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Spatial Analysis of EV Charging Demand for Intercity Bus Transport in Thailand

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Abstract
Thailand is a significant emitter of greenhouse gases (GHGs), with total emissions reaching approximately 385,941.14 ktCO$_2$eq in 2022. Of this, 77,021.31 ktCO$_2$eq, or 30.29% of emissions from the energy sector, originated from the transportation sector. The Thai government has prioritized mitigation efforts by promoting Battery Electric Vehicles (BEVs), particularly the transition to Battery Electric Buses (BEBs) in public transportation. While electrification initiatives are underway, the lack of a spatially guided approach to infrastructure placement along intercity bus corridors remains a critical gap. This study aims to estimate the spatial charging demand of Thailand's intercity bus network and identify potential infrastructure locations to support the adoption of Battery Electric Buses (BEBs). Potential charging points were determined based on the typical operational range of BEBs and interpolated along intercity bus routes. These points were then used to evaluate candidate infrastructure locations through a Charging Demand Score (CDS), an indicator that quantifies the relative demand for charging infrastructure at the grid-cell level across the study area. The results highlight several provinces with notably high charging demand, particularly along major intercity corridors in the North, Northeast, and South. These findings provide a valuable foundation for designing data-driven policies to support the electrification of Thailand's public transportation system.

1. Introduction

The transition to electric vehicles (EVs) in public transportation is a critical step toward reducing greenhouse gas emissions, and for countries like Thailand, the electrification of intercity bus transport presents both an opportunity and a spatial planning challenge (He et al., 2022). In 2022, Thailand emitted Greenhouse Gas (GHG) emissions of around 385,941.14 ktCO$_2$eq. 254,037.21 ktCO$_2$eq, or 65.89 percent of the national GHG emissions, was from the energy sector. In addition, 30.29 percent of the energy sector, or 77,021.31 ktCO$_2$eq, was from the transportation and intercity buses (Department of Climate Change and Environment, 2022). In response to concerns about national GHG emissions, the government has prioritized mitigation efforts within the transportation sector by promoting the adoption of Battery Electric Vehicles (BEVs). BEVs contribute to decarbonized transport by offering higher efficiency and utilizing cleaner energy sources than conventional internal combustion engine vehicles (ICEVs) (Great Plains Institute, 2019). Ministry of Transport's EV Development Plan aims to deploy 4,412 Battery Electric Buses (BEBs) in the Bangkok Metropolitan Area by 2030. In addition, Fiscal incentives and subsidies have been introduced to support BEB adoption, including a three-year corporate income tax exemption (Urban Infrastructure, 2023). From a policy perspective, the incentives are directed toward operated buses because they constitute a relatively small share of the national vehicle fleet; they are responsible for a disproportionate amount of road-based emissions due to their long operating hours and extended travel distances. Internal combustion engine Buses (ICEBs) are a notable source of GHG emissions and noise. Additionally, operational costs remain elevated due to fuel consumption and maintenance requirements over the long term (Nunno, 2018). Consequently, BEBs have been recognized as a potential measure for reducing GHG emissions, offering operational benefits such as reduced noise and lower maintenance and fuel costs than ICEVs (Borén, 2020).

Although national EV policies are advancing, there is currently no spatially informed strategy for deploying charging or battery-swapping stations along intercity bus corridors in Thailand (Kunawong et al., 2025). BEBs have a limited range, so a critical consideration in transitioning to BEBs is developing charging infrastructure that corresponds with established bus routes and vehicle ranges, which are influenced by battery capacity and driving conditions (Olsen and Kliewer, 2022). An unplanned placement of charging or battery-swapping stations may leave critical corridors uncovered. However, it is not merely the existence of charging stations that ensures operational success but their strategic placement along the network (Liu et al., 2024). Inadequate allocation can lead to detours, service delays, and inefficient energy utilization. This study aims to evaluate the spatial characteristics of Thailand's intercity bus network to estimate charging demand and identify potential infrastructure locations in preparation for an electrified intercity bus scenario.

Previous studies on EV charging infrastructure have primarily focused on urban public transit systems, depot scheduling (Jiang et al., 2022), or station placement based on simplified assumptions such as fixed distance thresholds (Zheng and Peeta, 2017). These approaches are often inadequate for addressing the continuous and long-range nature of intercity operations. In contrast, this study contributes a spatially explicit grid-based methodology that interpolates candidate charging points based on vehicle range and evaluates demand using an exponential decay function. This approach enables a corridor-specific assessment of potential charging infrastructure needs, filling a gap in current planning strategies and supporting infrastructure deployment that reflects actual bus operations.

