JOINT TRANSPORTATION
RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Recommendations for the Implementation of Heavy Fleet Routes and Facilities Location Optimization

Steven R. Dunlop, Thomas Brady, Olga Senicheva, David Ramirez, Dutt J. Thakkar, Akanksha Cheeti, Meghana Chava, Snehith Sankineni, Jayadeep Tagore, Harshit Malhotra, Sachin Deore

SPR-4701 • Report Number: FHWA/IN/JTRP-2024/25 • DOI: 10.5703/1288284317756

RECOMMENDED CITATION

Dunlop, S. R., Brady, T., Senicheva, O., Ramirez, D., Thakkar, D. J., Cheeti, A., Chava, M., Sankineni, S., Tagore, J., Malhotra, H., & Deore, S. (2024). *Recommendations for the implementation of heavy fleet routes and facilities location optimization* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/21). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317756

AUTHORS

Steven R. Dunlop, PhD
Managing Director of The Dauch Center
Mitch Daniels School of Business
Purdue University
(765) 494-7800
dunlops@purdue.edu
Corresponding Author

Thomas Brady, PhD
Professor of Operations Management
Department of Quantitative Business Studies
Purdue University Northwest

Olga Senicheva, PhD
Clinical Assistant Professor
Mitch Daniels School of Business
Purdue University

David Ramirez
Associate Project Manager - The Dauch Center
Mitch Daniels School of Business
Purdue University

Dutt J. Thakkar
Project Manager - The Dauch Center
Mitch Daniels School of Business
Purdue University

Akanksha Cheeti
Meghana Chava
Snehith Sankineni
Jayadeep Tagore
Harshit Malhotra
Sachin Deore
Graduate Researcher Assistants
The Dauch Center
Mitch Daniels School of Business
Purdue University

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2024/21	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Recommendations for the Implementation of Heavy Fleet Routes and Facilities Location Optimization		**5. Report Date** May 2024 **6. Performing Organization Code**
7. Author(s) Steven R. Dunlop, Thomas Brady, Olga Senicheva, David Ramirez, Dutt J. Thakkar, Akanksha Cheeti, Meghana Chava, Snehith Sankineni, Jayadeep Tagore, Harshit Malhotra, and Sachin Deore		**8. Performing Organization Report No.** FHWA/IN/JTRP-2024/21
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.** **11. Contract or Grant No.** SPR-4701
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		
16. Abstract This study's main objective was to enhance the efficiency of winter salting operations for the Indiana Department of Transportation (INDOT) through the following objectives. The first aim was to optimize the routing of salting vehicles from current facility locations to assigned road segments. The second and more pivotal objective was to identify the locations for future facilities based on "what-if" scenarios, such as the number of facilities and the composition of trucks at said facilities.		

17. Key Words winter operations optimization, fleet analysis, resource allocation analysis, route optimization	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classified (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 31	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

This project's main goal was to enhance the efficiency of winter salting operations for the Indiana Department of Transportation (INDOT) through the following objectives. First, we aimed to optimize the routing of salting vehicles from current facility locations to assigned road segments. The second and more pivotal objective was to identify the locations for future facilities based on "what-if" scenarios, such as the number of facilities and the composition of trucks at said facilities.

Findings

- The implementation of segment-based data management, in which reference posts were grouped into manageable road segments, resulted in an approximately 80% reduction in the original dataset size. This streamlined approach increased efficient data handling and analysis, enabling the processing of a large-scale road network on local computing resources.
- The analysis led to the identification of strategic locations for future salt and truck storage facilities. By considering factors like road segment characteristics, intersection data, and existing facility locations, the study provided insights for optimally situating new facilities to maximize coverage and operational efficiency for winter road maintenance.
- The application of clustering techniques significantly enhanced the efficiency of vehicle routing. By grouping customers into clusters based on proximity and shared characteristics, the approach successfully decomposed a complex logistical challenge into more manageable sub-problems.
- The study utilized two models (Models A and B) to address multi-lane, multi-vehicle routing challenges, with Model B being more computationally feasible. The analysis revealed three common route patterns—back and forth, loops, and misinformation paths. The back and forth and loops indicated efficient routing, while misinformation paths highlighted areas for improvement in assumptions around intersections and dependency on alternate facilities. The ratio of miles driven to miles assigned per facility provided a measure of efficiency, with a ratio of 1 indicating optimal routing without deadhead miles.
- The facility optimization model successfully determined the least number of facilities required to meet salting standards, along with their respective sizes, which were categorized as large, medium, or small. By integrating an optimization model with a clustering model, the study effectively allocated these facilities across virtual regions in Indiana. This strategy minimized the overage of salting capacity and ensured efficient use of resources, particularly focusing on the deployment of salt trucks with varying capacities.
- The application of a constrained K-means clustering algorithm further refined the positioning of facilities, considering factors like the number of trucks and their capacity. This led to a reduction in the average ratio of miles driven to miles assigned per facility. The optimal positioning of facilities, considering current and modified numbers, demonstrated a more efficient allocation of salting routes, thereby optimizing operational efficiency and resource utilization in winter road maintenance.

Implementation

This paper's recommendations focus on the strategic placement and sizing of salting facilities across Indiana to optimize winter road maintenance operations. By leveraging a two-tiered approach that combines an optimization model and a clustering model, it streamlines the allocation of resources (specifically salt trucks), enhances route efficiency, and minimizes resource waste.

The first stage of implementation used an optimization model to ascertain the minimum number and size of facilities that were essential for meeting the road salting requirements across the state. Critical parameters like dead head efficiency, routing efficiency, and truck capacities were calibrated to reflect realistic operational conditions. The model allows for dynamic adjustments to accommodate changes in the INDOT facility footprint and asset mix.

Post optimization, the study integrated a constrained K-means clustering algorithm to pinpoint the precise geographical locations for the facilities. This algorithm accounted for the number and capacity of trucks at each facility, alongside the initial allocations determined by the optimization model.

The implementation's success was measured by the reduction in the average ratio of miles driven to miles assigned per facility. This metric reflected the efficiency gains in route planning and resource utilization. Further adjustments were made to explore the impact of varying facility numbers and characteristics, with a focus on understanding the balance between facility count and operational efficiency.

The implementation demonstrated that the strategic placement and sizing of facilities, underpinned by robust optimization and clustering methodologies, could increase the route efficiency and improve the resource usage. The flexibility of the model to adapt to operational parameters changes and road networks makes it a valuable tool for ongoing and future applications in transportation logistics and infrastructure management. Future work may explore the integration of cost-based parameters and more granular data.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

1. INTRODUCTION

1.1 Project Objectives

This paper's main objective is to enhance the efficiency of winter salting operations for the Indiana Department of Transportation (INDOT) through the following two objectives.

- First, we aim to optimize the routing of salting vehicles from current facility locations to assigned road segments.
- The second and more pivotal objective is to identify the locations for future facilities based on "what-if" scenarios, such as the number of facilities and the composition of trucks at said facilities.

1.2 Introduction

1.2.1 Vehicle Routing Problem

Vehicle routing problems (VRP) represent a critical class of optimization problems in the field of logistics and supply chain management. Fundamentally, a VRP involves determining the most efficient set of routes for a fleet of vehicles to deliver goods or services to a set of locations. The core objective is to minimize operational costs, which typically include factors such as distance, time, cost, while adhering to a set of constraints. These constraints could include vehicle capacity, customer service requirements, and working hours.

Vehicle routing problems have many variations such as the following.

- *Classical VRP:* The basic form of VRP where the goal is to minimize the total distance for a fleet of vehicles originating from a single depot and returning after servicing a set of customers.
- *VRP with Time Windows (VRPTW):* An extension of the classic VRP where deliveries or services must occur within specified time windows.
- *Capacitated VRP (CVRP):* In this variation each vehicle has a limited carrying capacity, and the problem involves planning routes that respect these capacities.

These are just a small subset of the variations of vehicle routing problems that there are. Common inputs for these problems are the following.

- *Network Data:* Information on the road network including distances and time between different locations.
- *Vehicle Data:* Specifications for the vehicle fleet such as capacity, fuel efficiency, and operational cost.
- *Customer Data:* Information on the locations, service requirements, demand quantities, and time windows.
- *Operational Constraints:* Restrictions such as working hours, time limits, and route length limits.

Output for these problems include the following.

- *Routes:* Routes assigned to individual vehicles.
- *Operational Measures:* These measures include total distance, time spent, and fuel used.

VRPs are pivotal in optimizing resource utilization and reducing operational cost. However, VRPs are challenging to solve due to their complex and dynamic nature. They often involve a multitude of variables and constraints, such as varying customer demands, time windows, and vehicle capacities. Additionally, as VRPs belong to the class of NP-hard problems, the computational effort required to find an optimal solution increases exponentially with the number of destinations. This complexity necessitates sophisticated algorithms and heuristic approaches to derive practical and near-optimal solutions within reasonable time frames.

1.2.2 Facility Location Problem

A facility location problem is a type of optimization problem in operations research and logistics that deals with the selection of optimal locations for facilities, such as factories, warehouses, distribution centers, or service centers, to meet the demands of customers or clients. The primary objective of solving a facility location problem is to minimize the overall cost or maximize the efficiency of providing goods or services to a set of demand points while considering various constraints and costs associated with facility placement.

The basic components of a facility location problem typically include the following.

- *Facilities:* These are the locations where goods or services are produced, stored, or provided. The number of facilities, their capacities, and their potential locations are decision variables in the problem.
- *Demand Points:* These are the locations where customers or clients require goods or services. The demand at each point is known or estimated.
- *Costs:* Various costs are associated with facility placement, including set-up costs for establishing new facilities, operating costs, transportation costs between facilities and demand points, and sometimes costs related to the distance or time traveled.
- *Constraints:* Constraints may include limitations on the number of facilities that can be opened, capacity constraints for each facility, and service level requirements that must be met at each demand point.

The goal of solving a facility location problem is to determine which facilities should be opened, where they should be located, and how much demand each facility should serve to minimize the total cost or maximize the overall efficiency of the network. There are several variations of the facility location problem, each with its own specific objectives and constraints, including the following.

- *Single Facility Location Problem:* In this case, the goal is to find the best location for a single facility to serve all demand points.
- *Multiple Facility Location Problem:* This variant allows for the placement of multiple facilities, with the objective of minimizing costs while satisfying demand constraints.
- *p-Median Problem:* The objective is to choose p facilities from a set of potential locations to minimize the total distance or cost of serving all demand points.
- *p-Center Problem:* Similar to the p-median problem, but with the objective of minimizing the maximum distance

or cost between any demand point and its closest facility among the chosen p facilities.

- *Uncapacitated Facility Location Problem:* This version assumes that facilities have unlimited capacity and aims to minimize costs while choosing the facility locations.

Facility location problems are commonly encountered in supply chain management, transportation planning, network design, and facility siting decisions in various industries. Solving these problems optimally can help organizations save costs, improve efficiency, and enhance their overall operations. Various mathematical modeling techniques and optimization algorithms are used to address facility location problems, including linear programming, integer programming, and heuristic methods.

In the past, facility location problems were formulated and solved for winter road operations of different regions. Perrier et al. (2007) provide a survey of models and algorithms for winter road maintenance, specifically focusing on vehicle routing and depot location for spreading. The locations are divided into vehicle depot locations with the objective to minimize transportation and fixed vehicle depot costs and into materials depot locations with the objectives to minimize non-productive travel time, maximize use by multiple crews, minimize possible environmental damage, etc. Various problem types were analyzed, including finding optimal vehicle depot location, optimal materials depot location, a combined vehicle and materials depot location and fleet sizing, and a combined materials depot location and route assignment. The problems were formulated as an incapacitated facility location problem, a p-median problem, a capacitated arc routing problem, a linear integer program, a location-arc routing problem. Mostly heuristic techniques were used to solve the location problems.

2. DATA

2.1 Reference Posts (Mileposts)

Reference posts, also referred to as mileposts throughout this report, represent specific locations requiring salt treatment. Figure 2.1 provides a visual representation of all the mileposts that were included in the original dataset.

For each reference post entry in the dataset geographic information was provided on the increasing side of the road only. The number of lanes for both the increasing and decreasing sides of the road was provided. For this analysis, we assume that both the increasing and decreasing sides of the road have the same geographic coordinates. (This does not capture information on the occasions when the increasing and decreasing sides of the road do not run in parallel leading to error in the distance traveled by a truck.) Duplicates of these mile post entries were created in the dataset with the first occurrence corresponding to the increasing side of the road and the second corresponding to the decreasing side of the road. We see this in Figure 2.2 where darker shades correspond to a greater number of lanes across both the increasing and decreasing sides of the road.

