International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 04 April-2026 | Impact Factor: 3.5

AI-Based Electric Bus Charging Infrastructure Planning for Sustainable Urban Transportation

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How to Cite this Article:

Sunkara, S., A, Y., Krishna, M. V. & Srikar, P. O. (2026). AI-Based Electric Bus Charging Infrastructure Planning for Sustainable Urban Transportation. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(04). https://doi.org/10.55041/ijcope.v2i4.605

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Abstract:

More cities are using electric buses, which is an important move to cut down on pollution. supporting sustainable mobility. However, without a solid electric bus charging Infrastructure problems include things like stations not being spread out well, taking too long to charge, and not using resources efficiently. energy use can hinder progress. These problems can cause reduced reliability and. performance of electric bus networks. This paper proposes an AI-based electric bus. A system for planning charging infrastructure that uses machine learning to find the most effective solutions. locations for bus charging stations. We suggest a K-Means clustering approach that looks at big transportation data to find where the most demand is. charging. Our method creates a model by taking into account several factors, such as bus. By looking at routes, how busy the roads are, how many people want to travel, and where the bus depots are, we can spot patterns. Using These patterns can help select the best charging stations to improve accessibility. reduce traffic congestion. The proposed method improves charging locations, waiting times, energy use, and how well it reaches cities. This represents a significant

Better planning for infrastructure to support electric vehicles is helping to make their operations more efficient. Helping electric buses and promoting smart, sustainable transportation in cities.

Keywords: Electric Buses, Electric Bus Charging Infrastructure, Machine Learning, K-means Clustering Algorithm, Smart Cities, Urban Transport

INTRODUCTION

Cities around the world are growing faster than ever before, which means there's a bigger need for good and dependable ways to move people and goods. As cities grow, more cars are on the roads, leading to increased fuel use, heavy traffic, and harm to the environment. Most public transportation systems, which are usually run on diesel and other types of fossil fuels, are a big reason for air pollution and the release of harmful gases that cause global warming. These emissions can damage the environment and also cause major health problems for people living in cities. So, there's a big need to switch to cleaner and more sustainable ways of traveling.

Electric mobility has become a good and working way to deal with these problems. Electric buses are becoming popular because they can take many people at once and don't release any harmful gases from their exhaust. Electric buses help make the air cleaner, reduce noise, and save money on running costs in the long run. Governments and policymakers everywhere are spending more money on making public transport systems use electricity. This is part of their effort to support sustainable development and meet climate goals. Even though electric buses have many benefits, it's still hard to use them widely because of some real-world problems. One of the biggest problems is creating a good and dependable system for charging. Unlike regular buses that can be filled up with fuel fast, electric buses need charging spots that have to be thought about and placed in smart locations. How long the charging takes depends on how much power the battery can hold and what kind of charging method is being used. Poor planning of infrastructure can cause problems like slower operations, less use of available resources, and higher expenses.

Planning electric bus charging infrastructure is a difficult task that takes into account many things like how the buses travel, traffic on the roads, how well the batteries work, how much energy is needed, how long it takes to charge, and how much power the electricity grid can handle. Cities are always changing, with the number of people needing rides and the flow of traffic going up and down during the day. Traditional ways of planning might not work well when dealing with a lot of complexity and changes. This means there is a need for smarter, data-based methods that can help plan infrastructure better and keep systems running smoothly.

Artificial Intelligence (AI) has become a strong tool for tackling tough optimization and decision-making challenges in many areas, such as transportation. AI methods like machine learning, deep learning, and predictive analytics allow systems to handle big amounts of data and find useful patterns within it. These abilities make AI very good for planning where to put charging stations for electric buses. AI systems look at both past and current data to forecast how much energy will be used, find the best spots for charging stations, and create smart plans for when to charge.

This project suggests using an AI method to plan where electric buses should charge, helping to make city transportation more sustainable. The system uses information from various places, like GPS data for routes, traffic movement details, how many people want rides, and how batteries are used. With this information, AI can help figure out the best places for charging stations so that buses don't have to travel far to charge and don't spend too much time waiting. This makes sure the buses have enough power to finish all their trips. Predictive models can guess how much energy will be needed in the future and assist in creating infrastructure that can grow and handle more demand as it increases.

Another key part of this project is connecting renewable energy sources with the charging stations. Using renewable energy sources like solar and wind can help cut down the environmental effects of electric bus systems a lot. Renewable energy sources naturally change over time and are affected by the environment. AI can help deal with this change by forecasting how much energy will be produced and making sure energy is sent out in the best way possible. This helps use renewable resources well while keeping the charging network steady and dependable.