Although BEBs are gaining traction in public transportation systems, technical constraints such as limited range, charging time, and battery capacity continue to hinder their use in intercity operations. A literature review on BEBs indicates that their limited range per charge is generally shorter than that of ICEBs. The actual range is influenced by several factors, including battery capacity, topography, passenger load, and driving behavior. Table 1 summarizes the driving ranges associated with different battery capacities as reported in various international contexts.

Authors	Battery (kWh)	Limited Range (km)	Countries
Doulgeris (2024)	350 - 400	127 - 293	Greece
Mao (2024)	57 - 350	78 - 366	China
Chen (2021)	350	208 - 240	USA
Muhith (2024)	442	225 - 290	UK

Table 1. The diving ranges of BEBs.

As shown in Table 1, the average driving range for battery capacities around 350 kWh is approximately 200 to 300 kilometers. Therefore, the transition to electric public transportation must account for battery capacity and corresponding driving ranges to determine appropriate charging strategies and infrastructure requirements.

Charging time varies depending on the technology employed. Plug-in charging requires BEBs to remain stationary during the recharging process, while battery swapping enables rapid replacement of depleted batteries with charged ones at depots. This approach replaces depleted batteries with fully charged ones at stations, significantly reducing downtime. Nevertheless, battery swapping poses operational and logistical challenges (Hussain et al., 2024).

1. The lack of universal standards makes battery packs incompatible across different EV manufacturers.
2. High initial capital investment is needed for infrastructure, land, equipment, and battery inventory.
3. Battery Swapping Stations (BSS) operators must optimize charging to avoid overcharging, undercharging, or inefficient battery use.
4. Site selection affects accessibility, grid connectivity, and user adoption.
5. Maintaining a stockpile of charged batteries without knowing future demand can result in energy loss and higher costs.
6. Battery ownership is ambiguous: Most systems lease batteries, which can increase costs if users must pay service or leasing fees for multiple battery packs.
7. Repeated battery swaps expose connectors and mechanical systems to wear and potential failure.

Types	Authors	Charge Power (kW)	Battery (kWh)	SoC Change (%)	Charging Time
Swap Battey	Hu (2025)	-	103.4	-	5 mins
	Ahmad (2020)	-	320 - 590	-	3 mins
Plug-in	Jiang (2022)	96	260	30 - 100	1.9 hr
	Verbrugge (2022)	100	272	10 - 100	2.7 hr

Table 2. Types of charging technology.

As presented in Table 2, battery swapping enables the immediate replacement of a depleted battery with a fully charged one, typically requiring three to five minutes. However, this method necessitates a sufficient inventory of charged batteries at depots to support the operational schedule of BEBs on the route. Plug-in charging remains the conventional approach, though it generally involves longer charging durations, potentially affecting vehicle availability.

At present, there are many brands of BEBs around the world with different limited ranges, batteries, powers, and charging times. Table 3 shows an example of specifications.

Brands	Limited Range (km)	Battery (kWh)	Power (kW)	Charge Time (hr)
BYD K9	251	324	150	3
Yutong E12	290	374	215	7
Volvo 7900 Electric	200	470	200	3

Table 3. Examples of BEB specification.

Infrastructure planning plays a crucial role in enabling the deployment of intercity electric buses, as the placement and availability of charging or battery-swapping stations directly impact route feasibility. Stations should be located within the driving range of electric vehicles. Cities are suitable for setting up stations because they can cover the range of BEBs driving in the city. On the other hand, BEBs that drive on the route between cities and install stations need to consider travel demand, queuing time, and budget.

Factors	Explanation
Travel demand	A route with high travel demand should install a charging station (Hanig et al., 2025).
Queuing time	The long queuing time will decrease the number of EV usage (Lei et al., 2022).
Budget	Covers all costs and worth the investment (Wang et al., 2019).

Table 4. Factors for considering charging station installation.

As shown in Table 4, an important observation is that charging stations should be installed in locations that can support intercity travel using the minimum number of stations while maintaining low installation and operational costs. This approach maximizes coverage efficiency and cost-effectiveness in infrastructure planning (Zheng and Peeta, 2017).

