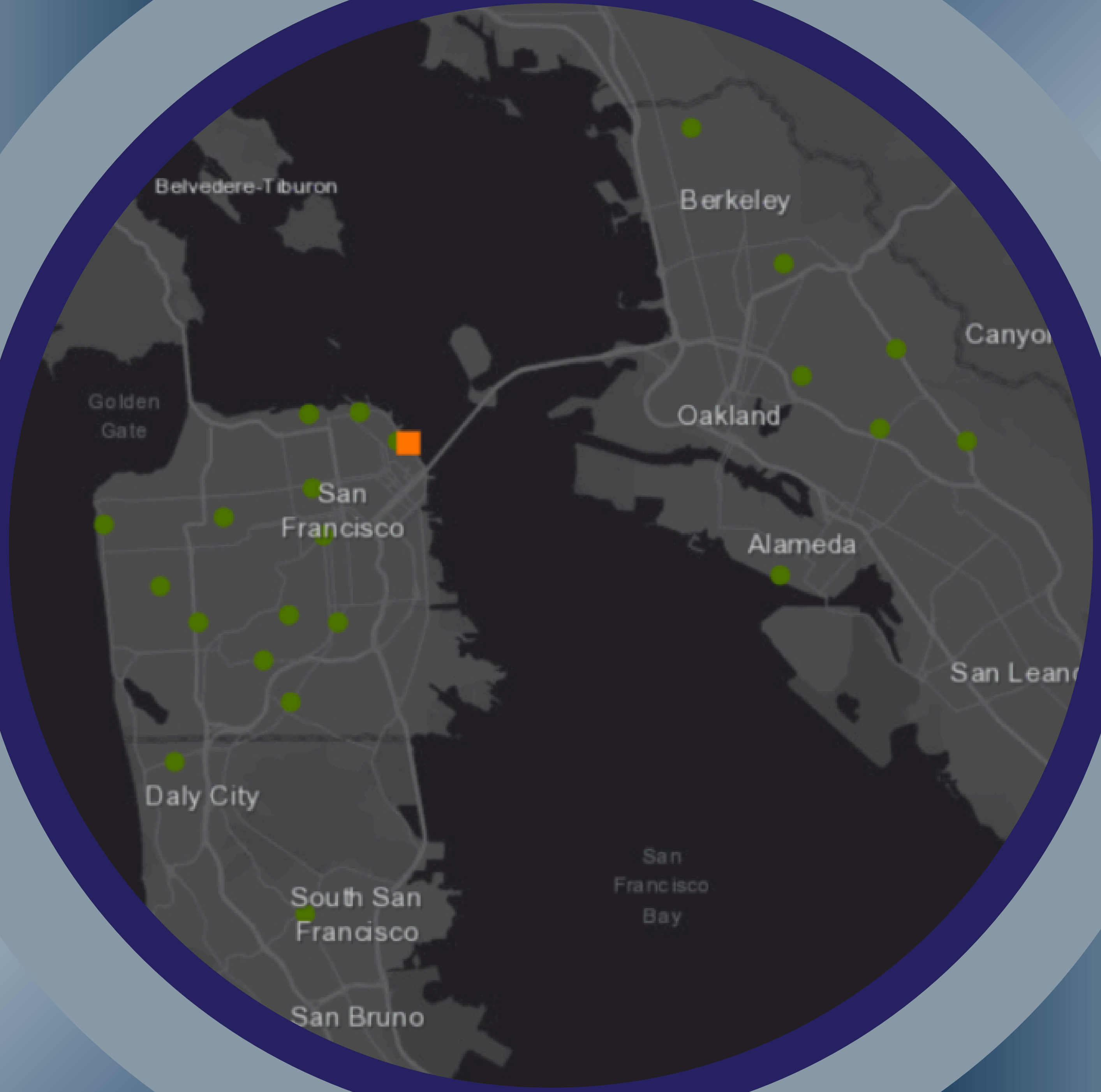
OR LAB PROJECT

GROUP 9

OPTIMIZING WASTE COLLECTION AND DISPOSAL ROUTING USING A MULTI-PHASE VRP APPROACH



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PROBLEM STATEMENT

Efficient vehicle routing is essential for reducing logistics costs and improving service quality in supply chains. This is particularly crucial in waste management systems, where optimized routes can significantly reduce operational costs, minimize environmental impact, and improve service reliability. This project addresses the **Vehicle Routing Problem (VRP)** in the context of urban waste collection and disposal, where the goal is to find optimal routes for a fleet of vehicles subject to various constraints such as **vehicle capacity, time windows, and customer demand.**

OBJECTIVE

1. Reduce overall operation time including collection, transport, and waiting times
2. Maximize vehicle capacity utilization while respecting load constraints
3. Ensure adherence to time windows for collection and disposal

CONSTRAITS

1. **Vehicle Capacity:** No vehicle can be loaded beyond its maximum capacity
2. **Time Windows:** Collection and disposal operations must occur within specified time slots
3. **Service Time:** Each bin collection and disposal operation requires a specific service duration
4. **Complete Service:** All waste bins must be serviced exactly once
5. **Flow Conservation:** Vehicles must start and end at designated facilities (depots, transfer stations)
6. Route Duration: Total route time cannot exceed vehicle operational hours

ASSUMPTIONS

- All customer **demands are known** in advance and **remain static** during execution.
- Each vehicle begins and ends its route at the **same central depot**.
- Each customer is **serviced exactly once** and by only one vehicle.
- **Travel times** between all location pairs are **symmetric and fixed**.
- Service times at each node is fixed.

THOUGHT BEHIND THE FORMULATION

Phase 1: Vehicle Routing Problem (VRP)
We started with a basic VRP model focusing on minimizing the total travel distance while ensuring each customer is **VIsited once.** This phase provided foundational insights into route structure and depot-based constraints.

Phase 2: Capacitated Vehicle Routing Problem (CVRP)
In this phase, we introduced **vehicle capacity constraints to simulate realistic loading conditions.** The model tracked individual customer demands and ensured that no vehicle exceeded its maximum capacity, making the routing solution more applicable to real-world logistics.

Phase 3: CVRP with Time Windows and Separate Pickup & Drop
The final phase incorporated **time window constraints** along with **distinct pickup and delivery locations.** This significantly increased model complexity and required accurate modeling of service times, vehicle schedules, and load balancing across both phases. The resulting model closely resembles practical applications such as school bus routing or courier services with time-sensitive pickups and deliveries.

