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Simulation Based Battery Swapping and Charging Station System Design in Logistic Hubs for Electric Trucks

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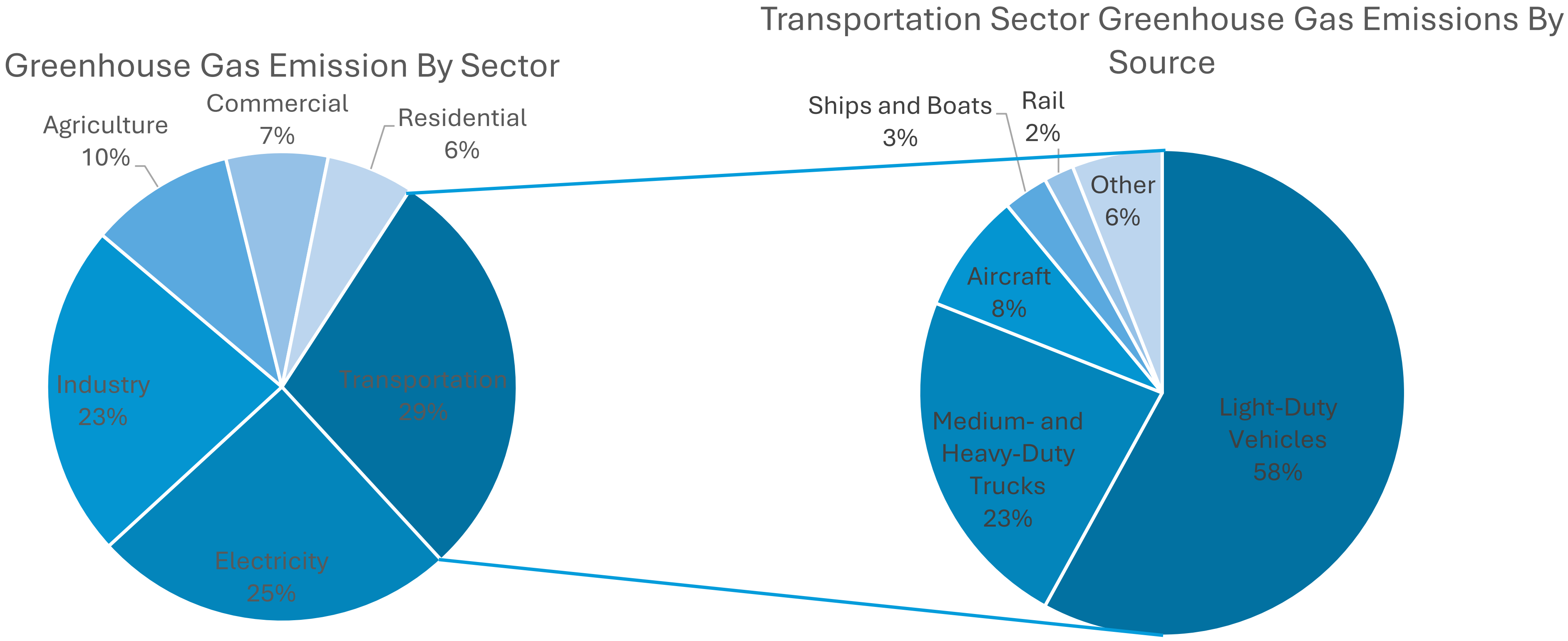
Motivation

Now

To transition into net-zero emission, the world targets to reduce the greenhouse gas(GHG) emission by 45% by 2030 and reach net zero by 2050.

https://balcasenergy.com/net-zero-by-2050/
https://www.un.org/en/climatechange/net-zero-coalition

Motivation



As of 2021, 29% of the GHG emissions are from transportation. Within this sector, 23% of the GHG emissions are from medium- and heavy-duty trucks.

Transitioning from conventional to electric trucks could reduce the GHG emissions, contributing to the achievement of the net-zero goal

https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

Motivation

To transition towards electric trucks, Battery Charging Stations can be deployed at the hyperconnected logistic hubs to ensure the trucks finish “re-fueling” their batteries within a “reasonable” time at the hub.

Network planning provides the following as the input of facility planning:

- Initial Battery Inventory Level
- Daily Arrival/Departure

Network planning (Monthly + Daily decisions)

