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RESEARCH BACKGROUND
Research Background

**BENEFITS:**  
*Increased Popularity of Superstreets.*

- **Economical Benefits:** *Less expensive than an interchange;*
- **Safety Benefits:** *Reduction in number & severity of the collisions;*
- **Operation Benefits:** *Provide signal progressions along the arterial; and*
- **Environmental Benefits:** *Reduction in pollutions.*
Research Background

**Literature Review**


- The distance between the main intersection and U-turn crossover is the dominating factor that influence a Superstreet’s safety performance (Liu, 2007; Hochestein, 2009; Hugues, 2010; Olarte, 2011).

- In fact, over the past decades, only limited studies (Olarte, 2011) have attempted to address the issues of design and operations of a Superstreet.

- A newly published report (FHWA, 2014) also indicated the lack of sufficient information in the area of designing a Superstreet.

*Existing Literature fall short on the subjects of Design and Evaluation of Superstreets.*
Critical Issues

Limitations of Existing Studies

- How to determine the U-turn offset length that dominates the geometric design of a Superstreet?
- What would be the criteria for determining the need of installing signals for a Superstreet?
- How to assess whether the bay length among a signalized Superstreet is sufficient to prevent any spillback from happening?
- How to design a proper signal timing plan, considering its unique geometric layouts?
- How to minimize the delay experienced by the minor road drivers due to the detour operations in a Superstreet.
02 THESIS FRAMEWORK
**THESIS FRAMEWORK**

1. **Minimum U-turn Offset Model for Un-signalized Superstreet**
   - a. Critical Components of U-turn offset
   - b. Key Input/Output
   - c. Model Development
   - d. SSAM Evaluation
   - e. Extended Applications

2. **Interval-based Bay Length Evaluation Models for a Signalized Superstreet**
   - a. Operational Analysis
   - b. Critical Issues
   - c. Model Development
   - d. Model Validation

3. **Two-stage Signal Optimization Model for a Signalized Superstreet**
   - a. General Algorithm
   - b. Signal Control Algorithm
   - c. Solution
   - d. Case Study
MINIMUM U-TURN OFFSET MODEL FOR A UN-SIGNALIZED SUPERSTREET
Critical Components of U-turn Offset

- $l_1$: Acceleration and merging length;
- $l_2$: Lane-changing length;
- $l_3$: Deceleration and initial queue length;
- $L$: Minimum U-turn offset.
Key Components

**Input:**

- **Acceleration Rate:** \( a_1 \)
- **Headway Distribution:** \( (\lambda, \bar{t}, t_m, t_{nr}) \)
- **Critical Gap Distribution:** \( (\mu, \sigma) \)

**Output:**

- **Acceleration & Merging Length:** \( l_1 \)
- **Lane-Changing Length:** \( l_2 \)
- **Deceleration & Initial Queue Length:** \( l_3 \)
- **Minimum U-turn Offset Length:** \( L \)

**Notation and Description**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>AASHTO recommended acceleration rate</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Parameter for major road headway distribution</td>
</tr>
<tr>
<td>( \bar{t} )</td>
<td>Average gap in second from major traffic</td>
</tr>
<tr>
<td>( t_m )</td>
<td>The minimum headway from major traffic</td>
</tr>
<tr>
<td>( t_{nr} )</td>
<td>The maximum headway from major traffic</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Mean of critical gap distribution</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Deviation of critical gap distribution</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>AASHTO recommended deceleration rate</td>
</tr>
<tr>
<td>( \rho = \frac{\text{arrival _ rate}}{\text{service _ rate}} )</td>
<td>Parameter for M/M/1 system</td>
</tr>
<tr>
<td>( l_1 )</td>
<td>Acceleration &amp; merging length</td>
</tr>
<tr>
<td>( l_2 )</td>
<td>Kth lane changing length</td>
</tr>
<tr>
<td>( l_3 )</td>
<td>Deceleration &amp; initial queue length</td>
</tr>
<tr>
<td>( L )</td>
<td>Minimum U-turn offset length</td>
</tr>
</tbody>
</table>

Output:

- **Acceleration & Merging Length:** \( l_1 \)
- **Lane-Changing Length:** \( l_2 \)
- **Deceleration & Initial Queue Length:** \( l_3 \)
- **Minimum U-turn Offset Length:** \( L \)
Merging Scenarios

The merging maneuver, based on the relative gaps between the leader and the follower, can be classified into three distinct types:

1) **Free merging:**

   - **Target Lane**
   - **Subject Lane**
   - **Leading Vehicle**

   - **Subject Vehicle**

2) **Forced merging:** the follower was ‘forced’ to break pedal to maintain safe space headway;

   - **Target Lane**
   - **Subject Lane**
   - **Following Vehicle**
   - **Leading Vehicle**

