Capacity Analysis of the Union Station Rail Corridor using Integrated Rail and Pedestrian Simulation

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Presentation Outline

- Introduction
- Railway Capacity Approaches
- Toronto Union Station Rail Corridor
- Data
- Analytical Capacity Methods
- Railway Simulation
- Integrated Rail and Pedestrian Simulation – Nexus
- Scenario Tests and Results
- Conclusion
Introduction
Motivation

- Growing train traffic at existing railway network
- Platform crowding and limited platform space

- Increased train arrivals could affect platform density while extended dwell time could delay train departures
- Whether the infrastructure could support the anticipated service expansion (i.e. RER)
- Comprehensive capacity analysis of a complex station area is necessary to identify the bottleneck
Railway Capacity Approaches
Railway System Capacity

**Railway**
- Maximum number of trains
  - for a specified time period
  - over a defined section/area
  - under certain service quality

**Passenger**
- Maximum number of passengers
  - for a specified time period
  - over a defined section/area
  - under certain service quality
## Railway Capacity

<table>
<thead>
<tr>
<th>Article Name</th>
<th>Author</th>
<th>Year</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>An analytical approach for the analysis of railway nodes extending the Schwanhäuser’s method to railway stations and junctions</td>
<td>De Kort et al.</td>
<td>1999</td>
<td>Analytical</td>
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<td>Development of Base Train Equivalents to Standardize Trains for Capacity Analysis</td>
<td>Lai et al.</td>
<td>2012</td>
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<td>A synthetic approach to the evaluation of the carrying capacity of complex railway node</td>
<td>Malavasi et al.</td>
<td>2014</td>
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<tr>
<td>A Model, Algorithms and Strategy for Train Pathing</td>
<td>Carey &amp; Lockwood</td>
<td>1995</td>
<td>Optimization</td>
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<tr>
<td>Optimal scheduling of trains on a single line track</td>
<td>Higgins et al.</td>
<td>1996</td>
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<td>A Job-Shop Scheduling Model for the Single-Track Railway Scheduling Problem</td>
<td>Oliveira and Smith</td>
<td>2000</td>
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<td>An assessment of railway capacity</td>
<td>Abril et al.</td>
<td>2008</td>
<td></td>
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<tr>
<td>US &amp; USRC Track Capacity Study</td>
<td>AECOM</td>
<td>2011</td>
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<td>Evaluation of ETCS on railway capacity in congested area: a case study within the network of Stockholm: A case study within the network of Stockholm</td>
<td>Nelladal et al.</td>
<td>2011</td>
<td>Simulation</td>
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<tr>
<td>Simulation Study Based on OpenTrack on Carrying Capacity in District of Beijing-Shanghai High-Speed Railway</td>
<td>Chen and Han</td>
<td>2014</td>
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<tr>
<td>Railway capacity analysis: methods for simulation and evaluation of timetables, delays and infrastructure</td>
<td>Lindfeldt</td>
<td>2015</td>
<td></td>
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</tbody>
</table>

### Problem:
- Results could vary largely due to different assumptions
- Few studies compared methods in different categories
- Virtually all dwell time is fixed (TCQSM, 2013)
Pedestrian Movements

- Traditional dwell time modeling
  - Boarding/Alighting/Through passengers, Regression models (San & Masirin, 2016)

- Pedestrian Modelling
  - Analytical modelling
  - Simulation

- Problem
  - Traditional dwell time models can not show the platform density, or reflect the flow complication due to infrastructure layout
  - Transit vehicle arrival/departure time is fixed
Integrated Simulation

- **Key assumptions for individual simulators:**
  - Fixed dwell time
  - Fixed train arrival/departure time

- **Current models:**
  - Rail simulation with mathematical dwell time model (Jiang et al., 2015) (D’Acierno et al., 2017)
  - Rail simulation with pedestrian simulation model (Srikukenthiran & Shalaby, 2017)
Problem Statement

- Few studies compared methods in different categories
- Interactive effects of pedestrian and train movements are not well captured by individual simulator
Study approach

Analytical Capacity Analysis
(TCQSM, Potthoff method, DB method, Compression method)

Railway Simulation
OpenTrack

Railway and Pedestrian Simulation
Nexus Platform – OpenTrack and MassMotion
Case Study

- Toronto Union Station Rail Corridor (USRC)
Union Station Rail Corridor (USRC)