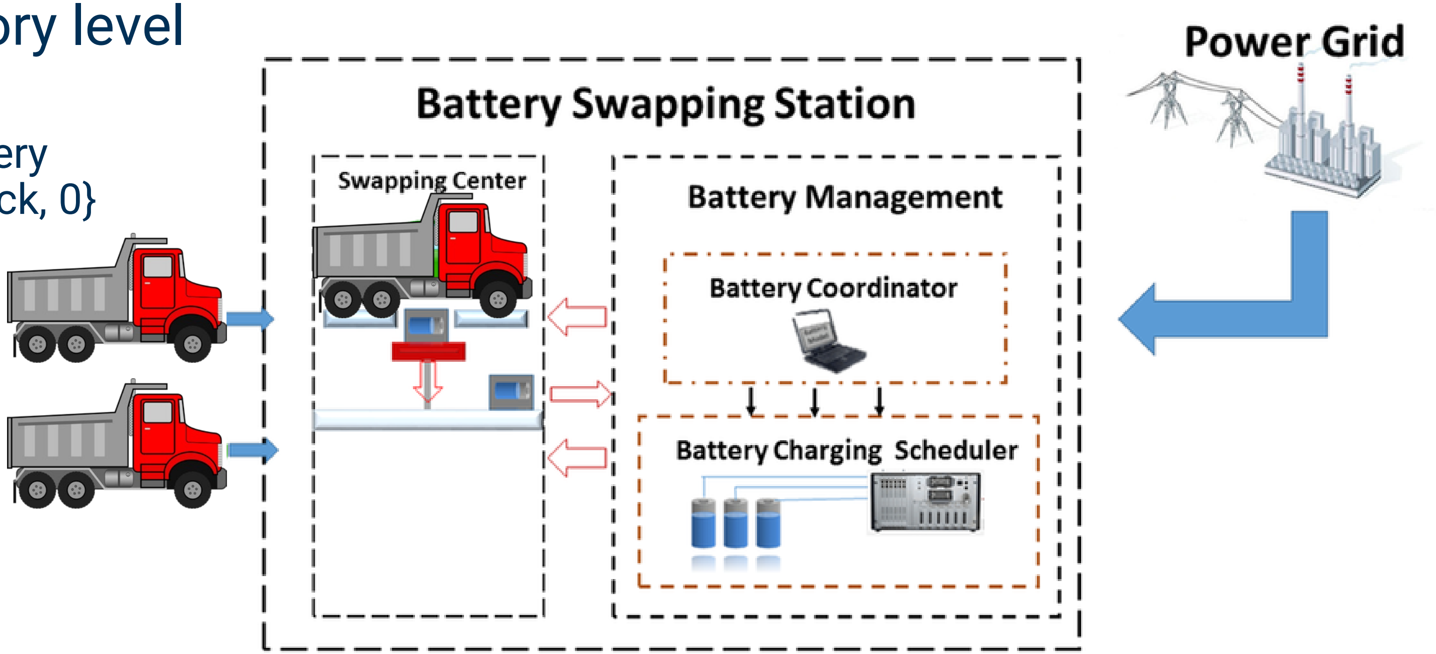
Facility planning (Daily decisions)
Further optimizing battery inventory within a day

Facility planning provides the following as the input of network planning:

- Dwell Time of Trucks
- Updated Battery Inventory Level

Problem Description

- During intra-day operation at the Battery Swapping Stations, we enable depleted batteries to be charged locally at the station.
  - Recharged battery can be swapped to the other arrived trucks
- Objective: reduce the battery inventory level while keep the extra dwell time low
  - Extra dwell time: max{dwell time with battery swapping − dwell time of conventional truck, 0}



Assumptions for Simulation Modeling

- Selected Hub Location : Atlanta, GA, Intersection of I-285 x I-85 N
- Using Network Generated from Network Planning:
  - Arcs flow into selected hub: (Distance calculated by the locations' latitude and longitude)

Hub Pair	Distance (miles)	Yearly Arrival (Trucks)	Yearly Arrival (%)
Atlanta – Atlanta	12.82	10,768	14.81
Athens – Atlanta	50.89	49,372	68.41
Greenville – Atlanta	120.63	2,816	3.87
Greenville – Atlanta	127.19	7,424	10.21
Nashville – Atlanta	209.08	1,952	2.69

- The battery level on arrived truck is based on the distance of the arc, and electric truck uses 2 kWh per mile.

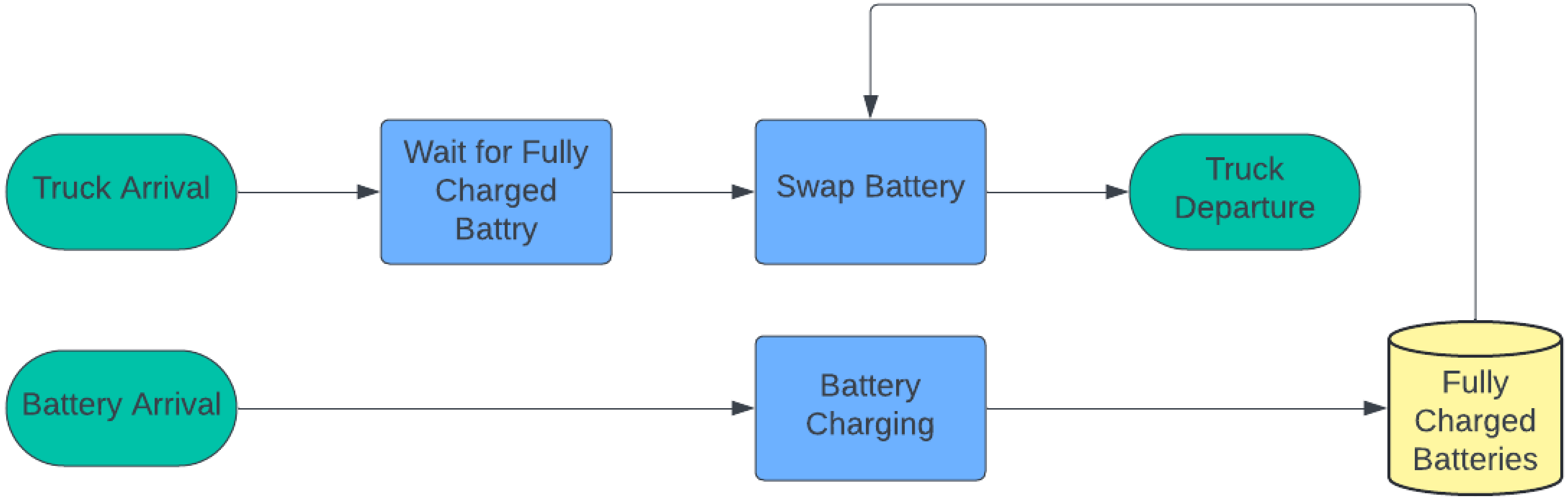
Assumptions for Simulation Modeling

- Only fully charged batteries will be swapped to incoming trucks
- The amount of time needed to charge a battery is linearly proportional to the depleted kWh of the battery.
- The depleted batteries (charging and waiting to be charged) will be transshipped at 8 AM daily.
- Fully charged batteries will arrive at the facility to make the number of total fully charged batteries equals to a fixed amount at 8 AM daily.

