Optimal Distribution of Electric Vehicles Charging Stations

Presented by Haoting Ge, Noah Garfinkle, and Ximi Qu (Group Three) for CEE 512: Logistics Systems Analysis

Presented on 11 December 2019

Motivation

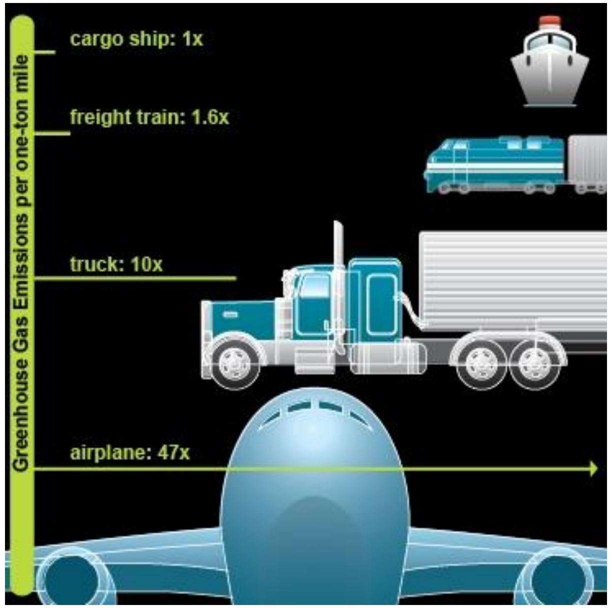
Motivation and Academic Significance

Freight delivery via semi-trucks is the foundation of many logistic networks in the United States.

Semi-trucks emit 16 percent of corporate greenhouse gasses and pose substantial fuel costs for logistics systems. [1]

Electric semi-trucks are now entering the market, with some countries specifying ambitious targets to replace all trucks with electric vehicles. [1]

Differing 'refueling' requirements of electric vs. diesel semi-trucks may require modification of routing timetables to enable charging.



http://business.edf.org/projects/green-freight-facts-figures

Project Objectives

The objective of this research project is to:

- Learn how to implement coupled variants of the routing and facility location models learned in class
- Explore tradeoffs between:
  - Route efficiency
  - Cost of installation and operation of new recharging infrastructure

Background

Literature review

What is a Location Routing Problem (LRP)?

- What is LRP trying to solve?

  How many facilities to locate,

  Where to locate facilities,

  How to assign customers to facilities

  How to route vehicles to serve customers
- Two step decision making

  Strategic Decision: the optimal number, the capacity, and the location of facilities

  Operational Decision: the optimal set of vehicle routes from fixed facilities decided in step 1
- The main difference between LRP and what we learned in class is that we must assign optimal depot locations simultaneously to evaluating optimal routing

Literature review

Solution Approaches

- Location Routing Problem
  - Exact Solutions
  - Heuristic Algorithms
  - Metaheuristic Algorithms

Literature review

- Exact Solution
  - A number of exact algorithms were presented in Laporte's (1983) paper. [5]
  - Integer programming exact algorithms (Laporte, 1989) [6]

Maximize

$$\sum_{i \neq j} c_{ij} x_{ij} \tag{1}$$

subject to

$$\sum_{i \in N} x_{ij} = 1 \qquad (j \in N) \tag{2}$$

$$\sum_{j \in N} x_{ij} = 1 \qquad (i \in N) \tag{3}$$

$$\sum_{\substack{i,j \in S \\ i \neq j}} x_{ij} \leqslant |S| - 1 \qquad \text{(for all } S \subseteq N \text{ such that } |S| \geqslant 2 \text{ and subtours with node set } S \text{ are illegal)} \tag{4}$$

$$\sum_{k=1}^{p-1} x_{i_k i_{k+1}} \leqslant p - 2 \qquad \text{[for all illegal vehicle routes } (i_1, \ldots, i_p)] \tag{5}$$

$$x_{kk} = x_{uu} \qquad \text{(for all } k \text{ and } u \text{ such that } u \text{ corresponds to a white depot node, and } k \text{ to a vehicle node of the same depot)} \tag{6}$$

$$x_{ij} = 0, 1 \qquad (i, j \in N). \tag{7}$$

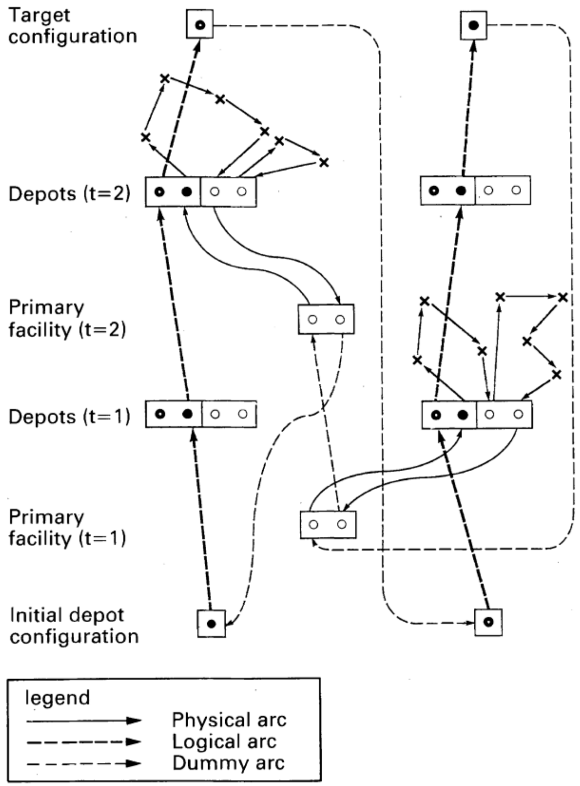


FIG. 4. *Feasible solution to a problem on the complete network. There are two periods, two depots and two vehicles per depot.*

Three-layer system

Literature review

- Heuristic Algorithms
  - The exact solution for LRP is NP-hard problem.
  - A bunch of heuristic algorithms were reviewed by Madsen (1983).
  - Maria (2005) proposed a two-phase heuristic:

    First phase: Decide the set of facilities and consider priori routes.

    Second phase: Optimize the routes

- Metaheuristic Algorithms
  - Tabu Search
  - Simulated Annealing
  - Genetic Algorithms

Case Study

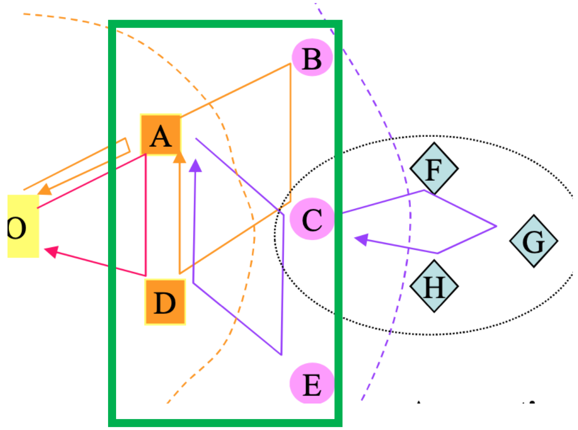
Case Study Background

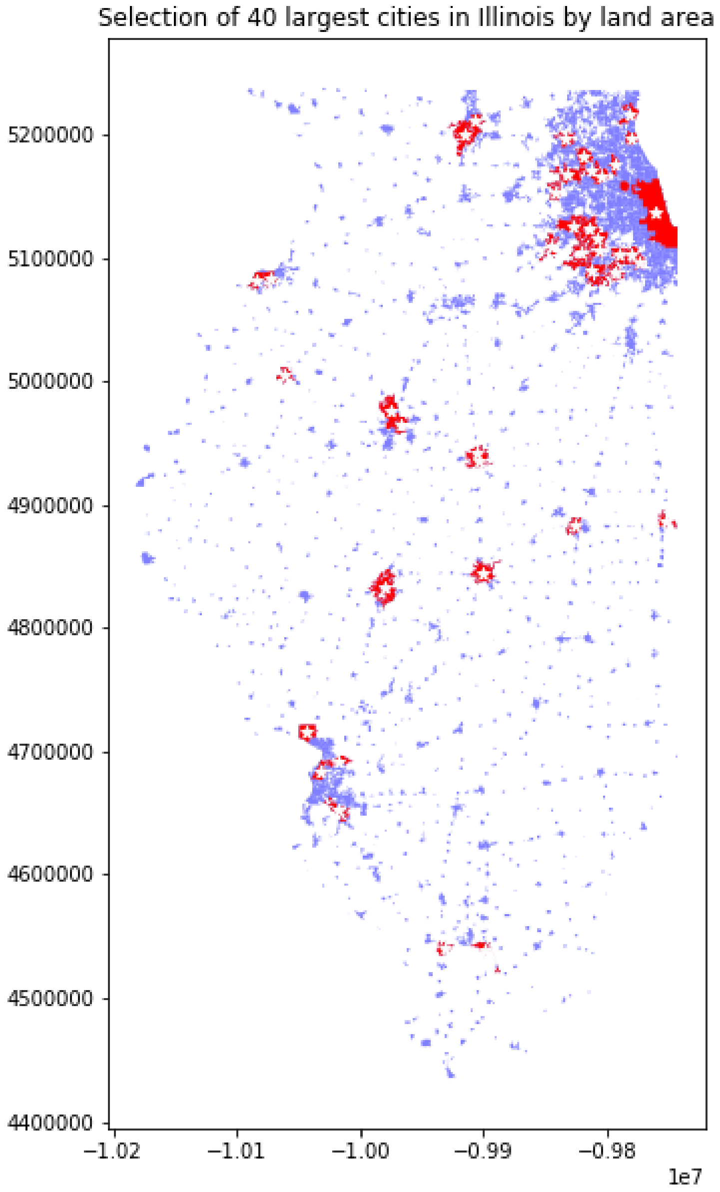
Electric Semi-Truck Freight Delivery Model

Our study focuses on creating a general model to integrate electric semi-trucks into an existing freight delivery network.