Given the original milepost data, we were required to remove some of the mileposts from within the dataset. This was due to a variety of reasons such as the roads were relinquished to the county, or the road only consisted of a couple of mileposts. To maintain the scalability of this analysis to future road networks we removed mileposts based on the following criteria rather than by individual mileposts (note that U_4211_299, U_421_300 were removed due to data error).

- Designated as “old” roads.
- Designated as “toll” roads.
- Fewer than five mileposts.

In total 139 reference posts were removed. These reference posts were removed from the analysis; however, they were still assigned to the closest geographical facility to be handled at the discretion of the facility manager.

To view a subset of the cleaned milepost data that was used in this analysis see Table A.1. To view a subset of data that was removed from this analysis see Table A.2.

2.2 Intersections

Intersections offer insight into how the road system is connected. Figure 2.3 overlays intersection points on top of reference posts.

Based on the intersection data we know what roads form an intersection; however, we do not know what reference posts form an intersection. We discuss how we approach this issue in the following example.

2.2.1 Intersection Example

To identify how an intersection is formed we allocated four reference posts to each intersection. Two come from “Road A” and two come from “Road B.” We do this in such a way that these four reference posts surround the intersection. (This is an assumption made that all intersections have at maximum four mileposts, if able.) The following are two special cases that can occur here.

1. The intersection occurs at the end/beginning of a road.
2. The true intersection does not have four connecting points, such as a merging road.

In the case of (a) we can determine if the intersection occurs at the end of the road. In the case of (b) we are unable to determine whether an intersection can truly travel to all the closest points. Therefore, for the purpose analysis, we assume that travel is possible between all closest points of connecting roads. Additionally, we treat all intersections as U-turn points.

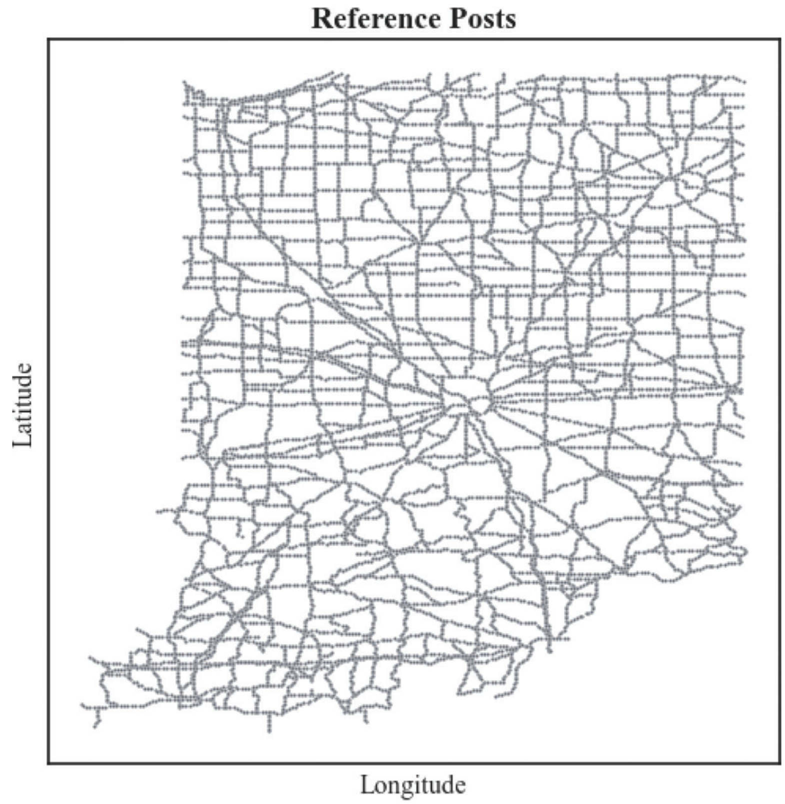


Figure 2.1 Reference posts.

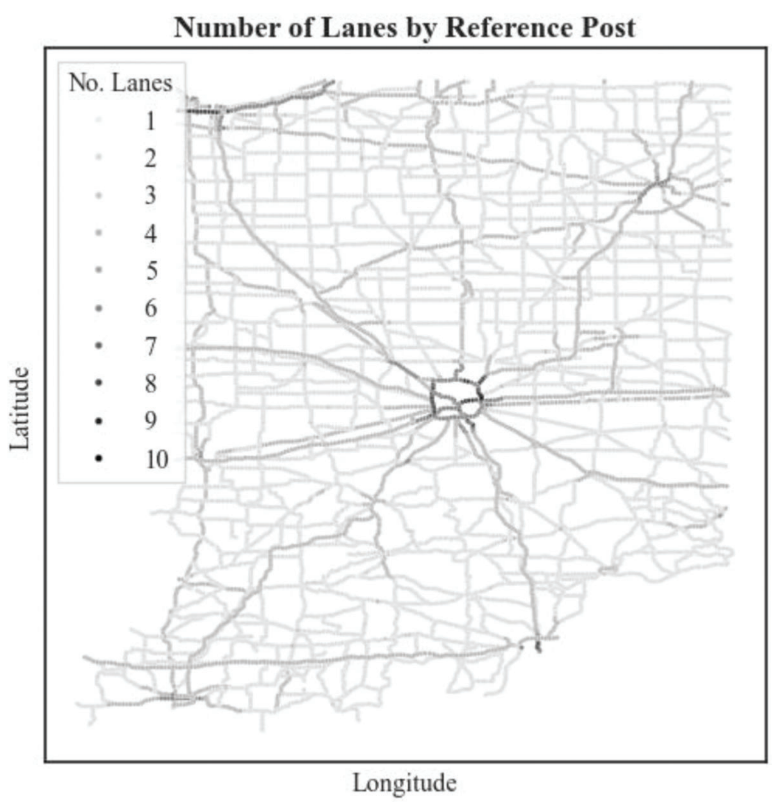


Figure 2.2 Number of lanes by reference post.

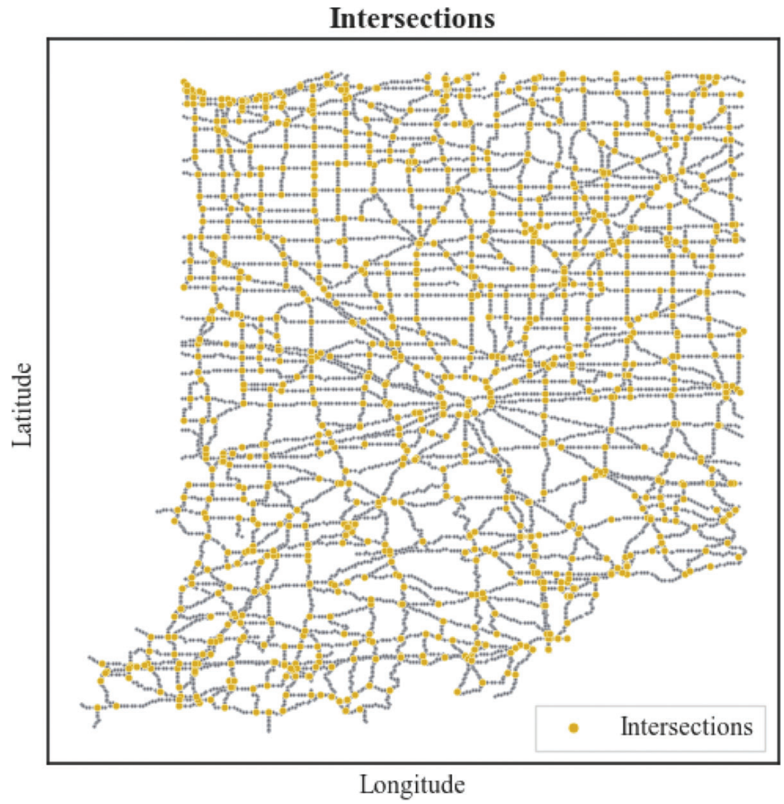


Figure 2.3 Intersections.

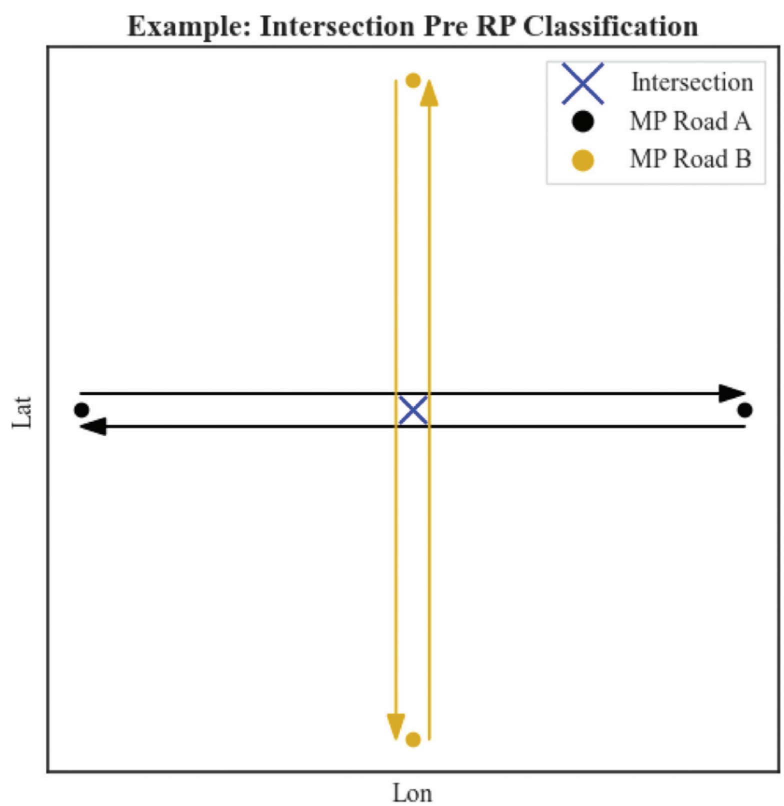


Figure 2.4 Intersection pre-RP classification.

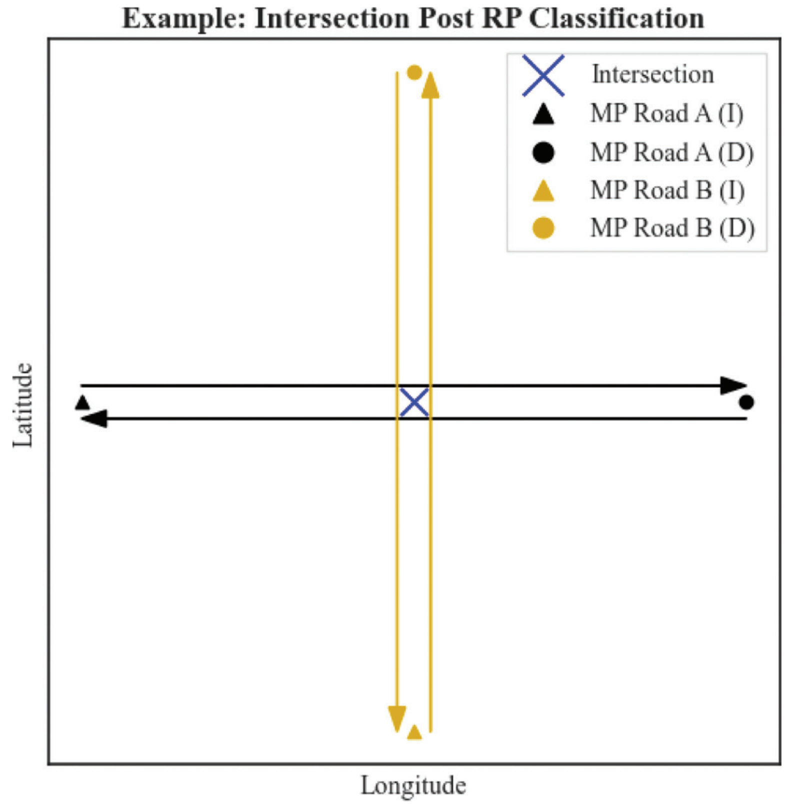


Figure 2.5 Intersection post RP classification.

In the example represented in Figure 2.4 and Figure 2.5 we have two roads, Road A and Road B. These roads are represented by the black and gold arrows, respectively. These roads intersect at the blue "X."

We then classify the closest reference post around each intersection as either the closest increasing or decreasing reference post. As seen above, triangles represent the closest reference post on the increasing side as they are the reference posts a truck must pass through when traveling N/E before reaching an intersection. On the other hand, circles represent the closest reference post on the decreasing side as they are the reference posts a truck must pass through when traveling S/W before reaching an intersection. This allows us to define travel between roads. Travel between roads will be discussed in greater detail in the arc matrix section.

To view a subset of the cleaned intersection data used in this analysis see Table A.3.

2.3 Facilities

Facility data included information on various facility types. We consider only two types of facilities in this analysis. These include facilities that store salt and those that store trucks. Figure 2.6 and Figure 2.7 show the locations of these facilities. In total there are 100 truck facilities and 111 salt facilities.