Simulation Setup

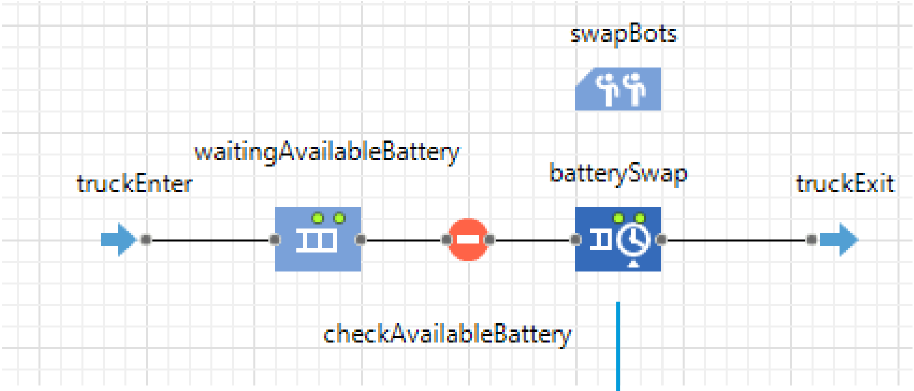
Process Flow of Trucks and Batteries:

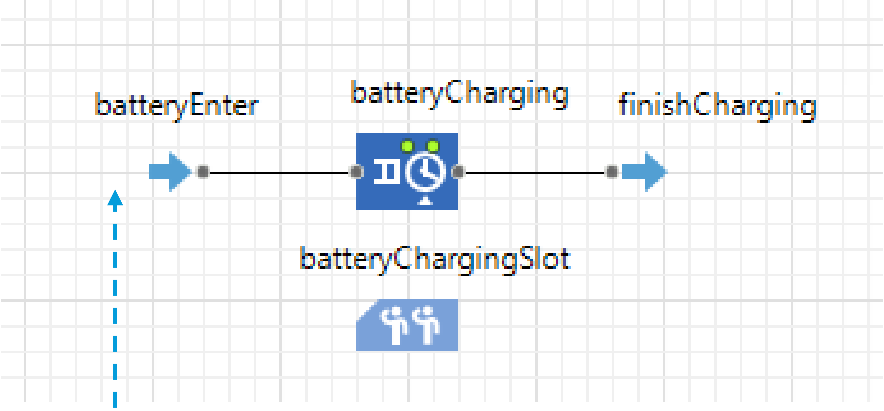
- Trucks will wait at the hub until there is at least one fully charged battery, then the depleted battery on truck will be swapped
- Depleted battery on the truck will enter battery charging queue, and once it finishes charging, it will enter the resource pool of fully charged batteries



Simulation Setup

- Process Flows in AnyLogic:





Battery agent enters battery process flow at batterySwap

Process Flow For Truck Agent

Process Flow For Battery Agent

Simulation Setup

- Parameters of the Simulation:
  - λ_i $i \in [1,2,\ldots,8]$: Truck Arrival Rates
    - A day is divided into 8 time regimes with a length of 3 hours each. Within each time regime, truck arrivals follows Poisson process at rate of λ_i .
  - b: Number of Batteries can be Charged at the Same Time
  - m: Number of Battery Swapping Bots
  - C: Capacity of Batteries
    - Assuming all the batteries in the system have same capacity
  - c: Charging Speed of Batteries
    - Assuming charging speed is independent of current battery level
  - μ: Service Time to Swap a battery
    - Service time follows exponential distribution with parameter μ.
  - N: Number of Batteries at the Battery Swapping Station (Decision Variable)

Simulation Setup

Selected Hub Location: Atlanta GA, Intersection of I-285 x I-85 N

λ_i: 72,692 / 365 = 200 Trucks per day

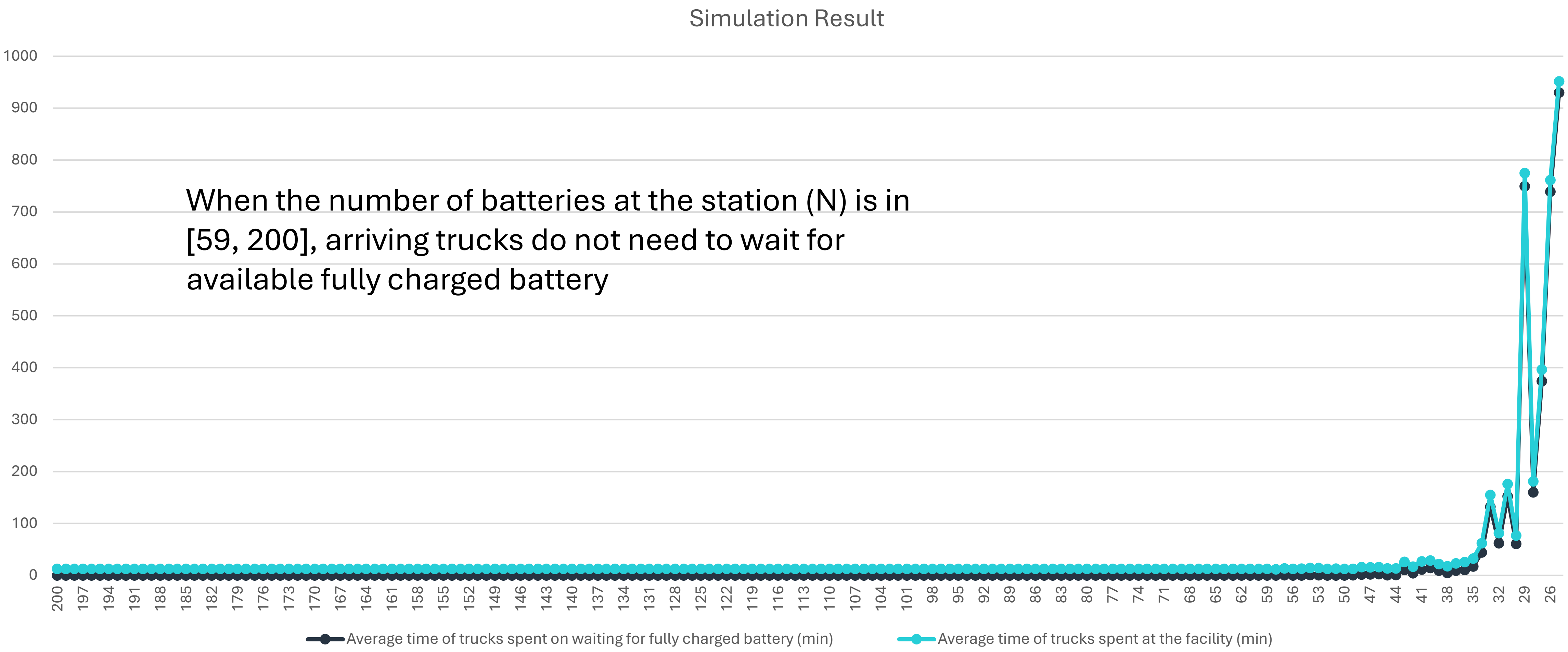
Time	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
Hourly Arrival Rate	4	5.33	6.66	9.33	13.33	10.67	9.33	8

