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U.S. DEPARTMENT OF ENERGY SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

TRUCK ROUTING OPTIMIZATION FOR LARGE-SCALE TRANSPORTATION NETWORKS

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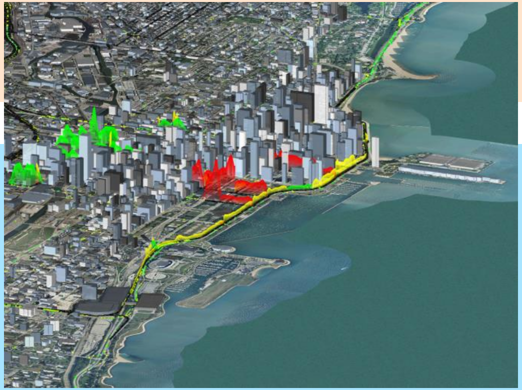
Research Background

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

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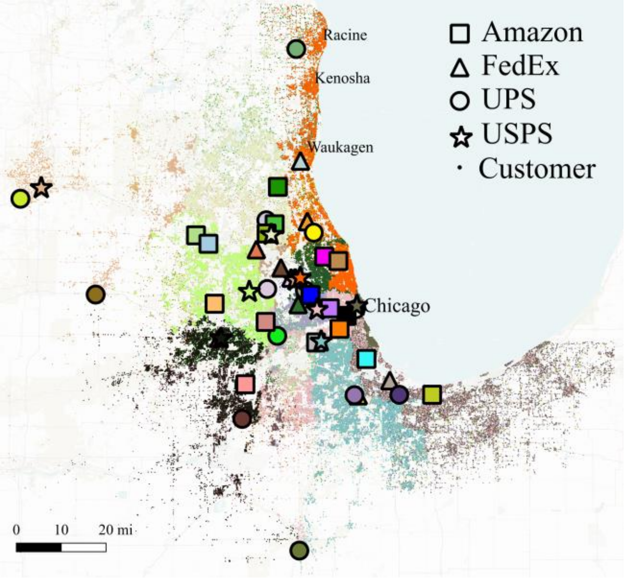
- **Goal of This Study**
  - Develop and implement an **automated e-commerce supply model**
    - Applying vehicle routing problem (VRP)
    - Integrated with POLARIS simulation tool
    - More efficient to compute, by eliminating the manually intensive procedures in SMART 1.0
    - Available to evaluate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

Target System

- **Metropolitan Areas**
  - Importing **traffic network**, **household characteristics**, and **companies' information** from POLARIS

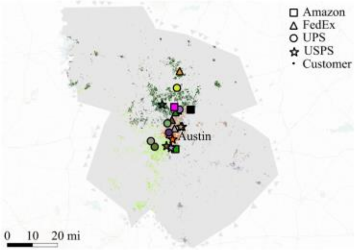


- **Detailed road networks** are applied to compute realistic travel time between locations
- **E-commerce delivery demand** is generated using NHTS (2017) dataset and related research (Spadafora and Rodriguez, 2021)
- **4 major providers** are considered; Amazon, FedEx, UPS, and USPS

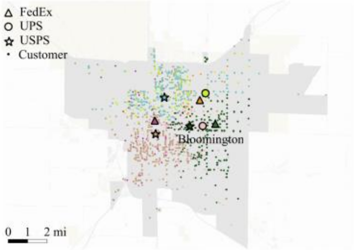
Target System

- **Target Areas:**

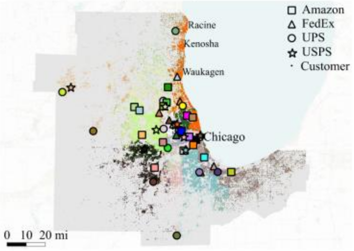
Area	# of households	# of households ordering	# of arcs	# of vertices	# of depots	# of providers
Austin	830,000	158,172	40,891	17,231	22	4
Bloomington	16,605	2,816	7,013	2,540	8	3
Chicago	4,017,583	606,669	57,267	19,377	53	4
Detroit	1,910,260	271,129	60,701	26,424	30	4



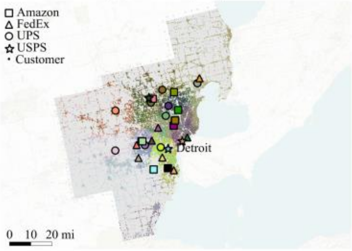
(a) Austin, TX.