   - **Subject Vehicle**

   Most dangerous

3) **Cooperative merging:**

   - **Target Lane**
   - **Subject Lane**
   - **Following Vehicle**
   - **Leading Vehicle**

   - **Subject Vehicle**

---

where $v_1$ is the speed of mainline traffic; 
$v_0$ is the speed of subject vehicle; 
$t_r$ is the average reaction time, 1.0s; 
h is a given time headway; 
l_v is the AASHTO recommended passenger car length, 20ft; 
a_2 is the AASHTO recommended deceleration rate, 11.2ft/s².

$$t^* \geq \frac{(v_1 - v_0)^2}{2a_2 v_1} + \frac{l_v}{v_1} + t_r$$

For any randomly given subject vehicle, the minimum acceptable headway must be no less than $t^*$.
Assumptions

During the merging process, subject vehicle has to accelerate from stop. Assuming

(1) The subject vehicle accelerates from $0_{mph}$ with a fixed acceleration rate until reaches speed limit $v_1$, and then stay at the same speed until reach the U-turn location;

(2) Critical headway $t_c$ follows a certain distribution, in this case, assume critical gap for drivers from side street follows normal distribution $N(\mu, \sigma^2)$;

(3) The headway follows negative exponential distribution since the car arrival follows Poisson distribution.
Acceleration & Merging Length

For a random vehicle, at time point $t$, the lane-changing probability can be:

$$ F(t) = P\{h \geq t_c(t)\} $$

Where $t_c$ denotes the critical gap for a certain driver at time point $t$.

If assuming that at time point $t + \Delta t$, where $\Delta t \to 0$,

$$ p_1(t + \Delta t) = p_1(t) + (1 - p_1(t))\Delta t(F(t)) $$

Since $\Delta t \to 0$, we can have $t_c(t + \Delta t) = t_c(t)$, then

$$ \frac{p_1(t + \Delta t) - p_1(t)}{\Delta t} = [1 - p_1(t)] \cdot F(t) $$

$$ -\ln[1 - p(t)]dP = \int_0^\infty F(t) \cdot dt $$

how to calculate $F(t)$?

$F(t)$ is not a constant but a function with respect to time. So we cannot have closed form of $P(t)$

$F(t)$ stands for the probability for a random driver merging into major road at any time point $t$. It is a function with respect to both time and human characteristic.
Merging Length

The probability of a driver having a critical gap equals $t_c^*$ at time point $t$ is

$$f(t_c^*)dt = \left[ \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(t_c^* - \mu)}{2\sigma^2} \right) \right] dt$$

Meanwhile, the headway distribution follows shifted negative exponential distribution as

$$\Pr(h \geq t_c) = \begin{cases} e^{-\lambda (t_c - t_m)}, & \text{for } t_c \geq t_m \\ 0, & \text{for } t_c < t_m \end{cases}$$

Where $\lambda = 1/(\bar{t} - t_m)$ while $\bar{t}$ is the average gap (s) and $t_m$ is the minimum headway(s).

A random vehicle to conduct a successful merging can be

$$\int_{t_c=0}^{\infty} \Pr(h \geq t_c) f(t_c) dt$$
Merging Length

There exist two thresholds $t_m, t_{nr}$ that stand for the lower bound and upper bound, respectively (Pollatschek, 2002).

Therefore, the overall merging probability can be expressed as:

$$\int_{t_c=0}^{\infty} \Pr(h \geq t_c) f(t_c) dt = \int_{t_c=0}^{\max(t_m,t_*)} \Pr(h \geq t_c) f(t_c) dt + \int_{t_c=\max(t_m,t_*)}^{t_{nr}} \Pr(h \geq t_c) f(t_c) dt + \int_{t_c=t_{nr}}^{\infty} \Pr(h \geq t_c) f(t_c) dt$$

since $\Pr(h \geq t_c) = 0$, $\int_{t_c=0}^{\max(t_m,t_*)} 0 * f(t_c) dt = 0$

Finally, we can have

$$\int_{t_c=0}^{t_{nr}} \Pr(h \geq t_c) f(t_c) dt = \int_{t_c=\max(t_m,t_*)}^{t_{nr}} \Pr(h \geq t_c) f(t_c) dt = e^{-2\mu\sigma^2 + \lambda^2\sigma^4 \over 2\sigma^2}$$

$$\int_{t_c=\max(t_m,t_*)}^{t_{nr}} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ \frac{-[t_c - (\mu - \lambda \sigma^2)]^2}{2\sigma^2} \right] dt$$

$N \sim (\mu - \lambda \sigma^2, \sigma^2)$

Lane-Changing Length

As $p_k(t)$ denotes the probability that the vehicle is in lane $k$ at time point $t$.

