TRUCK ROUTING OPTIMIZATION
FOR LARGE-SCALE
TRANSPORTATION NETWORKS

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Research Background

S.M.A.R.T. Mobility

- Systems and Modeling for Accelerated Research in Transportation Mobility Laboratory Consortium
  - Connected and Automated Vehicles
  - Mobility Decision Science
  - Multi-Modal Freight
  - Urban Science
  - ...

POLARIS Tool

- High-performance, open-source agent-based modeling framework
  - Simulates large-scale transportation systems
  - Estimates impacts on mobility at the regional level
Research Goal

- **Previous Works**
  - E-commerce delivery modeling in SMART 1.0 (~ 2020)
    - **Demand model**: estimate household e-commerce demand
    - **Supply model**: make routes which deliver goods from companies to households

  Labor-intensive
  Requiring up to 1-2 weeks to estimate all delivery routes

- **Goal of This Study**
  - Develop and implement an automated e-commerce supply model
    - Applying vehicle routing problem (VRP)
    - Integrated with POL#RIS simulation tool
    - More efficient to compute, by eliminating the manually intensive procedures in SMART 1.0
    - Available to evaluate the impacts of e-commerce delivery on the regional traffic network
Target System

- **Metropolitan Areas**
  - Importing *traffic network, household characteristics, and companies’ information* from POL*RIS*

  - *Detailed road networks* are applied to compute realistic travel time between locations
  - *E-commerce delivery demand* is generated using NHTS (2017) dataset and related research (Spadafora and Rodriguez, 2021)
  - *4 major providers* are considered; Amazon, FedEx, UPS, and USPS
Target System

- Target Areas:

<table>
<thead>
<tr>
<th>Area</th>
<th># of households</th>
<th># of households ordering</th>
<th># of arcs</th>
<th># of vertices</th>
<th># of depots</th>
<th># of providers</th>
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<tbody>
<tr>
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<td>40,891</td>
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<td>22</td>
<td>4</td>
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<tr>
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<td>7,013</td>
<td>2,540</td>
<td>8</td>
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<td>19,377</td>
<td>53</td>
<td>4</td>
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<tr>
<td>Detroit</td>
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<td>271,129</td>
<td>60,701</td>
<td>26,424</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>
Algorithm Background

- **Vehicle Routing Problem**
  - **Making routes**: each route departs from its depot, visits several customer locations, and returns to the depot
  - **Minimize total travel time**: find the best visiting order of customer locations to reduce the travel time (or dist.)
  - **Well-known optimization problem**: a lot of optimization methods and heuristic approaches are suggested

- **VRP algorithms cannot be applied directly**
  - Optimal solutions are reported within 100 customer locations
  - Heuristic algorithms are applicable on the network with thousands of customers.
  - It may be over the memory size to contain 600,000 x 600,000 travel time matrix
Algorithm Summary

- **Sequential VRP Algorithm**
  1. **Depot-level partitioning**: assigning zones to each depot (minimum zone-to-zone travel time)
  2. **Simplification procedure**: converting customer locations to super-locations (link-based)
  3. **Single-depot VRP model**: solving VRP for every depot and associated super-locations
Algorithm (1) Depot-Level Partitioning

- **Zonal Network**
  - POL:bRIS has traffic analysis zones (TAZs) for traffic planning model
  - Consider customer locations in a same zone as one large demand
  - Every zone is assigned to a single depot to minimize the total zonal travel time
Algorithm (1) Depot-Level Partitioning

- **Math Model: Assignment Problem**
  - Commercial optimization solver (GUROBI) is used to find the optimal solution