Using AI in infrastructure planning helps make operations more efficient and lowers costs. Intelligent systems can change when they charge based on what's happening right now, like if there's a lot of traffic or if something unexpected makes the schedule late. This ability to adjust helps make services more dependable and makes the whole transportation system work better overall. In addition, AI-driven solutions can help policymakers and urban planners make better decisions by offering accurate information and analyzing different scenarios. The growth of smart cities shows how important it is to include advanced technologies in urban infrastructure. AI-powered electric bus charging systems fit into the idea of smart transportation, which uses data and technology to make travel better, cut down on pollution, and improve how people live. By using these new and clever ideas, cities can get closer to their sustainability goals and build a cleaner, more efficient city environment.

PROPOSED

Overview of the Proposed System

The system suggests a new way to plan where to put charging stations for electric buses using AI. It helps make sure the stations are placed in the best spots, manages energy use wisely, and makes the whole bus system run more efficiently in cities. The system handles the shortcomings of old planning methods, which don't take into account real-time factors like traffic, how many people are using the service, and how energy is being used.

The suggested approach uses Artificial Intelligence, Machine Learning, IoT, and optimization methods to create a smart, flexible, and expandable system for planning infrastructure. The system can handle big sets of data, find patterns that aren't obvious, and make smart decisions that are as good as possible for:

- Charging station placement
- Energy demand prediction
- Charging schedule optimization
- Load balancing and energy management

This system helps with smart city projects by making transportation smarter, faster, and better for the environment.

Proposed System Architecture

The system's design uses layers to make it easier to manage, grow, and handle tasks quickly as they happen. The major layers include:

- Data Collection Layer
- Communication Layer
- Data Processing Layer
- AI and Optimization Layer
- Application Layer

Each layer has a particular job and works with the other layers to make sure the system runs smoothly.

Data Collection Layer

This layer collects real-time and past data that is needed to make decisions.

Components:

- GPS devices (bus location tracking)

- Battery Management Systems (BMS)
- Smart meters at charging stations
- IoT sensors for traffic and environmental data

Functions:

Continuous data acquisition

Monitoring energy consumption Tracking bus routes and performance Let dataset be:

D={x1,x2,x3,...,xn}

Where xi represents features such as:

- Route distance
- Passenger demand
- Battery level
- Traffic density

This layer makes sure data is collected correctly and instantly, which is important for making predictions using AI.

Communication Layer

This layer allows data to move smoothly between the hardware and the main systems.

Technologies Used: Internet of Things (IoT) Wi-Fi / 4G / 5G

Cloud connectivity

Functions:

- Real-time data transmission
- Secure communication
- Integration of distributed systems

This helps the data move smoothly and consistently throughout the system.

Data Preprocessing Module

Raw data is cleaned, made consistent, and changed into a proper format.

Normalization Formula

To scale values between 0 and 1:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

Where:

X = original value Xmin = min value Xmax = max value

This ensures uniformity and improves model performance.

Demand Prediction Module (AI-Based Forecasting)

This module predicts:

- Passenger demand
- Energy consumption
- Charging requirements

Machine Learning Model

A model based on regression or deep learning, like LSTM, is used.

Prediction Function

$$\hat{y} = f(x_1, x_2, ..., x_n)$$

Loss Function (Mean Squared Error)

$$MSE = \frac{1}{n}\sum(y_i - \hat{y}_i)^2$$

This minimizes prediction error.

Charging Station Placement Optimization

This module finds the best places to put charging stations.

Problem Definition

Objective: Minimize total cost and maximize accessibility.

$$Minimize : Z = \sum C_i x_i + \sum D_{ij} y_{ij}$$

Constraints

Coverage Constraint

$$\sum x_i \geq k$$

Demand Satisfaction

$$\sum y_{ij} \geq demand_j$$

Capacity Constraint

$$Load_i \leq Capacity_i$$

Optimization Techniques

• Genetic Algorithm (GA)

• K-Means Clustering (for grouping routes)

K-Means Objective

$$J = \sum_{i=1}^{k} \sum_{x \in C_i} ||x - \mu_i||^2$$

Route and Scheduling Optimization

This module helps buses run smoothly and keeps them working with very little time spent not operating.