Since the electric semi-truck's 'fueling time' and charging station setup are more costly compared to the traditional diesel semi-truck. We are looking for the most economical way to minimize those trade-offs.

Besides, we are generating a model for the middle hierarchy of the transshipment between terminals.





Case Study Data Preparation

Selection of the Cities

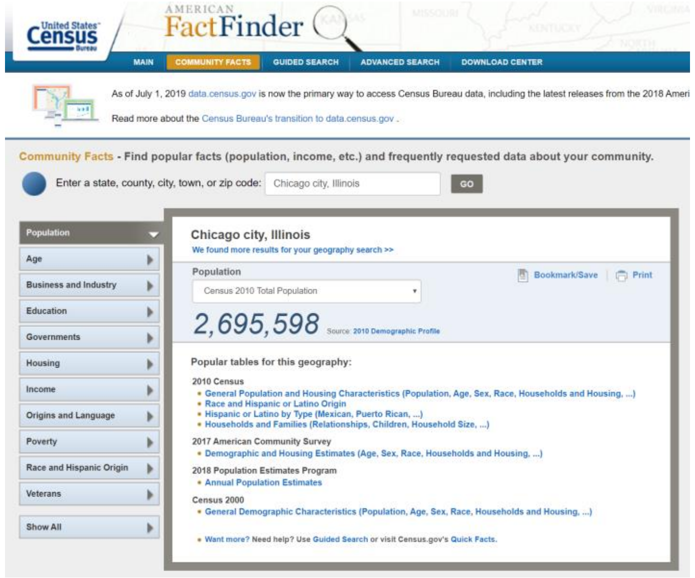
The case study is based in Illinois.

According to the geographic size of each city and due to the problem's formulation, 40 cities were selected.

Demand

We have assumed that demand is proportional to the population of each city, expressed in pounds of shipment.

City	Population	Demand	Until Land-Price	Facility-1	Facility-2
Chicago	2,695,598	53,912	$241	$5,761,625.00	$12,607,250.00
Joliet	147,433	2,949	$138	$3,328,250.00	$7,740,500.00
Rockford	152,871	3,057	$84	$2,052,500.00	$5,189,000.00
Springfield	116,250	2,325	$101	$2,454,125.00	$5,992,250.00
Peoria	115,007	2,300	$84	$2,052,500.00	$5,189,000.00
Aurora	197,899	3,958	$132	$3,186,500.00	$7,457,000.00
Decatur	76,122	1,522	$87	$2,123,375.00	$5,330,750.00
Naperville	141,853	2,837	$182	$4,367,750.00	$9,819,500.00
Elgin	108,188	2,164	$159	$3,824,375.00	$8,732,750.00
Godfrey	17,982	360	$135	$3,257,375.00	$7,598,750.00
Bloomington	76,610	1,532	$148	$3,564,500.00	$8,213,000.00
Barrington Hills	4,209	84	$214	$5,123,750.00	$11,331,500.00



https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml?src=bkmk

Case Study Data Preparation

Facility Cost

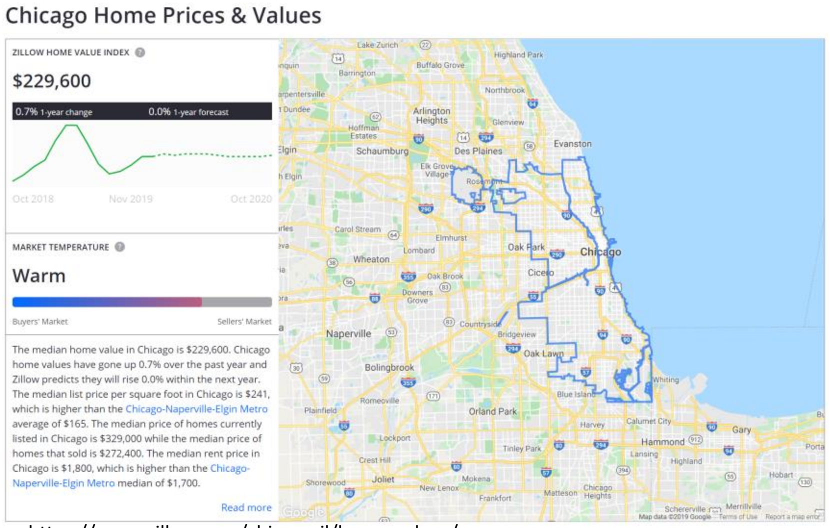
Including two major components:

- **Land Cost**

  The charging facility is considered to be a new addition to the existing terminals. The unit price of the land ($/ft^2) is based on the Zillow's house pricing.

- **Charging Instrument Cost**

  Based on the "Costs Associated With Non-Residential Electric Vehicle Supply Equipment" from the U.S. Department of Energy for estimation.



https://www.zillow.com/chicago-il/home-values/

In this study case, one of the objectives is to determine where the add-on charging facility should be built to the existing terminals. There will be two types of charging facility to serve two different types of trucks.

Due to the need of efficiency of the charging speed and quantity of the battery, the AC Level 2 and DC Fast Charging are used as our two types of facility-based model.

Charging Level	Vehicle Range Added per Charging Time and Power	Supply Power
AC Level 1	4 mi/hour @ 1.4kW 6 mi/hour @ 1.9kW	120VAC/20A *(12-16A continuous)*
AC Level 2	10 mi/hour @ 3.4kW 20 mi/hour @ 6.6kW 60 mi/hour @ 19.2 kW	208/240VAC/20-100A *(16-80A continuous)*
DC Fast Charging	24 mi/20minutes @24kW 50 mi/20minutes @50kW 90 mi/20minutes @90kW	208/480VAC 3-phase *(input current proportional to output power; ~20-400A AC)*

Figure 4. Description of charging level supply power and charging times. The power coming from the EVSE depends on the voltage from the electrical service and the EVSE amperage rating.

Ballpark EVSE Installation Costs

EVSE Type	Average Installation Cost (per unit)	Installation Cost Range (per unit)
Level 1	not available	$0-$3,000* *Source: Industry Interviews*
Level 2	~$3,000 *EV Project (INL 2015b)*	$600-$12,700 *EV Project (INL 2015b)*
DCFC	~$21,000 *EV Project (INL 2015d)*	$4,000-$51,000 *EV Project (INL 2015d) and (OUC 2014)*

Table 2. Ballpark costs for installation of Level 1, Level 2, and DCFC EVSE (not including the EVSE unit.)

Motivation | Background | Case Study | Problem Formulation | Results | Discussion

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Case Study Data Preparation

Vehicle Parameters

- **Ranges**

  The range of fully charged electric trucks. In our model, we set two different types of electric trucks. The smaller one has a range of 240 kilometers, while the larger one has a range of 640 kilometers.

- **Capacities**

  The maximum weight can be carried by an electric truck. The capacities of electric trucks are based on different kinds of internal combustion engine trucks. They are set to be 80,000 lbs (equivalent to a regular semi-trailer truck) and 40,000 lbs (single axle).