(b) Bloomington, IL.



(c) Chicago, IL.



(d) Detroit, MI.

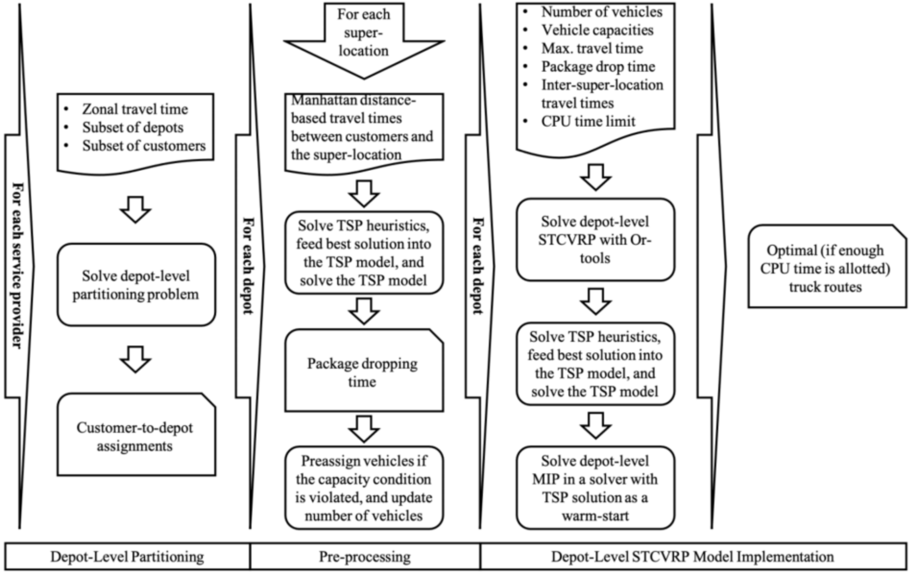
Algorithm Background

- **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



For each service provider

- Zonal travel time
- Subset of depots
- Subset of customers

Solve depot-level partitioning problem

Customer-to-depot assignments

For each depot

For each super-location

Manhattan distance-based travel times between customers and the super-location

Solve TSP heuristics, feed best solution into the TSP model, and solve the TSP model

Package dropping time

Preassign vehicles if the capacity condition is violated, and update number of vehicles

For each depot

- Number of vehicles
- Vehicle capacities
- Max. travel time
- Package drop time
- Inter-super-location travel times
- CPU time limit

Solve depot-level STCVRP with Or-tools

Solve TSP heuristics, feed best solution into the TSP model, and solve the TSP model

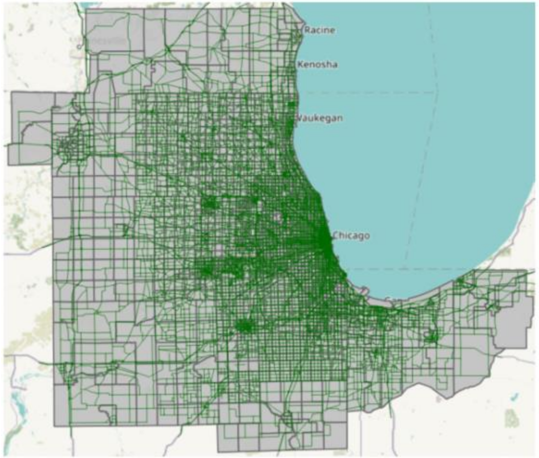
Solve depot-level MIP in a solver with TSP solution as a warm-start