Objective Function

Minimize : T=Travel Time+Charging Time+Waiting Time

Constraints

Battery must not fall below threshold:

SoC≥SoCmin

Charging must occur within available time slots

Scheduling Algorithm

AI-based dynamic scheduling changes routes as things happen in real time, based on:

• Traffic

• Demand

• Battery levels

Energy Management Module

This module helps use energy more efficiently and connects with renewable energy sources.

Energy Consumption Model

$$E = P \times t$$

Where:

E = energy consumed P = power

t = time

Battery State of Charge (SoC)

$$SoC = \frac{Current\ Charge}{Maximum\ Capacity} \times 100$$

Renewable Energy Integration

AI predicts renewable energy availability:

$$E_{total} = E_{grid} + E_{renewable}$$

Objective:

$$Maximize : E_{renewable}$$

AI Decision-Making Engine

This is the main part that brings together the results from all the smaller systems.

Functions:

• Real-time decision making

• Adaptive learning

• Predictive optimization

Model Update Rule

$$W_{new} = W_{old} - \alpha \nabla L$$

System Workflow

• Data is collected from sensors and databases

• Preprocessing ensures clean input

• AI models predict demand and energy needs

• Optimization algorithms determine station locations

• Scheduling module assigns routes and charging times

• Energy module manages power distribution

• System continuously updates using real-time data

Advantages of Proposed System

• Intelligent decision-making using AI

• Reduced operational cost

• Efficient charging infrastructure placement

• Improved service reliability

• Lower environmental impact

• Scalable for future smart cities

Conclusion of Proposed System

The suggestedAI system offers a complete approach for planning the charging setup for electric buses. By using machine learning, optimization methods, and energy management approaches, the system helps use resources efficiently and supports eco-friendly city transportation. The modular design makes it easy to adjust to real-life situations, which means it's a useful and flexible option for today's cities.

EXPERIMENTAL SETUP

The setup for the AI-Based Electric Bus Charging Infrastructure Planning System was created to test how well artificial intelligence can be used to best place charging stations in a city setting. The work was done with Python because it's easy to use, very adaptable, and has great tools for analyzing data and doing machine learning.

The system was created in a typical computer setup where Python 3.x is already set up. The main libraries used in the experiment are NumPy for doing math calculations, Scikit-learn for setting up machine learning models, and Matplotlib for creating charts and graphs. These tools made it easier to process, analyze, and show the results in pictures.

Because real-world data wasn't available, a made-up dataset was created to act like real bus stops in a city. A total of 50 bus stops were placed at different random spots on a two- dimensional map that shows a city. Each bus stop had a demand value, which shows how much passengers use it or how much charging is needed there. The demand values were created within a certain range to show different levels of activity in various areas. The main goal of the experiment was to find the best places for electric bus charging stations. For this purpose, the K-Means clustering algorithm was used. The number of clusters, which stands for the number of charging stations, was set in advance to five because of the assumed limits on the infrastructure. The algorithm sorted the bus stops into groups based on how close they are to each other, and the center of each group was chosen as the best place for a charging station.

Besides finding the location, the system also figured out how much power each charging station needed. This was done by adding up the demand values of all the bus stops inside

each group. This approach based on demand makes sure that stations in areas where many people need service get more capacity, which helps things run more smoothly and cuts down on crowded areas. The experiment's results were checked using numbers and pictures to show the outcomes clearly. The system showed the locations of charging stations and how much power each one could provide. A scatter plot was created to show how bus stops group together and where charging stations are placed, using different colors for each group. Overall, the setup clearly shows how AI methods can be used in planning infrastructure. It offers a flexible and expandable structure that can be built upon using real data and extra rules to make it work in real-world sustainable city transport systems.

RESULTS

The results show that using AI techniques can effectively help plan where to place electric bus charging stations. The K-Means clustering algorithm effectively grouped the bus stops into separate clusters according to their locations, and the centers of these clusters were chosen as the best spots for placing charging stations. The system also figured out how much each station could charge by adding up the demand numbers in each group, so that areas with more demand got more resources. The visualization clearly showed separate groups with charging stations located in the middle of each group, which helped electric buses travel shorter distances. The results show that the model can offer efficient, balanced, and scalable solutions for planning electric bus charging systems, even when using simulated data.

