

Safety-Aware Demand Assignment for Columbia Evening Shuttle

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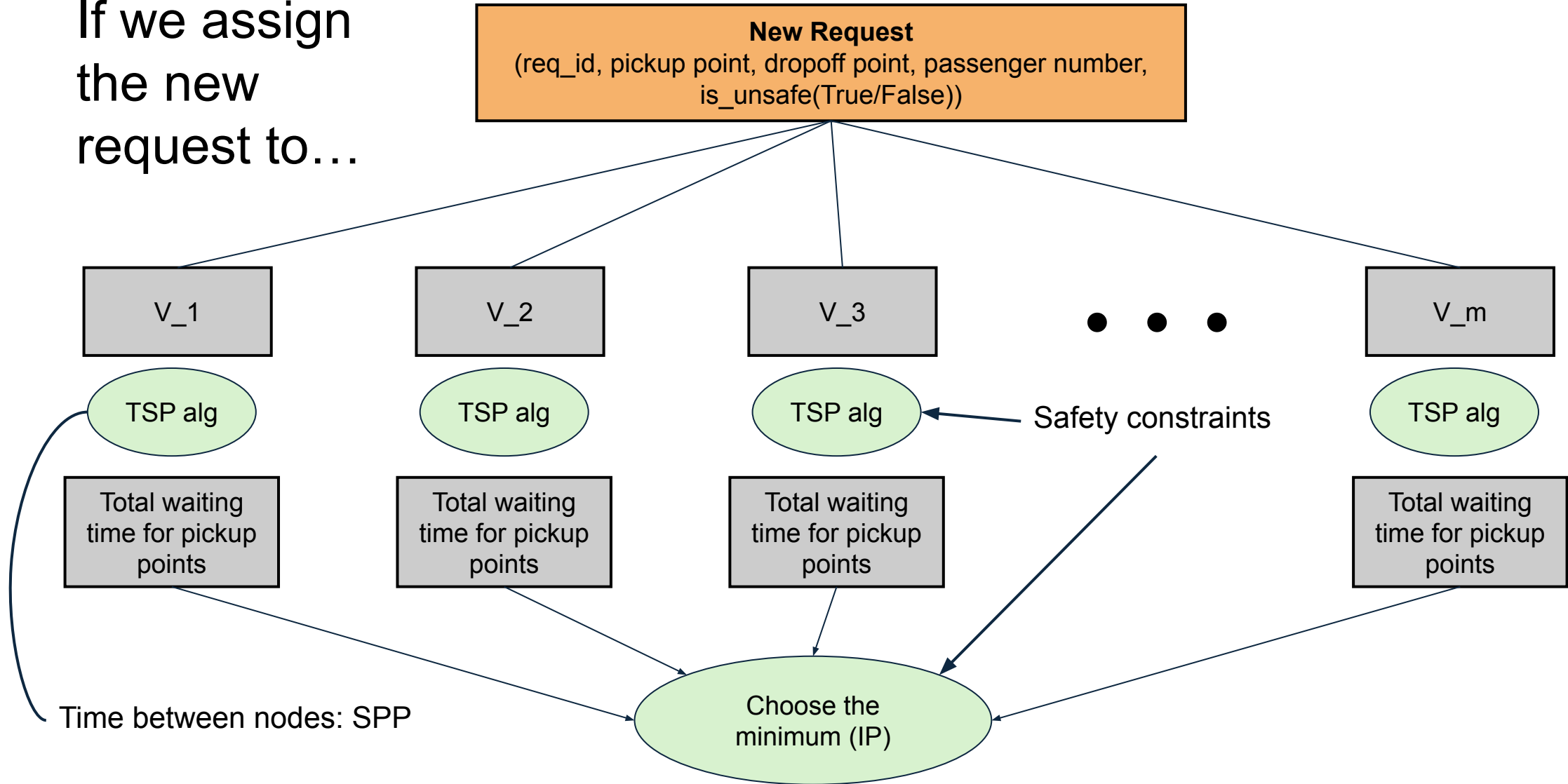
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Model Overview

Ultimate goals:

- Requests from unsafe zones are considered with priorities
- Passengers from unsafe zones cannot wait for so long
- Minimize the total waiting time (system efficiency)

If we assign
the new
request to...