Remember for 1st successful merging probability, we have:

$$p_1(t + \Delta t) = p_1(t) + (1 - p_1(t))\Delta t F(t)$$

For $k_{th}$ lane change, we can get

$$p_k(t + \Delta t) = p_k(t) + [1 - p_k(t)] \cdot p_{k-1}(t) \cdot \Delta t \cdot F(t)$$

$$p'_k(t) = [1 - P_k(t)] \cdot p_{k-1}(t) \cdot F(t)$$

Because both $F(t)$ and $p(t)$ are not a constant but functions with respect to time. So we cannot have closed form of $P_k(t)$.
Numerical Example

Given the headway distribution of arterial traffic and the predetermined overall successful rate, we can get the relationship between probability of $k^{\text{th}}$ lane changes and the required distance.

A numerical example is shown on the right-hand side:

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{ux}$</td>
<td>11 seconds</td>
</tr>
<tr>
<td>$t_m / t_{2a}$</td>
<td>2 seconds</td>
</tr>
<tr>
<td>$\bar{t}$</td>
<td>5.6 seconds</td>
</tr>
<tr>
<td>$\bar{\bar{t}}$</td>
<td>0.28</td>
</tr>
<tr>
<td>$\bar{\mu}$</td>
<td>0.67</td>
</tr>
<tr>
<td>$a_1$</td>
<td>4.0–4.5 ft/s$^2$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>11.2 ft/s$^2$</td>
</tr>
<tr>
<td>$v_1$</td>
<td>63–67 mph</td>
</tr>
</tbody>
</table>

Minimum U-turn Offset Model for an Un-Signalized Superstreet
SSAM Evaluation

US 301 @ Ruthsburg Rd, MD

- Stop control for EB minor road
- Yield control for WB minor road
- Studies Segment: South-Bound U-turn Segment

- Scenario 1: 1500ft southern U-turn offset (Field implementation)
- Scenario 2: 1100ft southern U-turn offset (Mean of model output)
- Scenario 3: 700ft southern U-turn offset (Shortened U-turn offset)

The only difference between three scenarios is the length of southern U-turn offset. The rest of geometrics are the same for all scenarios and are measured from the field.
SSAM Measurements

- Minimum Time To Collision (TTC)
- Minimum Post-Encroachment Time (PET)
- Initial Deceleration Rate (DR)
- Maximum Speed (MaxS)
- Maximum relative Speed Difference (DeltaS)
- Maximum Deceleration Rate (MaxD)
- Maximum “post collision” DeltaV (MaxDeltaV)

MaxDeltaV is the maximum speed change of either vehicle in the conflict.
U-turn Segment safety performance comparison (1100ft VS. 1500ft)

<table>
<thead>
<tr>
<th>SSAM Measures</th>
<th>Mean (1100ft)</th>
<th>Variance (1100ft)</th>
<th>Mean (1500ft)</th>
<th>Variance (1500ft)</th>
<th>t value</th>
<th>t critical</th>
<th>Significant</th>
<th>Mean Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC</td>
<td>0.217</td>
<td>0.184</td>
<td>0.217</td>
<td>0.144</td>
<td>-0.002</td>
<td>1.668</td>
<td>NO</td>
<td>0</td>
</tr>
<tr>
<td>PET</td>
<td>0.08</td>
<td>0.026</td>
<td>0.083</td>
<td>0.02</td>
<td>-0.018</td>
<td>1.668</td>
<td>NO</td>
<td>-0.003</td>
</tr>
<tr>
<td>MaxS</td>
<td>22.441</td>
<td>8.983</td>
<td>22.97</td>
<td>11.465</td>
<td>-0.868</td>
<td>1.668</td>
<td>NO</td>
<td>-0.529</td>
</tr>
<tr>
<td>DeltaS</td>
<td>8.678</td>
<td>9.953</td>
<td>9.942</td>
<td>27.489</td>
<td>-1.263</td>
<td>1.668</td>
<td>NO</td>
<td>-1.265</td>
</tr>
<tr>
<td>DR</td>
<td>-1.004</td>
<td>5.08</td>
<td>-1.203</td>
<td>5.582</td>
<td>0.443</td>
<td>1.668</td>
<td>NO</td>
<td>0.2</td>
</tr>
<tr>
<td>MaxD</td>
<td>-2.482</td>
<td>9.743</td>
<td>-2.838</td>
<td>10.67</td>
<td>0.587</td>
<td>1.668</td>
<td>NO</td>
<td>0.355</td>
</tr>
<tr>
<td>MaxDeltaV</td>
<td>4.485</td>
<td>2.711</td>
<td>5.113</td>
<td>7.253</td>
<td>-1.214</td>
<td>1.668</td>
<td>NO</td>
<td>-0.628</td>
</tr>
</tbody>
</table>

No statistically significant difference between 1500ft and 1100ft in terms of both number of conflicts and all SSAM measurements.

