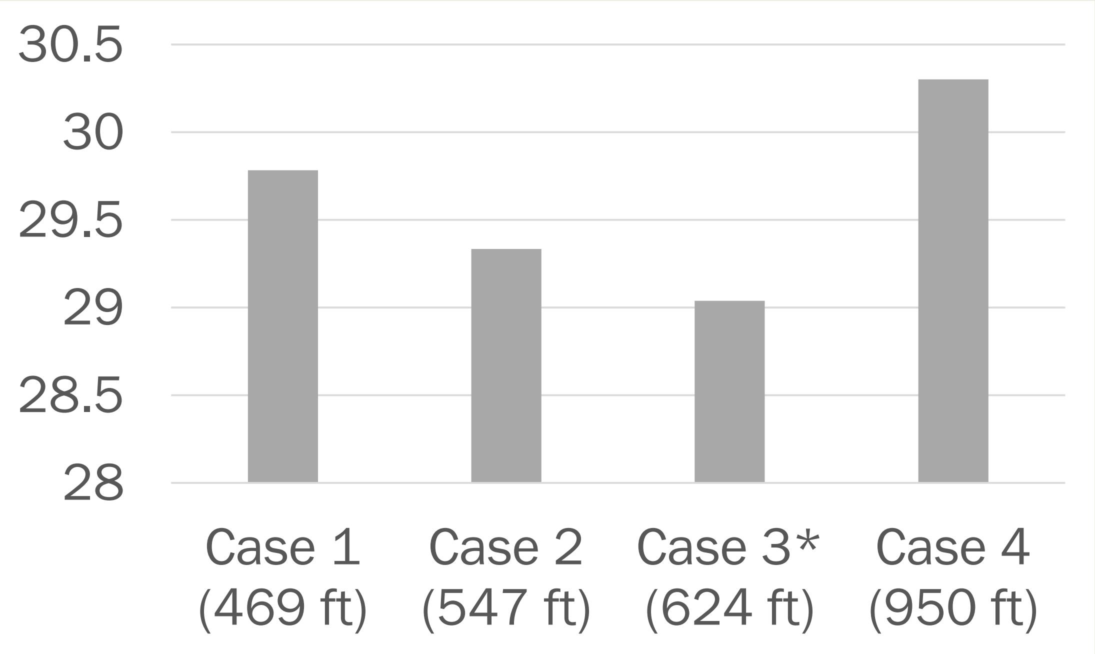
Case Study

- Optimization results and simulation design

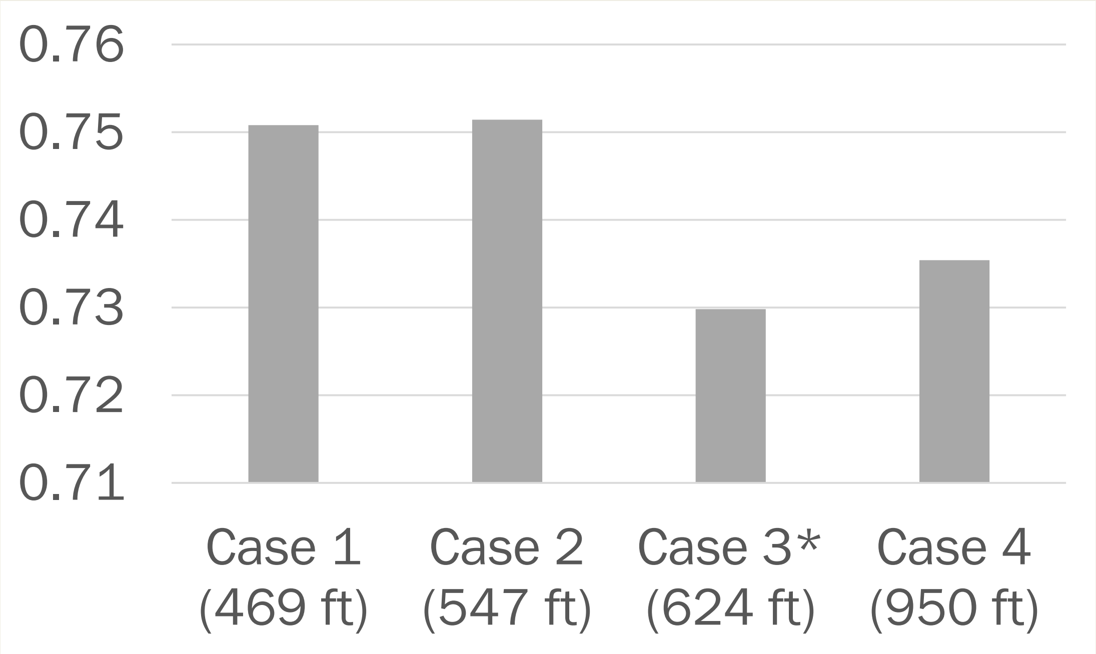
	Current volume		Projected volume(1.4 times)	
Cases	Crossover spacing (ft)	Offset (sec)	Crossover spacing(ft)	Offset (sec)
1. Actual	469	24	469	24
2. Shorter	547	43	547	43
3. Optimized	624	42	681	44
4. Long	950	49	950	49