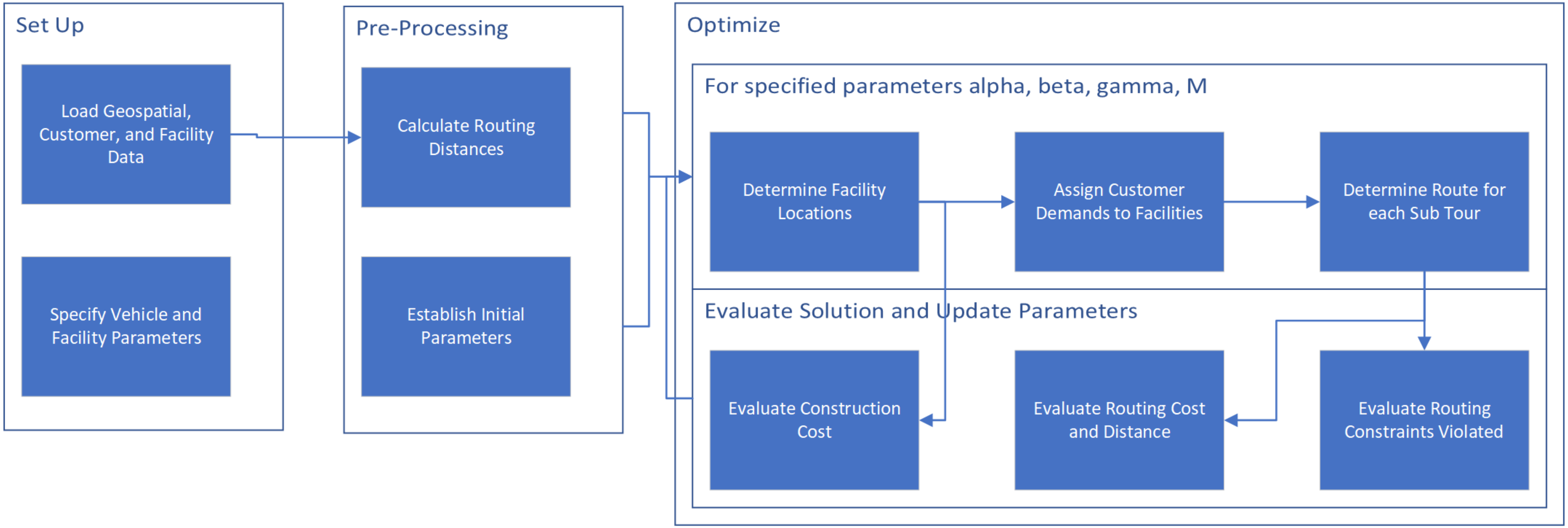
	Truck type 1	Truck type 2
Range (kilometers)	240	640
Capacity (lbs)	40,000	80,000

Table 1. The vehicle parameters

We used Tesla's Semi as the baseline for the vehicle parameters setup.

Problem Formulation

Solution Approach



Model Formulation: Variables

Variable	Description	Notes
i	Customer city index	$0 \leq i \leq 40$
j	Candidate distribution node city index	$0 \leq j \leq 40^{*}$
z	Shipping mode type index	$0 \leq z \leq 1^{**}$
x_{ij}	Assignment of customer i to depot j	$x_{ij} \in \{0,1\}$
y_{jz}	Decision to construct infrastructure of type z at candidate location j	$y_{jz} \in \{0,1\}$
c_{ij}	Distance to travel from city i to city j	$c_{ij} \in \mathbb{R}_{>0}^{***}$
d_i	Demand for product in pounds at city i	$d_i \in \mathbb{R}_{>0}$
α	Penalty for an additional meter added to a subtour, expressed in dollars per meter over facility lifetime	$\alpha \in \mathbb{R}$
β	Penalty for an additional meter between facility j and the terminal expressed in dollars per meter over facility lifetime	$\beta \in \mathbb{R}$
R_z	Maximum range of vehicle type z in meters	$R_z \in \mathbb{R}_{>0}$
TC_z	Maximum capacity of vehicle type z in pounds	$TC_z \in \mathbb{R}_{>0}$
$\gamma_{battery,j}$	Percentage of battery which can be used	$0 \leq \gamma_{battery} \leq 1$
M	Maximum number of facilities willing to construct	$M \in \mathbb{Z}_{>0}$

<u>Assumptions and Simplifications</u>

- The transportation network, demands, and costs are known
- Assignment of customer demands can only be to one depot
- Each depot serves a single TSP tour

*Each city has a candidate facility
**Standard and extended range vehicle and supporting infrastructure
***Euclidean distance

Model Formulation: Variables- Why α and β?

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α and β represent the tradeoff between strategic (facility location) and operational (routing) decisions.

α represents the lowest level of the routing problem, servicing customers

β represents the highest level of the routing problem, connecting the depot to each terminal.

Model Formulation: Variables- Why $\gamma_{battery,j}$

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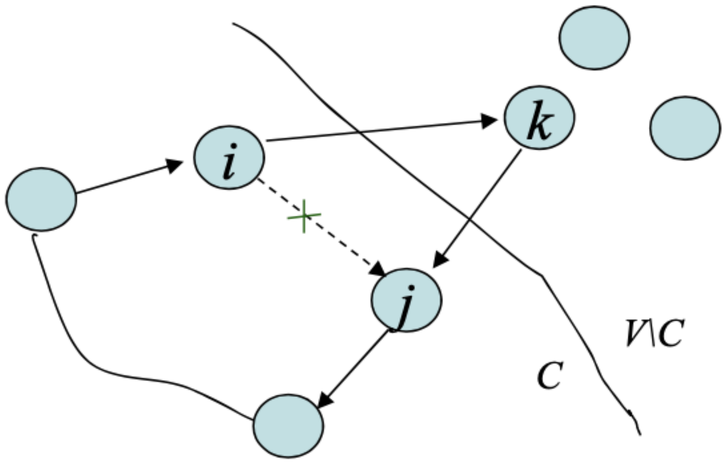
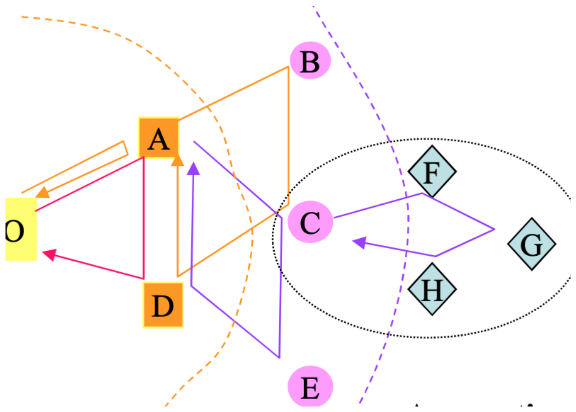


Model Formulation: Facility Location

$$\text{Min}(OBJ) = \sum_j \sum_i \sum_z \{\alpha(c_{0,j} + c_{i,j} + c_{i,0})x_{i,j} + 2\beta c_{0,j} y_{j,z} + f_{j,z} y_{j,z}\}$$

s.t.

Constraint	Formulation	Interpretation
Service	$\sum_j x_{i,j} = 1, \forall_i$	Every customer is served by only one facility
Capacity	$\sum_i d_i x_{i,j} \leq \sum_z TC_z y_{j,z}, \forall_j$	The sum of demands for customers served by a facility must be less than the vehicle capacity
Assignment	$x_{i,j} \leq \sum_z y_{j,z}, \forall_{i,j}$	Customers can only be assigned to an open facility of either type
Facilities	$\sum_j \sum_z y_{j,z} \leq M$	An optional limit on the total number of facilities which will be constructed. Could also be substituted for an optional total cost of facility construction.
Approximate Tour	$\sum_i x_{i,j} c_{i,j} \leq \sum_z y_{j,z} RV_z \gamma_{battery}, \forall_j$	An approximation of the total tour length
Facility Selection	$\sum_z y_{j,z} \leq 1, \forall_j$	Only allow either no infrastructure, standard range, or extended range infrastructure to be constructed at a site j



Model Formulation: Facility Location

$$\text{Min}(OBJ) = \boxed{\sum_j \sum_i \sum_z \{\alpha(c_{0,j} + c_{i,j} + c_{i,0})x_{i,j}} + 2\beta c_{0,j}y_{j,z} + f_{j,z}y_{j,z}\}$$

Routing Heuristic

s.t.

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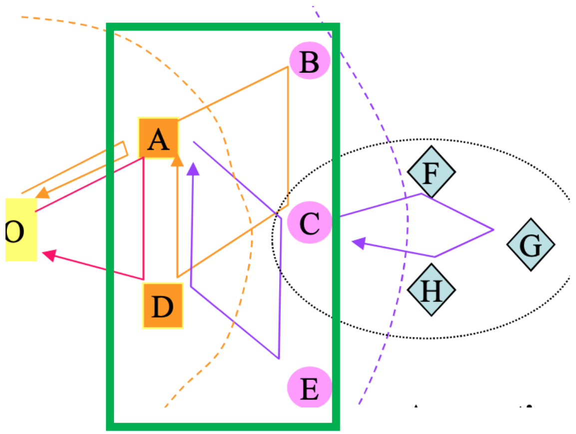

Model Formulation: Facility Location

$$\text{Min}(OBJ) = \boxed{\sum_j \sum_i \sum_z \{\alpha(c_{0,j}+c_{i,j} + c_{i,0})x_{i,j}} + 2\beta c_{0,j}y_{j,z} + f_{j,z}y_{j,z}\}$$

Routing Heuristic

s.t.