No significant difference in terms of conflict severity!
## Safety Comparison (Scenario 3 VS. Scenario 2)

- **U-turn Segment safety performance Comparison (700ft VS. 1100ft)**

<table>
<thead>
<tr>
<th>SSAM Measures</th>
<th>Mean (700ft)</th>
<th>Variance (700ft)</th>
<th>Mean (1100ft)</th>
<th>Variance (1100ft)</th>
<th>t value</th>
<th>t critical</th>
<th>Sigficanct</th>
<th>Mean Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC</td>
<td>0.19</td>
<td>0.187</td>
<td>0.217</td>
<td>0.184</td>
<td>-0.136</td>
<td>1.668</td>
<td>NO</td>
<td>-0.026</td>
</tr>
<tr>
<td>PET</td>
<td>0.078</td>
<td>0.028</td>
<td>0.08</td>
<td>0.026</td>
<td>-0.01</td>
<td>1.668</td>
<td>NO</td>
<td>-0.002</td>
</tr>
<tr>
<td>MaxS</td>
<td>22.952</td>
<td>8.076</td>
<td>22.441</td>
<td>8.983</td>
<td>1.044</td>
<td>1.668</td>
<td>NO</td>
<td>0.511</td>
</tr>
<tr>
<td>DR</td>
<td>-0.57</td>
<td>2.399</td>
<td>-1.004</td>
<td>5.08</td>
<td>0.909</td>
<td>1.677</td>
<td>NO</td>
<td>0.434</td>
</tr>
<tr>
<td>MaxD</td>
<td>-2.907</td>
<td>10.679</td>
<td>-2.482</td>
<td>9.743</td>
<td>-0.797</td>
<td>1.668</td>
<td>NO</td>
<td>-0.425</td>
</tr>
<tr>
<td>MaxDeltaV</td>
<td>6.791</td>
<td>10.316</td>
<td>4.485</td>
<td>2.711</td>
<td>3.943</td>
<td>1.67</td>
<td>YES</td>
<td>2.306</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conflict Types</th>
<th>Mean (700ft)</th>
<th>Variance (700ft)</th>
<th>Mean (1100ft)</th>
<th>Variance (1100ft)</th>
<th>t value</th>
<th>t critical</th>
<th>Sigficanct</th>
<th>Mean Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.86</td>
<td>1.86</td>
<td>NO</td>
<td>0</td>
</tr>
<tr>
<td>Rear-end</td>
<td>5.4</td>
<td>6.3</td>
<td>5</td>
<td>22</td>
<td>0.168</td>
<td>1.86</td>
<td>NO</td>
<td>0.4</td>
</tr>
<tr>
<td>Lane changing</td>
<td>2.8</td>
<td>0.7</td>
<td>1</td>
<td>2</td>
<td>2.449</td>
<td>1.86</td>
<td>YES</td>
<td>1.8</td>
</tr>
<tr>
<td>Total</td>
<td>8.2</td>
<td>7.2</td>
<td>6</td>
<td>36</td>
<td>0.748</td>
<td>1.86</td>
<td>NO</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- **Increased possible lane-changing collisions under 700ft than in 1100ft;**
- **More sever collisions under 700ft than in 1100ft.**
## Safety Comparison (Scenario 3 VS. Scenario 1)

- **U-turn Segment safety performance Comparison (700ft VS. 1500ft)**

<table>
<thead>
<tr>
<th>SSAM Measures</th>
<th>Mean (700ft)</th>
<th>Variance (700ft)</th>
<th>Mean (1500ft)</th>
<th>Variance (1500ft)</th>
<th>t value</th>
<th>t critical</th>
<th>Significant</th>
<th>Mean Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC</td>
<td>0.19</td>
<td>0.187</td>
<td>0.217</td>
<td>0.144</td>
<td>-0.159</td>
<td>1.664</td>
<td>NO</td>
<td>-0.027</td>
</tr>
<tr>
<td>PET</td>
<td>0.078</td>
<td>0.028</td>
<td>0.083</td>
<td>0.02</td>
<td>-0.031</td>
<td>1.664</td>
<td>NO</td>
<td>-0.005</td>
</tr>
<tr>
<td>MaxS</td>
<td>22.952</td>
<td>8.076</td>
<td>22.97</td>
<td>11.465</td>
<td>-0.036</td>
<td>1.664</td>
<td>NO</td>
<td>-0.018</td>
</tr>
<tr>
<td>DR</td>
<td>-0.57</td>
<td>2.399</td>
<td>-1.203</td>
<td>5.582</td>
<td>1.816</td>
<td>1.664</td>
<td>YES</td>
<td>0.633</td>
</tr>
<tr>
<td>MaxD</td>
<td>-2.907</td>
<td>10.679</td>
<td>-2.838</td>
<td>10.67</td>
<td>-0.13</td>
<td>1.664</td>
<td>NO</td>
<td>-0.069</td>
</tr>
<tr>
<td>MaxDeltaV</td>
<td>6.791</td>
<td>10.316</td>
<td>5.113</td>
<td>7.253</td>
<td>3.434</td>
<td>1.664</td>
<td>YES</td>
<td>1.678</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conflict Types</th>
<th>Mean (700ft)</th>
<th>Variance (700ft)</th>
<th>Mean (1500ft)</th>
<th>Variance (1500ft)</th>
<th>t value</th>
<th>t critical</th>
<th>Significant</th>
<th>Mean Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.86</td>
<td>NO</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Rear-end</td>
<td>5.4</td>
<td>6.3</td>
<td>7.2</td>
<td>21.7</td>
<td>-0.761</td>
<td>NO</td>
<td>-1.8</td>
<td></td>
</tr>
<tr>
<td>Lane changing</td>
<td>2.8</td>
<td>0.7</td>
<td>1</td>
<td>0.5</td>
<td>3.674</td>
<td>YES</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8.2</td>
<td>7.2</td>
<td>8.2</td>
<td>22.7</td>
<td>1.86</td>
<td>NO</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