Case Study

- Simulation results (current volume)
  - *The optimized crossover spacing outperforms other three cases.*
  - *Increasing the crossover spacing towards the optimal one can result in less traffic delay.*
  - *A crossover longer than enough may not be beneficial.*



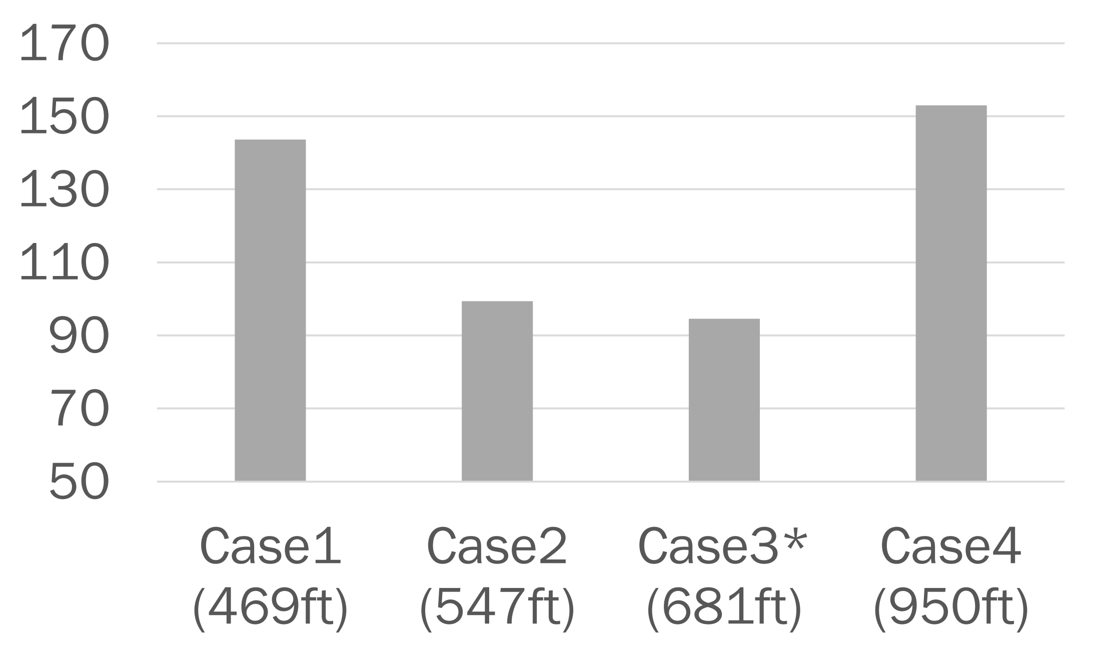
Average delay per vehicle (sec)