Model Overview

Assumptions:

- The safety condition is constant for different zones
- Only one request comes in at one time (Sequential)
- All requests will generate at one of the intersections in the service area
- No traffics, and vehicles are running with a constant speed
- Pickup time and dropoff time are both 0 for all vehicles (no waiting at each stop)

TSP Algorithms

- ❑ Goal: minimize **total travel time** and **passenger waiting time**
- ❑ Purpose: **To determine the optimal visiting order for each vehicle**

Decision Variables

- ❖ $x_{ij}=1$ if shuttle travels from node i to j .
- ❖ s_i : visit order of node i
- ❖ δ_r, μ_r : pickup & drop off positions of request r

Key Constraints

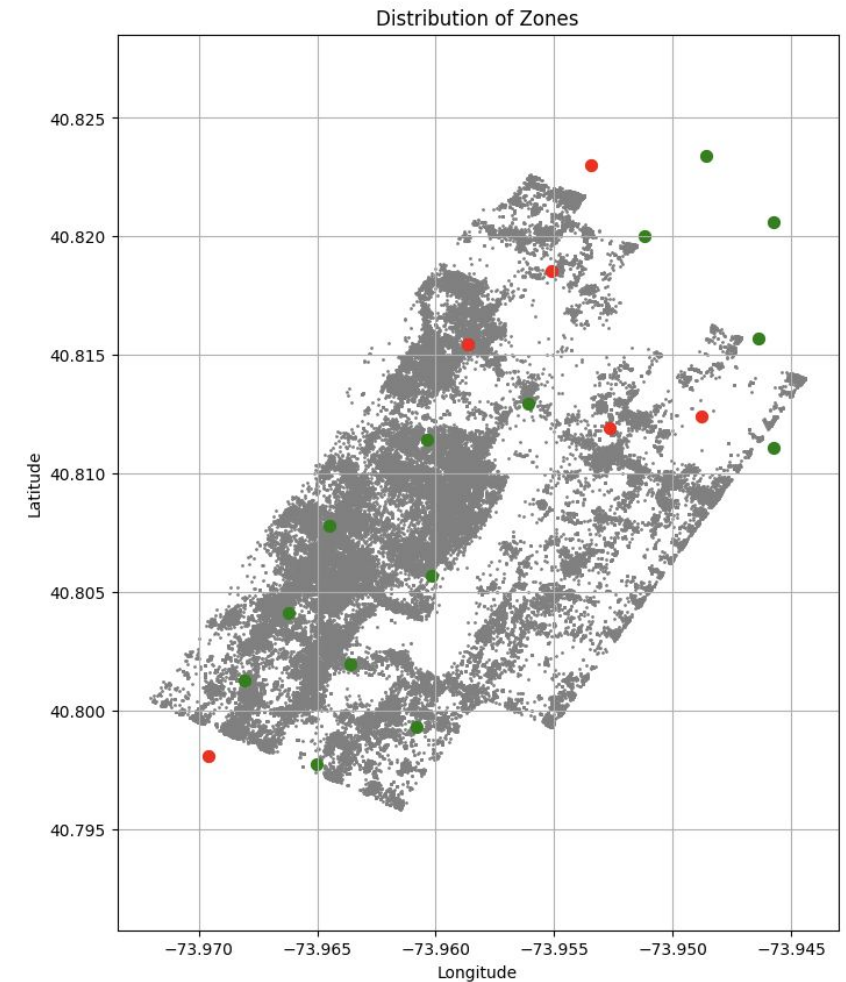
- ❖ Visit each node exactly once.
- ❖ MTZ constraints to eliminate subtours.
- ❖ Pickup before dropoff: $\mu_r \geq \delta_r + 1$
- ❖ To prioritize pickups in unsafe areas, each request r receives a safety indicator $unsafe_r$

Unsafe before safe

$$unsafe_r = \begin{cases} 1, & \text{if the origin is unsafe} \\ 0, & \text{otherwise} \end{cases}$$

$$\delta_{r_u} + 1 \leq \delta_{r_s}$$

$$\delta_{r_i} + 1 \leq \delta_{r_j}$$



Grey dots: historical **origins and destinations** of all trips
Green points: centroids of **safe zones**.
Red points: centroids of **unsafe zones**.
 Shuttle mainly operates inside this area.