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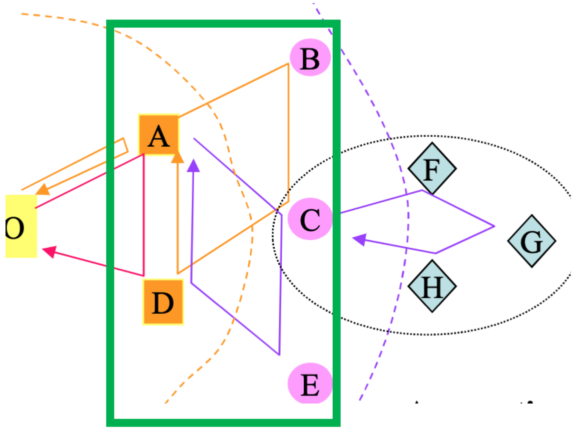

This constraint, and the vector γ_j, become critical to our solution approach

Model Formulation: Facility Location

$$\text{Min}(OBJ) = \sum_j \sum_i \sum_z \{\alpha(c_{0,j}+c_{i,j} + c_{i,0})x_{i,j} + \boxed{2\beta c_{0,j}y_{j,z}} + f_{j,z}y_{j,z}\}$$

Terminal Heuristic

Constraint	Formulation	Interpretation
Service	$\sum_j x_{i,j} = 1, \forall_i$	Every customer is served by only one facility
Capacity	$\sum_i d_i x_{i,j} \leq \sum_z TC_z y_{j,z}, \forall_j$	The sum of demands for customers served by a facility must be less than the vehicle capacity
Assignment	$x_{i,j} \leq \sum_z y_{j,z}, \forall_{i,j}$	Customers can only be assigned to an open facility of either type
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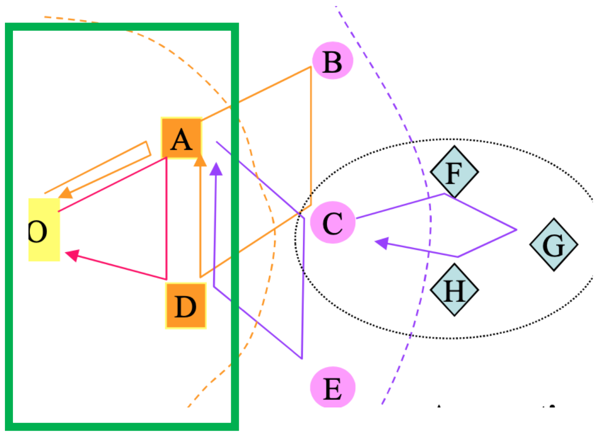
Facility Selection	$\sum_z y_{j,z} \leq 1, \forall_j$	Only allow either no infrastructure, standard range, or extended range infrastructure to be constructed at a site *j*



Model Formulation: Facility Location

$$\text{Min}(OBJ) = \sum_j \sum_i \sum_z \{\alpha(c_{0,j} + c_{i,j} + c_{i,0})x_{i,j} + 2\beta c_{0,j} y_{j,z} + f_{j,z} y_{j,z}\}$$

Facility Cost

s.t.

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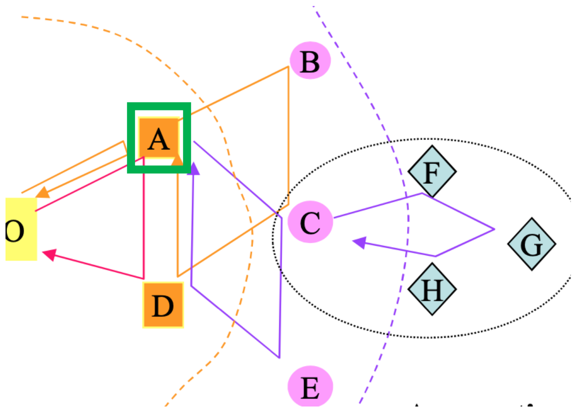


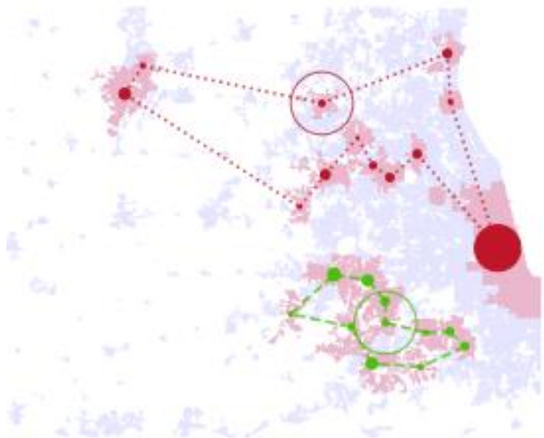
Model Formulation: Routing

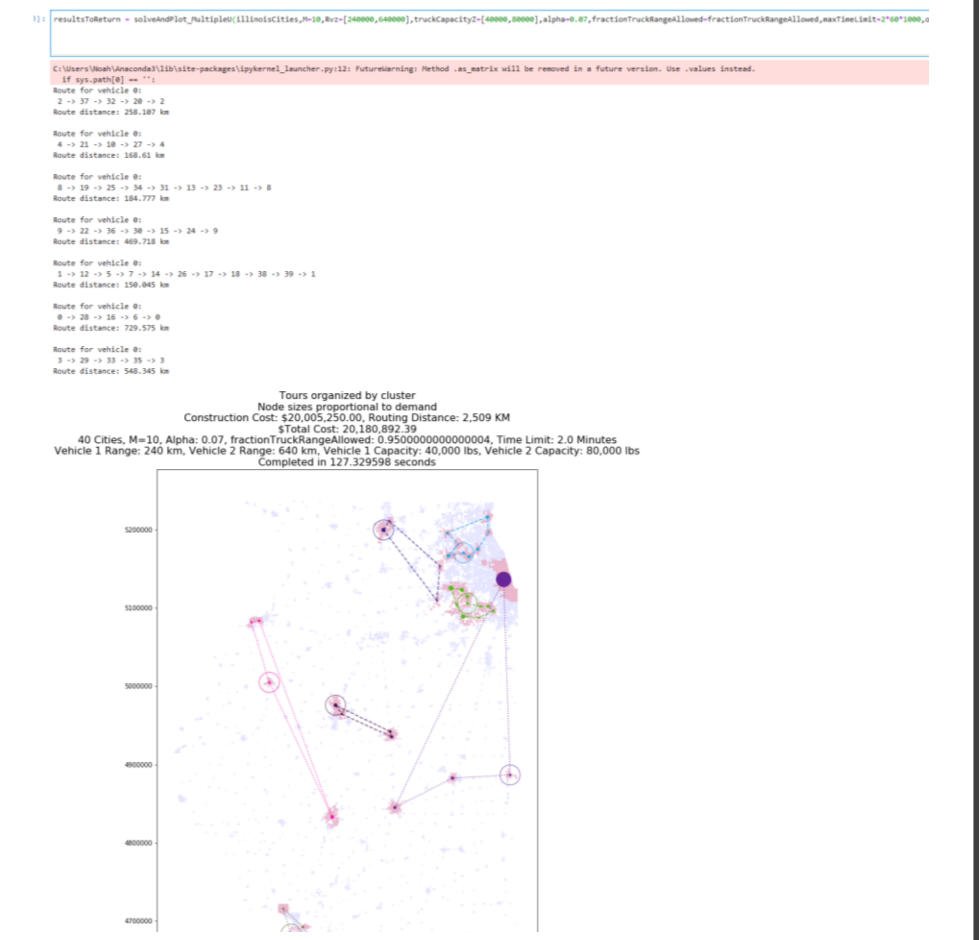
$\text{Min}(OBJ) = \sum_i \sum_{j\neq i, j=1} c_{ij} x_{ij}$

s.t.

Constraint	Formulation
Entry legs	$\sum_j x_{i,j} = 1, \forall_i$
Exit legs	$\sum_i x_{i,j} = 1, \forall_j$
Subtour Elimination	$u_j \geq u_i + N x_{ij} - (N-1), \forall_{i,j=1}$
Subtour Elimination	$u_1 = 1$
	$0 \leq x_{i,j} \leq 1$
	$1 \leq u_i \leq N, \forall_i$
	$x_{i,j} \in \mathbb{Z}_{>0}$
	$u_i \in \mathbb{Z}_{>0}$

Because our tours are generally small, solutions are generated using the routing libraries within ORTOOLS utilizing default parameters.