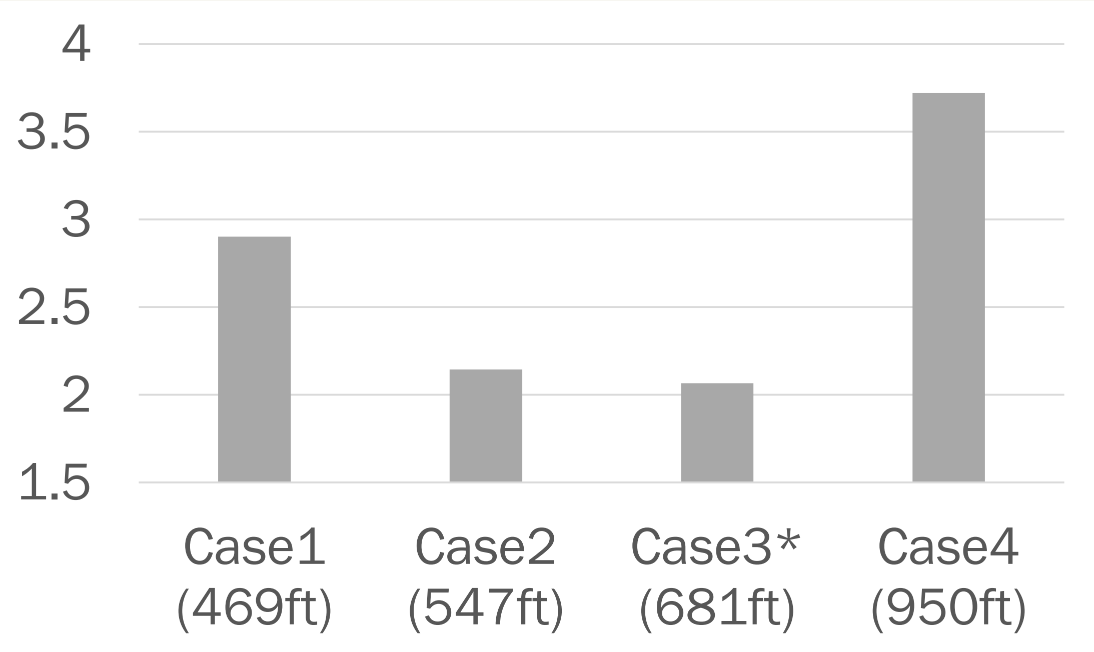
Average number of stops per vehicle

Case Study

- Simulation results (projected volume, 1.4 times)
  - *The benefit is more significant for the projected volume*



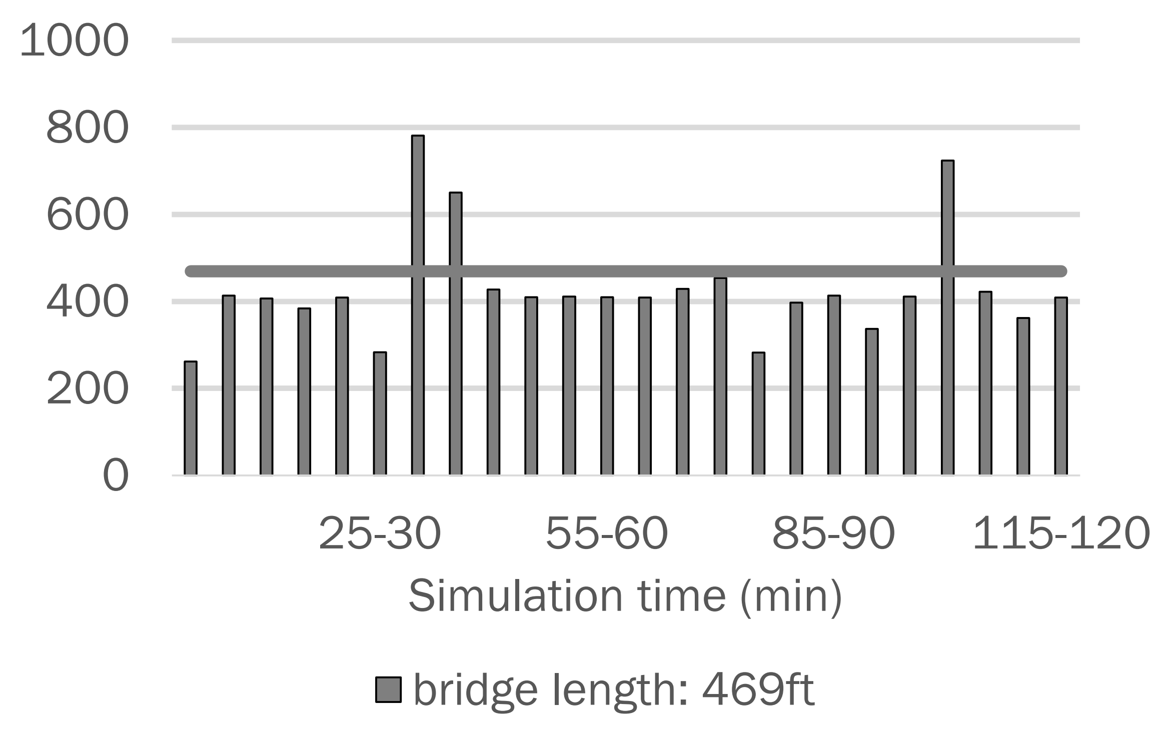
Average delay per vehicle (sec)