- **Zones aggregate many nearby trips into representative centroids.**
- **Safe / unsafe labels can be used as constraints or penalties in the TSP.**
- **This zonal view gives a higher level input to the routing model.**

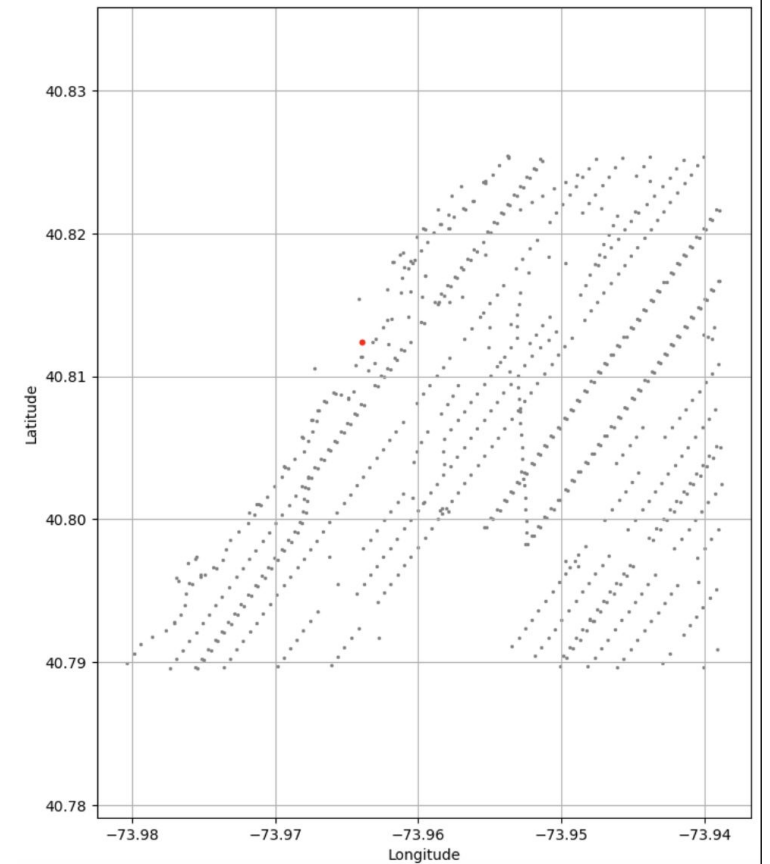
Solution Approach & Results

Bullet Points:

- **Heuristic initialization**
 - ◆ Nearest Neighbor → get a quick feasible route
 - ◆ 2-opt → improve local optimality
- **Used as warm-start for Gurobi integer solver**

Model outputs:

- ◆ The final optimal route
- ◆ Total passenger waiting time
- ◆ Waiting time for the new request



Grey points: intersection nodes used in the TSP model around one zone.
Red points: the **selected intersection** related to the current request (e.g., pickup or dropoff node).
The diagonal grid comes from the local Manhattan-style road network.

- The TSP model chooses one specific intersection (red) among many feasible nodes (grey).
- The regular grid shows that routes follow realistic street geometry, not abstract distances.
- By solving the TSP, we obtain an ordered sequence of these nodes forming the final shuttle route.

IP for Request Assignment



Decision Variable

$x_i = 1$: Vehicle i accepts the request
 $x_i = 0$: Vehicle i does not accept



Fallback Variable

$r = 1$: Request is rejected (fallback in our model)

Every time a request enters the system, this is the choice our model makes.

onboard_i	Current number of passengers in vehicle i
cap_max_i	Capacity limit of vehicle i
g_{pq}	New request passenger count (usually 1)
pickup_time_i	Time for vehicle i to drive to pickup point
trip_time_i	Time from pickup to dropoff
λ_{reject}	Penalty for rejecting a request
$W_{\text{max,unsafe}}$	Max waiting time allowed for unsafe regions
is_unsafe	1 if pickup zone is unsafe

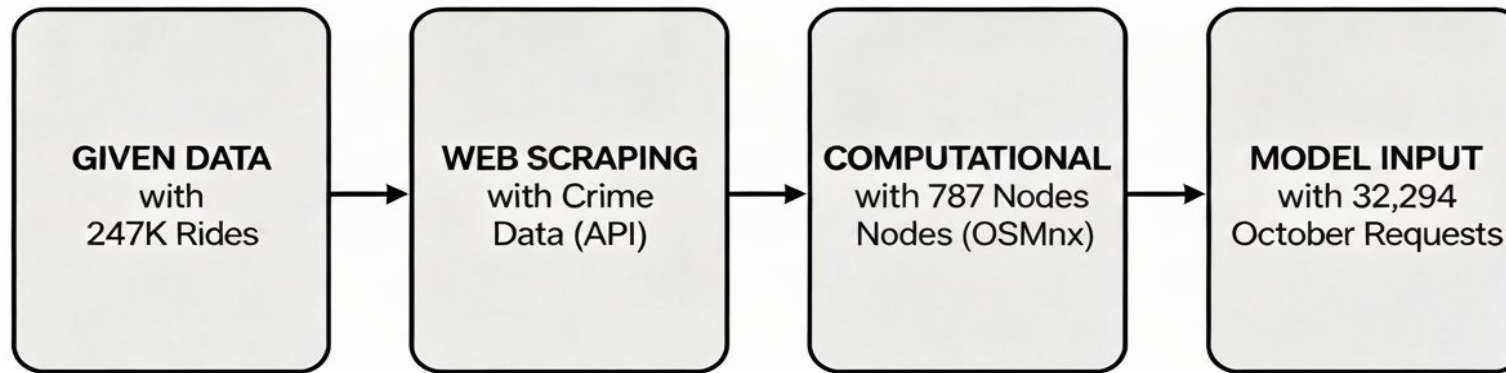
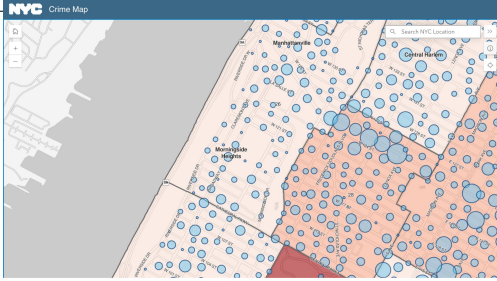
Objective:

$$\min \sum_{i \in V} (\text{pickup_time}_i \cdot x_i) + \lambda_{\text{reject}} \cdot r$$

Constraints:

- 1 $\sum_i x_i + r = 1$ *The request is either rejected or accepted*
- 2 $x_i g_{pq} + \text{onboard}_i \leq \text{cap_max}_i \quad \forall i \in V$ *Capacity Constraint*
- 3 $x_i, r \in \{0, 1\}$ *Binary variable*
- 4 $\sum_{i \in \mathcal{V}} x_i \leq 1$ *Vehicle Constraint*
- 5 $\sum_i \text{pickup_time}_i x_i \leq W_{\text{max, unsafe}}$ *Waiting time constraint (Applied only if Origin is unsafe)*

Data Acquisition & Processing



20 Safety Zones
(K-Means)

787 Intersections
(OSM)

Evaluation Metrics:

1. Wait time
2. Compliance Percentage

Core Results + Sensitivity Analysis

Fleet Size	Service Rate (%)	Wait Time (min)	Overall SLA (%)
70%	75.3	30.9	17.9
85%	84.9	27.0	28.3
100% (Baseline)	93.3	21.6	43.5
115%	96.0	17.3	57.8
130%	98.1	13.5	71.7

Core Results + Sensitivity Analysis

Maximum Wait time(min)	Service Rate (%)	Wait Unsafe (min)	Unsafe SLA (%)
8	92.9	19.1	28.0
10	93.2	20.0	30.7
12	93.3	21.5	31.5
15	93.0	23.1	33.4
18	92.7	24.3	35.4