- Built and opened in 1927
- 760,000 square feet of total floor space
- 14 track depots, 23 platforms, 350m long and 5m wide on average
- Toronto's transportation hub for GO Transit, VIA Rail and UP Express; as well as TTC
- Canada's busiest transportation facility: 200,000 passengers pass through Union Station on most business day

- 155,000 GO Train passengers and 10,000 bus passengers on a typical business day
- 208 daily GO Train trips
- 43 million annual passengers for GO train and bus
- 20 million annual passengers for TTC
- 2.4 million annual passengers for VIA
Scope

- Study time period: 8am to 9am
- One station away on any rail service
- Assume unlimited capacity at yards and through movements at the station
- Focus on maximum number of GO train trips during peak hour
Required Data

- **Infrastructure data**
  - Track layout
  - Signal location
  - Station layout

- **Operational data**
  - Speed limit
  - Train profile and configuration
  - Schedule
  - Delay data
  - Ridership
  - Passenger flow
Manual Data Collection

- Train Speed (GPS)
- Commonly-used Train Path Identification (Video Recording)
- Entry Delay at prior stations and Arrival Delay at Union Station (gotracker.ca)
Manual Data Collection

- Platform Staircase Passenger Volume Count
- Passenger Flow Count at Train Door
- Dwell Time
Analytical Capacity Methods
Analytical Methods

– Transit Capacity and Quality of Service Manual (TCQSM)

– Potthoff method

– Deutsche Bahn (DB) method

– UIC Compression Method
TCQSM

- **Min. headway at Mainline**
  - minimum train separation + operating margin
  
  \[ t_{cs} = \sqrt{\frac{2(L_t + d_e b)}{a + a_g G_0}} + \frac{L_t}{v_a} + \left( \frac{1}{f_{br}} + b \right) \left( \frac{v_a}{2(d + a_g G_i)} \right) + \frac{(a + a_g G_0) l_v^2 t_{os}^2}{2v_a} \left( 1 - \frac{v_a}{v_{max}} \right) + t_{os} + t_{jl} + t_{br} \]

  \[ h_{ni} = t_{cs} + t_{om} \]

- **Min. headway at Station Area**
  - minimum train separation + critical station dwell time + operating margin
  
  \[ h_{ni} = t_{cs} + t_{d,crit} + t_{om} \]

- **Min. headway at Mainline with switches**
  - if a train is encountered with a switch blocking when traveling at main line
  
  \[ h_j = t_{cs} + \sqrt{\frac{2(L_t + n \cdot f_{sad} d_{ts})}{a}} + \frac{v_{max}}{a + d} + t_{sw} + t_{om} \]
- TCQSM – Detailed calculation for line capacity, simple junction capacity calculation
- Need for methods calculating node capacity
Potthoff method and Deutsche Bahn (DB) method

- Assume trains could arrive at any instant of an assigned time period with the same probability
- Timetable not required
- Input:
  - Identify all possible train paths in a system
  - Summarize number of movements concerning each path ($n_i$)
  
<table>
<thead>
<tr>
<th>Path</th>
<th>1-I</th>
<th>1-II</th>
<th>1-IV</th>
<th>4-III</th>
<th>4-IV</th>
<th>III-2</th>
<th>IV-2</th>
<th>I-3</th>
<th>II-3</th>
<th>IV-3</th>
</tr>
</thead>
<tbody>
<tr>
<td># of movements</td>
<td>56</td>
<td>55</td>
<td>7</td>
<td>112</td>
<td>8</td>
<td>112</td>
<td>8</td>
<td>56</td>
<td>55</td>
<td>7</td>
</tr>
</tbody>
</table>

- Matrix of occupancy time for conflicting movements ($t_{ij}$)
  