MATHEMATICAL FORMULATION

Decision Variables

- x_{ij}^r – Binary variable: 1 if vehicle r travels from node i to node
  otherwise.
- t_i^r – Time at which vehicle r begins service at location i.
- q_i^r – Load carried by vehicle r after visiting node i.

Parameters

- d_{ij} – Travel time or distance between node i and node j.
- $[a_i, b_i]$ – Time window during which service at node i must begin.
- s_i – Service time at node i.
- q_i – Demand at node i (positive for pickup, negative for delivery).
- Q – Maximum capacity of each vehicle.
- M – A large constant used for time linearization.
- R – Set of available vehicles.
- N – Set of customer nodes.
- $depot$ – Start and end node for all routes.

MATHEMATICAL FORMULATION

Objective Function

Minimize the total travel time or distance:

$$\min \sum_{r \in R} \sum_{i \in N \cup \{depot\}} \sum_{j \in N \cup \{depot\} j \neq i} x_{ij}^r \cdot d_{ij}$$

Constraints

1. Each location is visited exactly once:

$$\sum_{r \in R} \sum_{j \in N \cup \{depot\} j \neq i} x_{ij}^r = 1 \quad \forall i \in N$$

2. Vehicle flow conservation:

$$\sum_{j \in N \cup \{depot\} j \neq i} x_{ij}^r = \sum_{j \in N \cup \{depot\} j \neq i} x_{ji}^r \quad \forall i \in N, \forall r \in R$$

3. Time window constraints:

$$a_i \leq t_i^r \leq b_i \quad \forall i \in N, \forall r \in R$$

4. Time propagation (subtour elimination):

$$t_j^r \geq t_i^r + s_i + d_{ij} - M \cdot (1 - x_{ij}^r) \quad \forall i \neq j, \forall r \in R$$

5. Capacity constraints:

$$q_i^r + q_j \leq Q + M \cdot (1 - x_{ij}^r) \quad \forall i, j \in N, \forall r \in R$$

6. Depot start and end:

$$\sum_{j \in N} x_{depot,j}^r - 1 \quad \mathit{and} \quad \sum_{i \in N} x_{i,depot}^r - 1 \quad \forall r \in R$$

7. Domain Constraints:

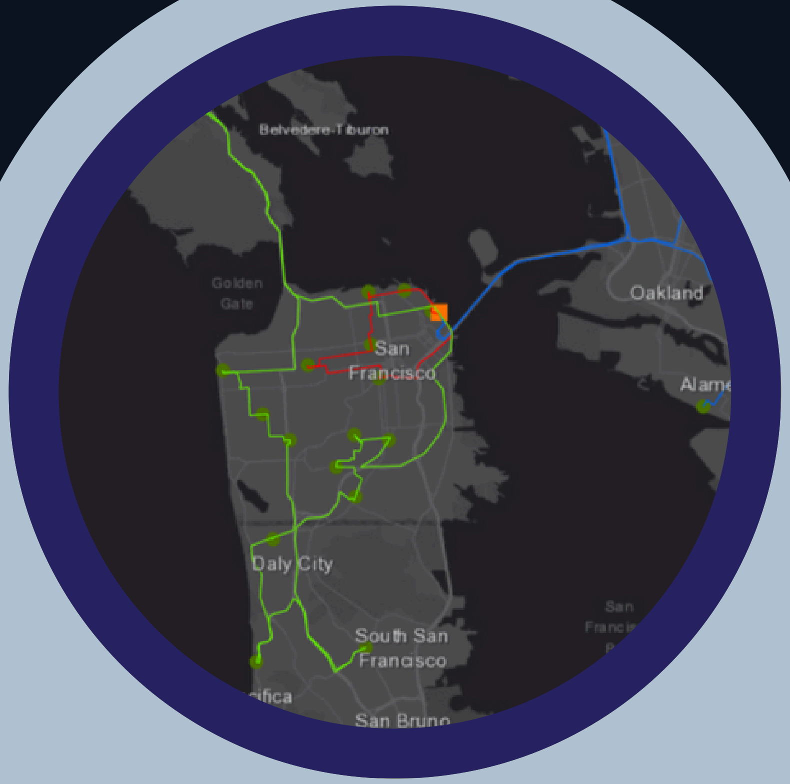
$$x_{ij}^r \in \{0, 1\}, \quad t_i^r \geq 0 \quad \forall i, j \in N \cup \{depot\}, \forall r \in R$$

TOOL USED: GOOGLE OR-TOOLS

- **Choice of Tools and Language**
  - Python was selected for its simplicity, readability, and rich ecosystem of libraries.
  - Google OR-Tools was chosen for its strength in handling complex routing and scheduling problems.
  - OR-Tools is open-source and tailored for combinatorial optimization, especially vehicle routing problems.
- **Suitability of OR-Tools for VRP:**
  - Specifically designed for problems like CVRPTW (Capacitated Vehicle Routing Problem with Time Windows).
  - Supports advanced constraints: routing, time windows, pickups/deliveries, and capacity limits.
- **Implementation and Integration:**
  - Python interface of OR-Tools allowed for clean and intuitive problem modeling.
  - Built-in heuristics/metaheuristics delivered high-quality solutions efficiently.
  - Integrated smoothly with Python’s data processing and visualization tools for a scalable, real-world solution.

CHRONOLOGY OF DEVELOPMENT

The implementation of our optimization model progressed through three key phases, each building upon the learnings and outcomes of the previous stage.



Phase 1: Vehicle Routing Problem (VRP)

We first implemented a basic VRP to minimize distance and ensure each customer is visited once.

Phase 2: Capacitated Vehicle Routing Problem (CVRP)

We added capacity constraints to ensure vehicles didn't exceed load limits, making the model more practical.

Phase 3: CVRP with Time Windows and Separate Pickup Drop

We built a CVRPTW model with time and pickup/drop constraints to reflect real-world routing challenges.

DATASET AND CONFIGURATION

Dataset Description

- Pickup Phase Summary: Utilized a 17×17 time matrix, with strict time windows and varying pickup demands (max 5 units). Four vehicles, each with a 20-unit capacity, were used to optimize routes from the depot to customer locations.
- Delivery Phase Summary: Modeled with a 21×21 time matrix and tighter time windows. Delivery demands were smaller (max 2 units), handled by five vehicles each limited to 7 units, ensuring timely and efficient drop-offs.