Heatmap Analysis

The heat map analysis was done to get a clearer picture of where the demand for electric bus charging is highest in the study area. In this analysis, the color's brightness shows how much demand there is in different places. Brighter colors like red and orange mean those areas have a lot of demand, while darker colors like blue and green show places with less demand. The heat map made from the dataset shows areas where there is a lot of passenger demand, and these areas also need more charging stations. It was noticed that the charging stations found by the AI model are near these busy areas, showing that the clustering method works well.

This picture makes it easier to spot areas where there is high demand and helps place charging stations in the best spots to

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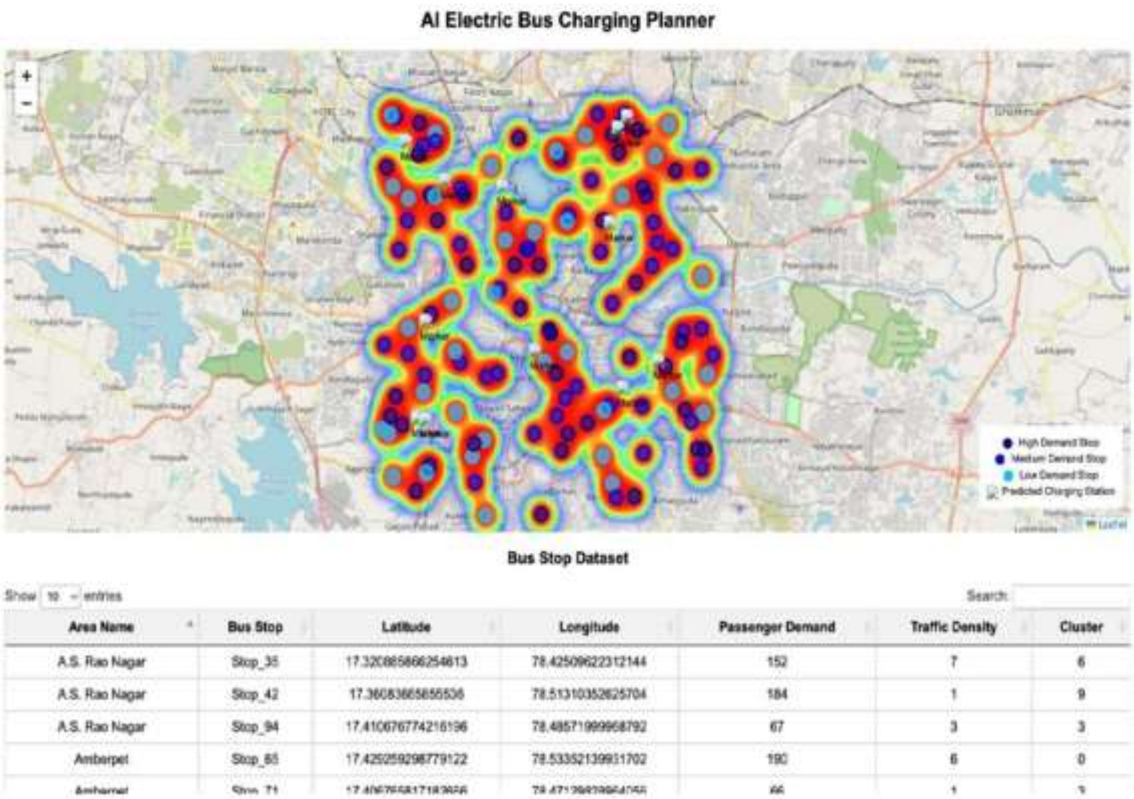
make them more efficient and easier to reach. The heat map analysis gives extra proof that the model is working well and helps make smarter choices when planning infrastructure.



Area Name	Bus Stop	Latitude	Longitude	Passenger Demand	Traffic Density	Cluster
A.S. Rao Nagar	Stop_35	17.320885866254613	78.42509622312144	152	7	6
A.S. Rao Nagar	Stop_42	17.36083665855536	78.51310352625704	184	1	9
A.S. Rao Nagar	Stop_94	17.410676774216196	78.48571999968792	67	3	3
Amberpet	Stop_65	17.425259298779122	78.53352139931702	190	6	0
Amberpet	Stop_71	[illegible]	[illegible]	66	1	[illegible]

Figure 1: Heatmap showing passenger demand intensity across bus stops.