<table>
<thead>
<tr>
<th>Path</th>
<th>1-I</th>
<th>1-II</th>
<th>1-IV</th>
<th>4-III</th>
<th>4-IV</th>
<th>III-2</th>
<th>IV-2</th>
<th>I-3</th>
<th>II-3</th>
<th>IV-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I</td>
<td>3.8</td>
<td>1.55</td>
<td>0.97</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-II</td>
<td>0.9</td>
<td>1.95</td>
<td>0.61</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1-IV</td>
<td>1.45</td>
<td>1.45</td>
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<td>1.47</td>
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<td>4-III</td>
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<td>1.67</td>
<td>0.61</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0.61</td>
<td>0</td>
</tr>
<tr>
<td>4-IV</td>
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<td>0</td>
<td>3.7</td>
<td>1.54</td>
<td>3.44</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>III-2</td>
<td>0</td>
<td>0</td>
<td>1.22</td>
<td>1.06</td>
<td>0</td>
<td>1.56</td>
<td>1.56</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IV-2</td>
<td>0</td>
<td>0</td>
<td>2.16</td>
<td>0</td>
<td>1.9</td>
<td>2.93</td>
<td>2.93</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I-3</td>
<td>2.74</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.17</td>
<td>3.17</td>
<td>3.17</td>
</tr>
<tr>
<td>II-3</td>
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<td>1.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.54</td>
<td>1.54</td>
<td>1.54</td>
</tr>
<tr>
<td>IV-3</td>
<td>0</td>
<td>0</td>
<td>2.56</td>
<td>2.74</td>
<td>2.74</td>
<td>0</td>
<td>0</td>
<td>3.17</td>
<td>3.17</td>
<td>3.17</td>
</tr>
</tbody>
</table>

- Priority Matrix (DB method, Optional)
Capacity indicator

- **Potthoff method**

\[
\frac{B + R}{T} \leq 1 \text{ (over capacity if bigger than 1)}
\]

- **Deutsche Bahn (DB) method**

\[
L_z = \frac{k \cdot P_b \cdot x^2}{T - x \cdot B} \quad (usually = 0.6); \\
x \geq 1 \text{ (over capacity if smaller than 1)}
\]

- **Symbols**
  - \(B\): Total time of occupation
  - \(R\): Average delay
  - \(T\): Study period
  - \(L_z\): average number of trains in the waiting queue (to evaluate operation quality)
  - \(k\): Probability with which the movements relating to the complex node are mutually exclusive
  - \(P_b\): Occupancy time considering priority
  - \(x\): Scale factor
Union Station Case

- Two complex interlocking areas located at west and east of the station
- Possible combination of routes could add up to 4000
- 30 and 24 identified commonly used train paths for west interlocking and east interlocking areas respectively
- Train paths shared by GO trains, VIA rail trains, and UP Express trains
- Some paths might be affected by the station dwell time
Matrices of occupancy time for conflicting movements

West Interlocking (30 x 30)

East Interlocking (24 x 24)
Potthoff method and Deutsche Bahn method

- Result for at capacity:
  - Capacity parameters:
    - Potthoff Method:
      | Method | Total | LSW | LSW_E | LSE | LSE_E | MI | KI | RH | BA | ST |
      |--------|------|------|-------|-----|-------|----|----|----|----|----|
      | Potthoff | 31   | 3    | 5     | 3   | 4     | 5  | 3  | 3  | 2  |
      | DB     | 26   | 3    | 4     | 3   | 3     | 5  | 2  | 2  | 2  |

- Deutsche Bahn Method:

- # of GO trains:
Compression Method

- Introduction

Blocking Time Model

Compression Method on a uni-directional track section before and after compression
Procedure

- Identify all possible train paths in an interlocking area
- A full $n \times n$ matrix is set up by listing the actual path against all excluded paths. The value in the specific cell means how long the train that is taking the excluded train path has to wait when the actual train path is being taken (Matrix of occupation time for conflicting paths)

<table>
<thead>
<tr>
<th>Actual Trip i</th>
<th>[min]</th>
<th>pA</th>
<th>pB</th>
<th>aP</th>
<th>aF</th>
<th>fB</th>
<th>fA</th>
<th>bF</th>
<th>bP</th>
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</thead>
<tbody>
<tr>
<td>pA</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>pB</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aP</td>
<td>1.5</td>
<td>1.8</td>
<td>1.3</td>
<td>1.3</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aF</td>
<td>2.4</td>
<td>2.2</td>
<td>2.9</td>
<td>2.4</td>
<td>2.4</td>
<td>2.9</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fB</td>
<td>2.4</td>
<td></td>
<td></td>
<td>2.4</td>
<td>2</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>fA</td>
<td>2.4</td>
<td>2</td>
<td>2.1</td>
<td>2</td>
<td>2.4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>bF</td>
<td>2.3</td>
<td>2</td>
<td>2.3</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bP</td>
<td>1.8</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Provide a sequence of paths as in the timetable

<table>
<thead>
<tr>
<th>Route</th>
<th>pB</th>
<th>pA</th>
<th>fB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>min</td>
<td>3</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