System Configuration

- Software Stack: Implemented using Python 3.11 with key libraries including Google OR-Tools 9.6 for optimization, NumPy and Pandas for data handling, GeoPandas for spatial tasks, and Matplotlib and Folium for visualization.
- Hardware & OS: Executed on a MacBook Pro with 16GB RAM running macOS Ventura 13.4, ensuring smooth processing and efficient model performance.

RESULTS AND ANALYSIS

Pickup(Phase-1)

- Total Load Collected: 49 units
- Total Time Taken: 63 minutes
- Vehicles Utilized: 3 out of 4
- Max Load by a Single Vehicle: 20 units
- Longest Route Duration: 28 minutes

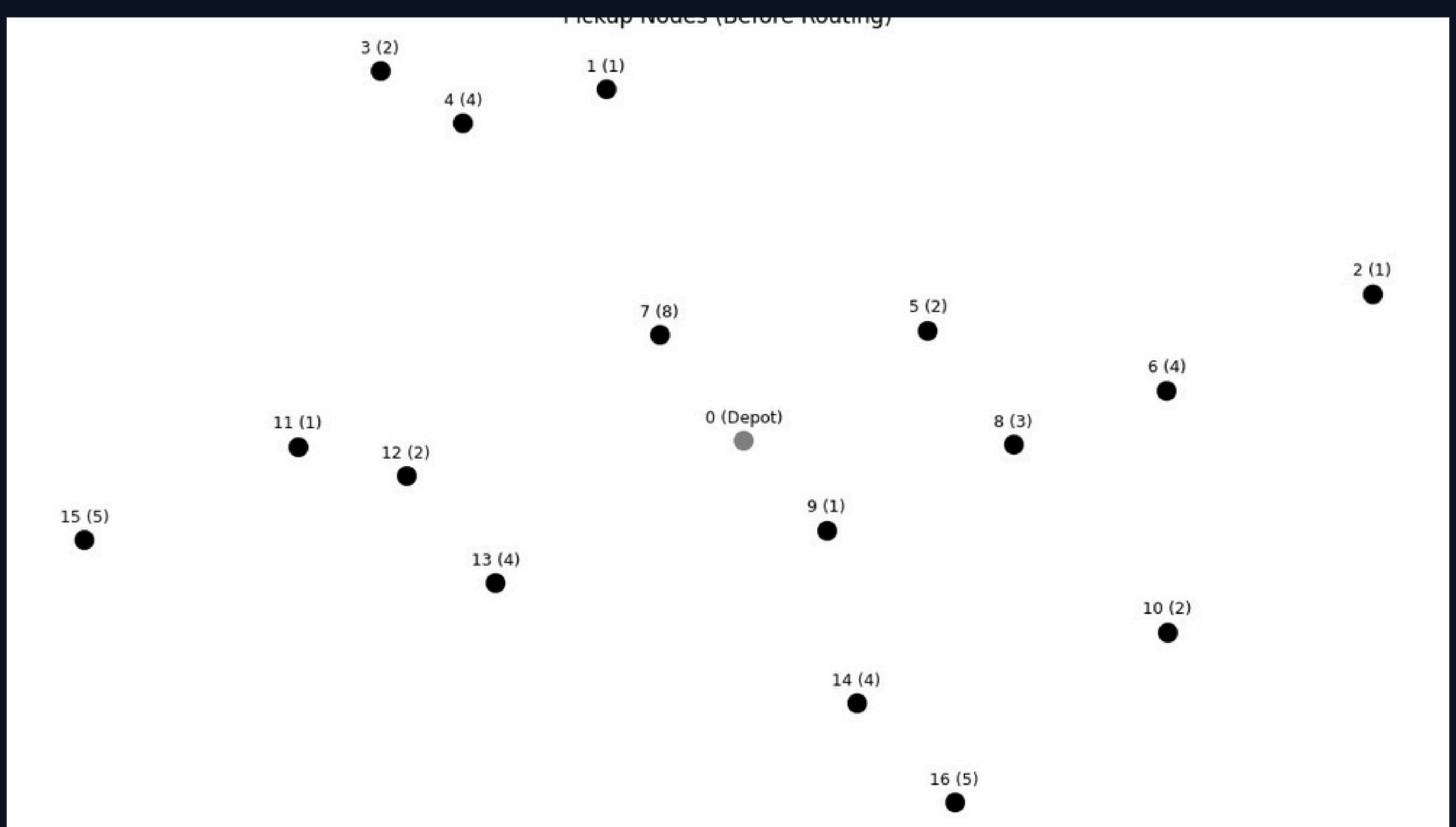
Delivery Phase (Phase 2)

- Total Load Delivered: 26 units
- Total Time Taken: 94 minutes
- Vehicles Utilized: 4 out of 5
- Max Load by a Single Vehicle: 7 units
- Longest Route Duration: 26 minutes