Model Solution

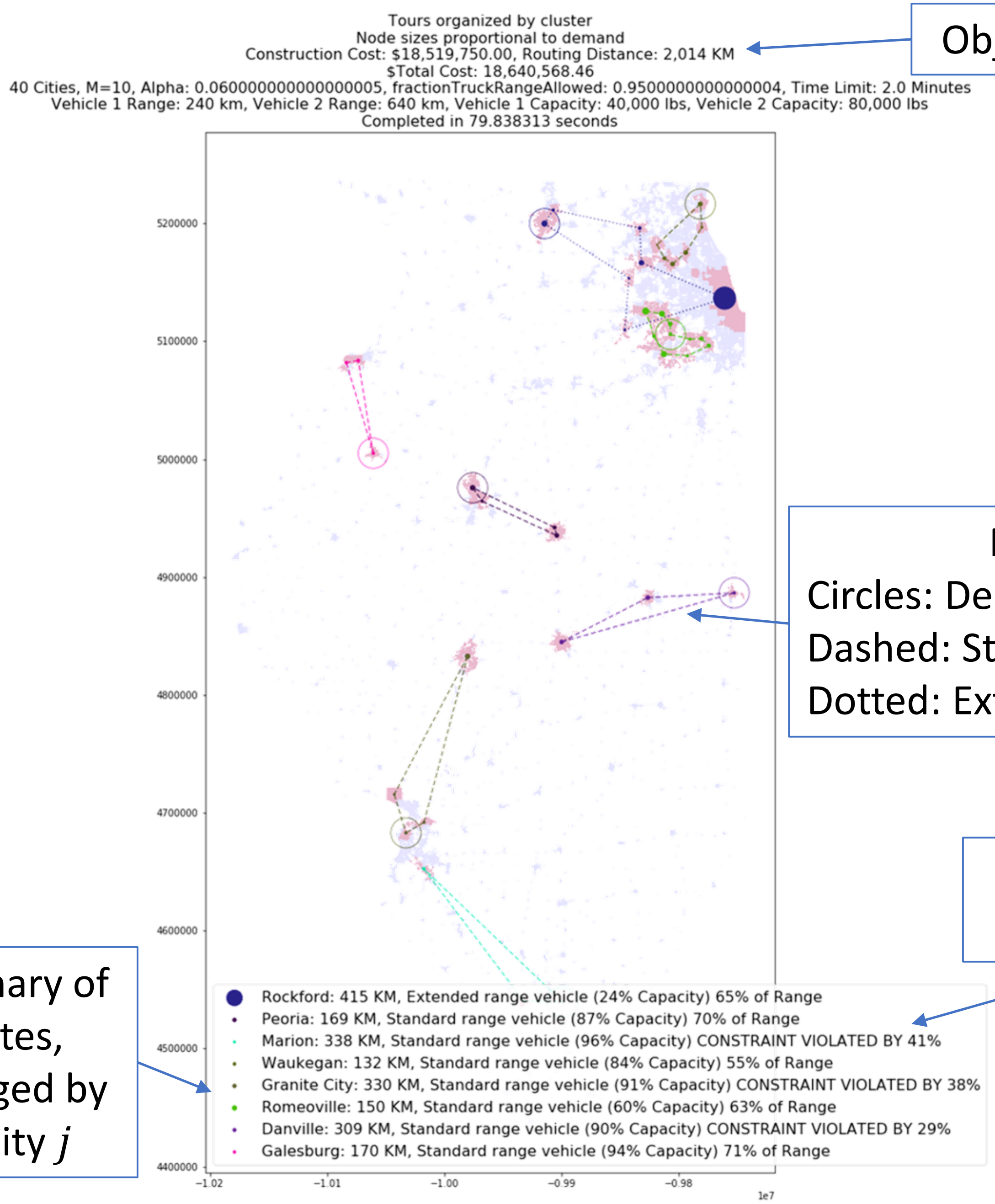
- Models formulated using Python 3.6
- Numerical optimization utilizes ORTOOLS library