- Calculate the occupancy time based on the path sequence and exclusion matrix
Rules

- Each route-occupation starts, considering the sequence of trains, as soon as possible after the preceding route regarding the referring exclusion time.
- The total of all occupation times results as the sum of the excluding times of concatenated routes.
- Possible simultaneous train movements on parallel routes are considered.
- Insert the first trip at the bottom of the calculation table again (last trip). Hence there is no “open end.”
- Occupancy Time Rate (OTR) calculation:
  \[
  \text{Occupancy Time Rate} \,[\%] = \frac{\text{Occupancy Time}}{\text{Defined Time Period}} \times 100\%
  \]
- Additional Time Rate (ATR):
  \[
  \text{Additional Time Rate} \,[\%] = \left[ \frac{100}{\text{Occupancy Time Rate}} - 1 \right] \times 100
  \]
- Capacity Consumption (CC) value:
  \[
  \text{Capacity Consumption} \,[\%] = \frac{\text{Occupancy Time} \times (1 + \text{Additional Time Rate})}{\text{Defined Time Period}} \times 100
  \]
- Concatenation rate: \( \varphi \):
  \[
  \varphi(\text{Concatenation Rate}) = \frac{K}{Z} \times 100\%
  \]
Procedure to insert trains

- **Main assumptions:**
  - All trains have through movements
  - Uniform headway at every depot
Results for capacity analysis

- Capacity Indicators

<table>
<thead>
<tr>
<th>Critical Indicator</th>
<th>Evaluating Capacity based on CC</th>
<th>Evaluating Capacity based on OTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Train Volume</td>
<td>West Interlocking</td>
<td>East Interlocking</td>
</tr>
<tr>
<td>Occupancy Time Rate (OTR)</td>
<td>73%</td>
<td>85%</td>
</tr>
<tr>
<td>Concatenation Rate</td>
<td>17%</td>
<td>47%</td>
</tr>
<tr>
<td>Additional Time Rate</td>
<td>215%</td>
<td>87%</td>
</tr>
<tr>
<td>Capacity Consumption (CC)</td>
<td>34%</td>
<td>98%</td>
</tr>
</tbody>
</table>

- # of Trains compared against other methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Total</th>
<th>LSW Lakeshore West</th>
<th>LSW_E Lakeshore Express</th>
<th>LSE Lakeshore East</th>
<th>LSE_E Lakeshore Express</th>
<th>MI Milton</th>
<th>KI Kitchener</th>
<th>RH Richmond Hill</th>
<th>BA Barrie</th>
<th>ST Stouffville</th>
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<tbody>
<tr>
<td>Current Schedule</td>
<td>25</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Potthoff</td>
<td>31</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>DB</td>
<td>26</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Compression (OTR)</td>
<td>55</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Compression (CC)</td>
<td>50</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>
Effect of adding 1 trip

<table>
<thead>
<tr>
<th>Method</th>
<th>Capacity Indicator</th>
<th>West Interlocking</th>
<th>East Interlocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potthoff</td>
<td>(B+R)/T</td>
<td>0.85</td>
<td>0.81</td>
</tr>
<tr>
<td>DB</td>
<td>x</td>
<td>1.00</td>
<td>1.02</td>
</tr>
<tr>
<td>Compression</td>
<td>OTR</td>
<td>73%</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>34%</td>
<td>98%</td>
</tr>
</tbody>
</table>

*Threshold for exceeding capacity: (B+R)/T >= 1 (Potthoff); x <= 1 (DB)
Discussion

- **Potthoff and DB:**
  - timetable not required;
  - highly averaged results

- **Compression Method:**
  - timetable required;
  - determined by the maximum occupancy of all train paths within the same section;
  - possible to maximize the capacity with careful scheduling on a timetable

- **Both require a matrix of occupancy time for conflicting paths:**
  - only a pair of paths needs to be evaluated for conflicts
  - size of the matrix grows exponentially with the increase of possible train paths

- **System stochasticity not considered**
Railway Simulation
Railway Simulation

- Simulation tools are recommended to analyze complex railway infrastructure

- General procedure for simulation:
  - Data collection
  - Model construction
  - Model calibration
  - Model validation

- OpenTrack was selected as the railway simulator
Model Construction

Main network (including maintenance yards)

Expansion network including express stations
Model Input

- Infrastructure layout
- Speed limits
- Train configurations (locomotive, rolling stock)
- Schedules
- Entry delay distributions
Entry Delay Distribution