Clustering of Bus Stops:

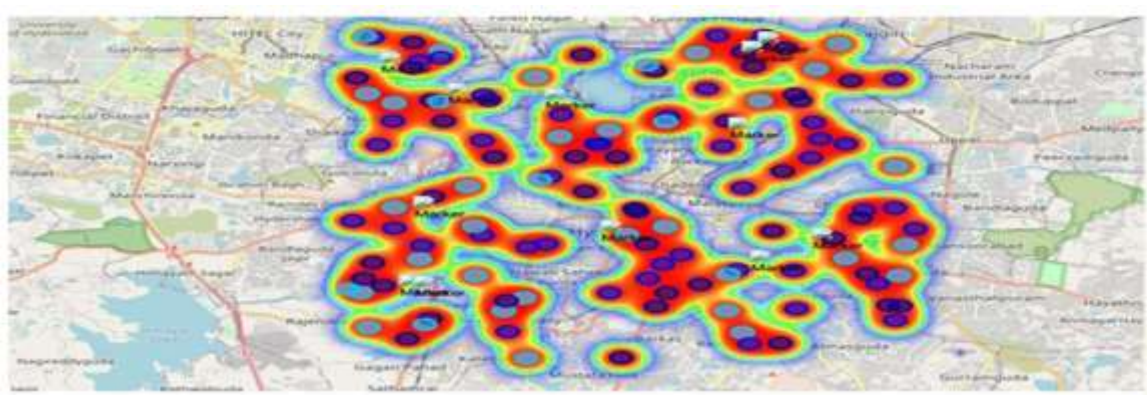


Figure 2: K-Means clustering of bus stops into demand-based groups.

The heat map above shows where electric bus charging demand is spread out in the city area. The map shows different colors to show how much demand there is in various places. Areas colored red and orange show places where there is a lot of demand. Yellow and green areas show places with some demand, and blue areas are where there is little demand.

Looking at the visualization, it's clear that demand isn't spread evenly throughout the city. Instead, there are a number of areas where demand is very high. These hotspots probably show places where many people gather, like shopping areas, big bus stops, and places with lots of people living nearby. The group of red areas shows that these places need more charging stations to help electric buses work well.

There are several areas on the map where electricity demand is very high, so it's better to spread out the charging stations in different places instead of putting them all in one spot. The AI model that groups things together supports this by putting charging stations close to these busy areas, which helps cut down on the distance people have to travel and makes the whole process more effective.

Additionally, the spread out areas with moderate and low demand show that fewer or smaller charging stations might be enough in those places. This helps in using resources more efficiently and prevents spending on extra infrastructure that isn't needed.

Charging Station Prediction:

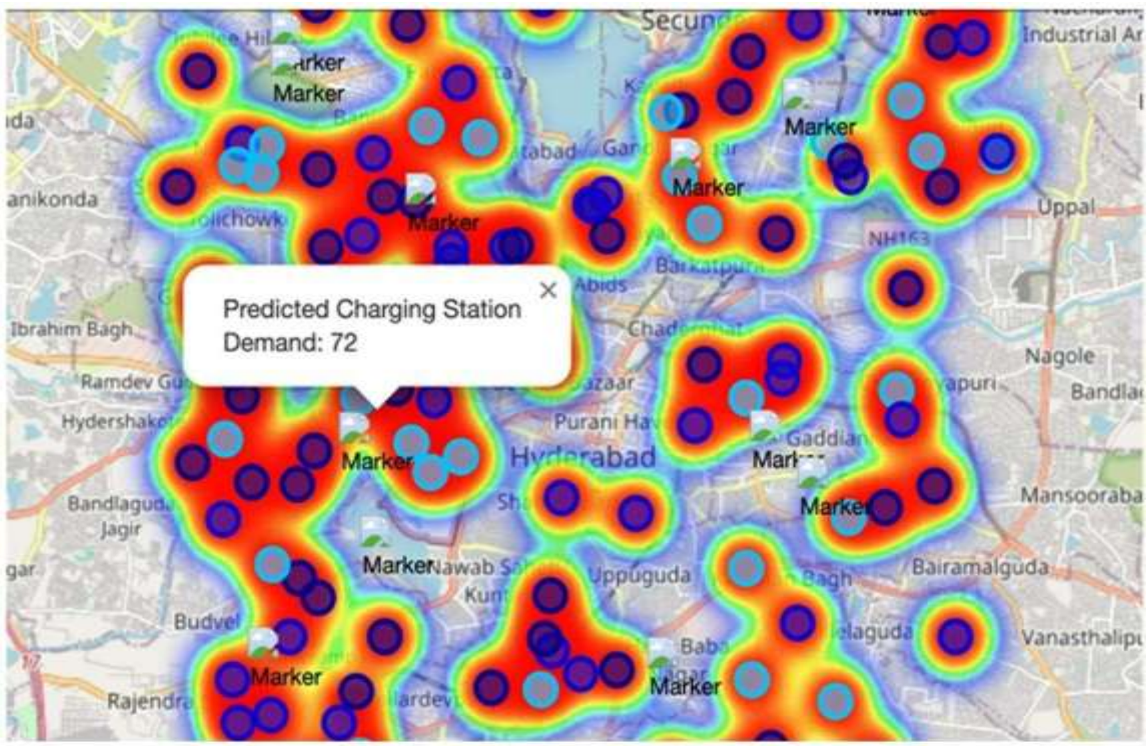


Figure 3 : Predicted charging station locations based on cluster centroids.

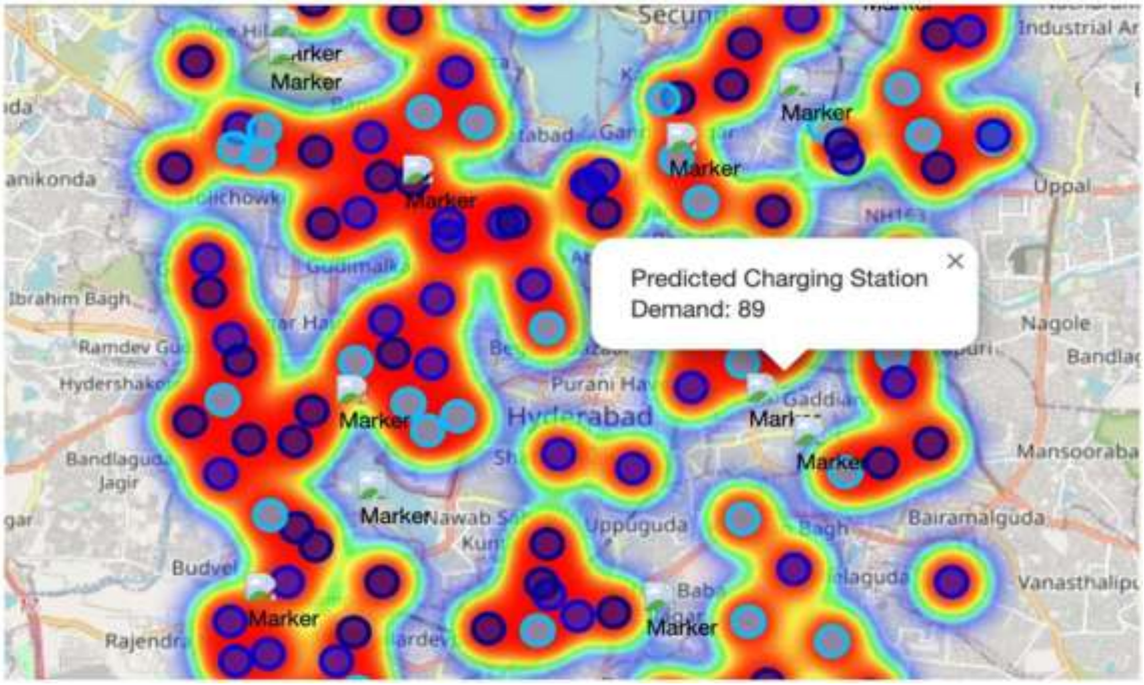


Figure 3.1: Predicted charging station locations based on cluster centroids.