To view a subset of the cleaned facility data, see Table A.3 and Table A.4.

2.4 Road Segments

In order to reduce data size, we create segments out of the reference posts. We do this in such a way that no information is lost. Characteristics of segments include the following.

1. All reference posts in a segment belong to the same road.
2. All reference posts in a segment contain the same number of lanes.
3. All reference posts in a segment are in the same direction (increasing/decreasing).
4. A segment will never cross an intersection. In the majority of cases a segment will either begin or end at an intersection point.
5. The number of mileposts in a segment will never exceed a predetermined maximum number of segments.

2.4.1 Segment Example

We see in Figure 2.8 and Figure 2.9 an example on what creating segments looks like. In this example we set the maximum number of mileposts parameter to three. (The total number of segments and this parameter are inversely related. The larger one becomes the smaller the other becomes.) As we see in this example it is possible to create segments of varying lengths; however, these segments will never cross over an intersection as those are the locations where a truck is able to cross over into a new road.

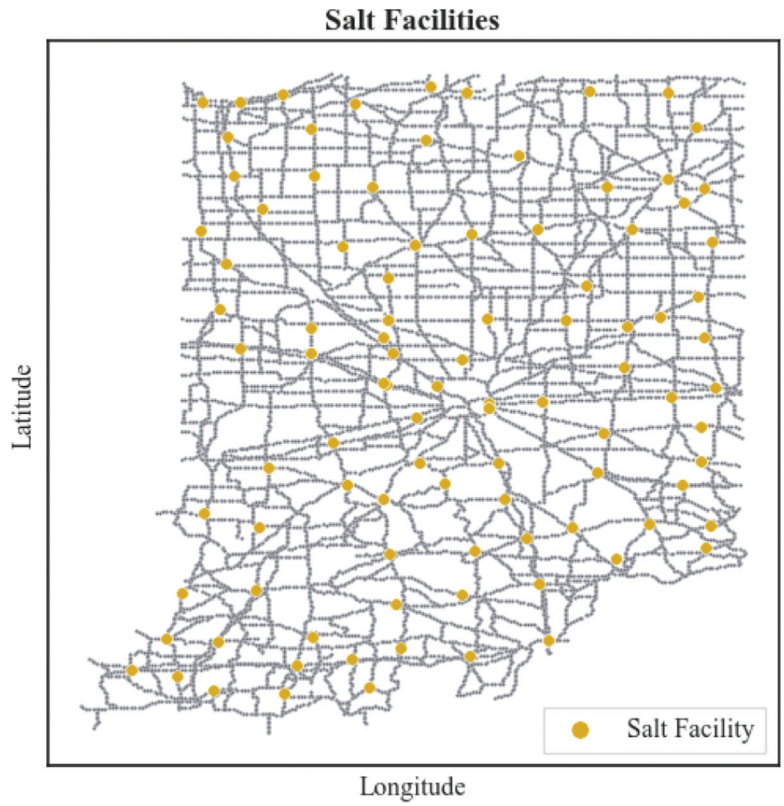


Figure 2.6 Salt facilities.

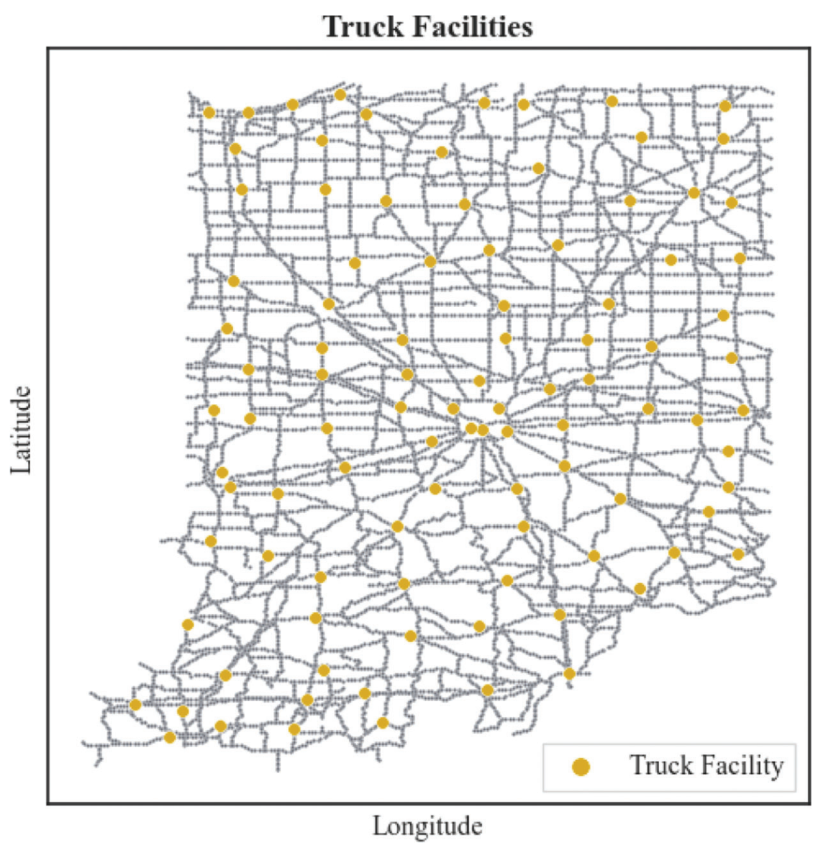


Figure 2.7 Truck facilities.

Figure 2.8 Pre-road segments.

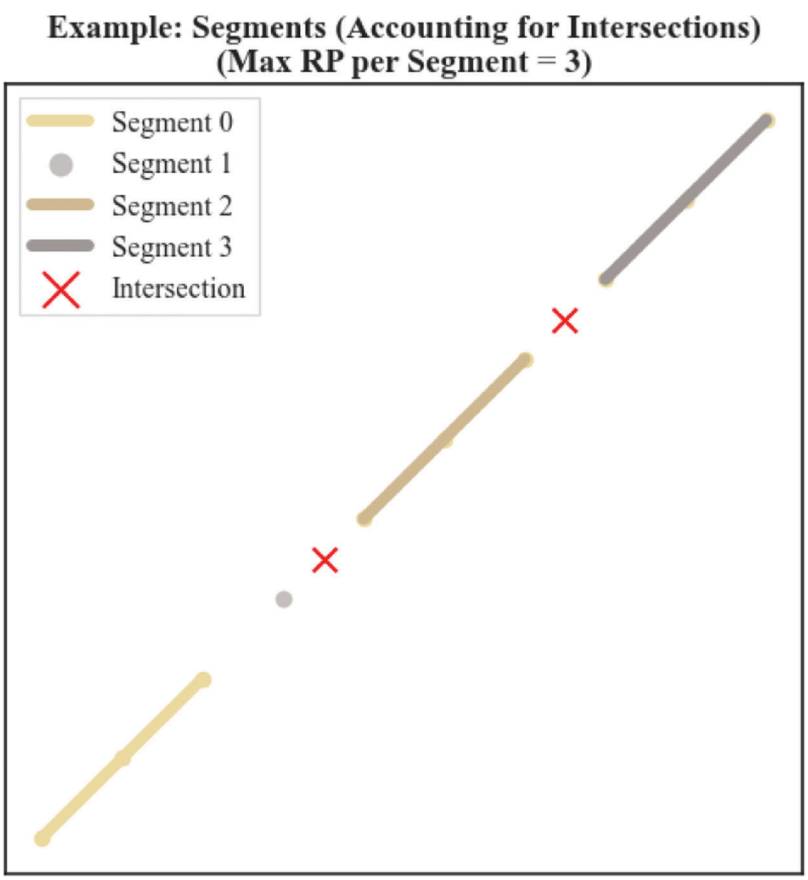


Figure 2.9 Post-road segments.

2.4.2 Optimal Number of Segments

As we modify the maximum number of reference posts to allow in a segment, we see a large reduction in the size of the data set where data reduction plateaus with a maximum number of mileposts in a segment being 25. (This is an upper bound on the number of mileposts that can belong to a segment. It is still possible to have segments of varying other lengths.) We see this in Figure 2.10. The original number of mileposts, on the increasing and decreasing sides of the road, is reduced by approximately 80%. (The initial case of max number of mileposts equal to one is the case where we work directly with the original milepost dataset, accounting for both increasing and decreasing sides of the road.) Still, simply by reducing the data size we are not guaranteed improving results of the analysis; however, the reduction in data size does allow for a problem of this size to be run on a local machine.

2.4.3 Seymour District Segments

Figure 2.11 shows the mileposts associated with the Seymour District while Figure 2.12 and Figure 2.13 show a visual representation of what the district looks like after segments are created from its mileposts. (Increasing and decreasing sides of the road have been offset for easier differentiation.)

As we see above, as the maximum number of reference post decreased from 25 to 5 the number of segments increases; however, the overall road network is still represented in the full segment dataset.

2.5 Arc Matrix

We have defined rules as to how intersections connect roads to one another as well as how travel along the same road can be simplified. Now we define an arc matrix that will be a matrix representation of this travel. Below are the rules that we define for travel of a truck.

1. Travel along the same road is allowed provided that the next stop is in the direction of travel and is the next segment belonging to the road (i.e., a truck cannot skip portions of a road).
2. If a truck reaches an intersection it can travel along the same road, make a U-turn, or hop onto either direction of the connecting road.
3. Facilities can travel to the closest intersection and all mileposts that are associated with said intersection.
4. If a segment is at the edge of the network (state lines) or the end of the road it can make a U-turn to the decreasing side of the road. This may mean that a truck must continue into the next state until a U-turn point is encountered.

2.5.1 Arc Matrix Example

In Figure 2.14 we see an example road system with arrows showing the direction of travel (i.e., Node A can travel to Node B and Node C). Below Figure 2.14 is a

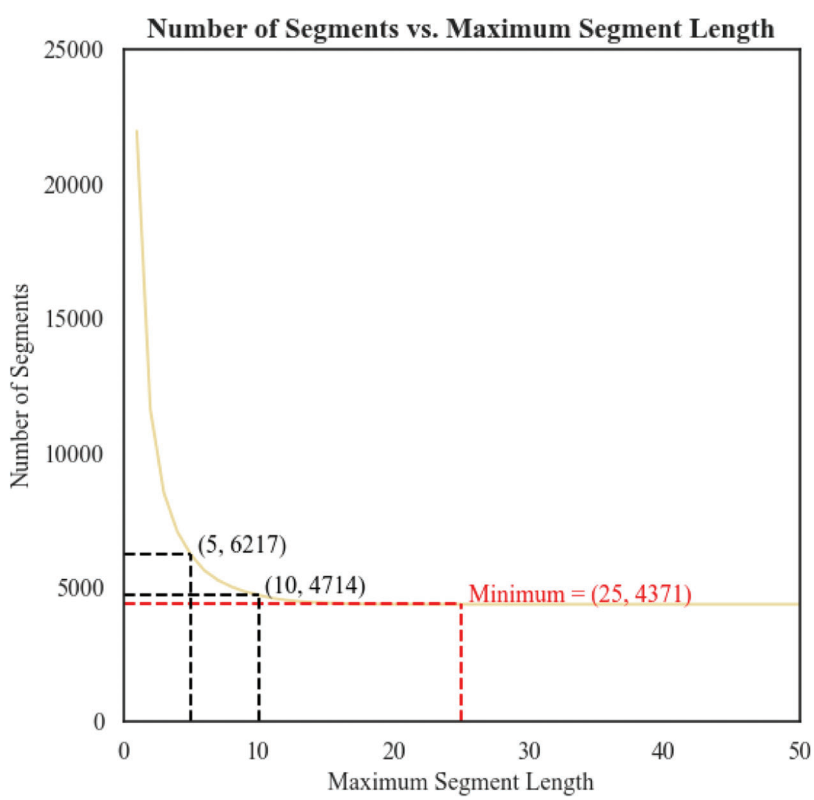


Figure 2.10 Number of segments vs. max segment length.