Google Optimization Tools

Microsoft Azure

Results

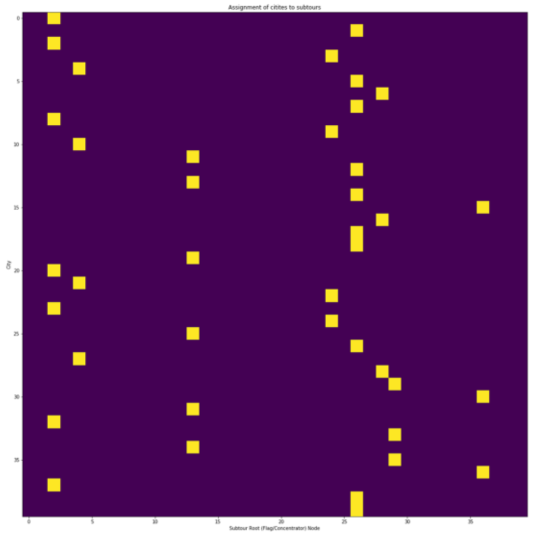
Guide to Interpreting Our Results



Objective functions

Routes:
Circles: Depots
Dashed: Standard EV
Dotted: Extended Range EV

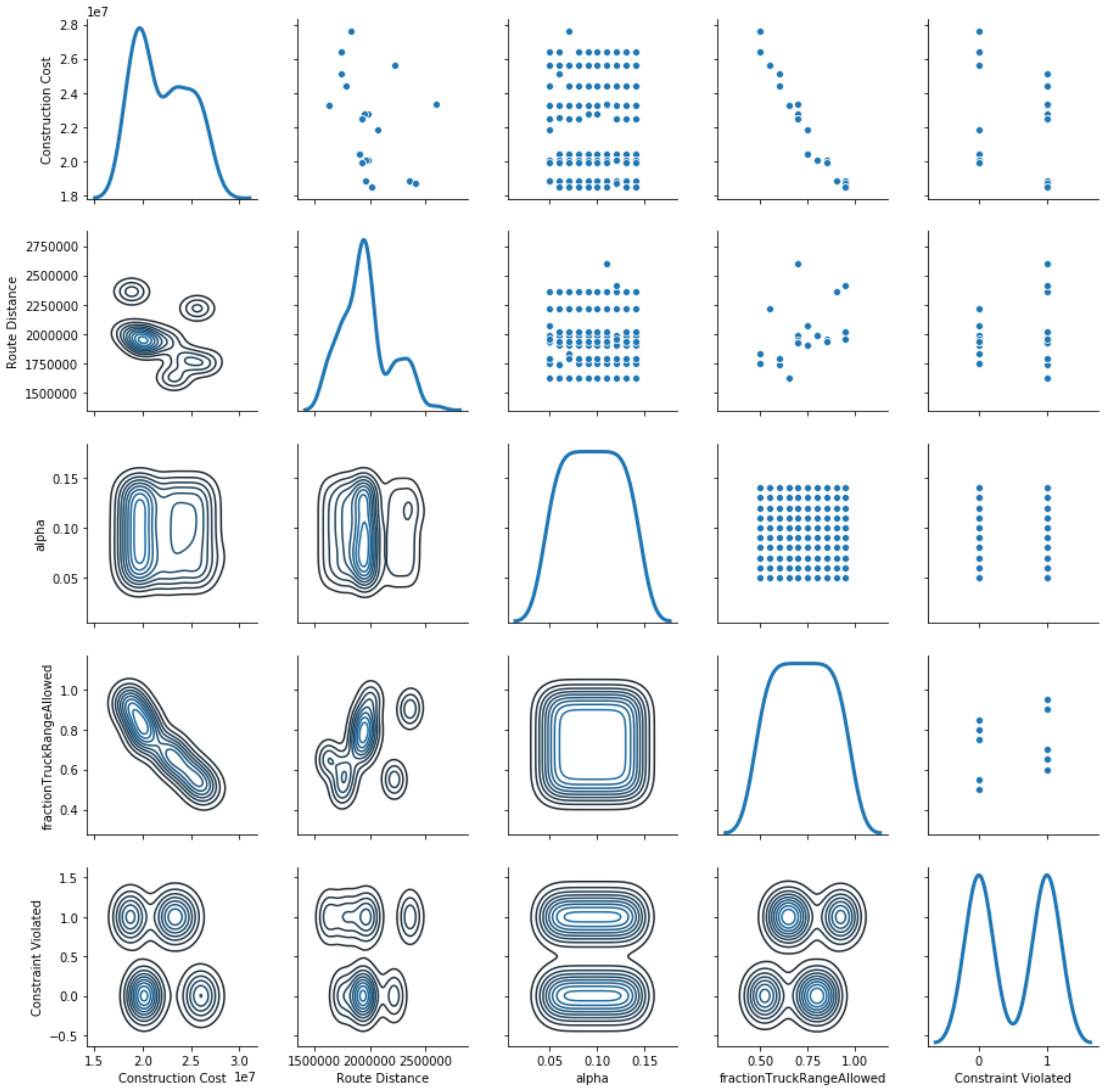
Constraint violations



Assignment of customer i to facility j

Summary of routes, arranged by facility j

Heuristic 1: Study model sensitivity to $\alpha, \gamma_{battery}$



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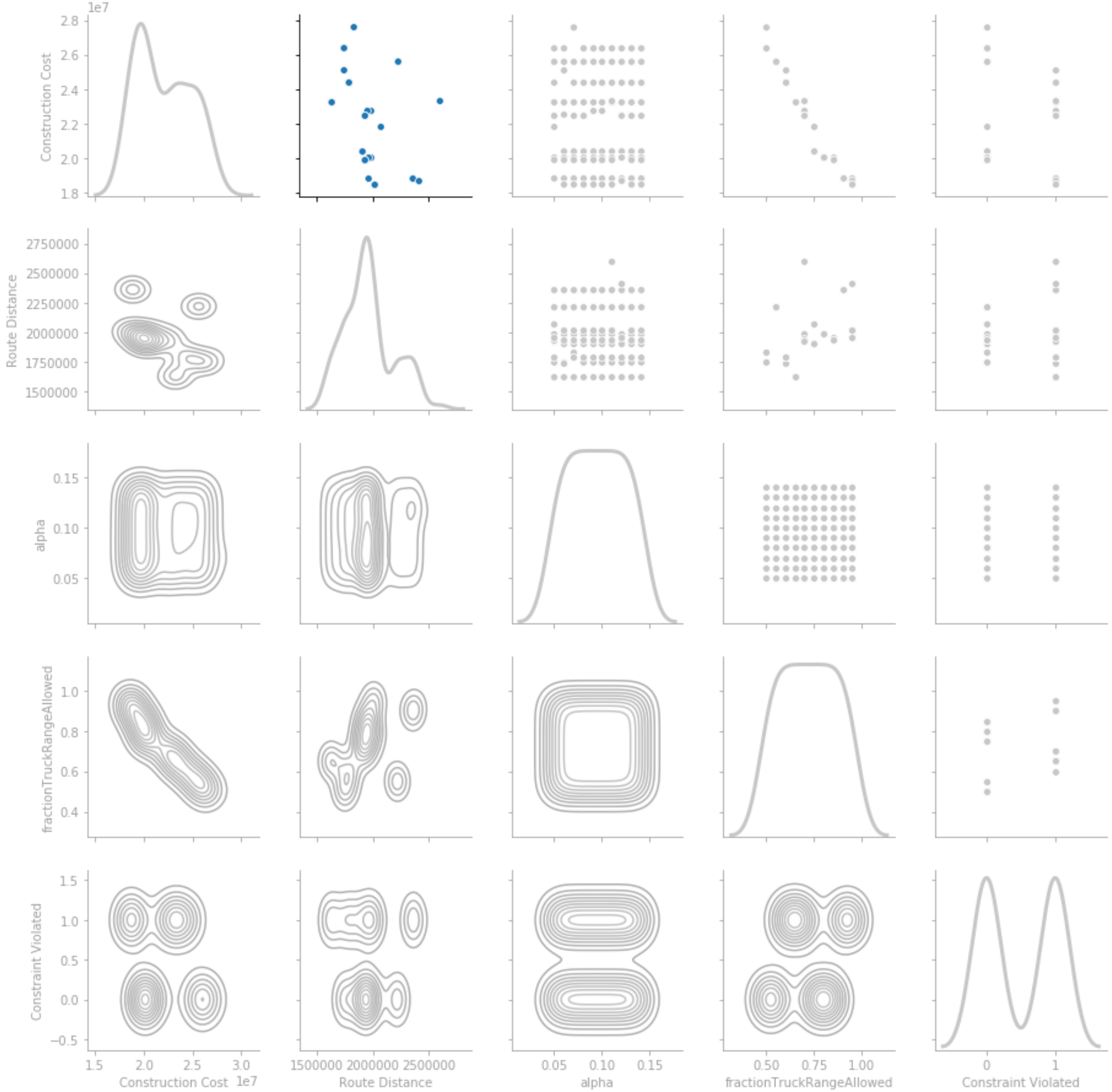
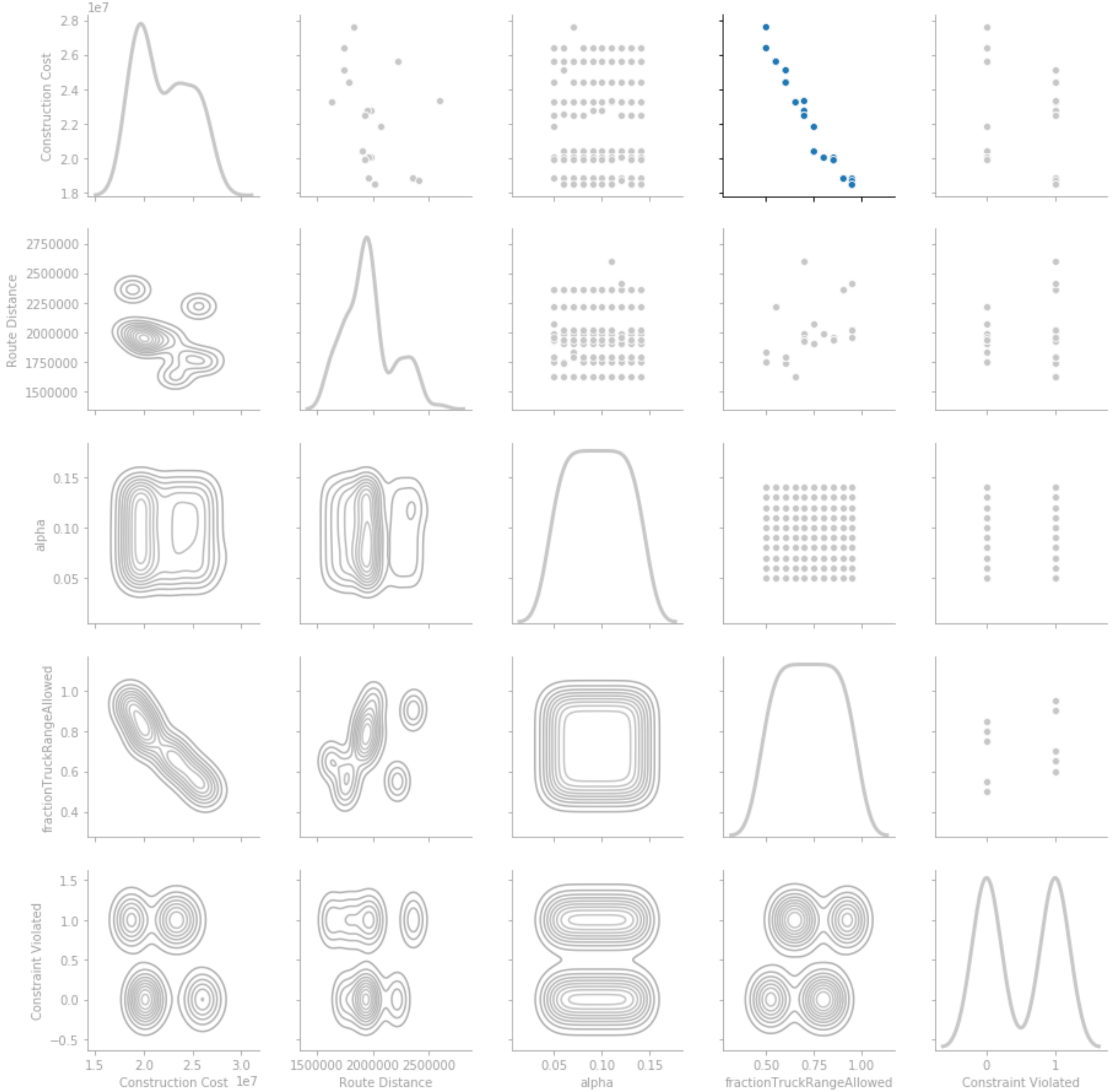


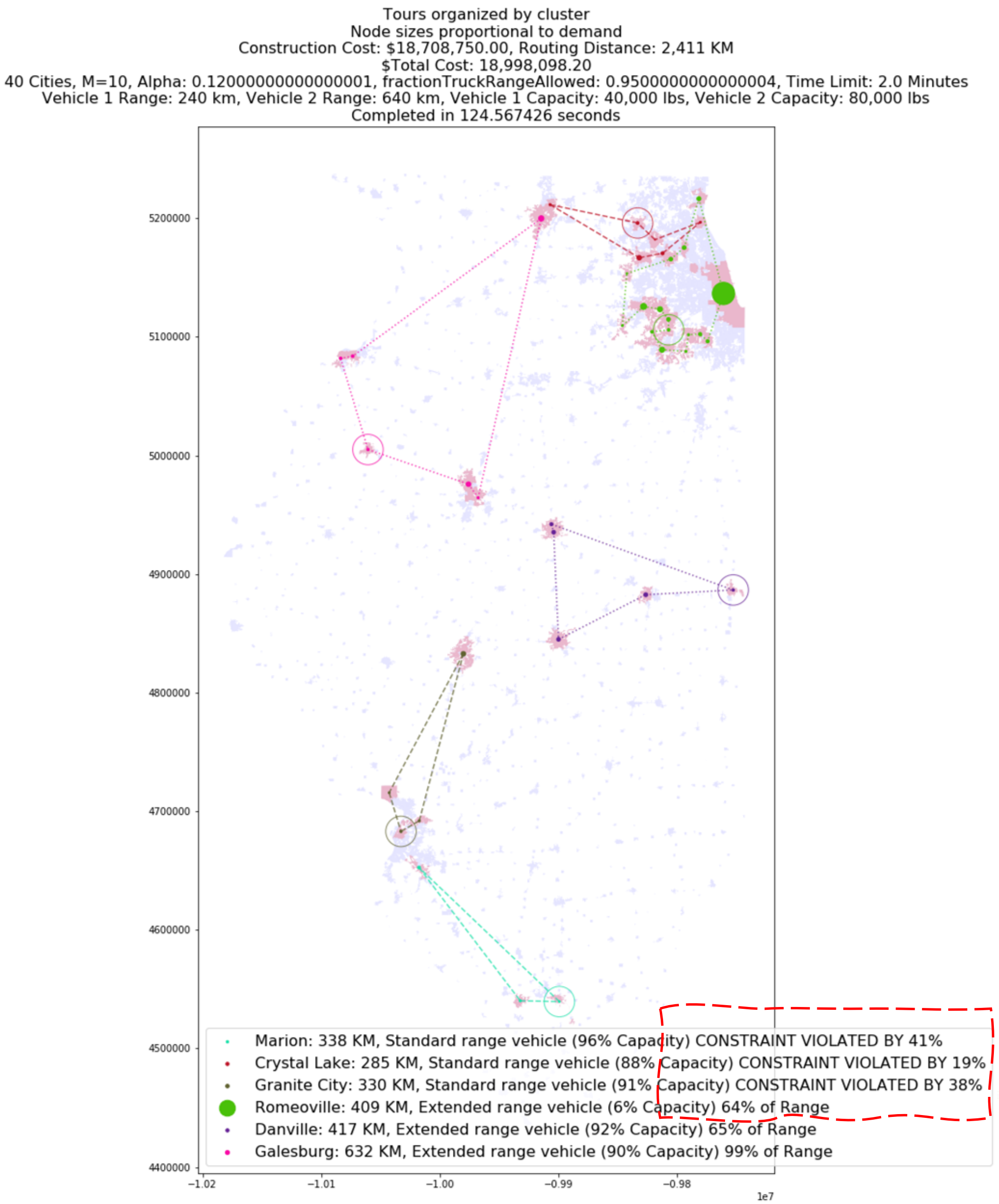
Heuristic 1: Study model sensitivity to $\alpha, \gamma_{battery}$