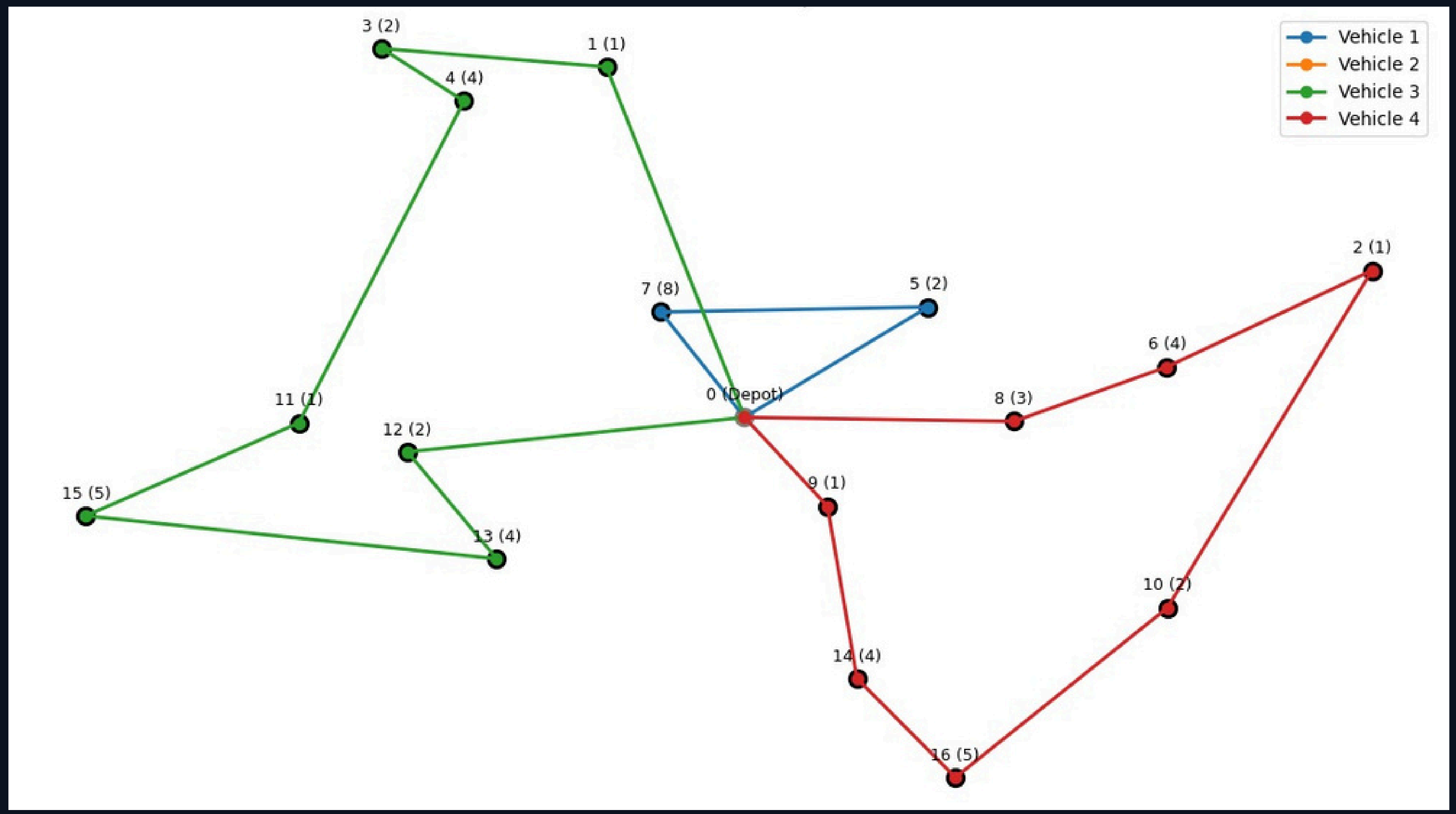
Key Highlights

- **Constraint Satisfaction:** All time and capacity constraints were met in both phases.
- **Fleet Optimization:** Unused vehicles reflect efficient route consolidation.
- **Efficiency:** Combined pickup and delivery time totaled just 157 minutes.
- **Scalability:** The model easily adapts to more nodes or changes with little adjustment.

GRAPHS

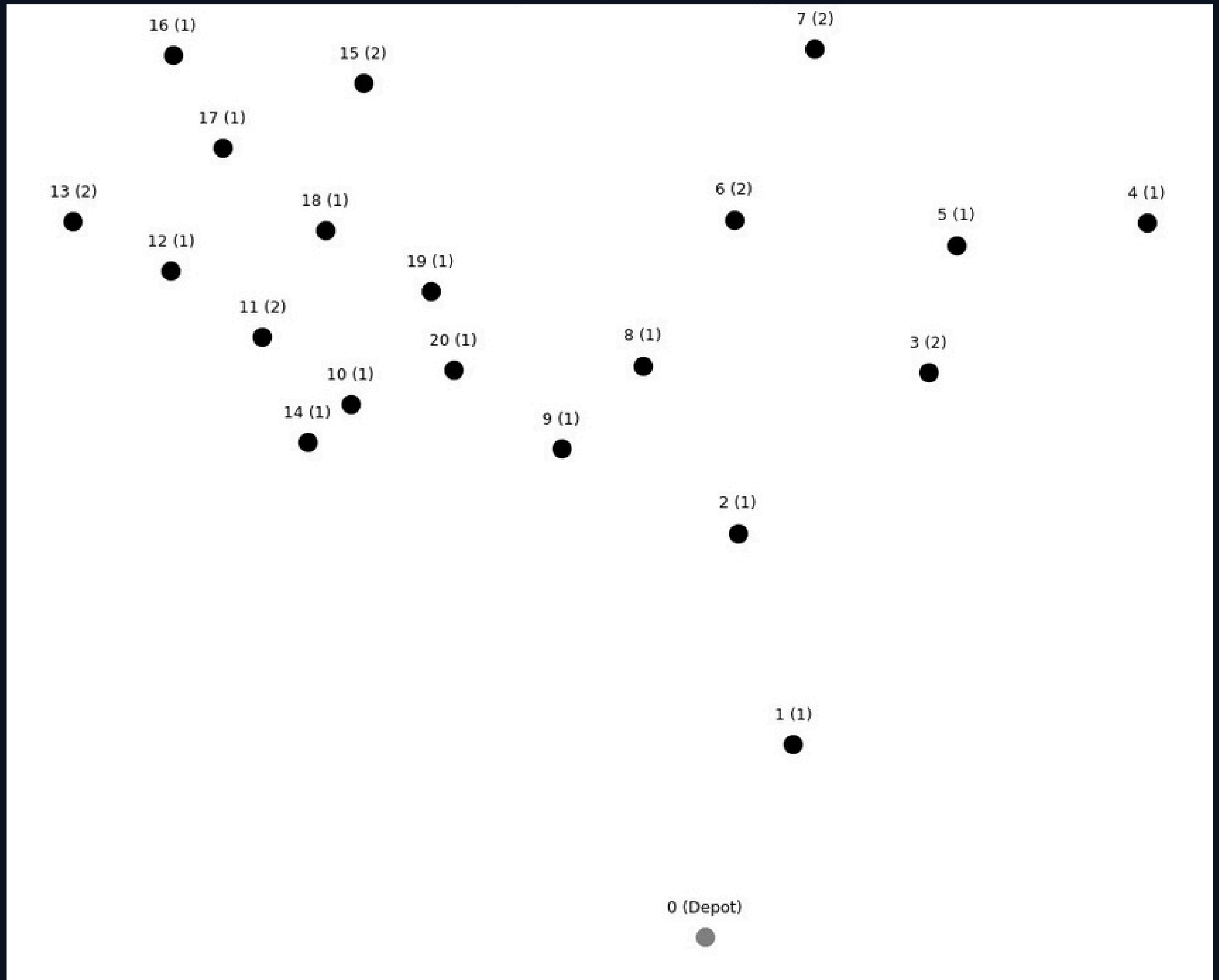


Pickup Nodes(Before Routing)