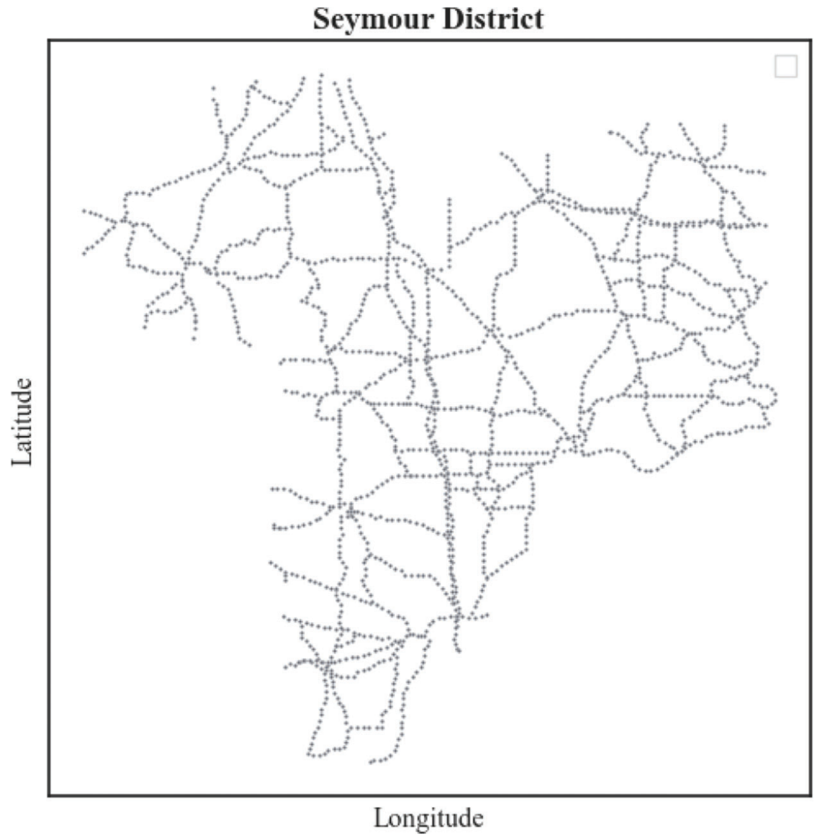


Figure 2.11 Seymour RP.

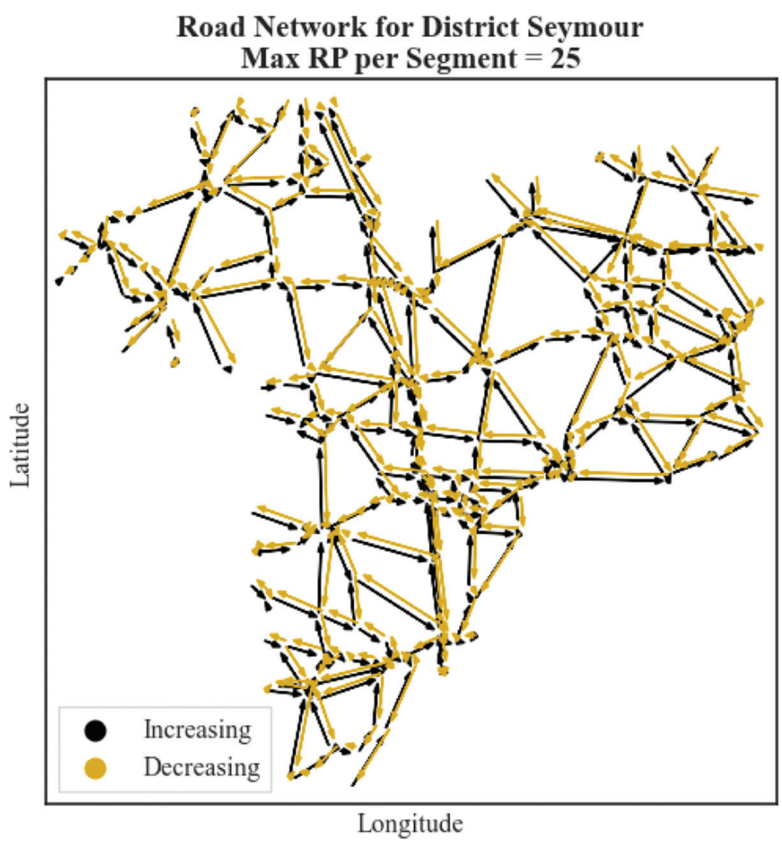


Figure 2.12 Seymour District Segments 25.

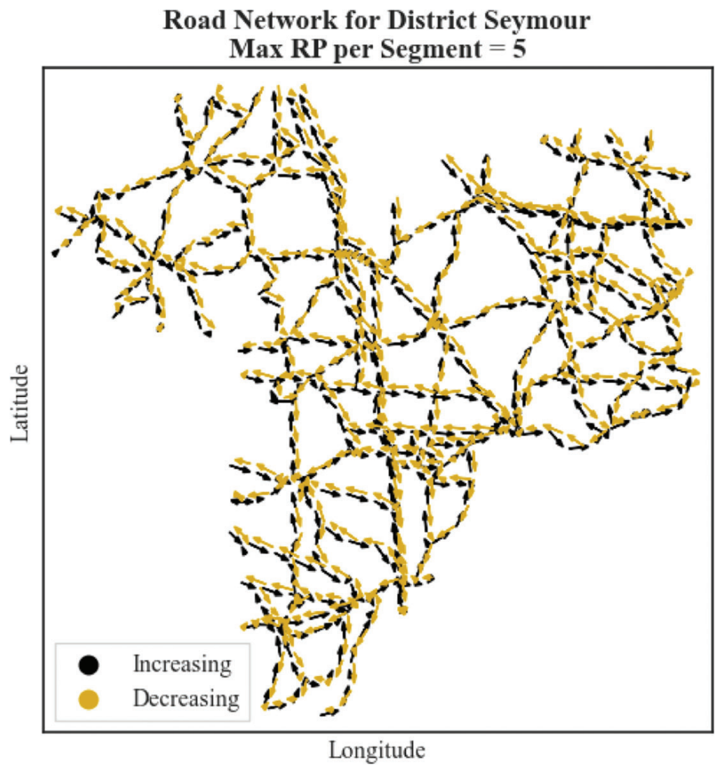
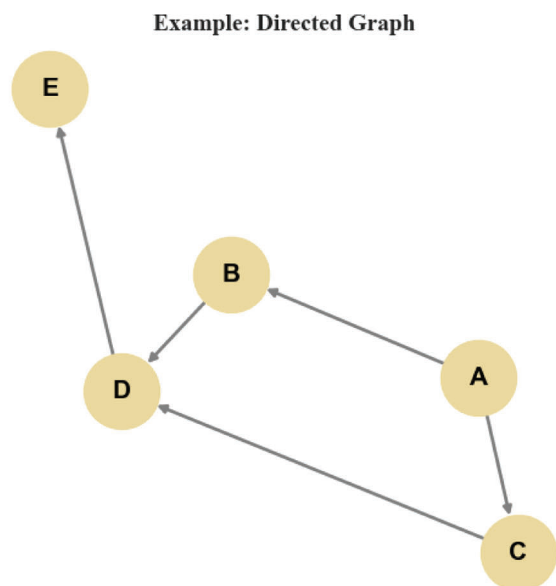


Figure 2.13 Seymour District Segments 5.



From:, To:	A	B	C	D	E
A	0	1	1	0	0
B	0	0	0	1	0
C	0	0	0	1	0
D	0	0	0	0	1
E	0	0	0	0	0

Figure 2.14 Arc matrix example.

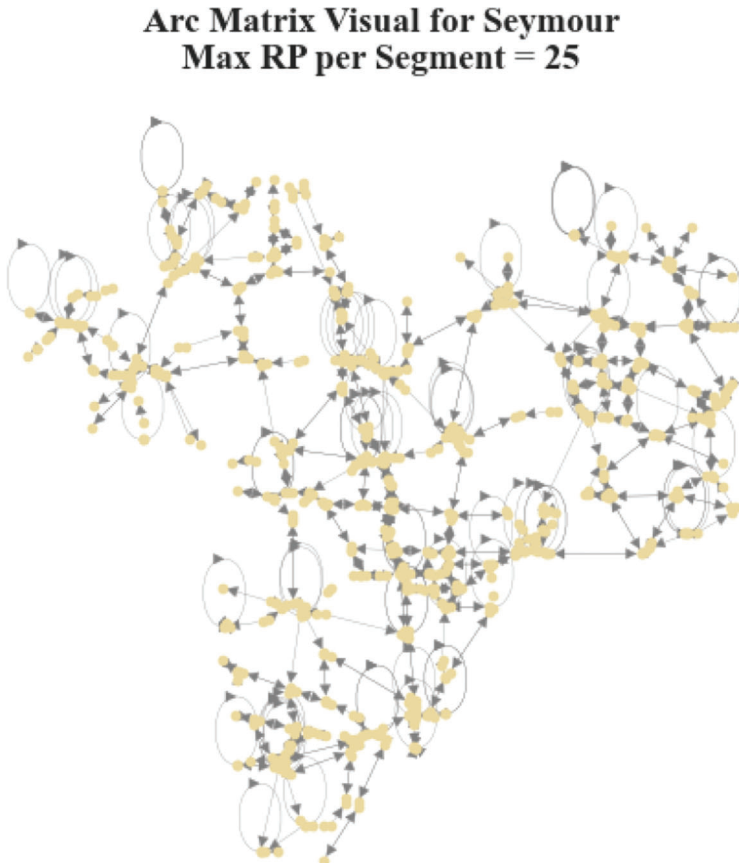


Figure 2.15 Visual representation of the arc matrix for the Seymour District.

table that is a matrix representation of this graph. The matrix representation of this travel between nodes can be seen in the first column "from" of the table below where (From: A; To: B) and (From: A; To: C) equal one.

2.5.2 Seymour Arc Matrix Visual

In a similar fashion we create such a matrix to represent travel between segments, intersections, and facilities. Figure 2.15 is a visual representation of the arc matrix for the Seymour District.

3. MULTILANE OPTIMIZATION

3.1 Clustering

Clustering is a fundamental technique in data analysis and optimization that involves grouping similar data points together based on certain criteria. In the context of vehicle routing problems, clustering plays a pivotal role in simplifying the complexity of these logistical challenges. Vehicle routing problems entail determining the most efficient routes for a fleet of vehicles to deliver goods or services to a set of customers, aiming to minimize transportation costs and optimize resource allocation.

By applying clustering methods, the problem is initially decomposed into smaller, more manageable subproblems, where customers are grouped into clusters based on proximity or shared characteristics. This segmentation not only reduces the overall problem size but also enables more efficient route planning by addressing clusters of customers as single entities, ultimately leading to improved transportation efficiency and cost savings.

3.1.1 Clustering Problem Formulation

We define the clustering problem as follows.
Minimize:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} d_{ij}x_{ij}$$

Subject to:

(1) $\sum_{i=1}^{n} x_{ij} * l_j \leq \ minCoverage * c_j \forall j \in K$

(2) $\sum_{i=1}^{n} x_{ij} = 1 \ \forall j \in K$

(3) $x_{ij} d_i j \leq Distance \ \forall i \in N, j$

Where x is a binary variable that is equal to 1 if and only if the i-th data point is assigned to the j-th facility, d is the distance between the i-th data point and the j-th facility, l are the maximum number of lane miles facility *j* can support, *minCoverage* is the minimum coverage ratio that a facility will handle, *c* is the capacity of facility *j*, *maxDistance* is the farthest away that a point can be.

Constraint (1): ensures that a facility will not support a greater mileage than it can handle. Constraint (2): ensures all reference posts/segment are assigned to one facility only. Constraint (3): ensures that any milepost assigned to a facility does not exceed its maximum capacity.

3.1.2 Clustering Results

Figures 3.1 and 3.2 show the distribution of segments assigned to the different facilities.

3.2 Multilane Optimization

Multilane, multivehicle, and capacitated routing represents a specific subset of routing problems that address the challenges associated with multi-lane road networks, multiple vehicles, and capacity constraints. In such problems, the goal is to determine optimal routes for a fleet of vehicles that can travel on roads with multiple lanes, considering lane-specific information, while ensuring that the vehicles' capacities are not exceeded.

Routing problems such as this are complex for various reasons including, but not limited to, combinatorial nature, capacity constraints, time windows, potential multi-objectives, and geographical constraints (one-way roads).