<table>
<thead>
<tr>
<th>Set</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{D}_s$</td>
<td>subset of depots operated by the service provider $s \in \mathcal{S}$.</td>
</tr>
<tr>
<td>$\mathcal{G}_s$</td>
<td>subset of customers served by the service provider $s \in \mathcal{S}$.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Param.</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{d_i}^j$</td>
<td>zonal travel time from $Z_d$ (the zone of depot $d \in \mathcal{D}_s$) to $Z_i$ (the zone of customer $i \in \mathcal{G}_s$) of provider $s \in \mathcal{S}$.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Var.</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{di}$</td>
<td>( \begin{cases} 1, &amp; \text{if customer } i \in \mathcal{G}_s \text{ is assigned to depot } d \in \mathcal{D}_s, \ 0, &amp; \text{otherwise.} \end{cases} )</td>
</tr>
</tbody>
</table>

- **Formulation**
  - \[
  \min_{x} \mathbf{T}^d = \sum_{d \in \mathcal{D}_s, i \in \mathcal{G}_s} T_{d_i}^{s} x_{di}, \]
    - (1) Minimizes the total zonal travel time between depots and customer zones
  - subject to,
    - \[
    \sum_{d \in \mathcal{D}_s} x_{di} = 1, \quad \forall i \in \mathcal{G}_s, \]
      - (2) Each zone is assigned to a single depot
    - \[
    \sum_{i \in \mathcal{G}_s} x_{di} \geq \left\lfloor \frac{|\mathcal{G}_s|}{|\mathcal{D}_s|} \right\rfloor, \quad \forall d \in \mathcal{D}_s; \]
      - (3) # Customers assigned to a certain depot must be bigger than the lower-bound (decisions for depot operation expenses)
Algorithm (2) Simplification Procedure

- Simplification of Customer Locations
  - Each depot still has lots of customer locations → Customers on a link is simplified into a super location
  - Super-location: mid point of every link on road network
Algorithm (2) Simplification Procedure

- Details
  1. Labeling every customer location to the closest super-location
  2. Solve traveling salesman problem (TSP) to compute the total service time in every super-location

- Unit speed between locations: 15mph
- TSP minimizes the total travel time to deliver all locations using Manhattan distance
- Dwell time on every location (for parcel delivery): 2mins

# Customer locations: 7
Total service time: 54 mins
Algorithm (3) Single-Depot VRP

- Delivery Planning using Results of (1) and (2)
  - Algorithm (1) gives the associated customer locations for every depot
  - Algorithm (2) reduces the number of locations & computes service time of each super-location
  - Finally, VRP finds the best routes
    - to minimize the total operation time ( = link-to-link travel time from POLARIS + service time)
    - under operational constraints of each vehicle:
      1. visiting customer locations <= 120
      2. operation time <= 10 hours
      3. travel distance <= 100 miles
Algorithm (3) Single-Depot VRP

- **Math Model: Single-depot Vehicle Routing Problem**
  - Commercial optimization solver with computation time limitation (2 hours)

\[
\begin{align*}
\min_{x^d} & \quad T^d = \sum_{l \in \mathcal{L}^d} T^d_{l, l', d} x^d_{l, l'}, \\
\text{subject to}, & \quad \sum_{l \in \mathcal{L}^d_{l',d}} x^d_{l, l'} = 1 \quad \forall l' \in \mathcal{L}^d_{l',d} \setminus \{0_d\}, \\
& \quad \sum_{l' \in \mathcal{L}^d_{l',d} \setminus \{0_d\}} x^d_{l, l'} = 1 \quad \forall l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, \\
& \quad \sum_{l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}} \delta_{0_d,l} = K_d, \\
& \quad \sum_{l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}} \delta_{0_d,l'} = K_d, \\
& \quad \sum_{l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}} \left( z_{l,l'} - z_{l,l'} + T^d_{l,l'} - T^d_{l,l'} \right) = 0 \quad \forall l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, \\
& \quad z_{l,l'} \leq \left( T^d_{l,l'} - T^d_{l,l'} \right) \delta_{l,l'} \quad \forall l \in \mathcal{L}^d_{l,d}, l' \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, \\
& \quad z_{l,l'} \geq \left( T^d_{l,l'} + T^d_{l,l'} + T^d_{l,l'} \right) \delta_{l,l'} \quad \forall l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, l' \in \mathcal{L}^d_{l,d}, \\
& \quad z_{0_d,l} \leq \bar{T}_{l,d,0_d} \quad \forall l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, \\
& \quad z_{0_d,l} = T^d_{l,0_d} \delta_{0_d,l} \quad \forall l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, \\
& \quad y_{l,l'} = Q_s x^d_{l, l'} \quad \forall l, l' \in \mathcal{L}^d_{l,d}, \\
& \quad \sum_{l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}} y_{l,l'} \leq \sum_{l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}} y_{l,l'} - D_t = 0 \quad \forall l \in \mathcal{L}^d_{l,d} \setminus \{0_d\}, \\
x^d_{l,l'} \in \{0, 1\}, y_{l,l'}, z_{l,l'} \in \mathbb{R}_{\geq 0} \quad \forall l, l' \in \mathcal{L}^d_{l,d}. 
\end{align*}
\]