Core Results + Sensitivity Analysis



Unsafe Zone Wait Times



17.9%
IMPROVEMENT

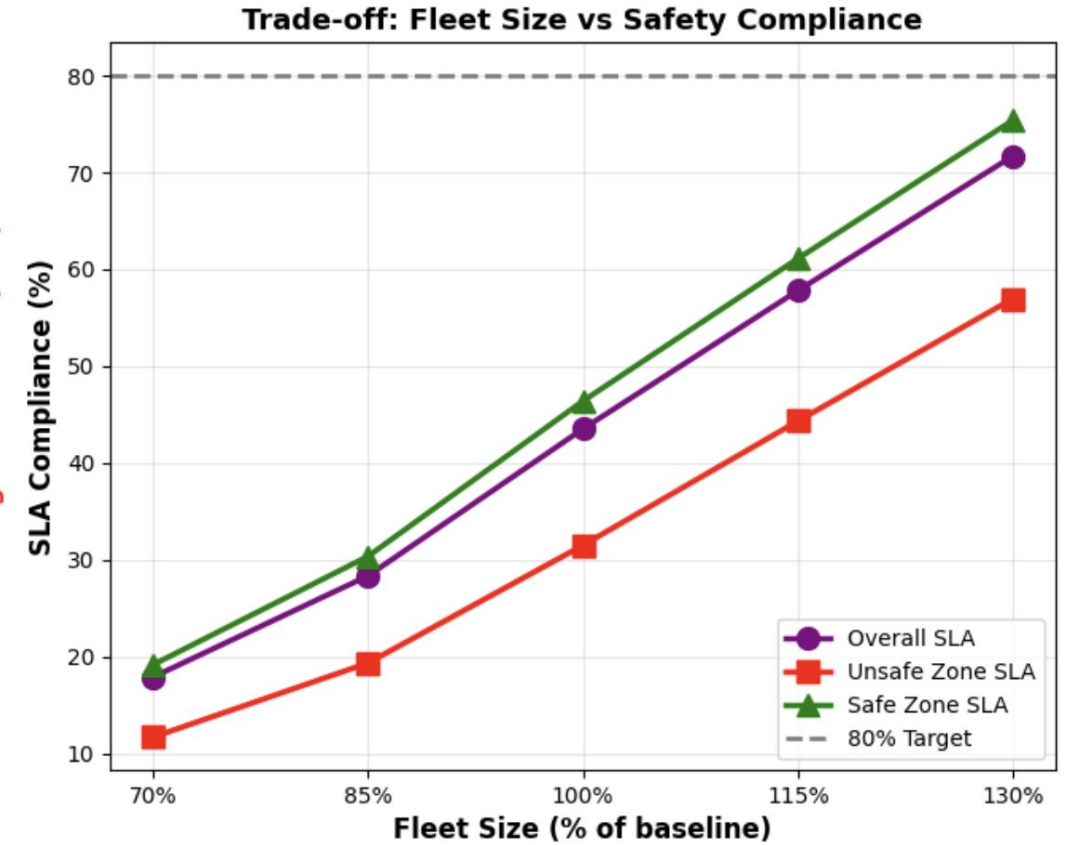
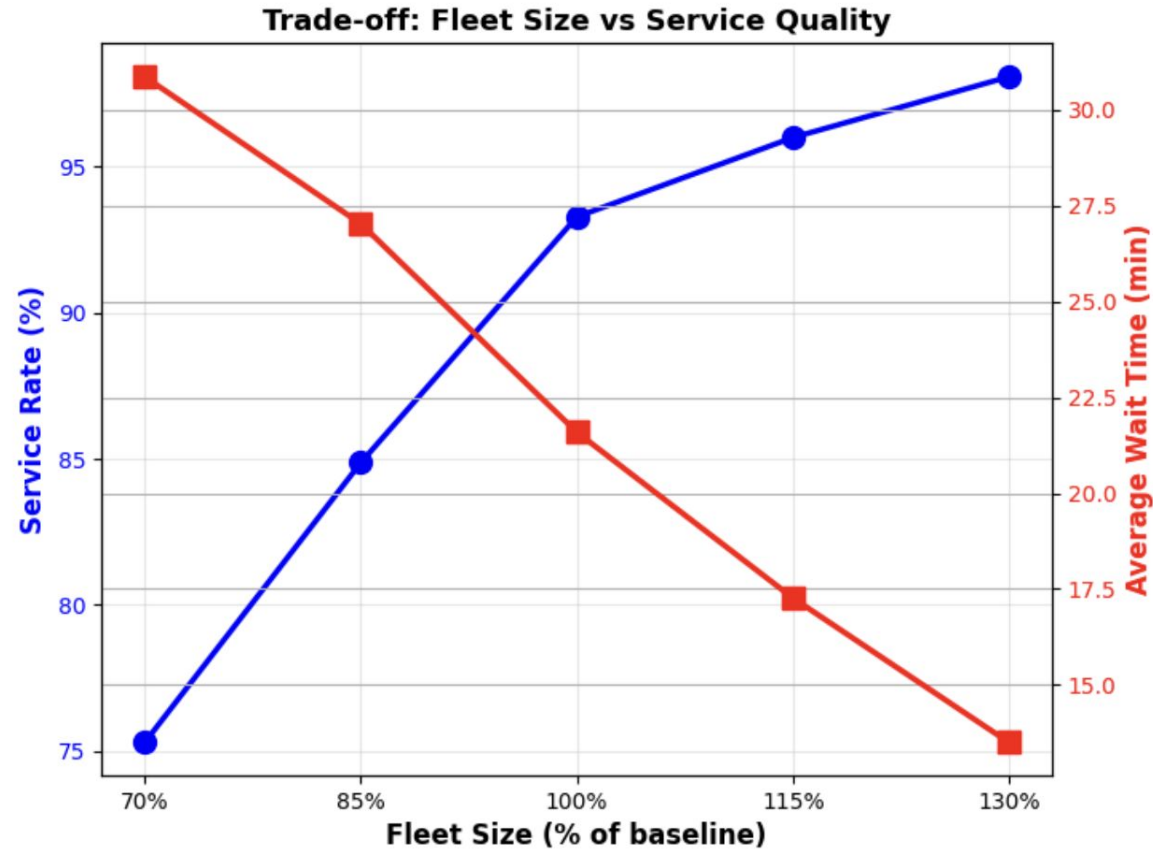


SLA Compliance



+14.9
percentage points

Tradeoff Analysis



Thank You