- Gotracker.ca
Performance Evaluation

- **Result evaluation:**
  - Simulated On-time Performance (SOTP)
    \[
    SOTP = \frac{\text{# of trips arrive within a specified range of schedule time}}{\text{total # of trips scheduled}} \times 100%
    \]
  - Simulated Average Delay

- **GO Transit’s target On-time performance (OTP):** 95%

- **OTP from data collection:** 96.4%
Base model calibration and validation
Sensitivity Result

- **Method**
  - LSW: Lakeshore West Line
  - LSW_E: Lakeshore West Express
  - LSE: Lakeshore East Line
  - LSE_E: Lakeshore East Express
  - KI: Kitchener Line
  - MI: Milton Line
  - BA: Barrie Line
  - RH: Richmond Hill Line
  - ST: Stouffville Line

- **Total # of Trains**
  - OpenTrack: 39

- **Total Train Volume**
  - LS: 25, 30, 35, 40
  - SOTP: 45, 50, 55, 60

- **Averaged Arrival Delay at Union (min)**
  - 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%

- **Simulated Average Arrival Delay**
  - OpenTrack: 39, 4, 5, 4, 4, 4, 5, 4, 4, 5

**Legend**
- SOTP
- 95% Threshold
- Simulated Average Arrival Delay
Discussion

- OpenTrack offers a more realistic result by taking the stochasticity into consideration as it attempts to simulate the real-world operation.

- The result of between OpenTrack and Compression Method with OTR confirms that practical capacity is around 60% to 75% of the theoretical capacity from the previous research (Kraft, 1982).

<table>
<thead>
<tr>
<th>Method</th>
<th>Total Trains</th>
<th>LSW</th>
<th>LSW_E</th>
<th>LSE</th>
<th>LSE_E</th>
<th>MI</th>
<th>KI</th>
<th>RH</th>
<th>BA</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Schedule</td>
<td>25</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Pothoff</td>
<td>31</td>
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<td>3</td>
<td>4</td>
<td>5</td>
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<td>3</td>
<td>3</td>
<td>2</td>
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<td>DB</td>
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<td>2</td>
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<tr>
<td>Compression (OTR)</td>
<td>55</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
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<tr>
<td>Compression (CC)</td>
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<td>7</td>
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<td>4</td>
<td>6</td>
<td>4</td>
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</tr>
<tr>
<td>OpenTrack</td>
<td>39</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<table>
<thead>
<tr>
<th>Method</th>
<th>Total Trains</th>
<th>LSW</th>
<th>LSW_E</th>
<th>LSE</th>
<th>LSE_E</th>
<th>MI</th>
<th>KI</th>
<th>RH</th>
<th>BA</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression (OTR)</td>
<td>55</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>OpenTrack</td>
<td>39</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
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</tr>
</tbody>
</table>

Ratio (%)

<table>
<thead>
<tr>
<th>Method</th>
<th>Total Trains</th>
<th>LSW</th>
<th>LSW_E</th>
<th>LSE</th>
<th>LSE_E</th>
<th>MI</th>
<th>KI</th>
<th>RH</th>
<th>BA</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>55</td>
<td>67%</td>
<td>71%</td>
<td>67%</td>
<td>67%</td>
<td>80%</td>
<td>83%</td>
<td>67%</td>
<td>57%</td>
<td>83%</td>
</tr>
</tbody>
</table>
Problems

- Dwell time was fixed at 5 minutes
- Only focus on train movements on the railway
- Pedestrian flow on the platform level could be complicated due to the platform layout and barriers
- The interactive effect between train and pedestrian movements was not captured
Integrated Rail and Pedestrian Simulation
- Nexus
Nexus
Dwell Time Components

Dwell Time

Segment 1
Doors Open

Segment 2
Last Passenger Exits

Segment 3
Doors Close

Segment 4

Lost Time

Passenger Flow Time

MassMotion

Arrival Time

Departure Time

Statistical Analysis

Internal Departure Schedule
Assume a fixed value of 2 minutes
Alighting Behavior – Observation at Union

Cumulative psg - Time

Cumulative Psg - Time

Cumulative Psg - Time

Cumulative Psg - Time
Problem Statement

- The unique behavior would influence the density and crowding on the platform differently.