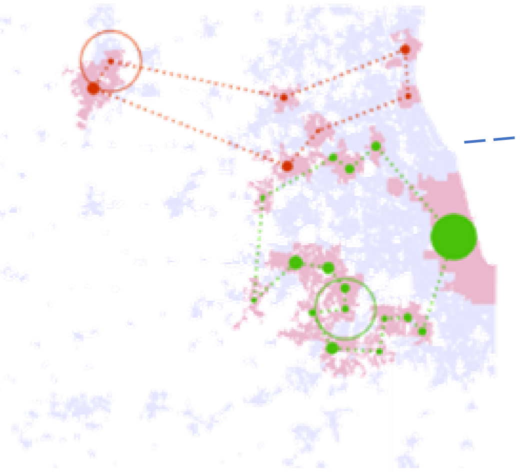
Motivation | Background | Case Study | Problem Formulation | Results | Discussion

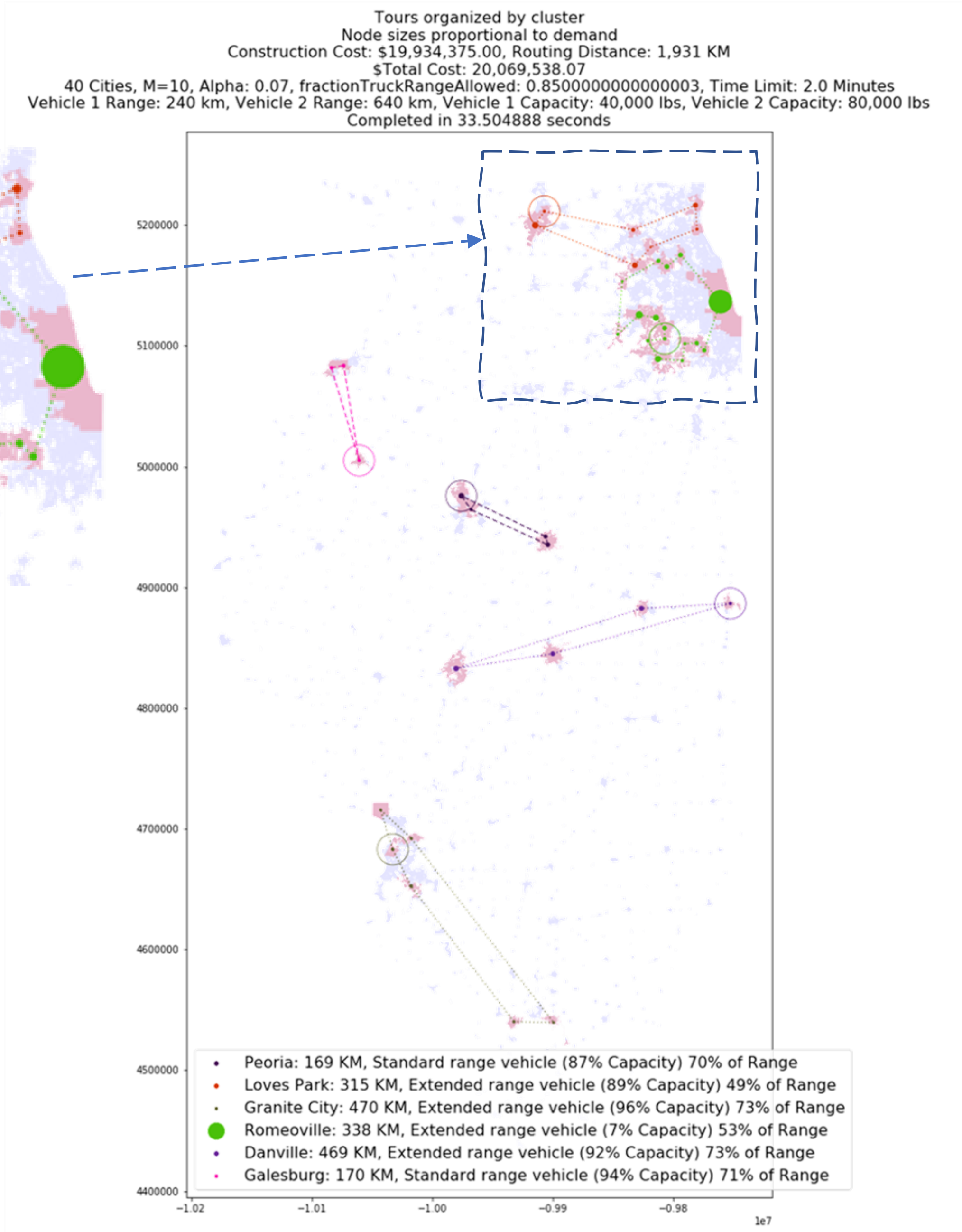
Solution Found

- Parameter search eliminates infeasible solutions
- Global search of assignment heuristic $\gamma_{battery}$
- Local optimization of assignment heuristic $\gamma_{battery}$
- Local optimization of assignment heuristic $\gamma_{battery}$



Solution Found





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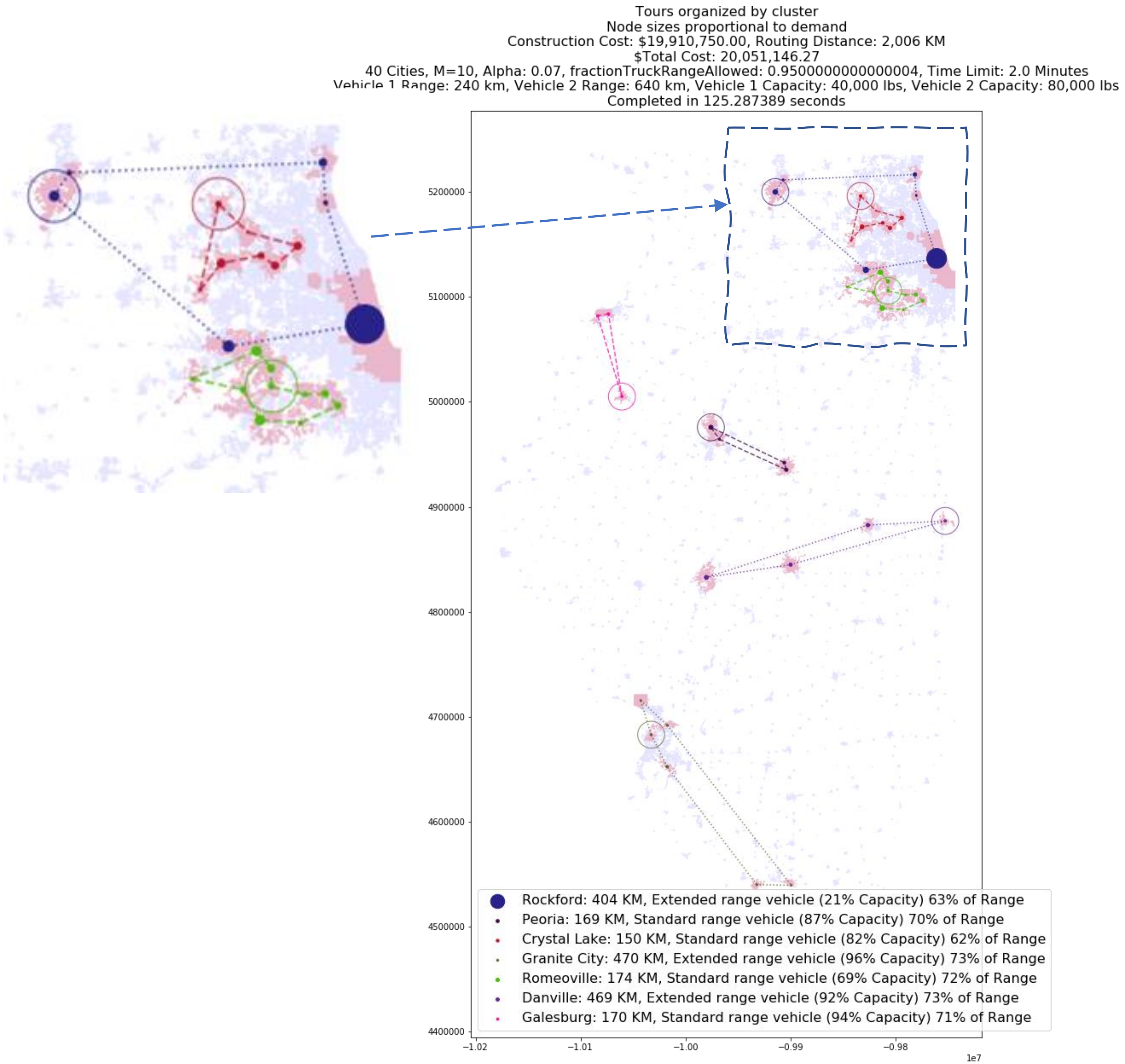