- **More severe collisions under 700ft**
- **Increased possible lane changing collisions for 700ft when comparing 1500ft**

### a. Increased possible lane-changing collisions under 700ft than in 1500ft;
### b. More severe conflicts under 700ft than in 1500ft.
The overall merging successful probability decreases with growing volume level.

A numerical example is shown on the right-hand side:

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{m}$</td>
<td>11 seconds</td>
</tr>
<tr>
<td>$t_{m}/t_{sa}$</td>
<td>2 seconds</td>
</tr>
<tr>
<td>$\bar{t}$</td>
<td>5.6 seconds</td>
</tr>
<tr>
<td>$\bar{\lambda}$</td>
<td>0.28</td>
</tr>
<tr>
<td>$\bar{\mu}$</td>
<td>0.67</td>
</tr>
<tr>
<td>$a_1$</td>
<td>4.0~4.5 ft/s²</td>
</tr>
<tr>
<td>$a_2$</td>
<td>11.2 ft/s²</td>
</tr>
<tr>
<td>$v_1$</td>
<td>63~67 mph</td>
</tr>
</tbody>
</table>

The Relationship between Traffic Demand and the Probability of Conducting Twice Lane-Changes
INTERVAL-BASED BAY LENGTH EVALUATION MODELS FOR A SIGNALIZED SUPERSTREET
Operation Analysis

Field Survey and VISSIM Calibration

- This study has conducted a field survey at a signalized Superstreet Intersection (MD3 & Waugh Chapel Rd) to calibrate key parameters in VISSIM;
- The collected data include queue lengths, signal plan and traffic flow rates.
- Extensive simulation results reveal that the exponentially increased delay when Q/L ratio approaches to 1.

Possible blockages among a Superstreet are shown below:

(A) Left-turn lane group partially blocks the right-through lane group
(B) Right-through lane group completely blocks the left-turn lane group
(C) Through lane group completely blocks the upstream lane groups

Figure. Scatter plot of average delay v.s. average QL ratio

Interval-Based Bay Length Evaluation Models for a Signalized Superstreet
Critical Issues

**Interval-based queue estimation models**

- Traffic flow and signal design can both contribute to the formation of queues in a superstreet
  - *Incoming traffic fluctuates over time*
  - *Signal coordination plan is another key factor to determine queue length*
  - *Develop interval-based queue estimation models to take into account of the both uncertainties.*

- **Two types of queues:**
  1. **External Queues:** only influenced by flow fluctuation
  2. **Internal Queues:** influenced by both flow fluctuation and signal coordination
Queue lengths under different signal coordination plan

- For main intersection through-Q: Q5, departures from Q6 and Q9 are two sources for its incoming flow.
- 1) through and right-turn movements from Q9;
- 2) departures from Q6

Worst Case = Largest arrival rate + worst signal coordination

Best Case = Smallest arrival rate + Best signal coordination
Spatial distributions of all potential queues among a Signalized Superstreet

- Type-1 (Q7, Q8, Q9, Q10): Through queues at major & minor road
- Type-2 (Q3, Q6): U-turn queues at the crossover intersection
- Type-3 (Q1, Q4): Left-turn queues at main intersection
- Type-4 (Q2, Q5): Through queues at main intersection
**Interval-based Queue Model**

- **Q5**: Through queues at the main intersection

  - Departures from Q6
  - Through and Right-turn departures from Q9

Arrivals at Q5:

For Q6, all the departures from it should merge into Q5, so at any time point $k$, the departures from Q6 to Q5 can be expressed as:

$$D^k = \begin{cases} 
0 & \text{During Red Time} \\
\min(\beta_{9TR}, A^k_{9TR} + q^k_{9TR}) & \text{During Green Time}
\end{cases}$$

where:
- $s_9$ is the saturation flow rate for link 9;
- $\beta_{9TR}$ is the through and right-turning ratio for Q9;
- $A^k_{9TR}$ is the arrived vehicle for through and right-turning movements in Q9 at time $k$;
- $q^k_{9TR}$ is the queued through and right-turning vehicles in Q9 at time $k$.

