Optimal Decision-making between Signalized and Uninterrupted Flow Strategies during Emergency Evacuation

Yue Liu, PhD, Assistant Professor
Zhenke Luo, PhD Student
Jing Mao, PhD Student

Department of Civil Engineering and Mechanic
University of Wisconsin at Milwaukee
414-229-3857, liu28@uwm.edu
Contents

1. Introduction
2. Model Formulation
3. Solution Approach
4. Case Study and Findings
5. On-going Research
Natural disasters have caused:

- Huge amount of economical loss
- Fatal injuries
Introduction

Through effective traffic management, responsible agencies can:

- Better utilize the available network capacity
- Improve the mobility and traffic safety
- Reduce the economic loss
Commonly used traffic management strategies:

1. Signals
2. Cross-elimination strategy
3. Lane reversal strategy
Introduction

Signal Control

Features

- Reduce evacuee detours
- Cause unacceptable delays when evacuation demand is high
Introduction

Cross-elimination (uninterrupted flow) strategy

Features

- Reduce the delays at intersection
- Increase the intersection capacity
- Increase the detour
- Request large amount of management resources
- Increase the anxiety of travelers
Introduction

This research develops a model to assist transportation authorities to best locate signals and uninterrupted flow intersections in real-world evacuation management.

- Avoid the unnecessary detour due to uninterrupted flow control
- Avoid the unacceptable delay due to signals
- Prioritize limited traffic management resources
- Achieve the best overall evacuation performance
Critical issues to be investigated in this research:

- How many uninterrupted flow and signalized intersections to be implemented?
- What are their most appropriate locations?
- How to properly design the turning restriction plans at those uninterrupted flow intersections?
Contents

1. Introduction
2. Model Formulation
3. Solution Approach
4. Case Study and Findings
5. On-going Research
Model Formulation

Evacuation Network Representation:

Conflict is not allowed

Conflict is allowed
Model Formulation

- A bi-level mathematical model is developed
- **The up level** determines the location and turning restriction plans
  - Objective: minimize the total evacuation time in the network
  - Constraints: travel delay, budget constraint, cross elimination and other logic constraints
- **The low level** routes evacuees according to a stochastic user equilibrium (SUE) principal
Model Formulation

The up level:

**Objective:** minimizing the total evacuation time

\[
\min \sum_{a \in \mathcal{A}, r \in \mathcal{R}, s \in \mathcal{S}, z \in \mathcal{Z}} \sum t_a f_{a,z}^{rs}
\]

**Decision Variables:**
Model Formulation

The up level:

Travel cost functions:

Delay on uninterrupted flow intersections

Delay on signal intersections

BPR-form function

HCM delay function
Model Formulation

The Up-level:

Conflict elimination constraints:

\[ y_{ab} + \sum_{cd \in \mathcal{Y}_a} y_{cd} \leq 1 + Mx_m \quad \forall a, b \in A, b \in \Gamma_a^{-1}, d \in \Gamma_c^{-1}, m \in N_m \]

Budget constraints:

\[ B \geq \sum_m B_m (1 - x_m) \quad \forall m \in N_m \]

Capacity constraints:

\[ \sum_{r \in N_R} \sum_{s \in N_S} f^{rs}_{a,z} \leq c_a \quad a \in A \]

Other operational constraints
Model Formulation

The Low-level:

A Path-based SUE network assignment

\[ F_{ab}(f, y) = f_{ab} - \sum_{r \in N_R} \sum_{s \in N_S} q^{rs} \frac{\partial W^{rs}}{\partial c^z} \delta_{ab, z}^{rs} = 0 \quad \forall a, b \in A, b \in \Gamma_a^{-1} \]

\[ c_z^{rs} = \sum_{a \in z} t_a + \sum_{a \in z} \sum_{b \in \Gamma_a^{-1}} M(1 - y_{ab}) \quad \forall r \in N_R, s \in N_S, b \in z \]

\[ W^{rs} = E[\min\{c_z^{rs}\}] \]

\[ W^{rs} = \frac{-1}{\theta} \ln \sum_z \exp(-\theta c_z^{rs}) \quad \forall r \in N_R, s \in N_S, z \in Z^{rs} \]
Content

1. Introduction
2. Model Formulation
3. Solution Approach
4. Case Study and Findings
5. On-going Research
Solution Approach

A Genetic-based Heuristic Algorithm

It may require an extremely long chromosome for large-scale applications locations and turning restrictions

- Avoid an extremely long chromosome

A bi-level genetic-based algorithm

Location plan

External module

Internal module

Turning restriction plan
Solution Approach

Coding in The External Module

Binary strings indicating the location plan

\[ F(x) = \{1,0,1,1,1,0,1,1,1,1,0,1,1,1,1,1\} \]
Solution Approach

Coding in the Internal Module

Binary strings indicating the turning restrictions

\[ F(L) = \{1,0,1,...,1,1,1,...,1,1,0,...\} \]
Solution Approach

Infeasibility Handling

External module
Add penalty if budget constraint is violated

\[ f(X_j) = \frac{1}{\alpha_0 \left[ \sum_m (1 - x_m) B_m - B \right] + F(X_j)} \quad \forall m \in N_m \]