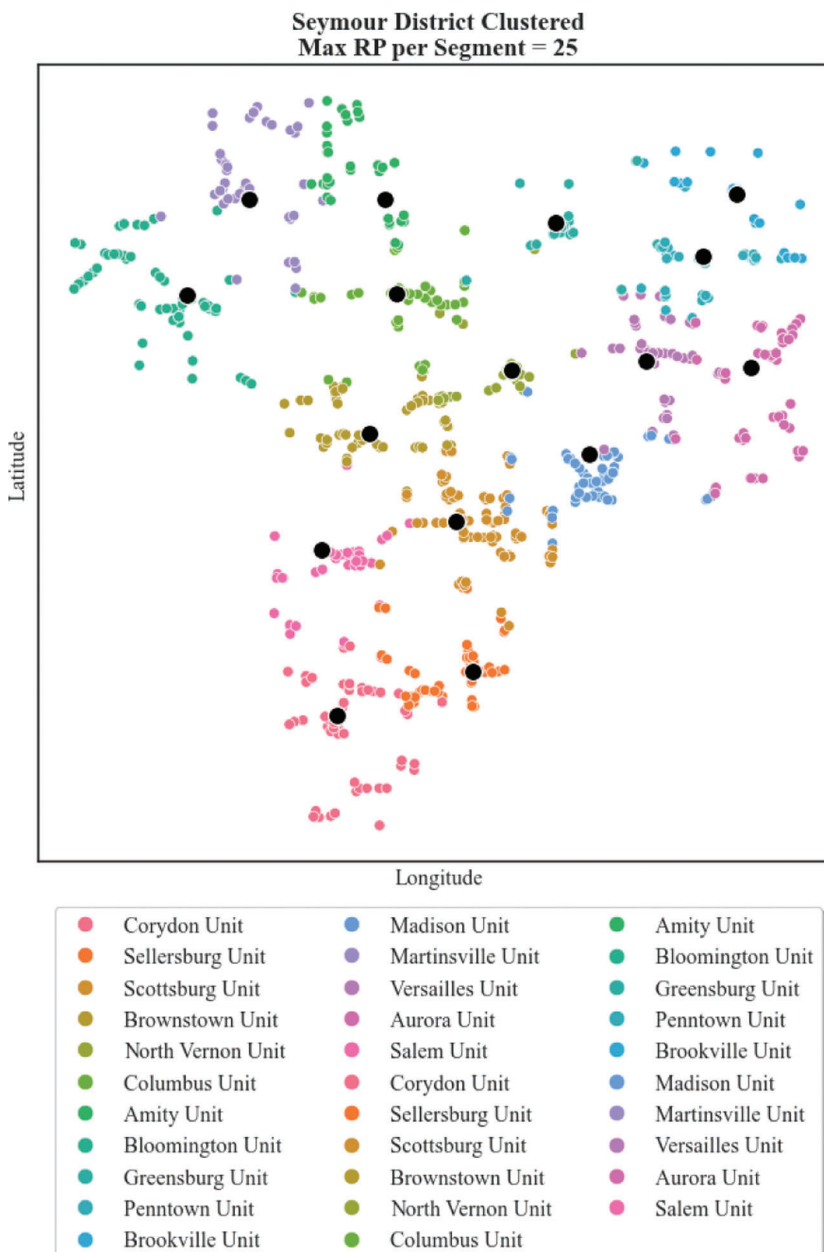


Figure 3.1 Seymour clustered 25.

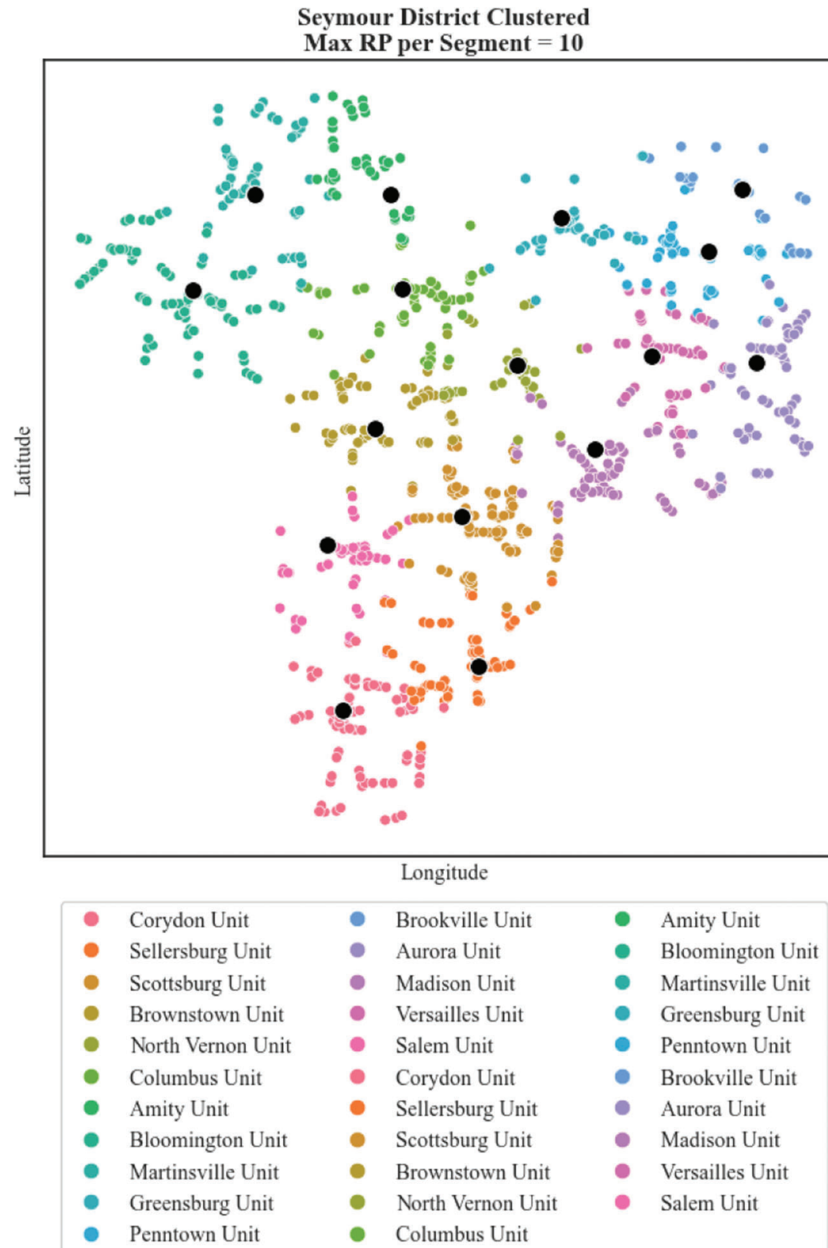


Figure 3.2 Seymour clustered 10.

A list of results for Bloomington can be found in Appendix B. (This list includes results for locations at which a solution was found. Some facilities had an infeasible solution.)

Each unit's results include (a) an excel file with the post names and directions for each truck at that unit, (b) a png image of each trucks route, and (c) and html file that can be opened in a browser tab that allows a user to explore a route in greater detail.

Due to time complexity and problem size, we defined two models, Models A and B. Model A is the strictest model and Model B is the most relaxed model. Due to computer resources available results are provided for Model B only. Model A hit time limits for solve time almost every iteration.

3.2.1 Problem Formulations

Let,

- K_h: set of vehicles at depot h, $h \in H$
- H: set of home nodes
- J: set of refill nodes
- M: set of demand nodes
- N: set of all nodes
- c_{kh}: capacity of vehicle k at home node h, $k \in K$, $h \in H$

- s_i: single lane salt demand of node i, $i \in N$
- v_i: Number of lanes at node i, $i \in N$
- A_{ij}: Arc matrix. 1 if travel between i and j is possible. 0 otherwise $(i, j) \in N$
- L: Large number

Decision Variables

- X_{ijk}: binary variable, 1 if a vehicle k travels from i to j. $(i, j) \in N$, $k \in K$
- R_{ik}: cumulative salt demand to reach node i by vehicle k. $i \in N$, $k \in K$

3.2.2 Model A

We define Model A as follows.

Minimize: $min \sum_{k \in K} \sum_{(i,j) \in N} d_{i,j} x_{i,j,k}$

Subject to:

(1) $\sum_{k \in K} \sum_{j \in N} x_{i,j,k} \geq v_i \;\; \forall i \in [H+J, N)$

(2) $\sum_{j=H+J}^{N} x_{h,j,k} = 1 \;\; \forall k \in K_h,\; h \in [0, H)$

(3) $R_{i,j} \leq c_k \;\forall k \in K, \forall i \in [H+J, N)$

(4) $R_{j,k} = 0 \;\; \forall k \in K, \;\forall j \in [0, H+J)$

(5) $R_{i,k} + s_j - R_{j,k} \leq (1 - x_{i,j,k})\, L \;\; \forall k \in K, (i, j) \in A$

(6) $\sum_{i=0}^{N} x_{i,j,k} = \sum_{i=0}^{N} x_{j,i,k} \;\; \forall k \in K, \; j \in N$

(7) $\sum_{(i,j) \in N} d_{i,j} x_{i,j,k} \leq D \;\; \forall k \in K$

(8) $A_{i,j}\, x_{i,j,k} = x_{i,j,k} \;\; \forall (i, j) \in N, \;\forall k \in K$

(9) $x_{i,j,k} \geq 0$, Binary, $\forall (i, j) \in N, k \in K$

(10) $R_{i,k} \geq 0, \;\forall k \in K, i \in V$

Constraint (1): each demand node must be visited at least the number of lanes it contains. Note this is not equal to v because a node may be used more times than required. Constraint (2): ensures each truck's route begins from its assigned home location. Constraint (3): keep demand within the capacity of a vehicle. Constraint (4): reset the vehicles capacity once it visits a refill location. Assume that home node contains salt. Constraint (5): ensures salt used at location is reflective of the incremental volume of that stop. Constraint (6): if a vehicle leaves a node it must return to that node. Constraint (7): distance constraint on how far each vehicle can travel. Note that this is "model" distance. This may change when converting to real distances on the road network due to construction, etc. Constraint (8): ensure that a vehicle is traveling along the correct path. Constraints (9) and (10): nonnegative constraints.

3.2.3 Model B

We define Model B as follows.

Minimize min $\Sigma_{k \in K} \Sigma_{(i,j) \in N} d_{i,j}\, x_{i,j,k}$

Subject to:

(1) $\Sigma_{k \in K} \Sigma_{j \in N} x_{i,j,k} = v_i \quad \forall i \in [H+J, N)$

(2) $\sum_{j=H+J}^{N} x_{h,j,k} = 1 \quad \forall k \in K_h, \;\; h \in [0,H)$

(3) $\sum_{i=0}^{N} x_{i,j,k} = \sum_{i=0}^{N} x_{i,j,k} \;\; \forall k \in K, \;\; j \in N$

(4) $\Sigma_{(i,j) \in N} d_{i,j}\, x_{i,j,k} \leq D \;\; \forall k \in K$

(5) $A_{i,j}\, x_{i,j,k} = x_{i,j,k} \;\; \forall (i, j) \in N, \forall k \in K$

(6) $\Sigma_{\setminus i,j \in N}\, x_{ijk} \leq W \;\; \forall k \in K$

(7) $x_{i,j,k} \geq 0$, Binary, $\;\forall (i, j) \in N, \;\; k \in K$

Constraint (1): each demand node must be visited at least the number of lanes it contains. Note this is not equal to v because a node may be used more times than required. Constraint (2): ensures each truck's route begins from its assigned home location. Constraint (3): if a vehicle leaves a node it must return to that node. Constraint (4): distance constraint on how far each vehicle can travel. Note that this is "model" distance. This may change when converting to real distances on the road network due to construction, etc. Constraint (5): ensure that a vehicle is traveling along the correct path. Constraint (7): nonnegative constraints.

3.2.4 Results

In general, three common routes occur.

1. *Back and Forth:* These are routes wherein a truck heads up the increasing side of the road and heads back down the decreasing side of the road. Figure 3.3 is an example from the Poseyville Unit.
2. *Loops:* These are routes where a truck completes a circular path. Figure 3.4 is an example from the Jasper Unit.
3. *Misinformation Paths:* These are paths that are either much longer than they should be or seem to follow a non-intuitive path. Potential reasons for seeing these paths have to do with the following.
   a. Assumptions around intersections. Because we must assume travel along all paths in an intersection when the case occurs that this is not the case the truck must often travel a long distance before it can turn around.
   b. Dependence on alternate facilities. In order to reduce the problem size, we solve for individual facilities. In the future, better results may be yielded when solving over an entire district compared to individual facilities.

In order to compare results across districts we create a ratio between the mile driven to the miles assigned to a facility. A value of 1 indicates that there were no dead-head miles. Figure 3.5 has the aggregate results for each district.

Figure 3.6 through Figure 3.11 are the results for each individual facility by district.

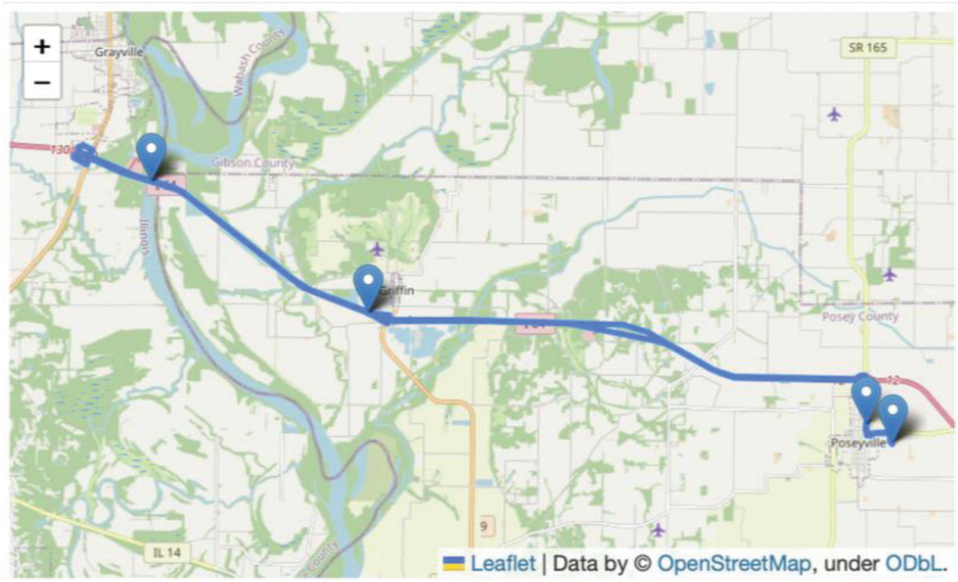


Figure 3.3 Example of back-and-forth route at the Poseyville Unit.