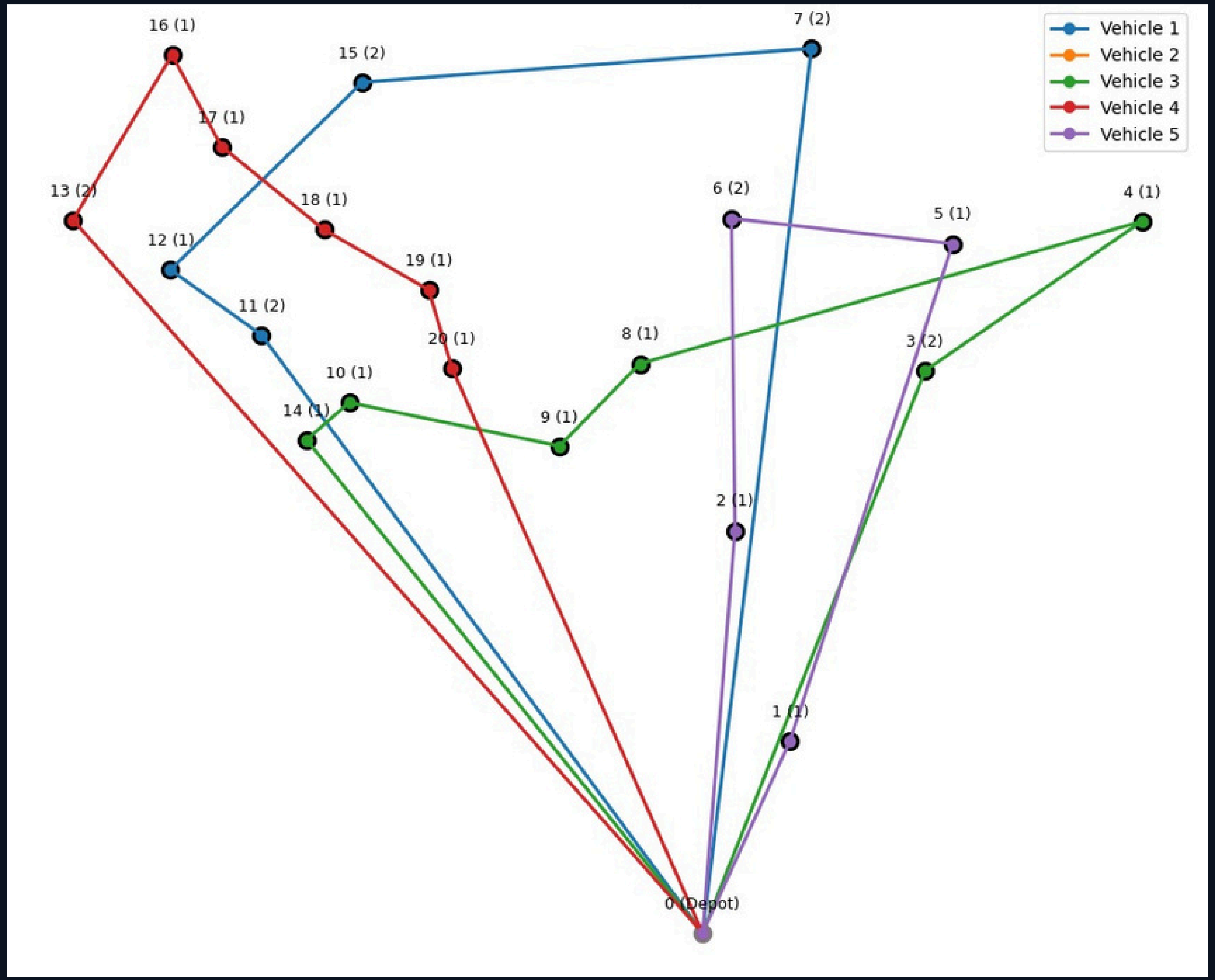


Vehicle Routes for picking CVPRTW

GRAPHS

