Report on EV Supercharger Network Optimization and Analysis

1. Introduction

The increasing adoption of Electric Vehicles (EVs) demands a reliable and optimized charging infrastructure. This report focuses on analyzing Tesla Supercharger data across the United States, with a special focus on California due to its high EV adoption. The goal is to understand station distribution, identify patterns in urban vs. rural coverage, and construct an optimization model that minimizes travel distance to charging stations while ensuring accessibility.

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2. Dataset Description

The dataset used in this analysis contains details about Tesla Supercharger stations in the USA, with the following key attributes:

- **Supercharger** – Name/ID of the charging station
- **Latitude & Longitude** – Geographical coordinates of the station
- **State** – US State where the station is located
- **City** – City of the charging station
- **Stalls** – Number of charging stalls available
- **kW** – Power capacity of the charging station (in kilowatts)
- **Elev(m)** – Elevation of the station above sea level (in meters)

This dataset allows exploration of geographical distribution, power capacity, and availability of charging stalls across different states.

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3. Exploratory Data Analysis (EDA)

3.1 Univariate Analysis

- California has the **highest number of Supercharger stalls**, concentrated in metropolitan areas like **San Francisco, Los Angeles, and San Diego**.
- Power capacities generally range between 72 kW and 250 kW, with newer stations providing higher outputs.
- Elevation levels vary widely, affecting accessibility in mountainous regions.

3.2 Multivariate Analysis

A **pair plot** of (kW, Elevation, Stalls, State) reveals correlations:

- Higher stall numbers are generally concentrated in low-elevation metropolitan areas.
- States with larger EV adoption (California, Texas, Illinois) show higher clustering of high-capacity chargers.

3.3 Nearest Neighbor Distance Analysis

- Using a **KDTree nearest neighbor search**, we calculated the distance from each station to its closest neighbor.
- Distances were converted into miles and visualized in a **scatter mapbox plot**, where connections between stations were color-coded based on distance bins.
- Results show dense clustering in metropolitan regions, while rural areas exhibit larger gaps, indicating potential coverage issues.

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4. Optimization Model

To ensure efficient placement of Supercharger stations, we model the problem as a **facility location optimization problem**.

4.1 Decision Variables

$$x_i = 1 \text{ if a station is placed/retained at location } i\text{, else } 0.$$
$$y_{ij} = 1 \text{ if demand node } j \text{ is served by station } i\text{, else } 0.$$

4.2 Objective Function

$$\text{Minimize } Z = \sum_i \sum_j d_{ij} \cdot y_{ij}$$

where d_{ij} is the distance between station i and demand node j.

This objective minimizes the **average travel distance** to the nearest charging station.

4.3 Constraints

1. **Assignment constraint**:

$$\sum_i y_{ij} = 1 \quad \forall j$$

   Every demand node must be assigned to exactly one station.

2. **Activation constraint**:

$$y_{ij} \leq x_i \quad \forall i, j$$

   A demand node can only be served if a station exists.

3. **Capacity constraint**:

$$\sum_j y_{ij} \leq C_i \quad \forall i$$

   Each station i has a limited number of charging stalls C_i.

4. **Station limit constraint (if applicable)**:

$$\sum_i x_i \leq P$$

   Only P stations can be built/retained under budget limits.

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5. Solution & Findings

- The optimization model ensures that charging stations are located such that **average travel distance is minimized**.
- In California, results showed that the **majority of stations cluster around metropolitan areas**, which aligns with demand but leaves **gaps in rural/remote areas**.

- The nearest-neighbor distance analysis confirmed that EV drivers in cities like Los Angeles or San Francisco are **never far from a charger**, while drivers in Central California may face **longer travel distances**.
- By optimizing placement, **the model identified additional rural locations where building new chargers would reduce travel distance gaps**.

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6. Conclusion

This analysis highlights the importance of strategically expanding EV charging networks. While California and other metropolitan-heavy states currently lead in infrastructure, **rural coverage gaps remain a challenge**. The optimization model provides a framework to minimize travel distances and ensure equitable accessibility for EV users.

Future improvements may include:

- Integrating **real-world traffic patterns** into the distance calculations.
- Considering **renewable energy integration** (e.g., solar-powered stations).
- Extending the optimization beyond California to cover all US states.