**Set**

\[\mathcal{D}_d\] a subset of customer locations to be served by a given depot \(d \in \mathcal{D}_s\) of service provider \(s \in \mathcal{S}\).

\[\mathcal{L}^d\] a set of locations called super-locations located in the middle of arcs. Note that two arcs in the opposite directions (sharing the same vertices) are represented by a single super-location.

\[\mathcal{L}^a_{l,d}\] a subset of locations including the depot \(\{0_d\}\) and \(g^d\).

\[\mathcal{L}^a_{l,d}\] a subset of super-locations that belong to the depot-level subproblems of depot \(d \in \mathcal{D}_s\).

**Param. Definition**

- \(D_t\): number of packages to be delivered at the super-location \(l\).
- \(K_d\): number of vehicles at depot \(d\).
- \(Q_s\): vehicle capacity of service provider \(s\).
- \(\bar{T}_d\): maximum allowed travel time for each vehicle of \(s\).
- \(T^d_{l,l'}\): travel time from super-location \(l\) to super-location \(l'\).
- \(T^d_{l,0_d}\): delivery time (i.e., package dropping time) at the super-location \(l\).

**Var. Definition**

- \(x^d_{l,l'}\): \(\begin{cases} 1, & \text{if a vehicle drives from super-location } l \in \mathcal{L}^a_{l,d} \text{ to super-location } l' \in \mathcal{L}^a_{l,d}, l \neq l', \\ 0, & \text{otherwise.} \end{cases} \)
- \(y_{l,l'}\): number of packages delivered at super-location \(l \in \mathcal{L}^a_{l,d}\) while en-route to \(l' \in \mathcal{L}^a_{l,d}\), i.e., after leaving \(l\), where \(l \neq l'\).
- \(z_{l,l'}\): total travel time from the depot to super-location \(l' \in \mathcal{L}^a_{l,d}, l \in \mathcal{L}^a_{l,d}\) is the predecessor of \(l'\) and \(l \neq l'\).
## Test Results

- **# Customer locations allocated to a depot**

<table>
<thead>
<tr>
<th>Area</th>
<th>Avg.</th>
<th>Min.</th>
<th>Max.</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austin</td>
<td>7,190</td>
<td>242</td>
<td>24,000</td>
<td>5,950</td>
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<tr>
<td>Bloomington</td>
<td>352</td>
<td>167</td>
<td>480</td>
<td>116</td>
</tr>
<tr>
<td>Chicago</td>
<td>11,447</td>
<td>905</td>
<td>25,200</td>
<td>7,466</td>
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<tr>
<td>Detroit</td>
<td>9,037</td>
<td>2,138</td>
<td>14,400</td>
<td>2,144</td>
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</tbody>
</table>

- **# Super-locations allocated to a depot**

<table>
<thead>
<tr>
<th>Area</th>
<th>Avg.</th>
<th>Min.</th>
<th>Max.</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austin</td>
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<td>25</td>
<td>2,663</td>
<td>712</td>
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<tr>
<td>Bloomington</td>
<td>191</td>
<td>83</td>
<td>269</td>
<td>68</td>
</tr>
<tr>
<td>Chicago</td>
<td>1,346</td>
<td>93</td>
<td>3,707</td>
<td>872</td>
</tr>
<tr>
<td>Detroit</td>
<td>1,733</td>
<td>332</td>
<td>4,290</td>
<td>835</td>
</tr>
</tbody>
</table>
Test Results