Optimal (if enough CPU time is allotted) truck routes

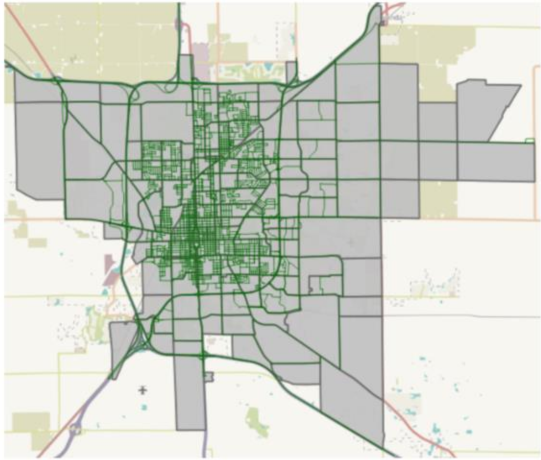
Depot-Level Partitioning | Pre-processing | Depot-Level STCVRP Model Implementation

Algorithm (1) Depot-Level Partitioning

- **Zonal Network**
  - POLARIS 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



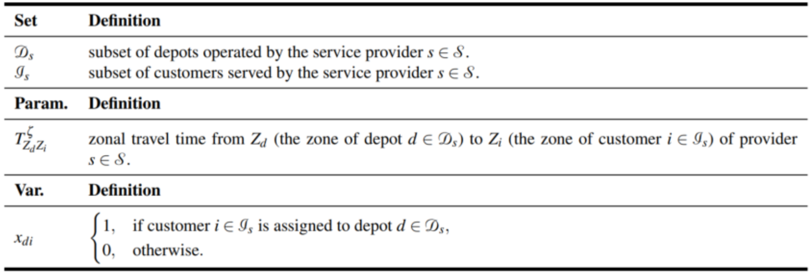
(a) Chicago metropolitan area.



(b) Bloomington, IL.

Algorithm (1) Depot-Level Partitioning

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



Set	**Definition**
$\mathcal{D}_s$	subset of depots operated by the service provider $s \in \mathcal{S}$.
$\mathcal{I}_s$	subset of customers served by the service provider $s \in \mathcal{S}$.
Param.	**Definition**
$T^{\zeta}_{Z_d Z_i}$	zonal travel time from Z_d (the zone of depot $d \in \mathcal{D}_s$) to Z_i (the zone of customer $i \in \mathcal{I}_s$) of provider $s \in \mathcal{S}$.
Var.	**Definition**
x_{di}	$\begin{cases} 1, & \text{if customer } i \in \mathcal{I}_s \text{ is assigned to depot } d \in \mathcal{D}_s, \\ 0, & \text{otherwise.} \end{cases}$

  - Formulation

$$\min_{\mathbf{x}} \mathbf{T}^{\delta} = \sum_{d \in \mathcal{D}_s, i \in \mathcal{I}_s} T^{\zeta}_{Z_d Z_i} x_{di},$$

subject to,

$$\sum_{d \in \mathcal{D}_s} x_{di} = 1 \qquad \forall i \in \mathcal{I}_s,$$

$$\sum_{i \in \mathcal{I}_s} x_{di} \geq \left\lfloor \frac{|\mathcal{I}_s|}{|\mathcal{D}_s|} \right\rfloor \qquad \forall d \in \mathcal{D}_s,$$