- b: 6 battery charging slot
  - assuming a 13.8 kV transmission line can provide power for 3 charging slots and ~10% of the transmission capacity (230 kV) is used for this charging facility
- m: 1 bot
- C: 450 kWh
- c: 400 kW
- μ: 5 minutes
- N: Decreasing from 200 batteries (Decision Variable)

Results Evaluation

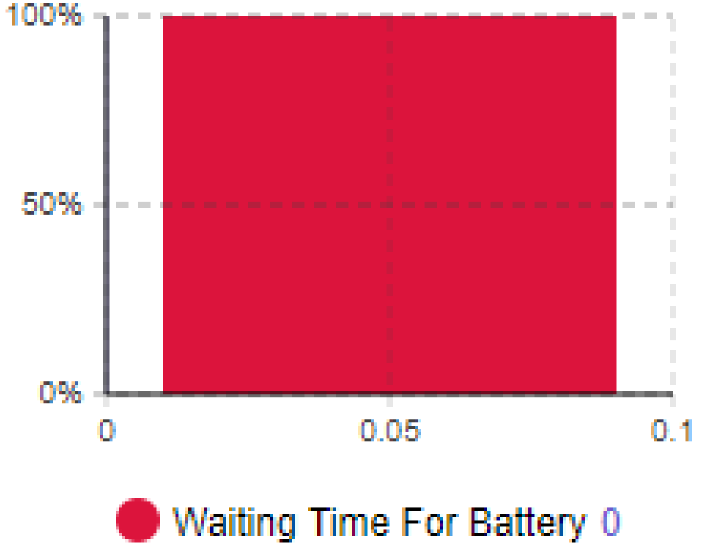
- For different numbers of batteries at the battery swapping station, the following performance indicators will be collected:
  - Average time of trucks spent on waiting for fully charged battery
  - Average time of trucks spent at the facility
  - Truck queue length of waiting for fully charged battery
  - Truck queue length of swapping battery
- Decide the optimal number of batteries, based on number of batteries, waiting time and queue length trade-off

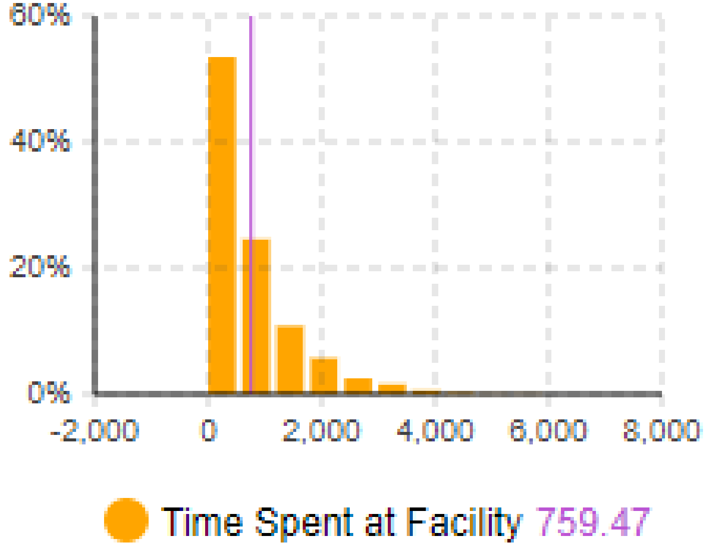
Result Discussion



When the number of batteries at the station (N) is in [59, 200], arriving trucks do not need to wait for available fully charged battery