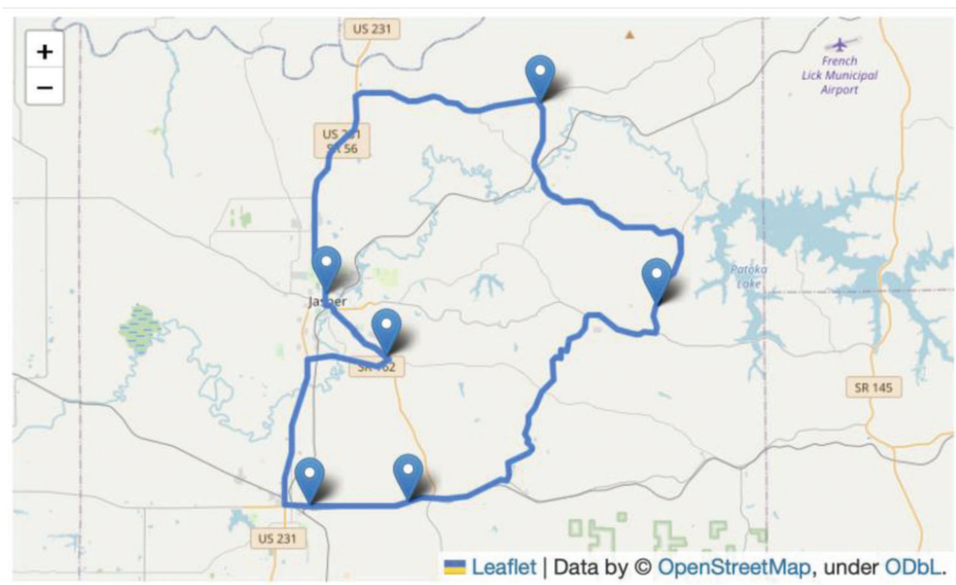


Figure 3.4 Example of loop route at the Jasper Unit.

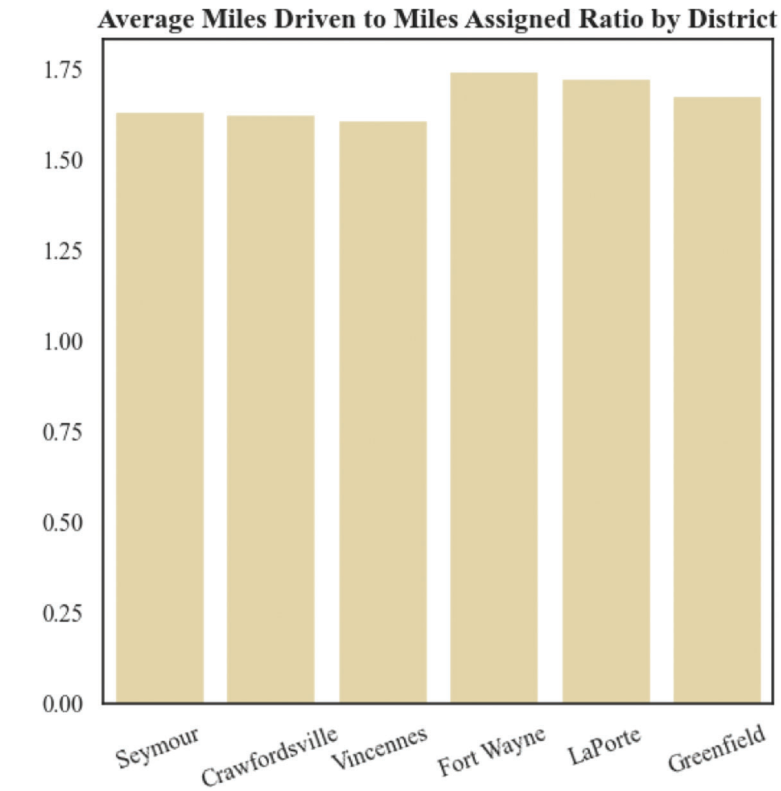


Figure 3.5 Aggregate ratio between the miles driven to the miles assigned to a facility for each district.

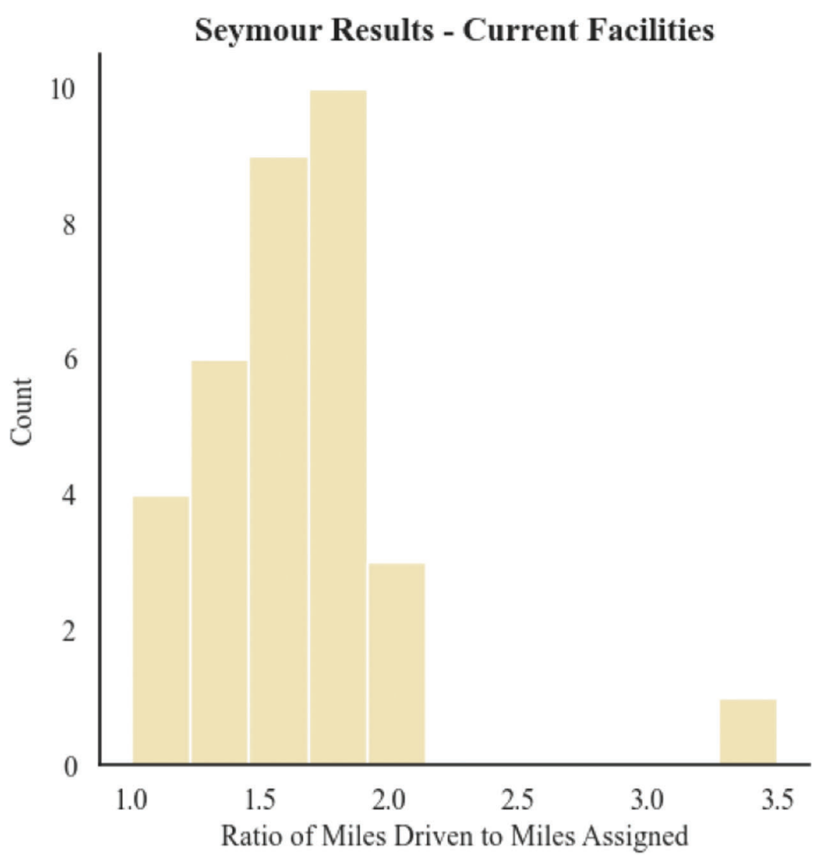


Figure 3.6 Aggregate ratio between the miles driven to the miles assigned to a facility for the Seymour District.

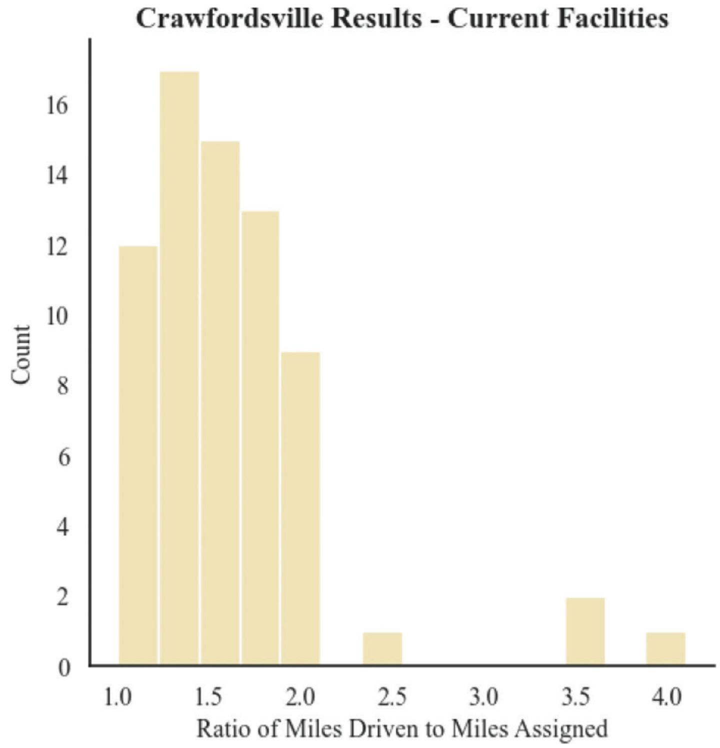


Figure 3.7 Aggregate ratio between the miles driven to the miles assigned to a facility for the Crawfordsville District.

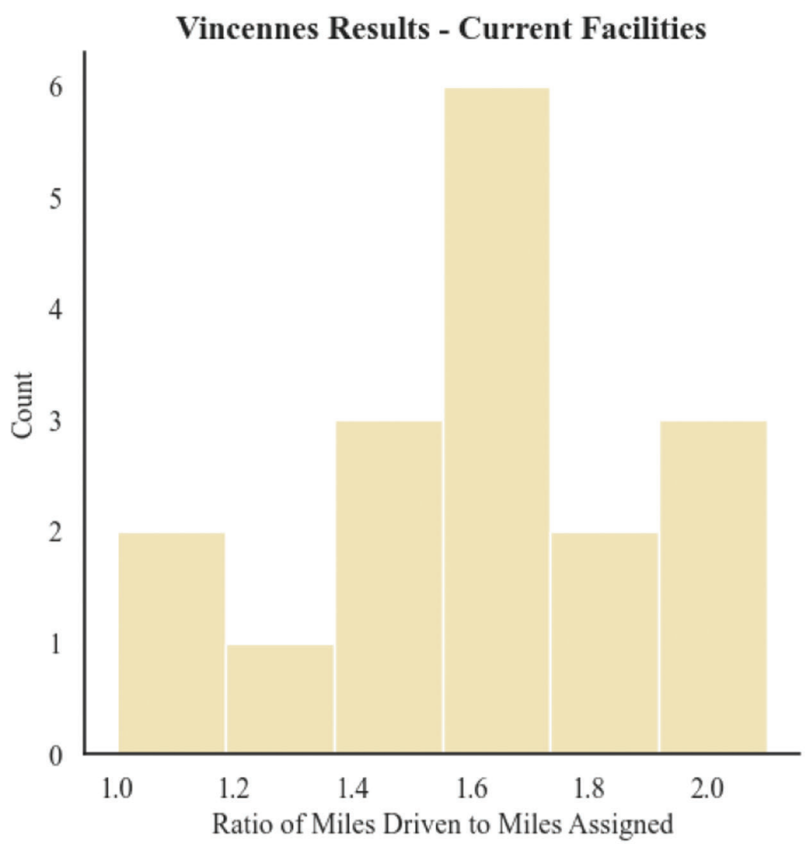


Figure 3.8 Aggregate ratio between the miles driven to the miles assigned to a facility for the Vincennes District.

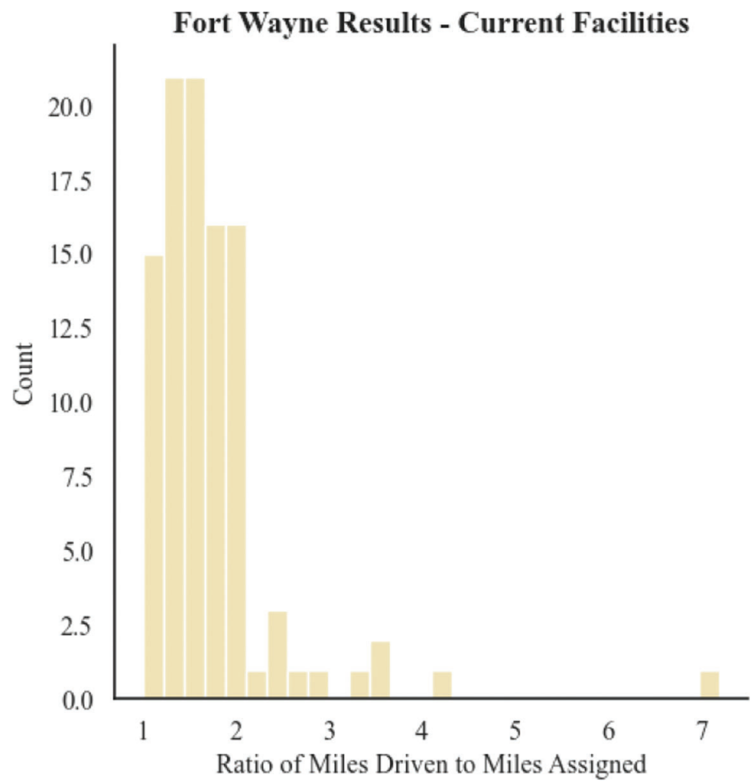


Figure 3.9 Aggregate ratio between the miles driven to the miles assigned to a facility for the Fort Wayne District.