$$A^k_5 = \alpha D^k_{9TR} + (1 - \alpha) D^{k-\tau}_6, \alpha = 0, 1$$

where:
- $\tau$ is the travel time from Q6 to Q5;
- $\alpha$ is a binary variable.
When Q5’s red and Q9’s green is concurrent, we could find the queue time \( t^* \) can be derived using:

\[
\bar{Q}_5 = \alpha \left[ \int_{t_0}^{t_0 + R_5} D_{t^{*-\sigma}} dt + \int_{t_1}^{t_1 + t^*} A_s \right. dt + \left. D_{t^{*-\sigma}} dt, \text{if} \ R^5 + t^* \leq g^9 > R^5 \right]
\]

where \( t_0 \) is the initial time of green phase of Q5 and \( t_0 \) is time to dissipate initial queue \( s \) is the saturation flow rate.

By taking into consideration of incoming traffic fluctuation, we can have the maximum queue interval as:

\[
\begin{align*}
Q_{5}^{\text{max}} &= \bar{Q}(A_{5}^{\text{max}}) \\
Q_{5}^{\text{min}} &= \bar{Q}(A_{5}^{\text{min}})
\end{align*}
\]
Model Validation

- Field Collected peak hour traffic data are used for the case study
  - Most of the simulated maximum queues fall within the estimated intervals.

![Diagram of the intersection with Q9 highlighted]

**Type 1: External Q**

The distribution of simulated maximal queue length (ft)

- Simulation results
- Queue lower bound
- Queue upper bound
- Measured link length

**MD 3 @ Waugh Chapel Rd**
Model Validation

- Field Collected peak hour traffic data are used for the case study
- Most of the simulated maximum queues fall within the estimated intervals.

- Type-4(Q2): Main through queue

The distribution of simulated maximal queue length (ft)
Model Validation

- Field Collected peak hour traffic data are used for the case study
  - Most of the simulated maximum queues fall within the estimated intervals.

- Type-2(Q3): U-turn queue

![Diagram of MD 3 @ Waugh Chapel Rd]

The distribution of simulated maximal queue length (ft)

- Simulation results
- Queue lower bound
- Queue upper bound
- Measured link length

The distribution of simulated maximal queue length (ft)
Model Validation

- Field Collected peak hour traffic data are used for the case study
  - Most of the simulated maximum queues fall within the estimated intervals.

- Type-3(Q1): Main left-turn queue

![Diagram of MD 3 @ Waugh Chapel Rd]

The distribution of simulated maximal queue length (ft)
05

TWO-STAGE SIGNAL OPTIMIZATION MODEL FOR A SIGNALIZED SUPERSTREET
Index for Movements

<table>
<thead>
<tr>
<th>Index</th>
<th>Movements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WB through at sub 1</td>
</tr>
<tr>
<td>2</td>
<td>Right-turn at sub 1</td>
</tr>
<tr>
<td>3</td>
<td>Left-turn at sub 1</td>
</tr>
<tr>
<td>4</td>
<td>U-turn at sub 2</td>
</tr>
<tr>
<td>5</td>
<td>EB through at sub 2</td>
</tr>
<tr>
<td>6</td>
<td>EB through at sub 3</td>
</tr>
<tr>
<td>7</td>
<td>Right-turn at sub 3</td>
</tr>
<tr>
<td>8</td>
<td>Left-turn at sub 3</td>
</tr>
<tr>
<td>9</td>
<td>U-turn at sub 4</td>
</tr>
<tr>
<td>10</td>
<td>WB through at sub 4</td>
</tr>
</tbody>
</table>

: index for sub-intersections. 1 stands for northern sub; 2 for western sub; 3 for southern sub and 4 stands for eastern sub.

Phase plan:
General Algorithm

Two-stage MILP

**Terminate Condition:**
After the change in CL is less than 1s?

**Stage 1:** Optimize green splits with queue constraints

- **Initialization**
  - Objective: Maximize Total throughput
  - Output: Common cycle length and green splits

- **Additional set of queue constraints**
  - External queue constraints
  - Internal queue constraints

- **Initial solution generation for Stage 2**

**Stage 2:** Determination of offset for each sub-intersection

- Objective: Maximize weighted bandwidth and Minimize weighted minor road waiting time
- Output: offset for each sub-intersection

- **Offset generation for Stage 1**

**Optimal Signal Timing Solution**
Stage 1 - Initial (Wong, 2003)

- **Control Objective:** Capacity Maximization

Objective Function: \( \text{Max}(\sum_{i \in I} \mu_i) \)