Result Discussion

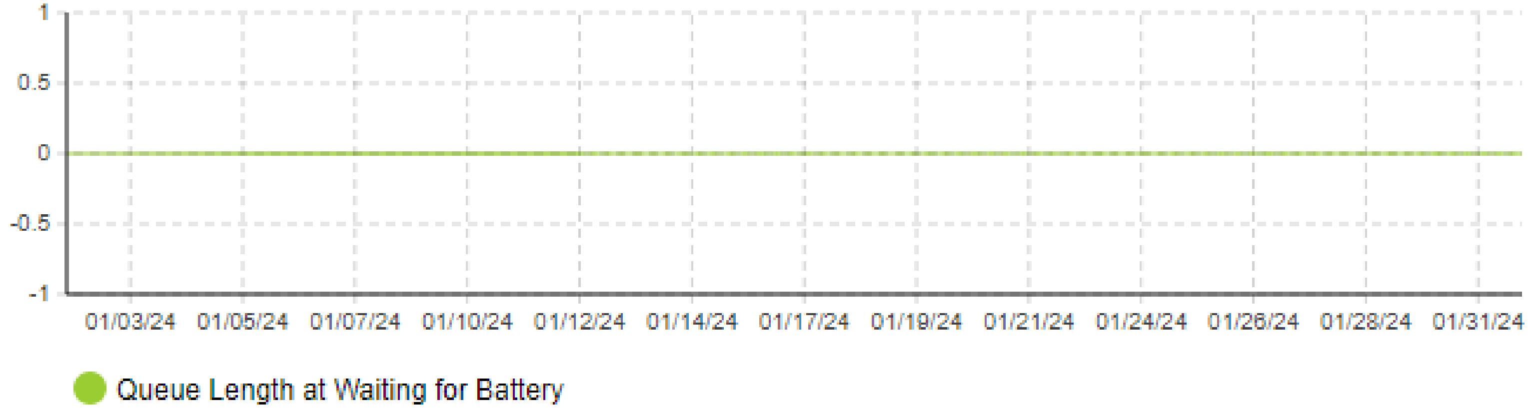




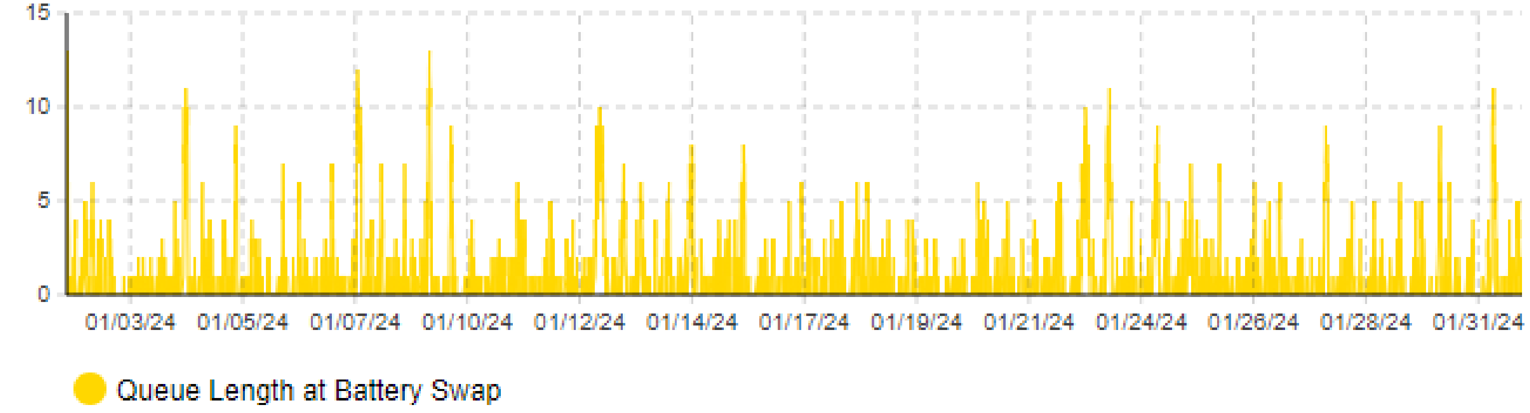
Result is the same for N in [59, 200]
No Waiting Time for Battery
Average Time Spent at Facility is 759.47 sec (12.66 min)

Result Discussion

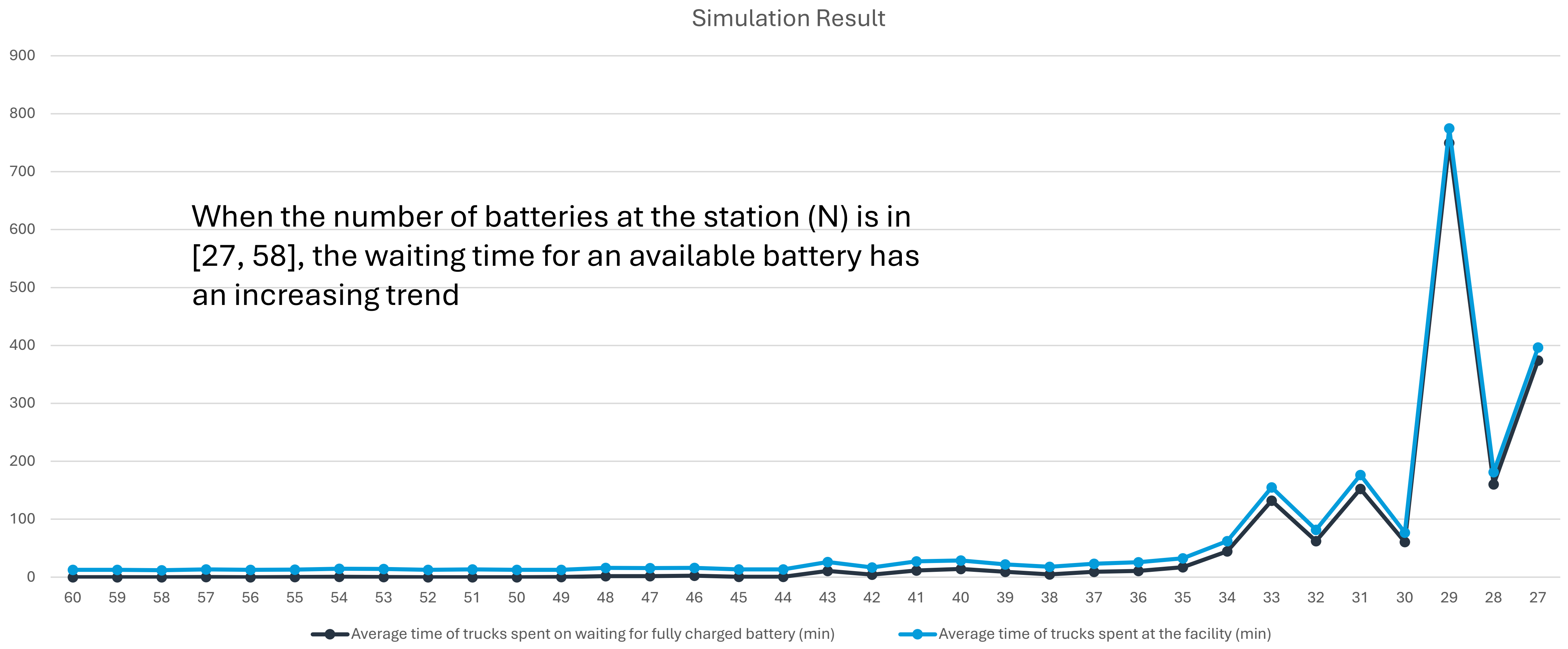
Maximum Queue Length at Waiting for Battery is 0