$$x_{di} \in \{0, 1\} \qquad \forall d \in \mathcal{D}_s, i \in \mathcal{I}_s.$$

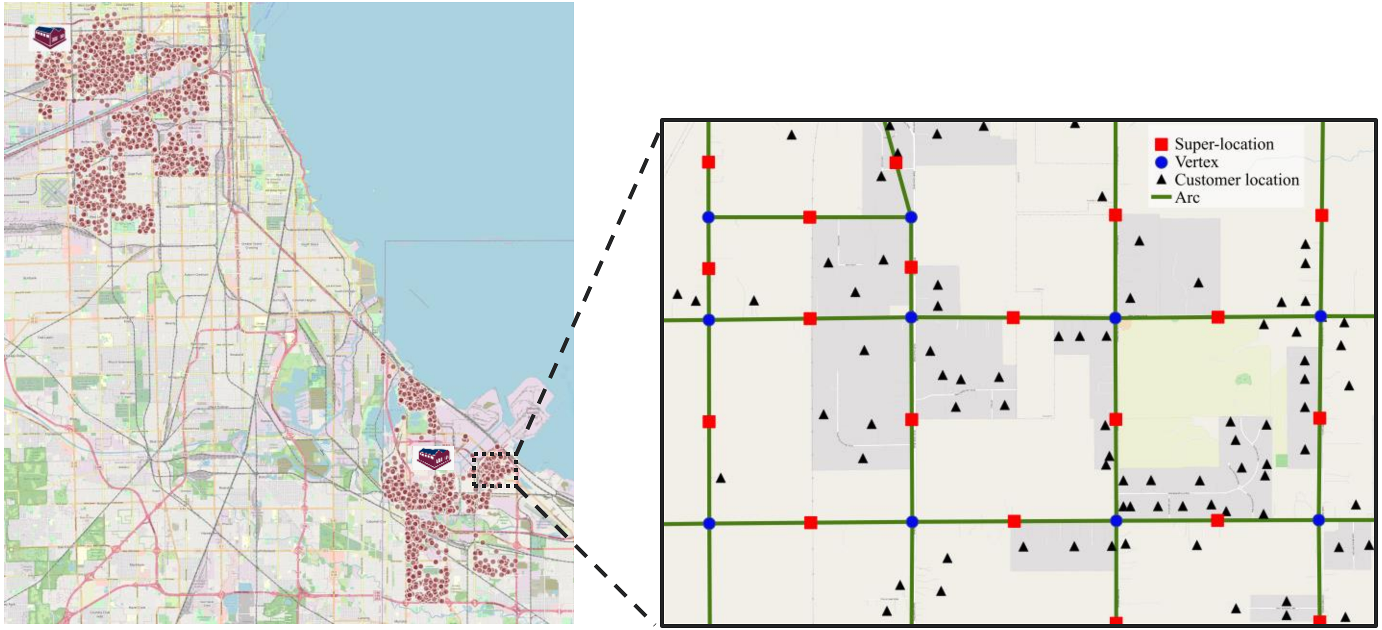
(1) Minimizes the total zonal travel time between depots and customer zones

(2) Each zone is assigned to a single depot

(3) # Customers assigned to a certain depot must be bigger than the lower-bound (decisions for depot operation expenses)

Algorithm (2) Simplification Procedure

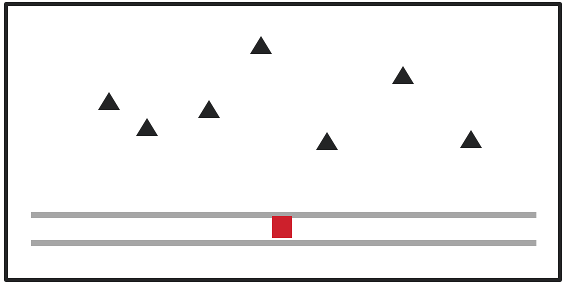
- **Simplification of Customer Locations**
  - Each depot still has lots of customer locations → Customers on a link is simplified into a super location
  - **Super-location**: mid point of every link on road network