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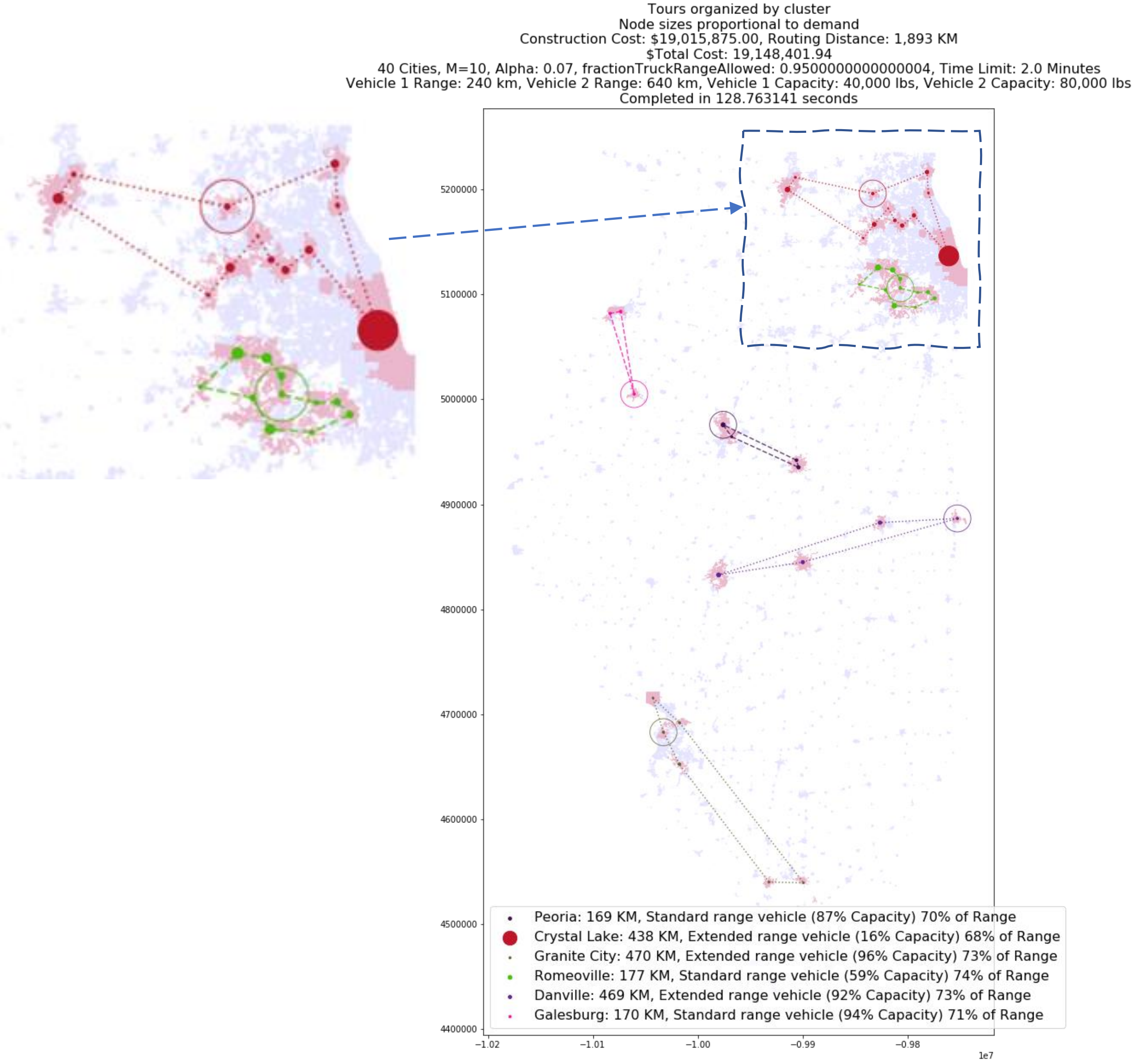

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Discussion

Discussion

Conclusions

- Impleme
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- Most imp
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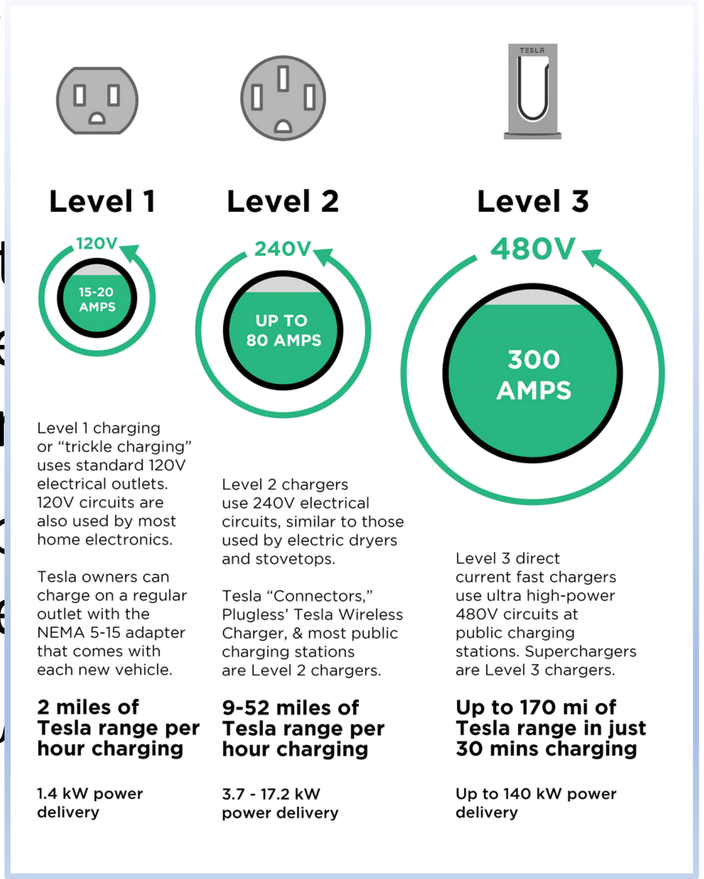
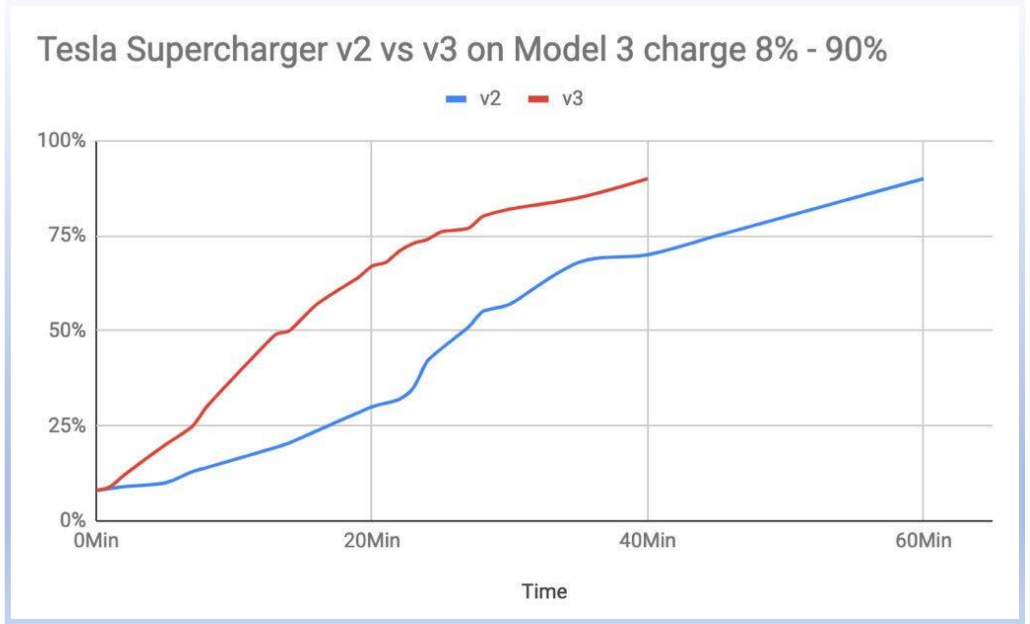


Limitations and Proposed Future Work

- Only one subtour per terminal
- No consideration for charging time



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Thank you for your time!

We welcome any questions. And cannot give discounts.

Parameter search identifies that our solution is sensitive to battery but not to alpha. This makes sense, because alpha is correlated to our TSP heuristic constraint