Maximum Queue Length at Battery Swap is 13

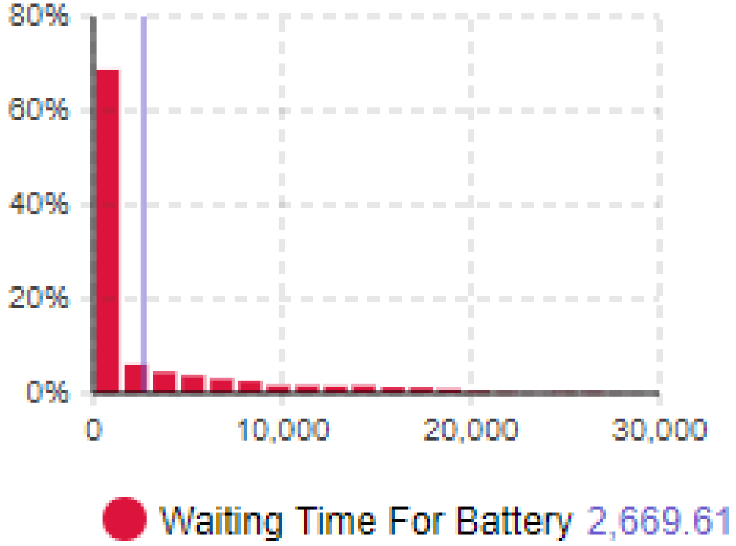


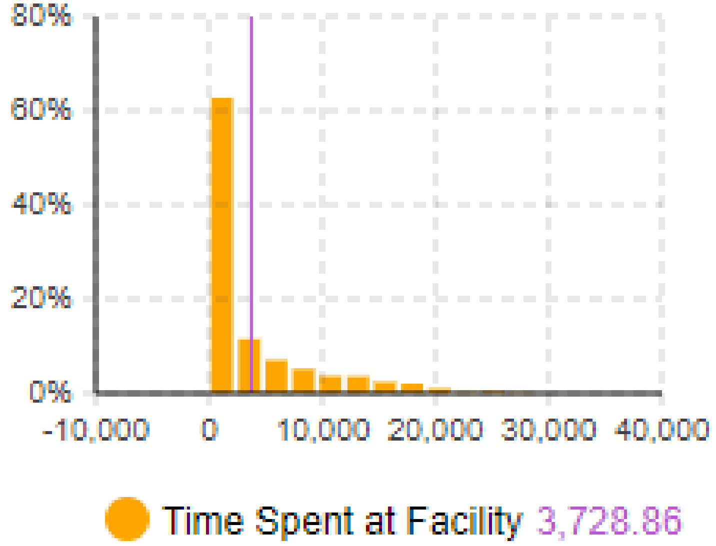
Result Discussion



When the number of batteries at the station (N) is in [27, 58], the waiting time for an available battery has an increasing trend