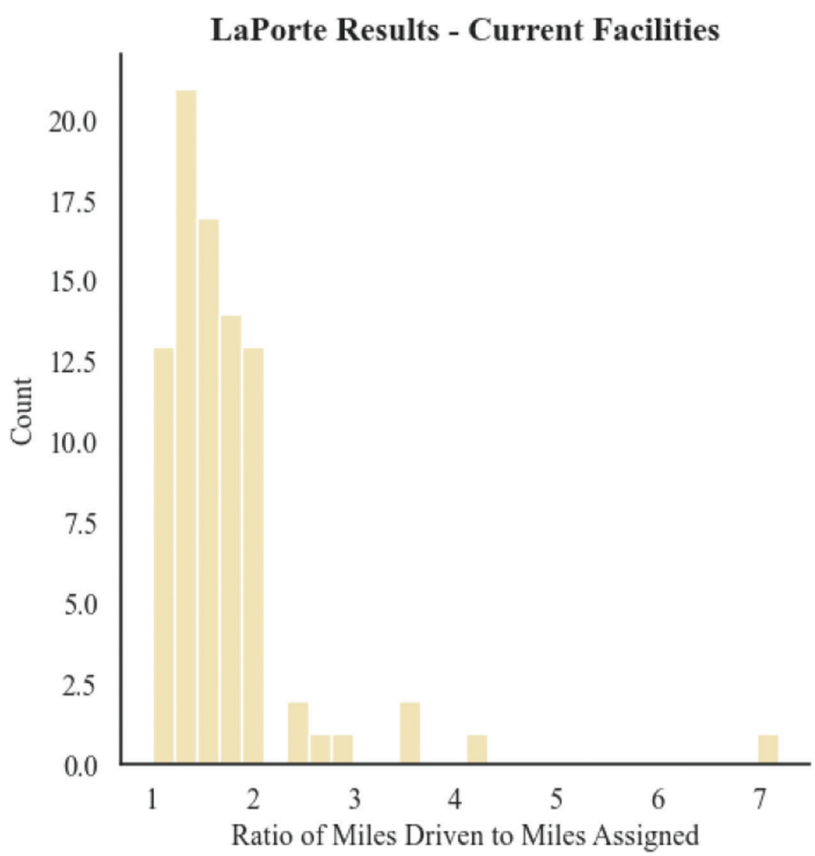


Figure 3.10 Aggregate ratio between the miles driven to the miles assigned to a facility for the LaPorte District.

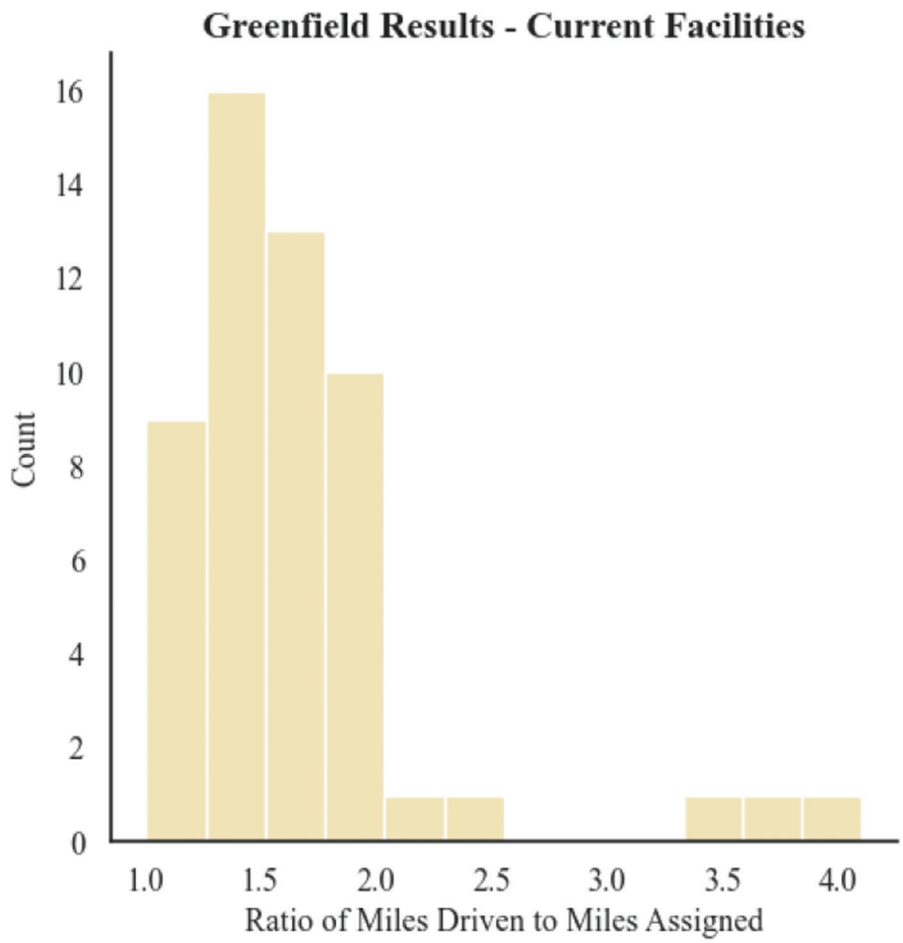


Figure 3.11 Aggregate ratio between the miles driven to the miles assigned to a facility for the Greenfield District.

4. FACILITY OPTIMIZATION

4.1 Problem Formulation

The facility optimization problem is to locate *X* facilities across the state of Indiana in a manner to minimize overage of salting capacity. A facility is defined as a home position for a set of assets. In this version, the only assets considered are salt trucks.

The facility optimization model is a two-stage approach. First, an *optimization model* determines the minimum number and size of facilities needed to serve the salting standards of the road network over the entire state of Indiana. This optimal number of facilities is then used as input to a *clustering model* which determines the exact positioning of the facilities across the state. The location of these facilities is then used to generate optimal snow salting and plowing routes on a truck-by-truck basis.

The facilities are allocated to a set of virtual regions, with a region defined as a given number of equal road mile divisions. A region is not related to or based on any resemblance to the INDOT concept of districts.

There are three different *sizes* of facilities considered by the model—large, medium, and small. The size of a facility is determined by the number of trucks that are assigned to a given facility as their home position. Trucks can be either 8- or 10-ton capacity. The number of trucks that define large, medium, and small facilities are set at 15, 10, and 5, respectively. These values are represented in the model as parameters that can be varied by the user.

4.2 Model Objective

The objective of the facility optimization model is to determine the least number of facilities and their respective sizes (number of trucks) while salting all miles of roads to defined state salting standards.

4.3 Model Output

The output of the facility optimization model is the optimal set of sized facilities (large, medium, or small) to each region. This set of facilities is then input to a *clustering model* that will define the exact position (longitude and latitude) of each state.

4.4 Optimization Model Formulation

The model was constructed in and runs under the standard Solver implementation in Microsoft Excel. A major design objective was to make the model user friendly and flexible to facilitate ease of use for multiple analyses perspective as the INDOT facility footprint and asset mix change over time.

The basic logic of the optimization model is as follows.

Ten virtual regions have been used in the initial development of the model. The total number of miles in the state are then allocated equally to each region.

Each potential facility size (large, medium, or small) is assigned a "total salting capacity" based on the following formula.

$$(Dead\ Head\ Efficiency * Salt\ Maximum\ Distance)/\ Routing\ Efficiency$$

where dead head efficiency is a percent factor that represents the efficiency of the route for each truck, the salt maximum distance is the maximum distance a truck can go before the salt load runs out, and routing efficiency is the gain in capacity due to the optimal routing. The output of this formula represents the distance that a truck can effectively salt. This value is then used to generate the total salting capacity which is the total number of miles a given facility size (number of trucks) can salt in the salting standard.

The model then seeks to determine the optimal number of facilities of each size in each region to minimize the excess salting capacity for the state.

The mathematical formulation of the model is as follows.

Parameters:

e_{dh} = dead head efficiency, a factor that sets the loss in capacity for trucks returning on routes without salting.

e_r = routing efficiency, a factor used to adjust capacity for salting due to the route optimization.

t_i = the number of trucks that are available at facility i, $i \in \{Large, Medium, Small\}$.

N = maximum total facilities, the maximum total number of facilities allowed.

n = minimum total facilities, the minimum total number of facilities required.

α = percent of 10-ton trucks, the percentage of 10-ton trucks in the fleet and assumed available at each facility. This parameter is used to calculate salting capacity for a facility.

β_i = mix percent, the percentage of total facilities that can be of size i, $i \in \{Large, Medium, Small\}$.

d = facility size spread, a parameter that constrains the range between the maximum and minimum number of sized facilities in a given area.

S = salt usage, the amount of salt in lbs/mile. This parameter is used to calculate the salting capacity for a given truck.

s_d = salting max distance, the maximum distance a truck can go before the salt load runs out. $s_d = \frac{(1-\alpha) * 8 * 2{,}000 + \alpha * 10 * 2{,}000}{S}$.

s_c = salting capacity, $s_c = \frac{e_{dh} s_d}{e_r}$.

M_j = salting miles per region j, $j \in \{1, \ldots, 10\}$.

M = total number of miles to be covered, $M = \Sigma_j M_j$

Decision variables:

x_{ij} = the number of each type of facility i, $i \in \{Large, Medium, Small\}$, to locate in each region j, $j \in \{1, \ldots, 10\}$.

Mathematical problem formulation:

1. $Max(1 - \frac{\sum_{ij} x_{ij} t_i s_c}{M})$

Subject to the following:

2. $\Sigma_j x_{ij} \leq \beta_i N, \forall i, i \in \{Large, Medium, Small\}$
3. $\Sigma_{i,j} x_{i,j} \leq N$
4. $\Sigma_{i,j} x_{ij} \geq n$
5. $\Sigma_i x_{ij} t_i s_c \geq M_j, \forall j, j \in \{1, \ldots, 10\}$
6. $Max_i(x_{ij}) - Min_i(x_{ij}) \leq d, \forall j, j \in \{1, \ldots, 10\}$
7. $x_{ij} \in I, x_{ij} \geq 0$

The objective function (1) is to minimize the excess "salting capacity."

Constraint (2): restricts the total number of large, medium, and small facilities to less than a user supplied parameter.

Constraint (3): restricts the total number of facilities to less than a user supplied parameter.

Constraint (4): restricts the total number of facilities to greater than a user supplied parameter.

Constraint (5): requires that the miles serviced in each region are greater than the total number of miles in the region.

Constraint (6): ensures that the range in the facility mix for a region do not exceed a user supplied parameter.

All decision variables must be integers greater than or equal to zero.

Figure 4.1 gives an overview of the model input. Figure 4.2 provides the implementation of the model in Excel Solver.

4.5 Model Parameters

The optimization model was set up to be user friendly and flexible. Table 4.1 lists the model parameters and the initial values for them. Definitions of the parameters follow.

4.5.1 Clustering Model

Clustering algorithm determines the exact position of the facility locations. As an input, it uses the number of facilities determined for each region by the optimization model. The regions are allocated equally on the state map. First, within each region, large, medium and small locations are randomly positioned. After that, we run the K-means constrained clustering algorithm to improve the positions of the initial random locations.

K-means constrained clustering:

K-means constrained clustering is an iterative approach to improve the initial coordinates of the locations. It uses the number of facilities for each region, number of 8-ton and 10-ton trucks per facility, mile posts (MP) coordinates and the initial coordinates of the facility locations. With every iteration, the algorithm tends to find a better couple of coordinates for each facility taking into account the size of the facility in terms of the miles covered by the assigned trucks.

For each region, let j be a facility location within a certain region. The facility location could be large, medium or small based on the initial allocation.