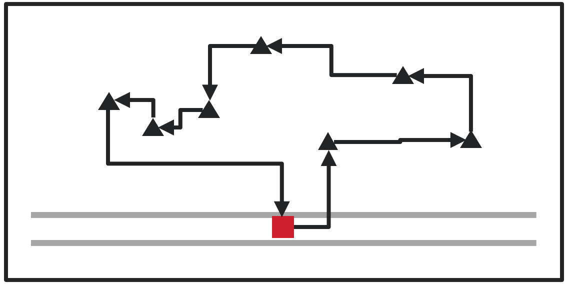
Algorithm (2) Simplification Procedure

- **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)

$$\min_{\mathbf{x}^{\delta},\mathbf{y},\mathbf{z}} \mathbf{T}^{\alpha} = \sum_{l,l' \in \mathcal{L}_d^{\alpha}} T_{ll'}^{\alpha} x_{ll'}^{\delta},$$

subject to,

$$\sum_{l \in \mathcal{L}_d^{\alpha}} x_{ll'}^{\delta} = 1 \qquad \forall l' \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

$$\sum_{l' \in \mathcal{L}_d^{\alpha}} x_{ll'}^{\delta} = 1 \qquad \forall l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

$$\sum_{l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\}} x_{0_d l}^{\delta} = K_d,$$

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$$\sum_{l' \in \mathcal{L}_d^{\alpha}} \left(z_{ll'} - z_{l'l} - T_{ll'}^{\alpha} - T_l^{\theta} \right) = 0 \qquad \forall l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

$$z_{ll'} \leq \left(\overline{T}_d - T_{l'0_d}^{\alpha} \right) x_{ll'}^{\delta} \qquad \forall l \in \mathcal{L}_d^{\alpha}, l' \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

$$z_{ll'} \geq \left(T_{ll'}^{\alpha} + T_{0_d l}^{\alpha} + T_l^{\theta} \right) x_{ll'}^{\delta} \qquad \forall l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\}, l' \in \mathcal{L}_d^{\alpha},$$

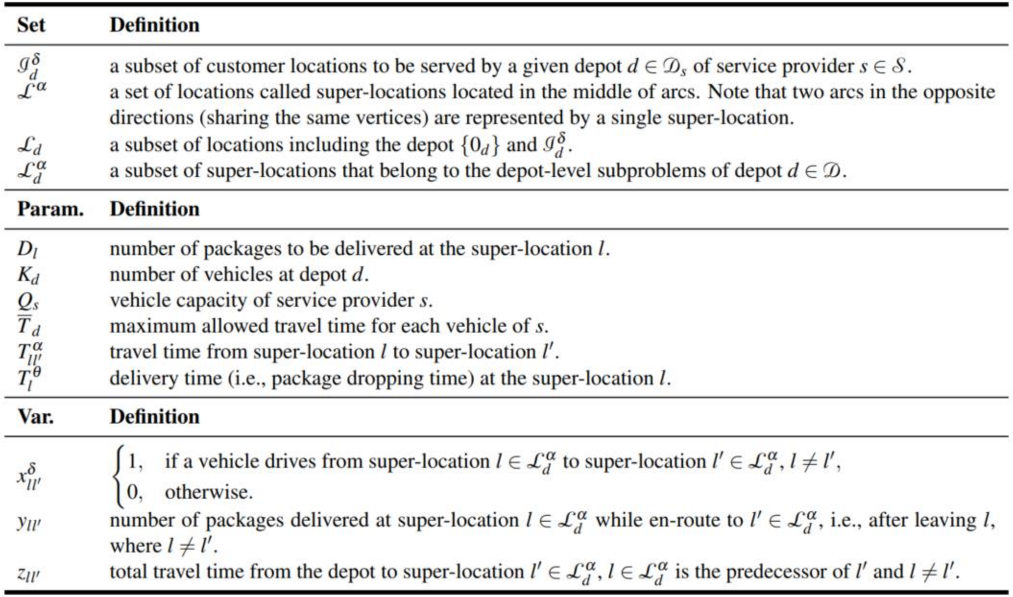
$$z_{l0_d} \leq \overline{T}_d x_{l0_d}^{\delta} \qquad \forall l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