Result Discussion

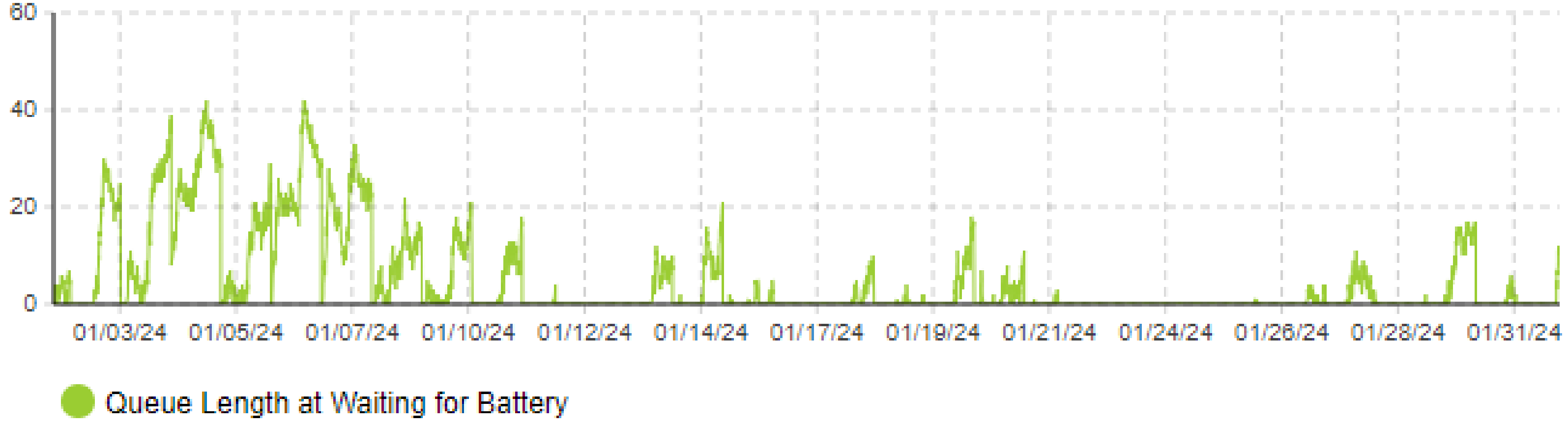




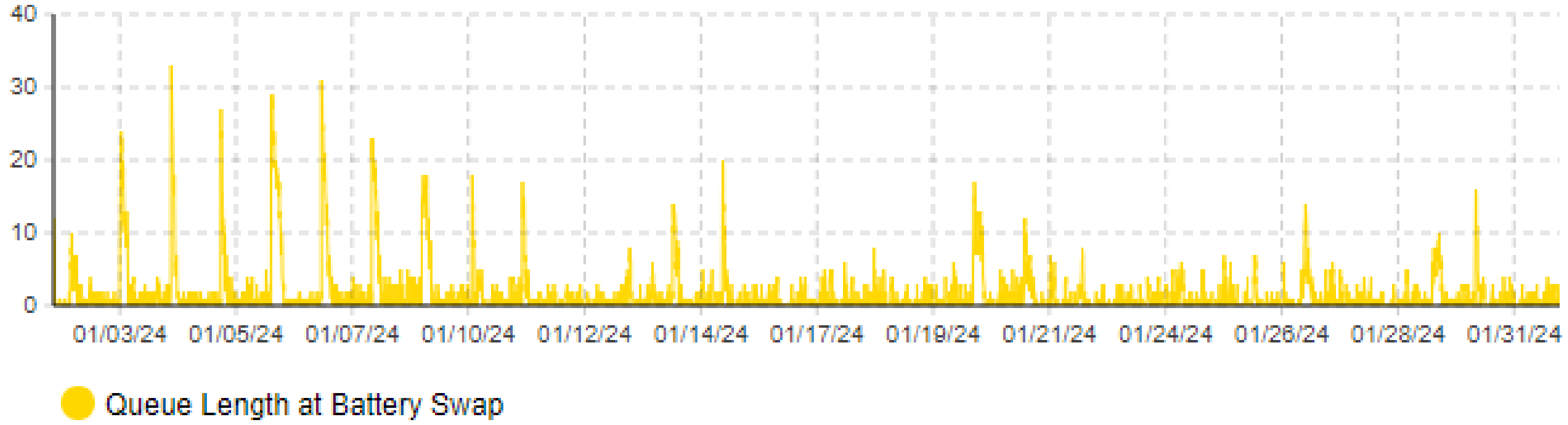
Detailed Waiting Time Distribution for N = 34
Average Waiting Time for Battery is 2669.61 sec (44.49 min)
Average Time Spent at Facility is 3278.86 sec (62.15 min)

Result Discussion

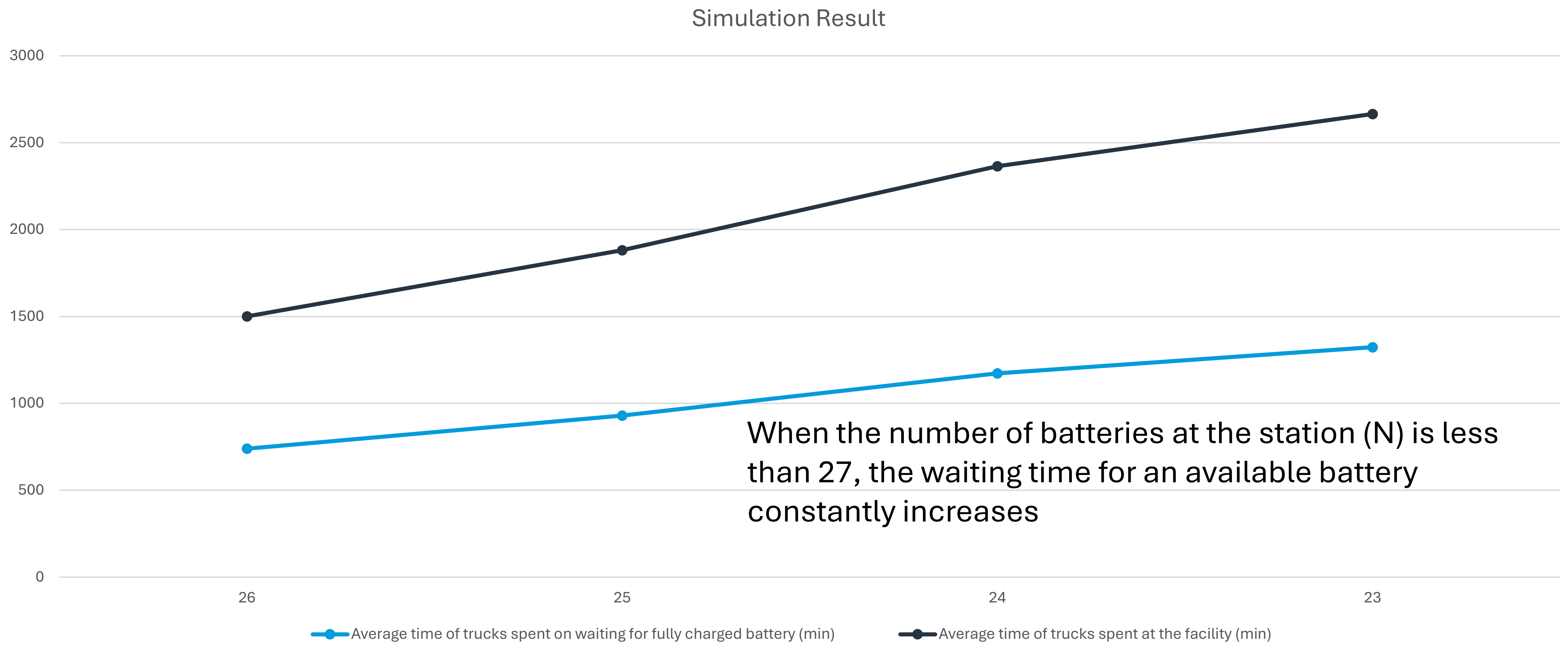
Maximum Queue Length at Waiting for Battery is 41