- **Subject to:**
  - Traffic rate will not exceed the saturation flow rate: \( \mu_i \alpha_{ij} q_{ij} \leq s(\phi_{ij} - \xi \times t_i) \)
  - Cycle length constraints: \( \frac{1}{C_{\text{max}}} \leq \xi \leq \frac{1}{C_{\text{min}}} \)
  - Green ratio constraints: \( g_{\text{min}} \times \xi \leq \phi_{ij} \leq g_{\text{max}} \times \xi \)
  - Sum of green time cannot exceed cycle length: \( \phi_{ij_1} + \phi_{ij_2} = 1; j_1, j_2 \in J \) and \( j_1 \neq j_2 \)

Initial solution for stage 2: *Cycle length and Green splits*

**General Algorithm**

**Terminate Condition:**
After the change in CL is less than 1s

**Initial Inputs**
- Demand Pattern
- Signal Phasing Plan

**Stage 1: Optimize green splits with queue constraints**

**Initialization**
- Objective: Maximize Total throughput
- Output: Common cycle length and green splits

**Additional set of queue constraints**
- External queue constraints
- Internal queue constraints

**Green split solution for Stage 2 (not initial)**

**Stage 2: Determination of offset for each sub-intersection**

- Objective: Maximize weighted bandwidth and Minimize weighted minor road waiting time
- Output: offset for each sub-intersection

**Offset generation for Stage 1**

**Optimal Signal Timing Solution**
Critical Paths

- **Path 1, 4:** Through and left-turn movements from the minor road, including 3 signals which are 1-2-3 or 3-4-1;
- **Path 2, 5:** Through and right-turn movements on arterial, including 2 signals which are 2-3 or 4-1;
- **Path 3, 6:** Left-turn movements on arterial, including 2 signals which are 2-1 or 4-3.

**Stage-2 Control Objective:**

Green Band Maximization & Minor Road Waiting Time Ratio Minimization

Objective Function: \( \text{Max}(\sum_{p \in P} \eta_p b_p - f_k \sum_{i \in K} D_{ik}) \)
Stage 2

- Minor Road Waiting time constraints:

\[ D_{11} \]

\[ D_{21} \geq 0 \]

\[ D_{21} \]

\[ x_{11} = 0 \]

\[ x_{11} = 1 \]

\[ x_{11} \geq \frac{\theta_2 + \phi_5 - \theta_1 - \phi_1 - t_{12}}{M} \]

\[ x_{11} \leq \frac{\theta_2 + \phi_5 - \theta_1 - \phi_1 - t_{12} + 1}{M} \]

\[ x_{11} = 0, 1 \text{ are binary variables} \]
Stage 2

- Minor Road Waiting time constraints:

$x_{21} \geq \frac{\theta_2 + \phi_3 + t_{23} - \theta_3 - \phi_6}{M} \quad \Rightarrow \quad D_{11} \geq \phi_1$

$x_{21} \leq \frac{\theta_2 + \phi_3 + t_{23} - \theta_3 - \phi_6 + 1}{M} \quad \Rightarrow \quad D_{31} \geq (1 - \theta_2 - \phi_3 - t_{23} + \theta_3) - (1 - x_{11})M - (1 - x_{21})M$

$x_{31} \geq \frac{\theta_1 + \phi_1 + t_{12} + t_{23} - \theta_3 - \phi_6}{M} \quad \Rightarrow \quad D_{31} \geq (1 - \theta_1 - \phi_1 - t_{12} - t_{23} + \theta_3) - x_{11}M - (1 - x_{21})M$

$x_{31} \leq \frac{\theta_1 + \phi_1 + t_{12} + t_{23} - \theta_3 - \phi_6 + 1}{M} \quad \Rightarrow \quad D_{11}, D_{31} \geq 0$

$x_{21}, x_{31} = 0, 1$ are binary variables

$D_{11} + D_{21} + D_{31} \leq \lambda \xi^* (t_{12} + t_{23})$
Two-stage Signal Optimization Model for a Signalized Superstreet

**General Algorithm**

**Terminate Condition:**
After the change in CL is less than 1s

**Initial Inputs**
- Demand Pattern
- Signal Phasing Plan

**Stage 1: Optimize green splits with queue constraints**

**Initialization**
- Objective: Maximize Total throughput
- Output: Common cycle length and green splits

**Additional set of queue constraints**
- External queue constraints
- Internal queue constraints

**Stage 2: Determination of offset for each sub-intersection**

- Objective: Maximize weighted bandwidth and Minimize weighted minor road waiting time
- Output: offset for each sub-intersection

**Offset generation for Stage 1**

**Optimal Signal Timing Solution**

**Initial solution generation for Stage 2**

**Termination Condition Satisfied?**

No

YES
Spatial Distribution of Potential Queues

- External Queues: Q2, Q5, Q7, Q10;
- Internal Queues: Q1, Q6, Q3, Q8, Q4, Q9.