$$z_{0_d l} = T_{0_d l}^{\alpha} x_{0_d l}^{\delta} \qquad \forall l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

$$y_{ll'} = Q_s x_{ll'}^{\delta} \qquad \forall l, l' \in \mathcal{L}_d^{\alpha},$$

$$\sum_{l' \in \mathcal{L}_d^{\alpha}} y_{ll'} - \sum_{l' \in \mathcal{L}_d^{\alpha}} y_{l'l} - D_l = 0 \quad \forall l \in \mathcal{L}_d^{\alpha} \setminus \{0_d\},$$

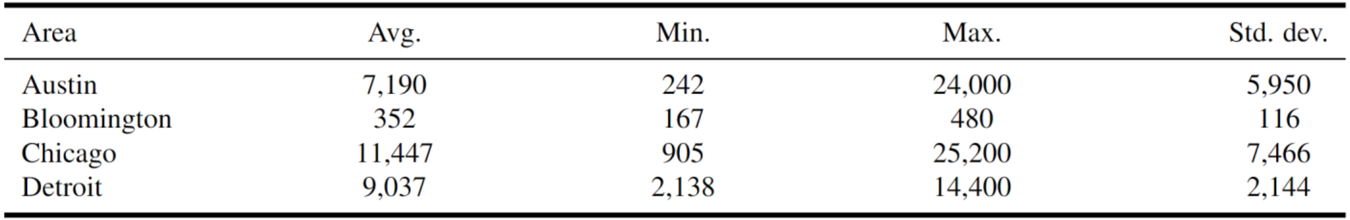
$$x_{ll'}^{\delta} \in \{0,1\}, y_{ll'}, z_{ll'} \in \mathbb{R}_{\geq 0} \qquad \forall l, l' \in \mathcal{L}_d^{\alpha}.$$



Set	**Definition**
$\mathcal{G}_d^{\delta}$	a subset of customer locations to be served by a given depot $d \in \mathcal{D}_s$ of service provider $s \in \mathcal{S}$.
$\mathcal{L}^{\alpha}$	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.
$\mathcal{L}_d$	a subset of locations including the depot $\{0_d\}$ and $\mathcal{G}_d^{\delta}$.
$\mathcal{L}_d^{\alpha}$	a subset of super-locations that belong to the depot-level subproblems of depot $d \in \mathcal{D}$.
Param.	**Definition**
D_l	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.
$\overline{T}_d$	maximum allowed travel time for each vehicle of s.
$T_{ll'}^{\alpha}$	travel time from super-location l to super-location l'.
T_l^{θ}	delivery time (i.e., package dropping time) at the super-location l.
Var.	**Definition**
$x_{ll'}^{\delta}$	$\begin{cases} 1, & \text{if a vehicle drives from super-location } l \in \mathcal{L}_d^{\alpha} \text{ to super-location } l' \in \mathcal{L}_d^{\alpha}, l \neq l', \\ 0, & \text{otherwise.} \end{cases}$
$y_{ll'}$	number of packages delivered at super-location $l \in \mathcal{L}_d^{\alpha}$ while en-route to $l' \in \mathcal{L}_d^{\alpha}$, i.e., after leaving l, where $l \neq l'$.
$z_{ll'}$	total travel time from the depot to super-location $l' \in \mathcal{L}_d^{\alpha}$, $l \in \mathcal{L}_d^{\alpha}$ is the predecessor of l' and $l \neq l'$.