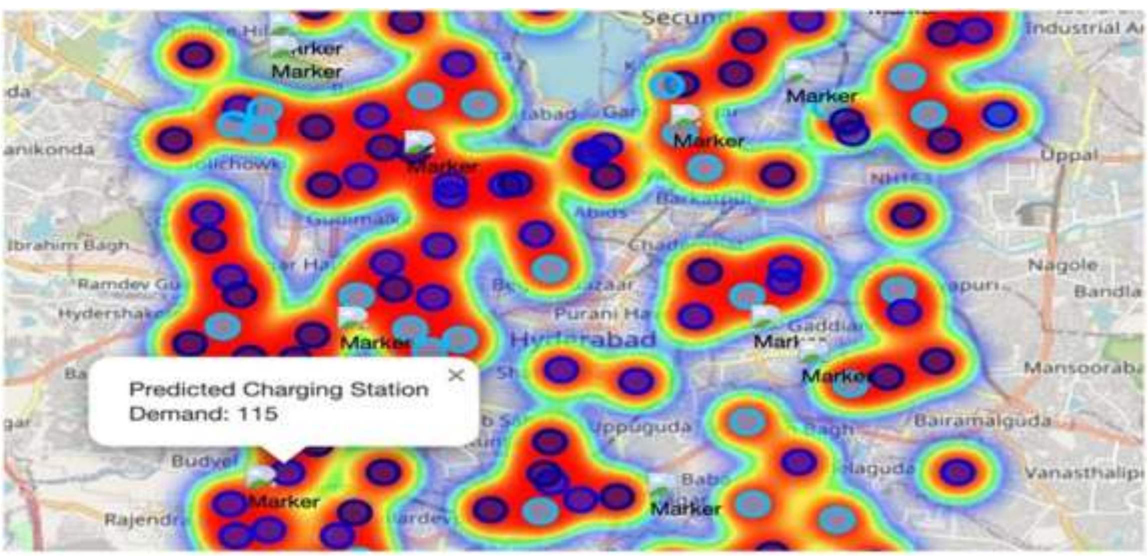


Figure 3.2 : Predicted charging station locations based on cluster centroids.

Dataset Analysis:

Bus Stop Dataset

Show 10 entries Search:

Area Name	Bus Stop	Latitude	Longitude	Passenger Demand	Traffic Density	Cluster
A.S. Rao Nagar	Stop_0	17.41122244282672	78.43609232667445	150	7	7
A.S. Rao Nagar	Stop_10	17.3372690016861	78.46810762835023	180	3	8
A.S. Rao Nagar	Stop_31	17.374569372733223	78.41089533824615	129	9	6
A.S. Rao Nagar	Stop_52	17.39554141523106	78.4275338757266	189	2	7
Amberpet	Stop_27	17.409879150562602	78.52141065312831	196	10	1
Amberpet Main	Stop_94	17.388914503104452	78.40662814407534	118	3	6
Ameerpet	Stop_111	17.36274045322872	78.4429414892356	53	6	10
Ameerpet Circle	Stop_15	17.321329739461788	78.4663063044643	56	3	0
Ameerpet Circle	Stop_22	17.351921228710086	78.52868792097473	179	6	2
Ameerpet Circle	Stop_106	17.309732434938006	78.52640235226258	177	4	2

Showing 1 to 10 of 120 entries Previous 1 2 3 4 5 … 12 Next

Figure 4 : Visualization of optimal charging station locations using K-Means centroids.

Centroid Visualisation:

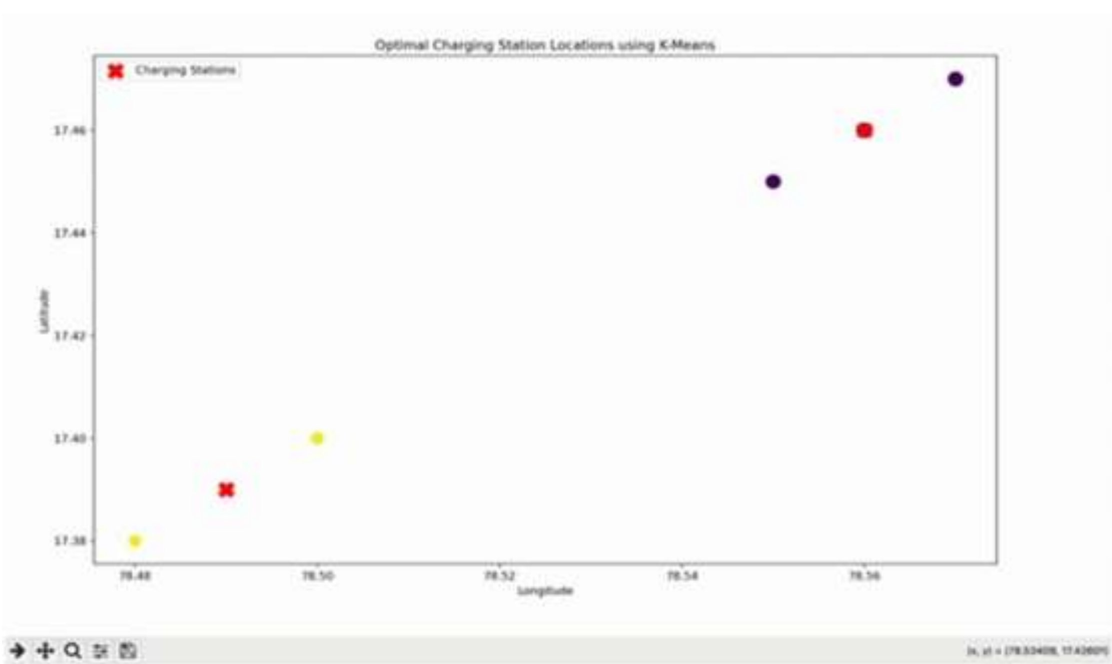


Figure 5: Visualisation of optimal charging station locations using K-Means centroids.