Internal module
Add penalty if turning restriction constraint is violated

\[ f(L_j) = \sum_{a \in A} \sum_{r \in N_a} \sum_{s \in N_b} t_{a, r} f_{a, s}^{rs} + \sum_m M (1 - x_m) \cdot Max[0, y_{ab} + \sum_{cd \in \chi_{ab}} y_{cd} - 1] \]
Solution Approach

Convergence Criteria:

In both external and internal module

(1) Improvement between two adjacent generations is lower than a threshold value for a certain number of generations; or

(2) Reach the pre-set maximal generations
Contents

1. Introduction
2. Model Formulation
3. Solution Approach
4. Case Study and Findings
5. On-going Research
Case Study and Findings

Test Network: a compact urban area
Case Study and Findings

Experimental Design:

- An average of $5,000 to implement uninterrupted flow operations at an intersection
- Three demand levels:
  - Level I (10,000 vph), Level II (20,000 vph), and Level III (30,000 vph)
- Four budget plans:
  - A: $10,000, (2 uninterrupted flow intersections) B: $20,000 (4), C: $30,000 (6)
  - and D $40,000 (8)
- A total of 12 scenarios
Case Study and Findings

Performance Evaluation:

The proposed model v.s. the existing practice (Alternative-I)
Case Study and Findings

Results and Findings:

I. Computational Performance (model implemented in MATLAB)

<table>
<thead>
<tr>
<th>Demand level</th>
<th>Budget plan A</th>
<th>Budget plan B</th>
<th>Budget plan C</th>
<th>Budget plan D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Iteration</td>
<td>Computation Time (min)</td>
<td>Iteration</td>
<td>Computation Time (min)</td>
</tr>
<tr>
<td>level I</td>
<td>26</td>
<td>12.17</td>
<td>28</td>
<td>18.07</td>
</tr>
<tr>
<td>level II</td>
<td>28</td>
<td>12.53</td>
<td>31</td>
<td>18.56</td>
</tr>
<tr>
<td>level III</td>
<td>29</td>
<td>13.36</td>
<td>31</td>
<td>19.24</td>
</tr>
</tbody>
</table>

Note: Computation performance is evaluated in a PC with Intel Pentium Dual-Core 1.80 GHz CPU and 6 GB RAM.
# Case Study and Findings

## Results and Findings:

II. Discrepancy between the proposed model and alternative-I

<table>
<thead>
<tr>
<th>Budget Plans</th>
<th>Demand Level</th>
<th>Uninterrupted Flow Intersection Locations (Node ID)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Optimal plan</td>
</tr>
<tr>
<td>A</td>
<td>I</td>
<td>14, 16</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>8, 9</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>8, 20</td>
</tr>
<tr>
<td>B</td>
<td>I</td>
<td>8, 14, 16, 20</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>8, 9, 16, 20</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>9, 11, 16, 20</td>
</tr>
<tr>
<td>C</td>
<td>I</td>
<td>2, 4, 8, 9, 16, 20</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3, 8, 9, 16, 19, 20</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>3, 8, 9, 16, 19, 20</td>
</tr>
<tr>
<td>D</td>
<td>I</td>
<td>3, 8, 9, 16, 19, 20, 24, 25</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3, 8, 9, 16, 19, 20, 24, 25</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>3, 8, 9, 16, 19, 20, 24, 25</td>
</tr>
</tbody>
</table>
Case Study and Findings

Results and Findings:

III. Effectiveness of the proposed model

Comparison between the proposed model and Alternative-I under all demand levels and budget plans
Case Study and Findings

Results and Findings:

III. Effectiveness of the proposed model
The improvement over Alternative-I is higher when the demand level is high

<table>
<thead>
<tr>
<th>Budget Plans</th>
<th>Demand Level</th>
<th>The Total Evacuation Time (veh*hr)</th>
<th>Improvement over Alternative-I (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The proposed Model</td>
<td>Alternative-I</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>I</td>
<td>423</td>
<td>465</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>855</td>
<td>1124</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>1674</td>
<td>2274</td>
</tr>
<tr>
<td>B</td>
<td>I</td>
<td>372</td>
<td>442</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>764</td>
<td>978</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>1352</td>
<td>1877</td>
</tr>
<tr>
<td>C</td>
<td>I</td>
<td>324</td>
<td>396</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>618</td>
<td>794</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>1157</td>
<td>1542</td>
</tr>
<tr>
<td>D</td>
<td>I</td>
<td>298</td>
<td>355</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>584</td>
<td>752</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>978</td>
<td>1358</td>
</tr>
</tbody>
</table>
Case Study and Findings

Results and Findings:

IV. Sensitivity Analysis

The total evacuation time keeps decreasing along with the increasing in budget.
Case Study and Findings

Results and Findings:

IV. Sensitivity Analysis

The more uninterrupted flow intersections are implemented, the lower the total evacuation time can be achieved.
Case Study and Findings

Results and Findings:

IV. Sensitivity Analysis

Under a given budget plan, the location plans are not sensitive to the demand levels.

Budget plan B, Demand Level I

Budget plan B, Demand Level II

Budget plan B, Demand Level III
A planning tool ready for use
Contents

1. Introduction
2. Model Formulation
3. Solution Approach
4. Case Study and Findings
5. On-going Research
On-going Research

- Extend the model to a dynamic version (see our upcoming TRB 2013 paper: 13-3279)
- Incorporate other management methods (e.g. lane reversal)
- Incorporate more realistic choice behaviors of evacuees
THANKS!