- The time that last passenger exit the train would affect the departure time of the train, especially for trains that become out of service after they arrive at Union, as trains cannot leave if passengers are still on board.

- Traditional Passenger flow time modeling cannot represent both effects properly (Total passenger flow time and density).
Method

- Main Idea: represent the observed alighting curve with two linear lines with different flow rates
- Each record of train door passenger count is studied, break point is selected based on visual inspection; linear regression is performed on the resulting segment a and segment b respectively; $R^2$ values for the slopes of both lines are examined

Variables Extracted:
- Total passengers: $TP$
- Turning point (%): $\rho$
- Passengers in segment a: $TP_a$
- Flow rate in segment a: $f_a$
- Passengers in segment b: $TP_b$
- Flow rate in segment b: $f_b$
Data Analysis

- **Statistical analysis for** \( \rho, f_a, f_b \)

- **Correlation analysis**

<table>
<thead>
<tr>
<th></th>
<th>Total_Psg</th>
<th>Total_Psg_seg_a</th>
<th>Turning_Point</th>
<th>Seg_a_Flow_Rate</th>
<th>Psg_seg_b</th>
<th>Seg_b_Flow_Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total_Psg</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total_Psg_seg_a</td>
<td>0.911666804</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Turning_Point</td>
<td>-0.037696351</td>
<td>0.354965918</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seg_a_Flow_Rate</td>
<td>0.239571138</td>
<td>0.200437577</td>
<td>-0.068153854</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Psg_seg_b</td>
<td>0.715672756</td>
<td>0.367111995</td>
<td>-0.678531836</td>
<td>0.197095319</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Seg_b_Flow_Rate</td>
<td>0.578958678</td>
<td>0.347539801</td>
<td>-0.391475978</td>
<td>0.349225841</td>
<td>0.726731882</td>
<td>1</td>
</tr>
</tbody>
</table>
Model Proposed

Cumulative passenger volume

Alternative Observed Model

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. total time (sec)</td>
<td>104.1</td>
<td>107.1</td>
</tr>
<tr>
<td>Max. Total time (sec)</td>
<td>211.0</td>
<td>221.1</td>
</tr>
</tbody>
</table>

\[ f_b = TP \cdot 0.807 - 0.525 \\
= TP \cdot (1 - \rho) \cdot 0.807 - 0.525 \]
Pedestrian Simulation

- MassMotion
Model Calibration

- **Calibration:**
  - adjust queue cost at certain areas
  - adjust wait cost
  - alter agent characteristics (i.e. body radius and direction bias)

- **GEH statistical method**
  - compare observed and simulated traffic/pedestrian volumes at links (staircases)

\[ G_H = \sqrt{\frac{2(m - c)^2}{m + c}} \]

- Visual inspection
Model Calibration and Validation

- Validation
Model Input

- Individual simulation models (MassMotion, OpenTrack)
- General Transit Feed Specification dataset (GTFS)
- Complete list of agents with OD itinerary
Model calibration and validation

**Observed OTP vs SOTP in OpenTrack and Nexus**

<table>
<thead>
<tr>
<th>Location</th>
<th>OTP (Observed, Excluding Incident)</th>
<th>SOTP - OpenTrack</th>
<th>SOTP - Nexus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchener</td>
<td>91.8%</td>
<td>92.3%</td>
<td>91.6%</td>
</tr>
<tr>
<td>Barrie</td>
<td>93.9%</td>
<td>94.6%</td>
<td>93.5%</td>
</tr>
<tr>
<td>Stouffville</td>
<td>96.0%</td>
<td>96.6%</td>
<td>95.8%</td>
</tr>
<tr>
<td>Milton</td>
<td>98.0%</td>
<td>98.6%</td>
<td>97.8%</td>
</tr>
<tr>
<td>Richmond Hill</td>
<td>99.0%</td>
<td>99.5%</td>
<td>98.8%</td>
</tr>
<tr>
<td>Lakeshore</td>
<td>100%</td>
<td>100%</td>
<td>99.2%</td>
</tr>
<tr>
<td>West Lakeshore</td>
<td>100%</td>
<td>100%</td>
<td>99.6%</td>
</tr>
<tr>
<td>East</td>
<td>100%</td>
<td>100%</td>
<td>99.8%</td>
</tr>
<tr>
<td>Total</td>
<td>98.4%</td>
<td>98.5%</td>
<td>98.2%</td>
</tr>
</tbody>
</table>