APPLICATIONS/ DISCUSSIONS/ ABLATION STUDY

Applications

The suggested AI-powered system for planning electric bus charging infrastructure has several useful uses in today's city settings. One of the main uses is in city public transport, where local governments can use the model to find the best spots for charging stations for electric buses. This helps plan better routes, cuts down on time lost, and makes the service more dependable.

This system is also very helpful in building smart cities, where planning smart infrastructure is really important. Using AI to make decisions helps the model support planning cities based on data and assists in moving toward more sustainable ways of moving around. This can also be used for planning electric vehicle (EV) infrastructure, helping governments and private companies plan where to place charging stations for cars, taxis, and delivery vehicles.

Another important use is in energy management, where the system helps balance the power demand between various charging stations. By finding places where electricity is needed the most, it helps spread the power more effectively and stops the system from getting too busy. The model can also help in making policies and planning investments, so officials can make better choices about building infrastructure and how to spend money.

This system is also really useful for studying and creating new ideas in academic research, giving a solid base for looking into advanced AI methods related to transportation and sustainability.

Discussion

The suggested system shows how Artificial Intelligence can efficiently handle the difficulties of planning charging stations for electric buses. Using clustering methods helps find the best places for charging stations, which cuts down on travel distance and makes operations run more smoothly. The demand-based allocation helps the system work better by making sure that areas with high demand get enough resources.

One of the system's key advantages is how easy it is to use and how well it can grow. It works well with bigger data sets and more complicated city areas. The tools used to show the results in the project help people understand them better, which is helpful for those who plan and make decisions.

However, the system also has certain limitations. K-Means clustering works under the idea that data is spread out evenly and needs the number of groups to be decided before it starts. In real life, city designs are more complicated, and the need for things can change as time goes on. Using synthetic data can make the results less realistic.

Even with these challenges, the system has a solid base that can help make future improvements. By using real-time data, smart AI methods, and extra factors like traffic and battery life, the model becomes more precise and useful for actual use.

Ablation Study

The study removed different parts of the system to see how each part affected its overall performance. This analysis makes it easier to see how much each part contributes and helps find places where things can get better.

At first, the system was tested without using any demand values and only used spatial clustering. In this case, the charging stations were set up just based on where they were located, and not taking into account how much they were being used. This led to poor resource distribution, where some areas with high demand didn't get enough service, while areas with low demand got more resources than needed.

In the next step, capacity was allocated based on demand. This greatly boosted the system's performance because charging stations in busy areas got more capacity. This helped to lessen traffic and made use of the infrastructure more effectively.

More testing was done by changing the number of groups (charging stations). It was noticed that having too few stations caused crowdedness and longer trips, while having too many stations made things more expensive and led to less usage.

This shows how important it is to choose the right number of groups to get good results.

The ablation study shows that both grouping things in space and distributing resources based on need are important parts of the system. Putting all these factors together helps make things work better, uses resources more wisely, and makes building and planning structures more realistic.

CONCLUSION

The suggested AI-based system for planning electric bus charging infrastructure offers a smart and efficient way to make urban transportation more sustainable. By using Artificial Intelligence methods, especially clustering algorithms, the system effectively finds the best spots for electric bus charging stations by looking at how areas are spread out and where the need is highest. This helps use resources better, cuts down how far buses have to go, and makes the whole operation run smoother.

Adding capacity based on demand helps the system work better by making sure areas with lots of people need charging get enough stations, which reduces traffic and waiting times. Using methods like clustering graphs and heat maps helps show how demand is spread out and where stations should be placed, making the system easier to understand and helpful for people making decisions.

Even though the model was made with fake data and basic ideas, it still shows how AI can help with real problems in planning infrastructure. The system can grow, change, and add new features using real-time data and advanced tools.

In short, this project shows how using data in city planning is important and helps create transportation systems that are efficient, friendly to the environment, and sustainable.

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