- **Computational requirements for VRPs**
  - **Acceptable**: optimal solution cannot be better than current solution more than 10%
  - Suggested algorithm could find acceptable solutions within few minutes in almost every case

<table>
<thead>
<tr>
<th>Area</th>
<th>Scenario</th>
<th># inst.</th>
<th>Optimal</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td># MIP inst.</td>
<td>MIP time (s)</td>
<td>MIP gap (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>62</td>
<td>17</td>
<td>6.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>62</td>
<td>20</td>
<td>6.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>62</td>
<td>19</td>
<td>7.52</td>
</tr>
<tr>
<td>Austin</td>
<td>V = 25</td>
<td>66</td>
<td>55</td>
<td>6.6</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V = 50</td>
<td>60</td>
<td>1</td>
<td>23.87</td>
<td>5.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V = 100</td>
<td>60</td>
<td>0</td>
<td>N/A</td>
<td>10.75</td>
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</tr>
<tr>
<td></td>
<td>All</td>
<td>186</td>
<td>56</td>
<td>6.91</td>
<td>7.83</td>
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</table>

<table>
<thead>
<tr>
<th>Area</th>
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<th># inst.</th>
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<tr>
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<td># MIP inst.</td>
<td>MIP time (s)</td>
<td>MIP gap (%)</td>
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<tr>
<td></td>
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<td>158</td>
<td>63</td>
<td>12.1</td>
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<tr>
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<td></td>
<td></td>
<td>2</td>
<td>158</td>
<td>66</td>
<td>11.2</td>
</tr>
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<td></td>
<td></td>
<td>3</td>
<td>158</td>
<td>68</td>
<td>12.4</td>
</tr>
<tr>
<td>Chicago</td>
<td>V = 25</td>
<td>159</td>
<td>62</td>
<td>10.3</td>
<td>2.25</td>
<td></td>
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<tr>
<td></td>
<td>V = 50</td>
<td>159</td>
<td>46</td>
<td>17.2</td>
<td>6.47</td>
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<tr>
<td></td>
<td>V = 100</td>
<td>156</td>
<td>0</td>
<td>N/A</td>
<td>9.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>474</td>
<td>197</td>
<td>11.9</td>
<td>7.95</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>Scenario</th>
<th># inst.</th>
<th>Optimal</th>
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<th></th>
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<tbody>
<tr>
<td></td>
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<td># MIP inst.</td>
<td>MIP time (s)</td>
<td>MIP gap (%)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>90</td>
<td>30</td>
<td>8.08</td>
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<td></td>
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<td>90</td>
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<td>39.9</td>
<td>6.09</td>
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<tr>
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<td>0</td>
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<td>12.12</td>
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</tr>
<tr>
<td></td>
<td>All</td>
<td>270</td>
<td>90</td>
<td>7.7</td>
<td>9.02</td>
<td></td>
</tr>
</tbody>
</table>

*Note: N/A = not applicable*
Test Results

- Sensitivity Analysis
  - What if vehicle capacity increases?

- VMT: Vehicle Miles Traveled
- VHT: Vehicle Hours Traveled
Conclusions

- **Computational Efficiency of Suggested Algorithm**
  - Sequential approach is useful to find acceptable solutions within short time (Total run time incl. data preparation < 3 hours on Chicago network)
  - Characteristics of traffic network (TAZs, link-based simplification, zonal travel time, link travel time …) are captured to enhance the model details

- **Optimization Problem embedded in POLARIS**
  - VRP + detailed regional traffic network enables realistic decision support
  - Various simulation studies can predict the impact on the decision-making
  - Current study: impact analysis when trucks are electrified
References


Acknowledgement

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Questions?

For more information, please see