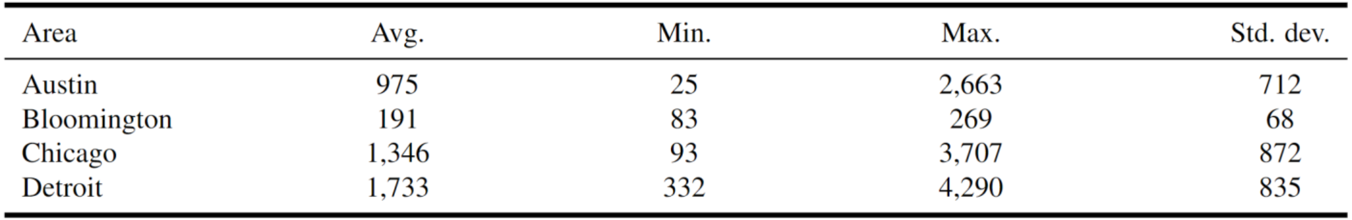
Test Results

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



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

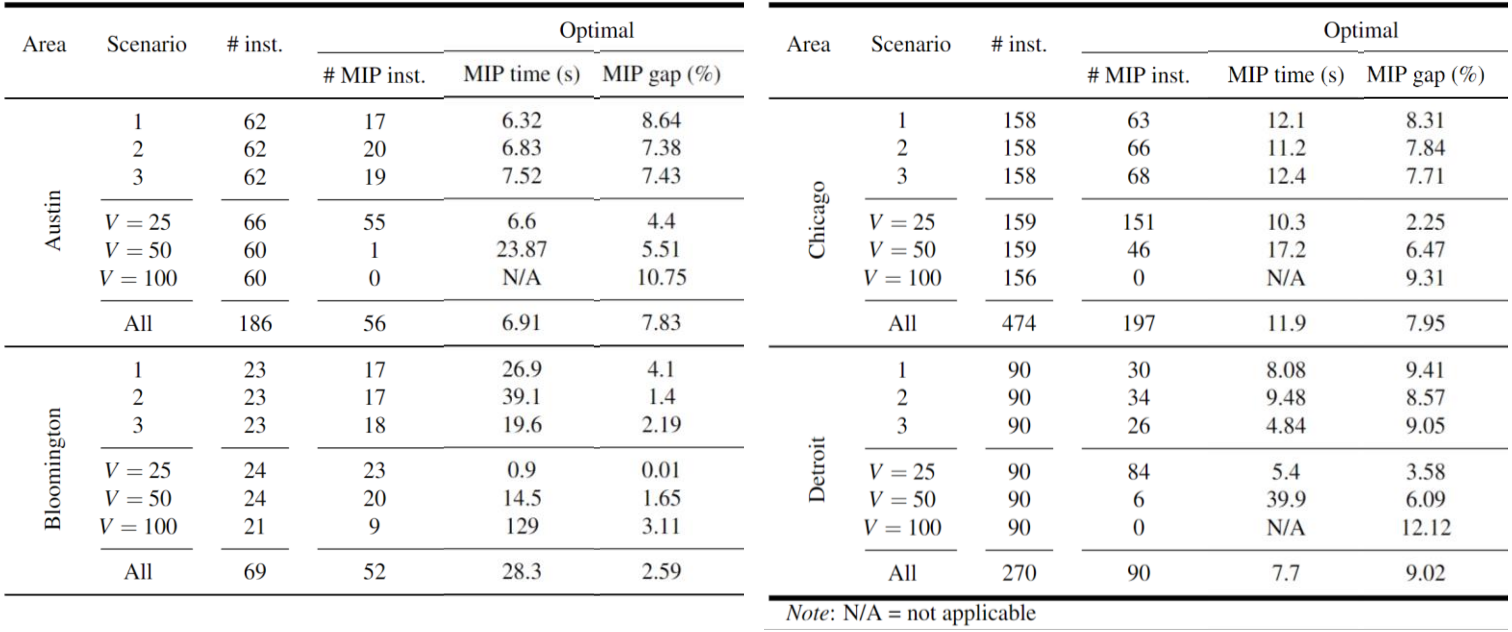
- **# Super-locations allocated to a depot**



Area	Avg.	Min.	Max.	Std. dev.
Austin	975	25	2,663	712
Bloomington	191	83	269	68
Chicago	1,346	93	3,707	872
Detroit	1,733	332	4,290	835