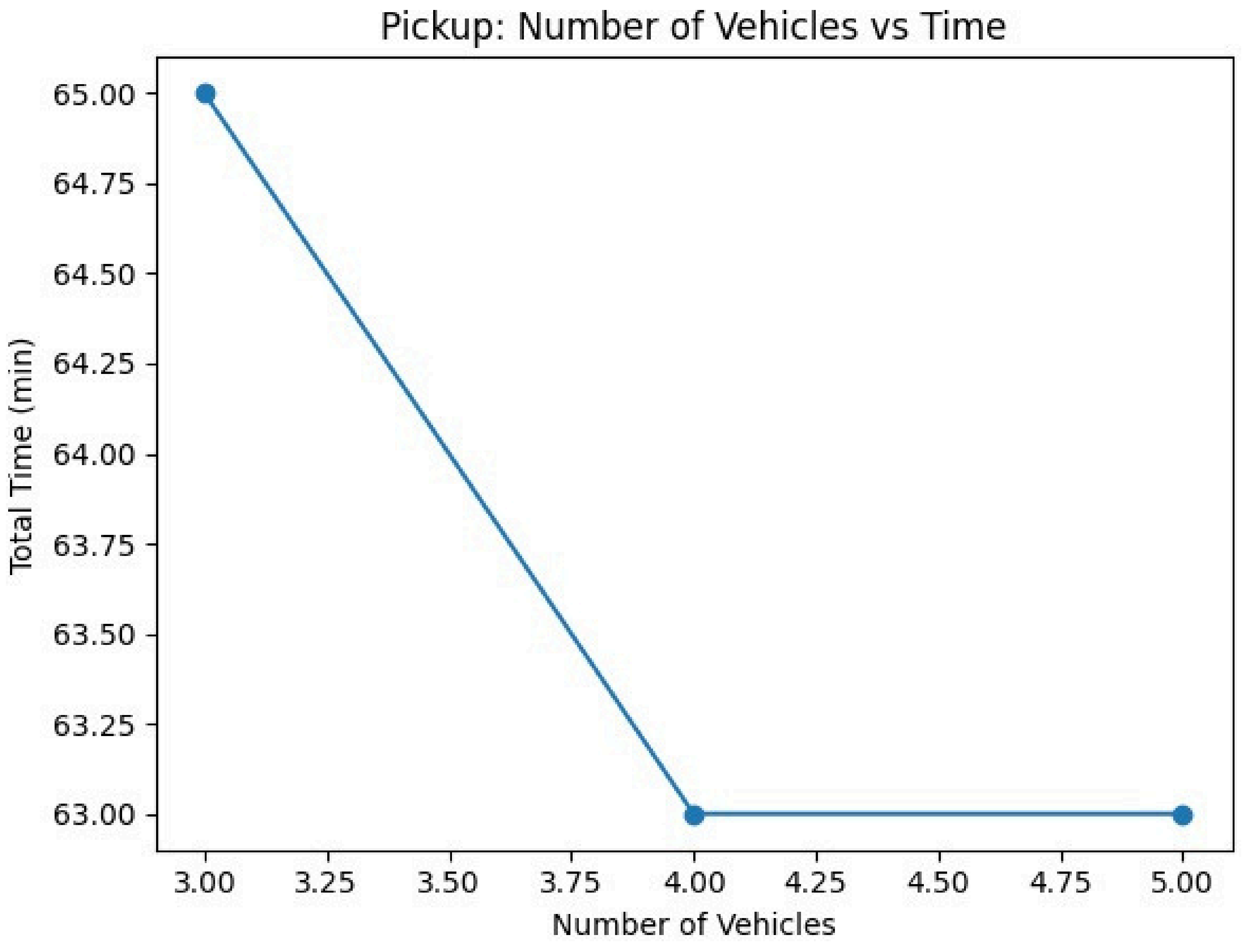


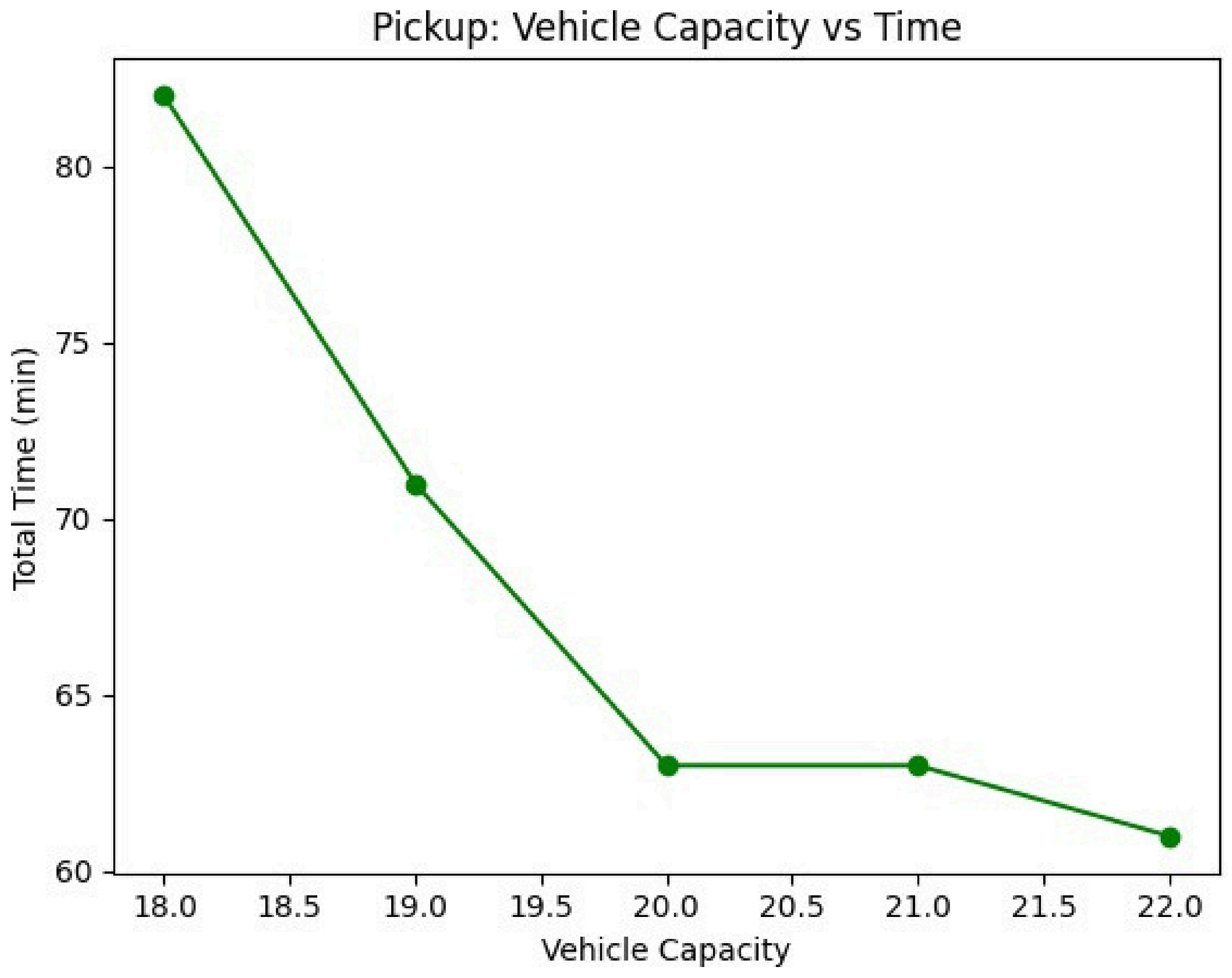
Delivery Nodes(Before Routing)