1. Initialize the coordinates x_j and y_j of the facility location with the random coordinates within the region.

TABLE 4.1
The model parameters and the initial values for them

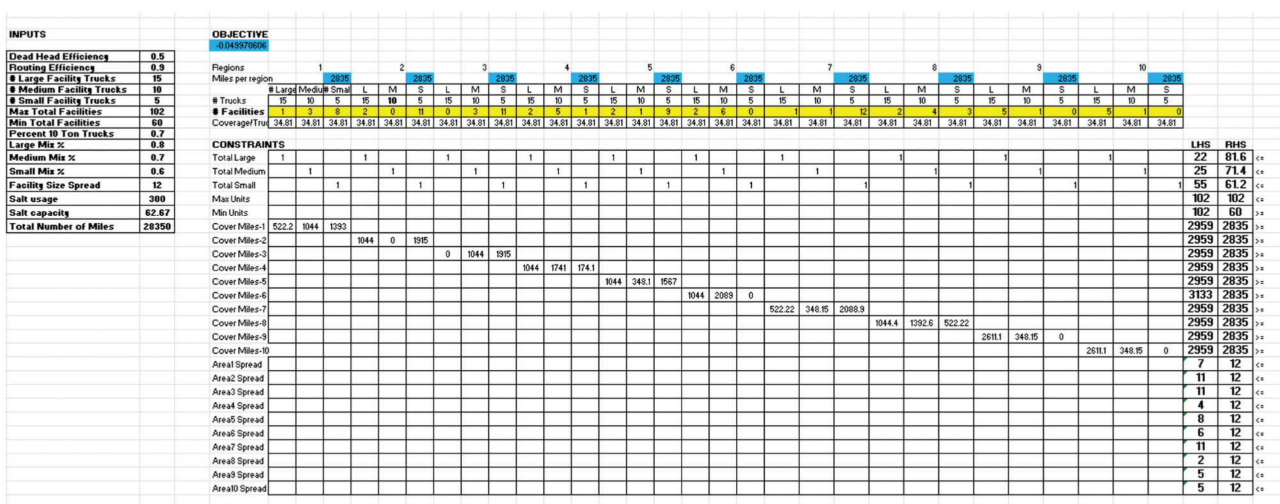
Dead Head Efficiency	0.5
Routing Efficiency	0.9
No. of Large Facility Trucks	15
No. of Medium Facility Trucks	10
No. of Small Facility Trucks	5
Max Total Facilities	100
Min Total Facilities	60
Percent of 10-Ton Trucks	0.7
Large Mix Percent	0.8
Medium Mix Percent	0.7
Small Mix Percent	0.6
Facility Size Spread	12
Salt Usage	300
Total Number of Miles	28,350

2. Assign MP to the facility based on the size of the facility: $a_j = \frac{w_j}{\sum_j w_j} n$, where n is the total number of MP in the region, w_j is the weight of the facility.
   The weight is calculated based on the number of 8-ton and 10-ton trucks assigned to the facility: $w_j = 8t_j + 10T_j$, where t_j is the number of 8-ton trucks assigned to the facility, T_j is the number of 10-ton trucks assigned to the facility.
3. Do the clustering algorithm for the region:

   $Min\ \Sigma_{i,j}\ d_{ij}\ x_{ij}$

   Subject to:
   $\Sigma_i\ x_{ij} \leq (1 + \epsilon)a_j, \ \ \forall j$
   $\Sigma_i\ x_{ij} \geq (1 - \epsilon)a_j, \ \forall j$
   $\Sigma_j\ x_{ij} = 1, \ \ \forall i$
   $d_{ij}\ x_{ij} \leq d_{max}, \ \ \forall i, j$
   $x_{ij} \in \{0, 1\}, \ \ \forall i, j$
   where d_{ij} is the distance between the MP i and the facility location j, x_{ij} is a binary variable that is equal to 1 if the MP i is assigned to the cluster of the facility j, d_{max} is the maximum distance between MP and its assigned facility, and ϵ is a small positive number that allows for some flexibility in the desired number of MP assigned to each facility.
4. Recalculate x_j and y_j for each facility location j.
   x_j = average of MP x-coordinates assigned to this location cluster.
   y_j = average of MP y-coordinates assigned to this location cluster.
5. Replace the facility location coordinates with new x_j and y_j and redo steps 3 and 4 until the MP assigned to each cluster do not change.
6. For each cluster:
   6.1 Find (x', y') such that $Min\ \Sigma_i\ ((x' - x_i)^2 + (y' - y_i)^2)$.
   6.2 Set $(x_j, y_j) = (x', y')$ for each cluster.

To increase the routing efficiency, the closest current location or an intersection was found for each (x_j, y_j). Then the routing problem was solved for the new coordinates to ensure that the total distance travelled, and the total deadhead miles were less or equal to the current amount.



INPUTS

Dead Head Efficiency	0.5
Routing Efficiency	0.9
# Large Facility Trucks	15
# Medium Facility Trucks	10
# Small Facility Trucks	5
Max Total Facilities	102
Min Total Facilities	60
Percent 10 Ton Trucks	0.7
Large Mix %	0.8
Medium Mix %	0.7
Small Mix %	0.6
Facility Size Spread	12
Salt usage	300
Salt capacity	62.67
Total Number of Miles	28350

OBJECTIVE
-0.049970606

Regions	1			2			3			4			5		
Miles per region			2835			2835			2835			2835			2835
	# Large	# Mediu	# Smal	L	M	S	L	M	S	L	M	S	L	M	S
# Trucks	15	10	5	15	10	5	15	10	5	15	10	5	15	10	5
# Facilities	1	3	8	2	0	11	0	3	11	2	5	1	2	1	9
Coverage/Truc	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81
CONSTRAINTS															
Total Large	1			1			1			1			1		
Total Medium		1			1			1			1			1	
Total Small			1			1			1			1			1
Max Units															
Min Units															
Cover Miles-1	522.2	1044	1393												
Cover Miles-2				1044	0	1915									
Cover Miles-3							0	1044	1915						
Cover Miles-4										1044	1741	174.1			
Cover Miles-5													1044	348.1	1567
Cover Miles-6															
Cover Miles-7															
Cover Miles-8															
Cover Miles-9															
Cover Miles-10															
Area1 Spread															
Area2 Spread															
Area3 Spread															
Area4 Spread															
Area5 Spread															
Area6 Spread															
Area7 Spread															
Area8 Spread															
Area9 Spread															
Area10 Spread															

Regions	6			7			8			9			10					
Miles per region			2835			2835			2835			2835			2835			
	L	M	S	L	M	S	L	M	S	L	M	S	L	M	S			
# Trucks	15	10	5	15	10	5	15	10	5	15	10	5	15	10	5			
# Facilities	2	6	0	1	1	12	2	4	3	5	1	0	5	1	0			
Coverage/Truc	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81	34.81			
CONSTRAINTS																LHS	RHS	
Total Large	1			1			1			1			1			22	81.6	<=
Total Medium		1			1			1			1			1		25	71.4	<=
Total Small			1			1			1			1			1	55	61.2	<=
Max Units																102	102	<=
Min Units																102	60	>=
Cover Miles-1																2959	2835	>=
Cover Miles-2																2959	2835	>=
Cover Miles-3																2959	2835	>=
Cover Miles-4																2959	2835	>=
Cover Miles-5																2959	2835	>=
Cover Miles-6	1044	2089	0													3133	2835	>=
Cover Miles-7				522.22	348.15	2088.9										2959	2835	>=
Cover Miles-8							1044.4	1392.6	522.22							2959	2835	>=
Cover Miles-9										2611.1	348.15	0				2959	2835	>=
Cover Miles-10													2611.1	348.15	0	2959	2835	>=
Area1 Spread																7	12	<=
Area2 Spread																11	12	<=
Area3 Spread																11	12	<=
Area4 Spread																4	12	<=
Area5 Spread																8	12	<=
Area6 Spread																6	12	<=
Area7 Spread																11	12	<=
Area8 Spread																2	12	<=
Area9 Spread																5	12	<=
Area10 Spread																5	12	<=

Figure 4.1 Facility location model—input in Excel.

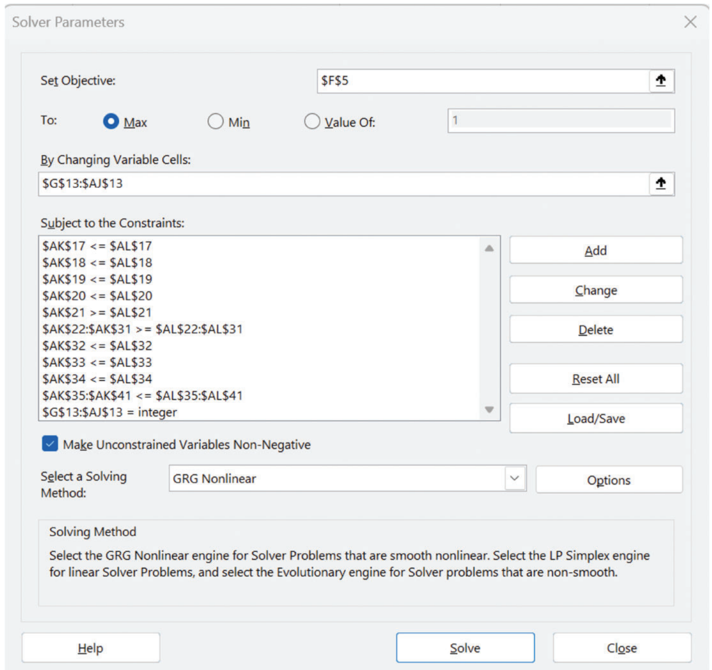


Figure 4.2 Facility location model—input details in Excel.

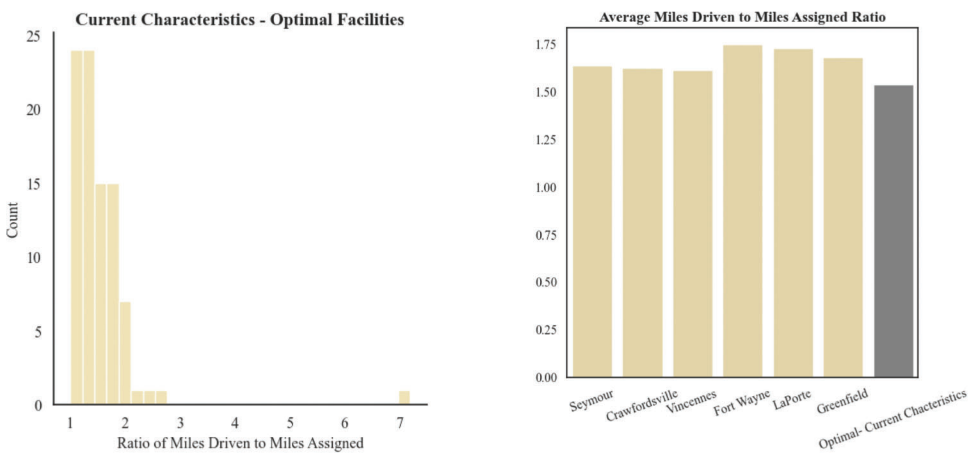


Figure 4.3 Reduction in the average ratio of miles driven to miles assigned by facility.

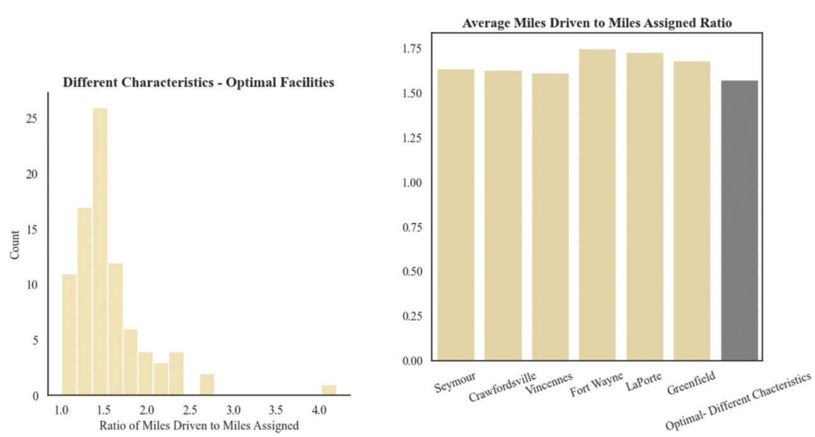


Figure 4.4 Slight increase in the average ratio of miles driven to miles assigned by facility.

4.6 Optimal Locations: Current Number and Characteristics of Facilities

As we see in Figure 4.3, by altering the locations of these facilities we do see a reduction in the average ratio of miles driven to miles assigned by facility.

4.7 Optimal Locations: Modified Number and Characteristics of Facilities

As we see in Figure 4.4, the average ratio is slightly higher when compared to the previous optimal values. This is likely to do with the reduction in the number of facilities.

REFERENCE

Perrier, N., Langevin, A., & Campbell, J. F. (2007). A survey of models and algorithms for winter road maintenance. Part IV: Vehicle routing and fleet sizing for plowing and snow disposal. *Computers & Operations Research*, *34*(1), 258–294.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

Dunlop, S. R., Brady, T., Senicheva, O., Ramirez, D., Thakkar, D. J., Cheeti, A., Chava, M., Sankineni, S., Tagore, J., Malhotra, H., & Deore, S. (2024). *Recommendations for the implementation of heavy fleet routes and facilities location optimization* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2024/21). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317756