**Relative Frequency for Arrival Delay**

- Obs. - Freq
- Sim. - Freq (OpenTrack)
- Sim. - Freq (Nexus)

**Stair Split Obs. vs Nexus**

<table>
<thead>
<tr>
<th>Stair</th>
<th>Split (%)</th>
<th>Split (%)</th>
<th>Split (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>MassMotion</td>
<td>Nexus</td>
</tr>
<tr>
<td>Stair 1</td>
<td>13%</td>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>Stair 2</td>
<td>9%</td>
<td>10%</td>
<td>9%</td>
</tr>
<tr>
<td>Stair 3</td>
<td>6%</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>Stair 4</td>
<td>9%</td>
<td>10%</td>
<td>9%</td>
</tr>
<tr>
<td>Stair 5</td>
<td>15%</td>
<td>13%</td>
<td>11%</td>
</tr>
<tr>
<td>Stair 6</td>
<td>13%</td>
<td>12%</td>
<td>11%</td>
</tr>
<tr>
<td>Stair 7</td>
<td>11%</td>
<td>11%</td>
<td>12%</td>
</tr>
<tr>
<td>Stair 8</td>
<td>11%</td>
<td>11%</td>
<td>12%</td>
</tr>
<tr>
<td>Stair 9</td>
<td>14%</td>
<td>11%</td>
<td>11%</td>
</tr>
</tbody>
</table>
Evaluating System Performance

- Simulated On-time Performance (SOTP, %)
- Simulate average arrival delay at Union (min)
- Average dwell time (min)
- Hourly inbound and outbound passenger volume (Person)
- Average percentage of inbound and outbound passengers per second at LOS F (%)
- Average duration at LOS F for each inbound and outbound passenger (Sec)

<table>
<thead>
<tr>
<th>LOS</th>
<th>Platforms (queueing)</th>
<th>Stairways</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Density (\text{person/m}^2)</td>
<td>Space (\text{m}^2/\text{person})</td>
</tr>
<tr>
<td>A</td>
<td>(x&lt;=0.826)</td>
<td>(x&gt;1.21)</td>
</tr>
<tr>
<td>B</td>
<td>(0.826&lt;x&lt;=1.075)</td>
<td>(1.21&gt;x&gt;=0.93)</td>
</tr>
<tr>
<td>C</td>
<td>(1.075&lt;x&lt;=1.538)</td>
<td>(0.93&gt;x&gt;=0.65)</td>
</tr>
<tr>
<td>D</td>
<td>(1.538&lt;x&lt;=3.571)</td>
<td>(0.65&gt;x&gt;=0.28)</td>
</tr>
<tr>
<td>E</td>
<td>(3.571&lt;x&lt;=5.263)</td>
<td>(0.28&gt;x&gt;=0.19)</td>
</tr>
<tr>
<td>F</td>
<td>(5.263&lt;x)</td>
<td>(0.19&gt;x)</td>
</tr>
</tbody>
</table>
Scenario Tests
Scenario Tests

OpenTrack Model → NEXUS → Train Schedule

MassMotion Model → NEXUS

Population File

OpenTrack Sensitivity Test:
39 trains, 5 min dwell time

Person Capacity:
Peak Hour Factor (PHF)

\[ P = T \cdot N_c \cdot P_c \cdot (PHF) \]

39 trains/h  12 Cars/Train  162 seats + 256 standees/car
Scenario Tests

Current schedule and passenger volume

OpenTrack Sensitivity Test final schedule and current level of train load

Train load increased by adjusting the PHF to 0.49

PHF increased by 0.1 or 0.05 stepwise

Remove 2-minute buffer time (segment 3 and 4)

Remove terminal passenger alighting behavior

Scenario 1

Scenario 2-5

Scenario 5A

Scenario 5B
Scenario Tests Results

- Nexus Base Model (PHF=0.36, 2-min buffer, alighting behavior, internal departure time)
- Nexus Scenario Test 1 (PHF=0.34, 2-min buffer, alighting behavior)
- Nexus Scenario Test 2 (PHF=0.49, 2-min buffer, alighting behavior)
- Nexus Scenario Test 3 (PHF=0.60, 2-min buffer, alighting behavior)
- Nexus Scenario Test 4 (PHF=0.65, 2-min buffer, alighting behavior)
- Nexus Scenario Test 5 (PHF=0.70, 2-min buffer, alighting behavior)
- Nexus Scenario Test 5A (PHF=0.70, alighting behavior)
- Nexus Scenario Test 5B (PHF=0.70)