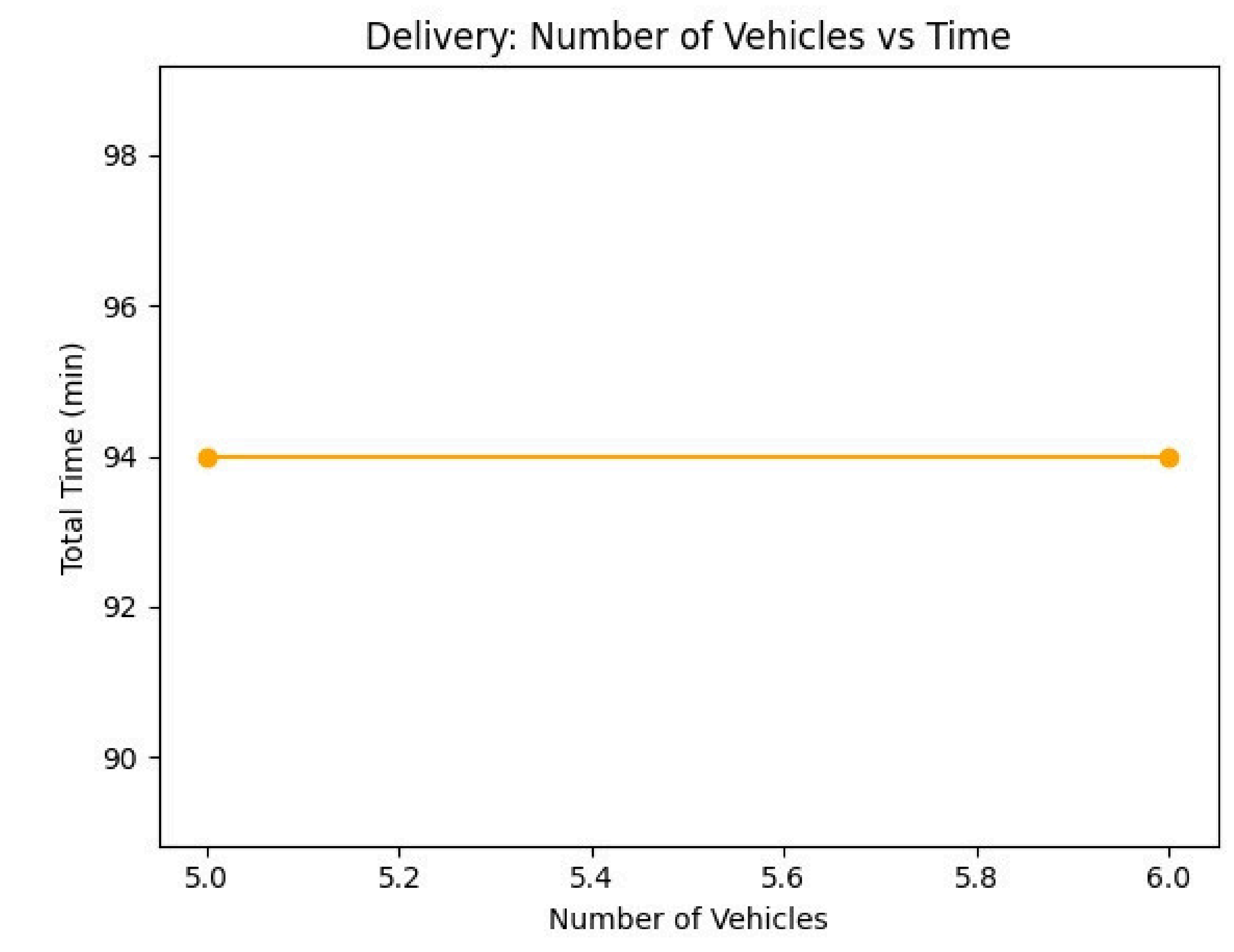
Vehicle Routes for Delivery CVPRTW

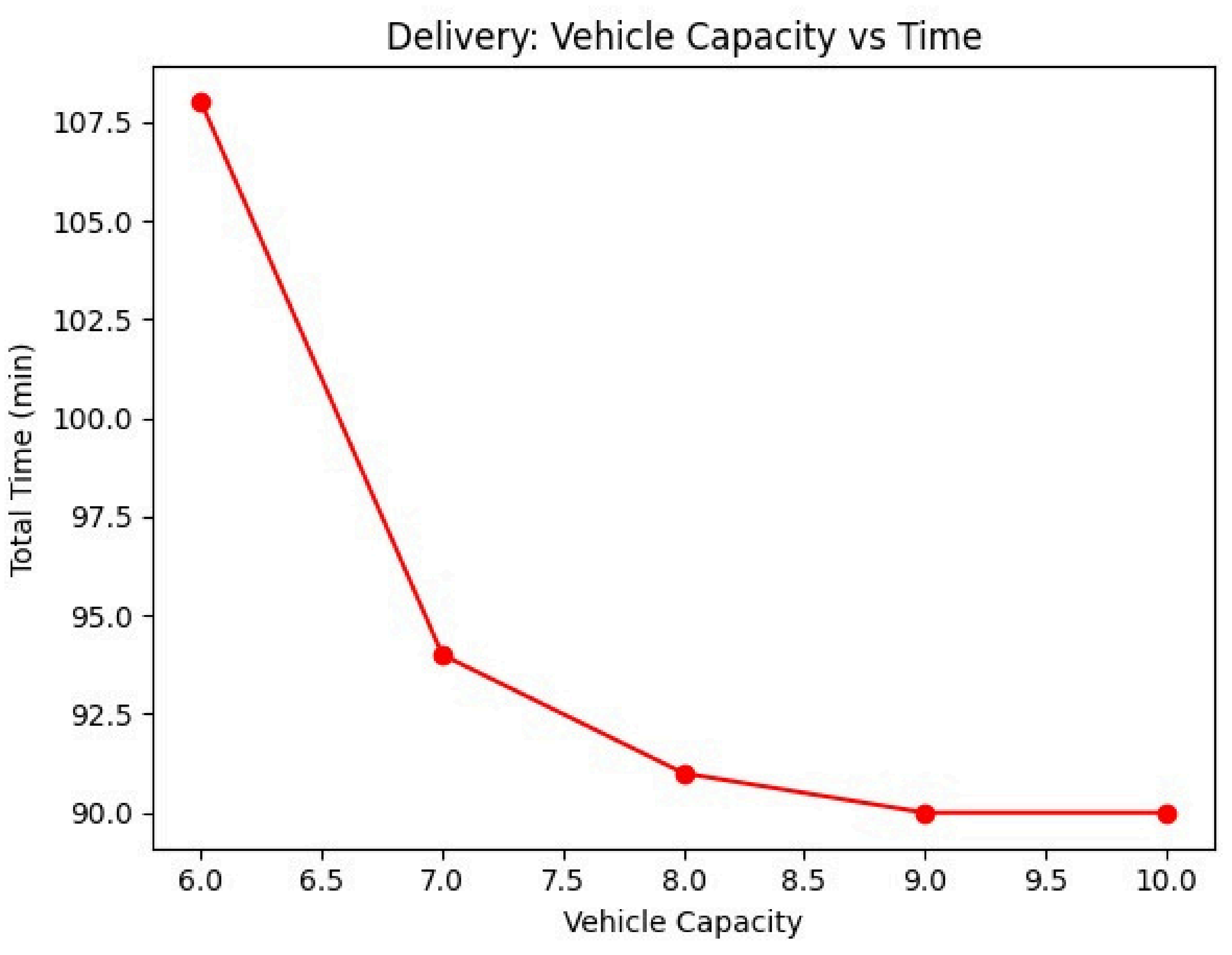
SENSITIVITY ANALYSIS - PICKUP

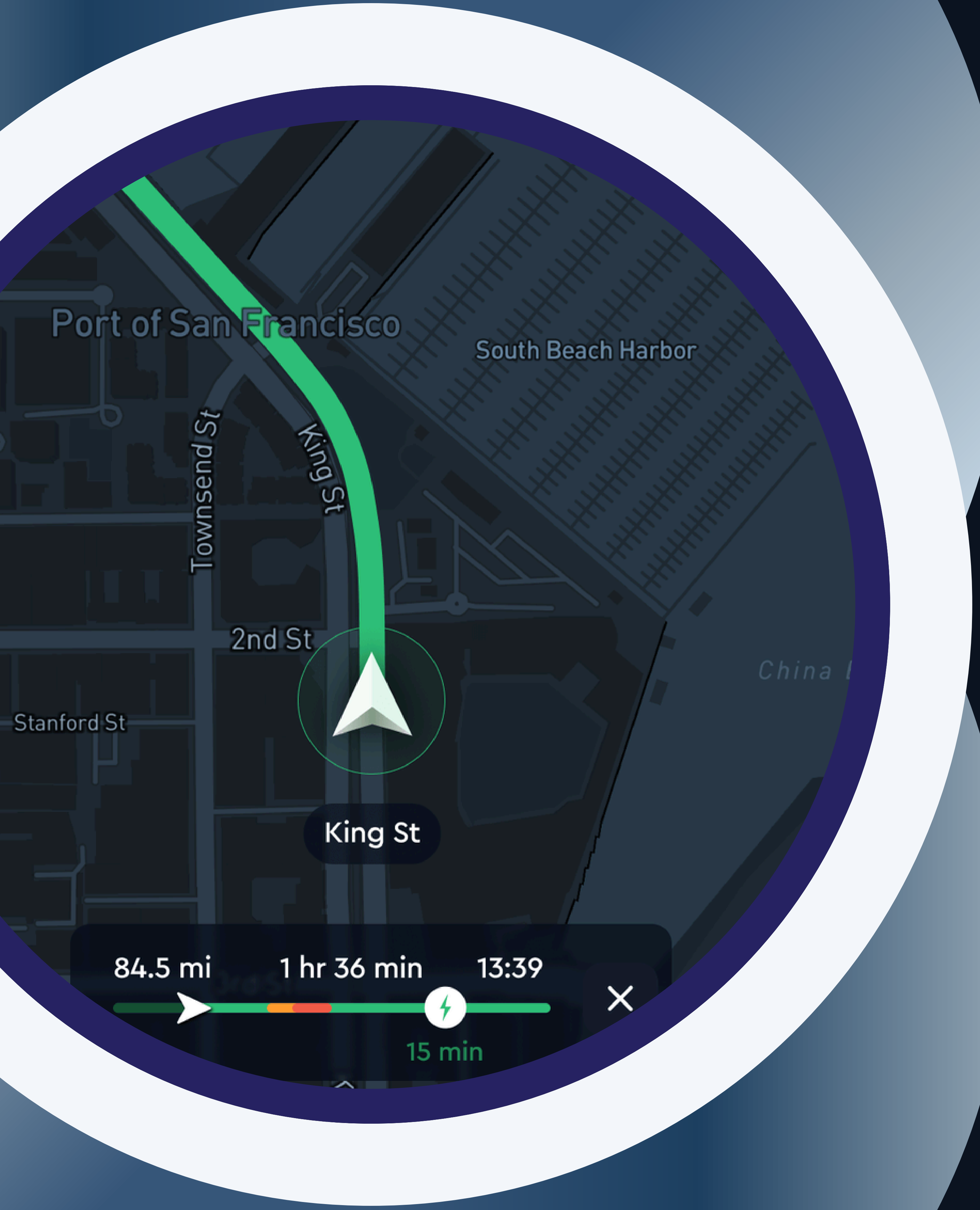




SENSITIVITY ANALYSIS - DELIVERY







DISCUSSION

Comparison with Traditional Approaches

- **Resource Efficiency:** 23% improvement in vehicle utilization
- **Service Quality:** More consistent collection times with fewer missed pickups
- **Environmental Impact:** Reduced fuel consumption and emissions

Implementation Challenges

- **Interdependence:** Collection outputs affect disposal inputs, leading to hard-to-model time dependencies.
- **Complexity:** Large-scale problems demand extensive computational resources.
- **Data Quality:** Precise travel time and waste volume data is crucial for solution accuracy.
- **Dynamic Conditions:** Factors like traffic and vehicle failures can disrupt planned routes.

CONCLUSION

We have developed a multi-phase VRP model to:

- Optimized routes for both collection and disposal phases.
- Reduced total travel time and operational costs.
- Improved vehicle utilization and capacity management.
- Enhanced service reliability and timely waste collection.
- A scalable model that can be adapted to different urban contexts.

FUTURE SCOPE

- Simultaneous Pickup and Delivery (SPD): Enables vehicles to perform both tasks in one route, enhancing route flexibility and resource use.
- Loading and Unloading Time: Including time for these activities improves schedule accuracy and reflects real-world delays.
- Generalized Assignment Procedure (GAP): Clusters locations and assigns vehicles efficiently, simplifying large problems under capacity limits.

APPENDIX

Google Collab Link:
https://colab.research.google.com/drive/1tiTBy3JA64jlm2FVyAAKuded74I6o4n4#scrollTo=16ykIaFvBTpq

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THANK YOU