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

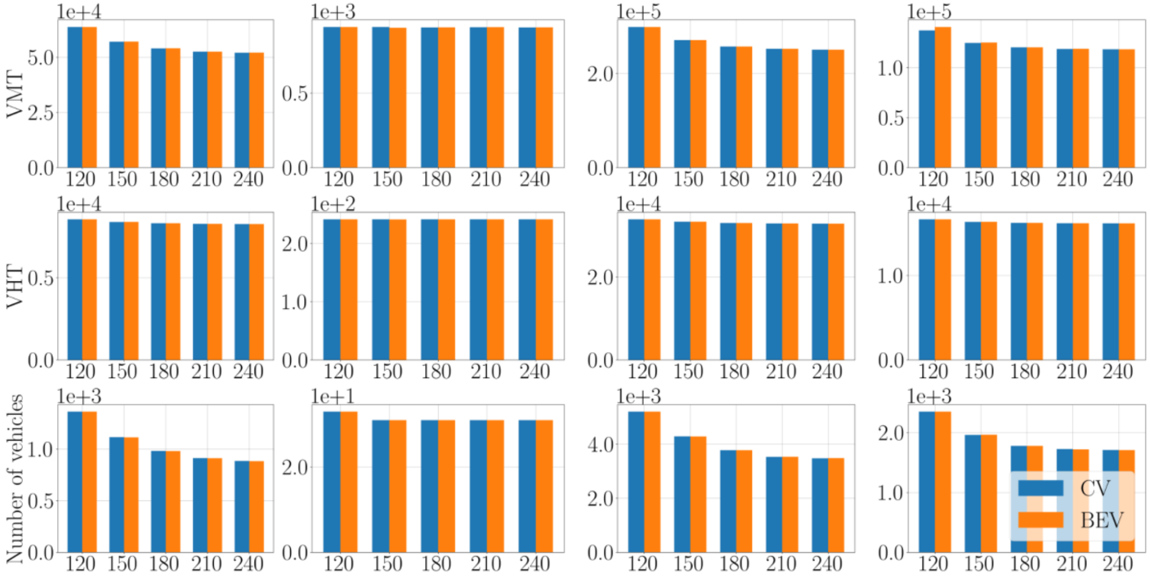


Area	Scenario	# inst.	Optimal		
			# MIP inst.	MIP time (s)	MIP gap (%)
Austin	1	62	17	6.32	8.64
	2	62	20	6.83	7.38
	3	62	19	7.52	7.43
	$V = 25$	66	55	6.6	4.4
	$V = 50$	60	1	23.87	5.51
	$V = 100$	60	0	N/A	10.75
	All	186	56	6.91	7.83
Bloomington	1	23	17	26.9	4.1
	2	23	17	39.1	1.4
	3	23	18	19.6	2.19
	$V = 25$	24	23	0.9	0.01
	$V = 50$	24	20	14.5	1.65
	$V = 100$	21	9	129	3.11
	All	69	52	28.3	2.59
Chicago	1	158	63	12.1	8.31
	2	158	66	11.2	7.84
	3	158	68	12.4	7.71
	$V = 25$	159	151	10.3	2.25
	$V = 50$	159	46	17.2	6.47
	$V = 100$	156	0	N/A	9.31
	All	474	197	11.9	7.95
Detroit	1	90	30	8.08	9.41
	2	90	34	9.48	8.57
	3	90	26	4.84	9.05
	$V = 25$	90	84	5.4	3.58
	$V = 50$	90	6	39.9	6.09
	$V = 100$	90	0	N/A	12.12
	All	270	90	7.7	9.02

Note: N/A = not applicable

Test Results

- **Sensitivity Analysis**
  - What if vehicle capacity increases?



(a) Austin (b) Bloomington (c) Chicago (d) Detroit

- 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

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Acknowledgement

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Questions?

For more information, please see

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