- SLP (%) (SOTP=1-SLP)
- Average Delay (min)
- Average Dwell Time (min)
- Average Hourly Inbound Passenger Volume (Person)
- Average Hourly Outbound Passenger Volume (Person)

- Scheduled Inbound Passenger Volume (Psg/Train)
- Average Duration at LOS F per Outbound Passenger (Sec)
- Average Duration at LOS F per Inbound Passenger (Sec)
- Average Percentage of Outbound Passengers>=50% per Sec at LOS F
- Average Percentage of Inbound Passengers per Sec at LOS F
Scenario Tests Results

SOTP, Average Delay with the increase of IB Psg Volume (Train arrivals = 39/Hr)

- SOTP (%)
  - OpenTrack Sensitivity Test SOTP - 97.1%
  - Target OTP - 95%

- Avg Delay Std Dev
  - 2 min

- OpenTrack Average Delay (min)
- Inbound Passenger Volume/Train

Time (Min)
- Percentage
- 10.00 to 100.0%
- 0.00 to 10.00

Value: 9%
Scenario Tests Results

SOTP, Dwell Time with the increase of IB Psg Volume (Train arrivals = 39/Hr)

- SOTP (%)
- OpenTrack Dwell Time (min)
- Average Dwell Time (min)
- Dwell Time > 5 min (%)
- Dwell Time Std Dev
- OpenTrack Sensitivity Test SOTP - 97.1%
- Target OTP - 95%

Inbound Passenger Volume/Train

Time (Min)

Percentage

-10.0% to 10.0%

-20.0% to 20.0%

-30.0% to 30.0%

-40.0% to 40.0%

-50.0% to 50.0%

-60.0% to 60.0%

-70.0% to 70.0%

-80.0% to 80.0%

-90.0% to 90.0%

-100.0% to 100.0%
Scenario Tests Results

*total delay time (number of passengers × delay)
Scenario Tests Results

![Graph showing Passenger LOS F metrics](image-url)

- SOTP (%)
- Average % of IB Psg per Sec at LOS F
- Average Duration at LOS F per IB Psg (Sec)
- Average Duration at LOS F per OB Psg (Sec)
- Average % of OB Psg per Sec at LOS F

Inbound Passenger Volume/Train:

- 60 sec
- 30%
Scenario Tests Results

Inbound

Outbound

Scenario 1

Scenario 5
Scenario Tests Results

Base Model

Scenario 5
Further Scenarios

<table>
<thead>
<tr>
<th></th>
<th>Nexus Scenario Test 5</th>
<th>Nexus Scenario Test 5A</th>
<th>Nexus Scenario Test 5B</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOTP (%)</td>
<td>94%</td>
<td>95%</td>
<td>86%</td>
</tr>
<tr>
<td>Average Delay (min)</td>
<td>4.75</td>
<td>4.39</td>
<td>0.74</td>
</tr>
<tr>
<td>Average Dwell Time (min)</td>
<td>6.24</td>
<td>4.75</td>
<td>-0.90</td>
</tr>
<tr>
<td>Average Percentage of Inbound Passengers per Sec at LOS F</td>
<td>69%</td>
<td>70%</td>
<td>71%</td>
</tr>
<tr>
<td>Average Duration at LOS F per Inbound Passenger (Sec)</td>
<td>92.07 94.19</td>
<td>106.31</td>
<td>-0.99</td>
</tr>
</tbody>
</table>
Conclusion
Conclusions

- Analytical methods are not sufficient to capture the stochasticity of a complex area.
- Railway simulation fails to account for the impact of pedestrian movements.
- Both pedestrian movements and train movements have interactive effect on the total capacity of a complex station area.
Contribution

- Performed a comprehensive comparative analysis among various analytical and simulation methods on the capacity of a node area
- Affirmed that practical capacity is around 60% to 75% of the theoretical capacity
- Observed unique terminal passenger alighting behavior, proposed a simple initial model
- Identified the benefit of using integrated simulation model
Future Work

- Apply Nexus for new service concepts like RER
- Study optimization methods
- Consider the capacity of maintenance yards, turn-back movements at the Union Station
- Further develop the alighting behavior model for the terminal station by considering other factors
- Apply Nexus in other complex transit systems which are sensitive to delays
Acknowledgements

ARUP

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