Maximum Queue Length at Battery Swap is 32

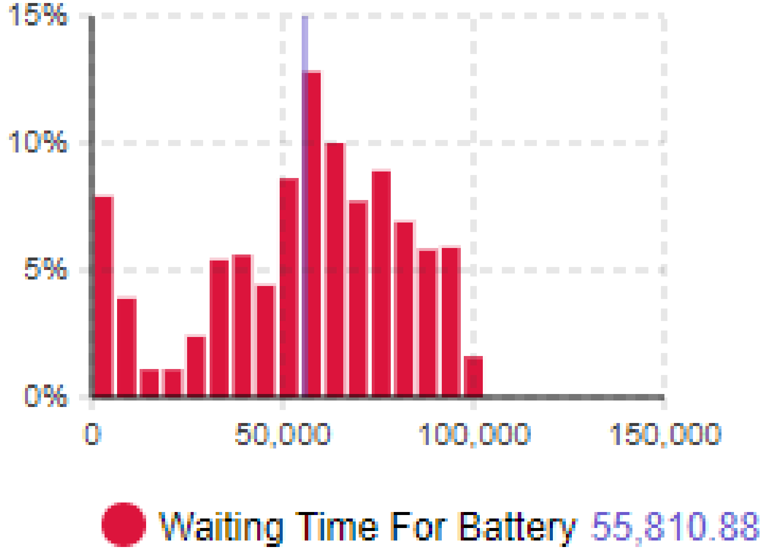


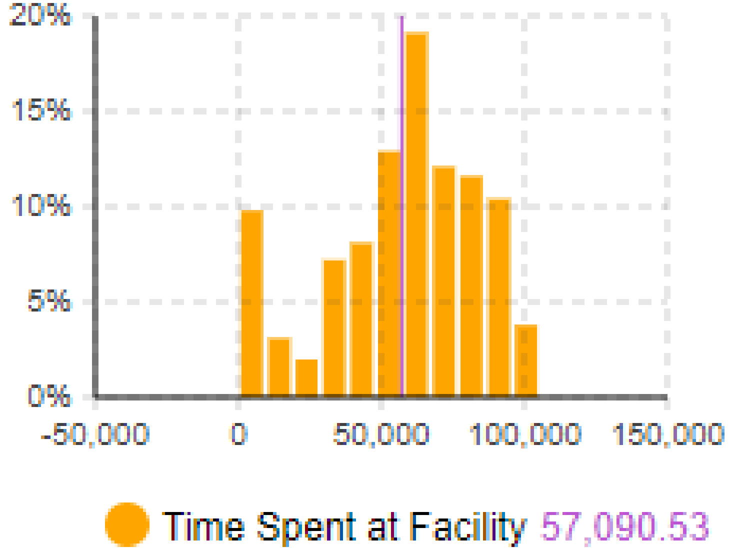
Results Evaluation



When the number of batteries at the station (N) is less than 27, the waiting time for an available battery constantly increases

Result Discussion



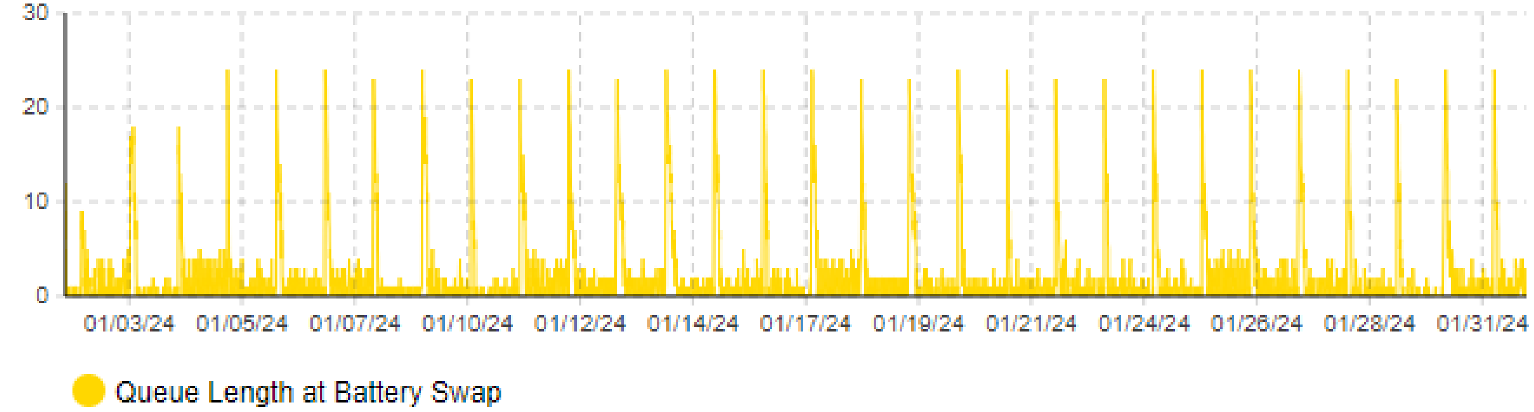


Detailed Waiting Time Distribution for N = 25
Average Waiting Time for Battery is 55,810.88 sec (930.18 min)
Average Time Spent at Facility is 57,090.86 sec (950.51 min)
The waiting time will keep increasing as simulation continues running

Result Discussion

Queue Length at Waiting for Battery keeps building up

Maximum Queue Length at Battery Swap is 33



Future Works

- Exhaustive Search for Optimal Number of Batteries → Decision Making With Reinforcement Learning
- Linear Charging Speed → Charging Speed Depending on Battery Level
- One Battery per Truck → Modular Batteries on Truck

Thank You!