Motivation for adding queue constraints: Cycle Length is the key contributing factor to the queue formations!
Stage 1 - Queue Constraints

- While keeping the previous *Objective function* & *All Constraints* in *Initial*;

- Maximum Queue won’t exceed the link length:
  --For *External Queues*:

  - For Q7:

    \[ L_7 \leq \frac{(1-\phi_{37} + t_l \cdot \xi) \cdot \alpha_7 q_7 \cdot s}{(s - \alpha_7 q_7) \cdot \xi} \]

    \[(1-\phi_{37} + t_l \cdot \xi) \cdot \alpha_7 q_7 \cdot s \leq L_7 (s - \alpha_7 q_7) \cdot \xi\]
Stage 1 - Queue Constraints

- Internal Queues:
  - For U-turn Queue (Q4):
    - Define binary variables:
      \[ Q'_4 \leq \left( \frac{\theta_2 + \phi_{25} - t_{12} - \theta_1 - \phi_{11}}{M} \right) \alpha_{24} q_{LT}^2 - (1 - y_4)M \]
      \[ Q'_4 \geq \theta_4 \leq \frac{\theta_2 + \phi_{25} - t_{12} - \theta_1 - \phi_{11}}{M} + 1 \]
    - \( f_1 \), binary parameter, = 1 if \( \theta_1 > \theta_2 - t_{12} \), o.w. = 0

Q4 cannot exceed link length 4:
Case Study

- Input demand:

<table>
<thead>
<tr>
<th>Input Demand</th>
<th>Unit: Veh/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>494</td>
<td>2363</td>
</tr>
<tr>
<td>516</td>
<td>491</td>
</tr>
<tr>
<td>2340</td>
<td>259</td>
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<td>312</td>
<td>504</td>
</tr>
<tr>
<td>54</td>
<td>2340</td>
</tr>
</tbody>
</table>

Using the MD 3@ Waugh Chapel Rd field collected traffic data, the model has ran 4 times to get the optimized signal plan.

The maximum waiting time for minor Rd drivers are not exceeding the upper bound.
Case Study

- Cycle length = 67s
- Green Splits

\[ b_1 = 0; b_4 = 0 \]

No band for Path 1 & 4.
Case Study

- **Comparison Solution (Synchro)**
  - Cycle Length: 120s
  - Green Splits:

  - **SUB 1**
    - Offset = 51s
    - Offset = 113s
    - Offset = 0s
    - Offset = 42s

  - **SUB 2**
    - Offset = 28s
    - Offset = 0s
    - Offset = 28s

  - **SUB 3**
    - Offset = 17s
    - Offset = 0s
    - Offset = 40s

  - **SUB 4**
    - Offset = 42s
    - Offset = 43s

Two-stage Signal Optimization Model for a Signalized Superstreet
Case Study

- **Simulation Results Comparison** *(30 cases, 2hr duration per case)*
  - Maximum Queue Length Comparison for Q1—(Main Through Q)

![Graph showing maximum queue length comparison](image.png)
Case Study

- Simulation Result Comparisons (30 cases, 2hr duration per case)
  - Maximum Queue Length Comparison for Q3--(Main left-turn Q)
Case Study

- **Simulation Result Comparisons** (30 cases, 2hr duration per case)
  - Maximum Queue Length Comparison for **Q9**—(U-turn Q)

![Graph showing maximum queue length comparison for Q9](image)

Two-stage Signal Optimization Model for a Signalized Superstreet
Case Study

- Simulation Result Comparisons (30 cases, 2hr duration per case)
  - Maximum Queue Length Comparison for External Queues

Two-stage Signal Optimization Model for a Signalized Superstreet
Case Study

- Simulation Result Comparisons
  - Average Intersection Delay Comparison

![Average Intersection Delay](image)

Two-stage Signal Optimization Model for a Signalized Superstreet
CONCLUSIONS
Contributions

A. Proposed the procedures and formulations to compute the *minimum required U-turn offset length* for an un-signalized Superstreet;

B. Developed the *interval-based models* for evaluating the *bay length* design in a signalized Superstreet under the given demand variation;

C. Presented an efficient *two-stage signal optimization* model to prevent queue spillback on intersection links and to *minimize the delays* experienced by minor road drivers.

This research offers reliable tools to assist traffic professionals in the design of Superstreets with and without signal control.
Future Work

- Field calibration and evaluation on the minimum U-turn offset length model for an Un-signalized Superstreet.

- Evaluation of the impacts of a Superstreet on its neighboring intersections.

- Coordination of a signal plan for a signalized Superstreet with its neighboring intersections on the same corridor.
THANKS FOR YOUR TIME

HAPPY TEACHER'S DAY