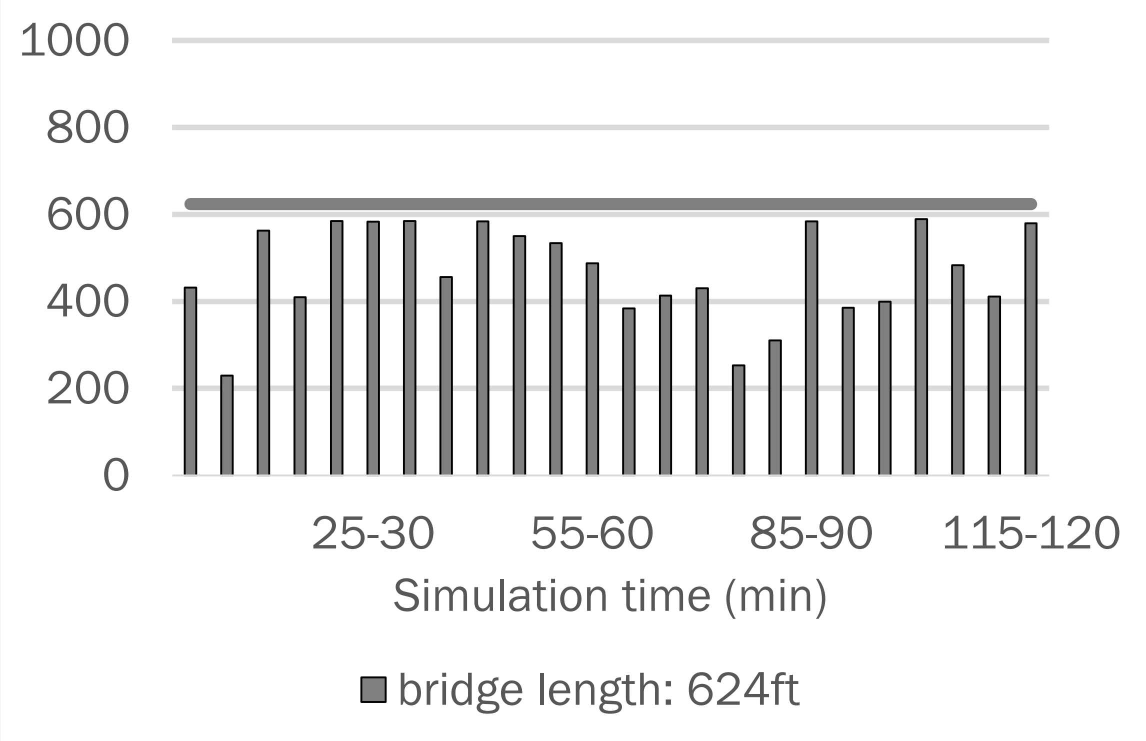
Average number of stops per vehicle

Case Study

- Time-dependent queue length at the South intersection
  - *The concurrently optimized crossover spacing and offset is able to eliminate queue spillback due to traffic fluctuation.*



Time-dependent queue length in Case 1



Time-dependent queue length in Case 3

Conclusions and Future Study

- An optimization model to fully account for the interdependent relation between the crossover spacing and the signal offset in a DDI
- Simulations to evaluate the performance of the proposed model
  - *DDI with the concurrently optimized crossover spacing and offset can yield the shortest delays and travel times*
  - *the DDI with the optimized design features can effectively cope with potential queue spillback at the crossovers*
- Future study
  - *a method to determine whether or not to set signals for all off-ramp flows at those DDI sub-intersections*
  - *a method to estimate the impacts to the adjacent intersections and close exits on the freeway*

Q & A

- Acknowledgement
  - *The authors are grateful for the kindly help from MO DOT on providing traffic volume data for the test site.*
  - *This study is supported by Maryland SHA ATTAP Program to Traffic and Safety and Operations Lab. at University of Maryland, College Park.*

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