2. Methodology

2.1 Data and Preprocessing

The dataset used in this study was obtained from the Department of Land Transport, Thailand, in December 2024. It covers intercity bus routes across various regions of the country and includes information such as route categories, route numbers, origin and destination names, and route distances. For the purpose of analysis, two route categories defined by Thai transport authorities were considered: Category 2, referring to intercity routes originating from Bangkok and connecting to provincial destinations, and Category 3, referring to routes operating between provinces within regional areas, excluding Bangkok. While these classifications are specific to Thailand, they broadly represent long-haul national routes and regional inter-provincial routes, respectively. A summary of the route attributes is presented in Table 5. It is important to note that this analysis does not incorporate the number of trips per route; all routes are assumed to have equal trip frequency. This assumption introduces a limitation that should be considered when interpreting the results related to infrastructure demand.

Attribute	Value
Number of bus routes	628
Longest distance (km)	1888
Shortest distance (km)	8
Average distance (km)	305

Table 5. Attributes of the intercity bus route dataset.

The original dataset did not contain geographic coordinates for the origin, destination, or bus route geometry. To enable spatial analysis, origin and destination names were cleaned to ensure consistency and accuracy. The cleaned origin and destination names were then used to retrieve geographic coordinates via the Google Geocoding API. When both origin and destination locations were identified at the province or district levels, their coordinates were assigned based on the geographic centroids of the corresponding administrative units. Subsequently, the route geometries were estimated using the Google Directions API, which generated polyline paths representing the most likely travel routes between each origin and destination pair. Figure 1 illustrates the spatial distribution of bus routes based on the coordinates derived from this procedure. This approach offers a solution for large-scale analysis but may introduce spatial inaccuracies, as administrative centroids do not always align with the actual locations of bus terminals. However, this source of error has a low impact on long-range routes, as the relative spatial error introduced is small compared to the overall route length.

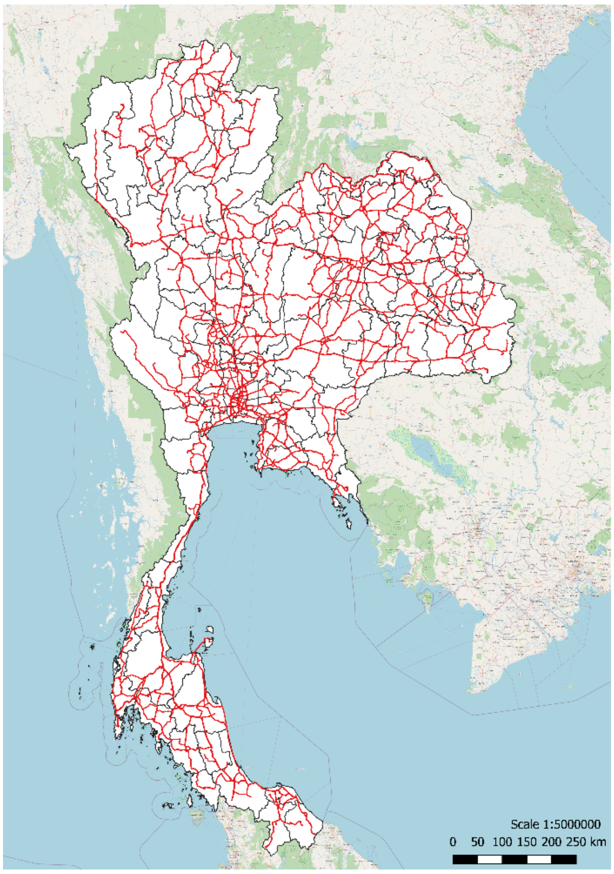

Figure 1. Spatial distribution of intercity bus routes in Thailand. Route geometries were estimated using the Google Directions API based on geocoded origin-destination pairs derived from administrative centroids.

As illustrated in Figure 1, the map presents the spatial distribution of intercity bus routes across Thailand. Each red line represents an individual route, constructed using origin and destination coordinates derived from the geographic centroids of the respective districts or provinces. The visualization reveals a comprehensive network covering the country, with particularly high route density in the central region and along main road corridors connecting major provincial capitals.

To identify potential locations where BEBs would require recharging along each route, the potential locations were interpolated at 250-kilometer intervals. This distance value is estimated based on the operational range of BEBs as specified in Table 3. The locations of these interpolated points are presented in Figure 2. These candidate charging points were then used to estimate a charging demand for each location, serving as a proxy for the spatial intensity of charging needs across the network.

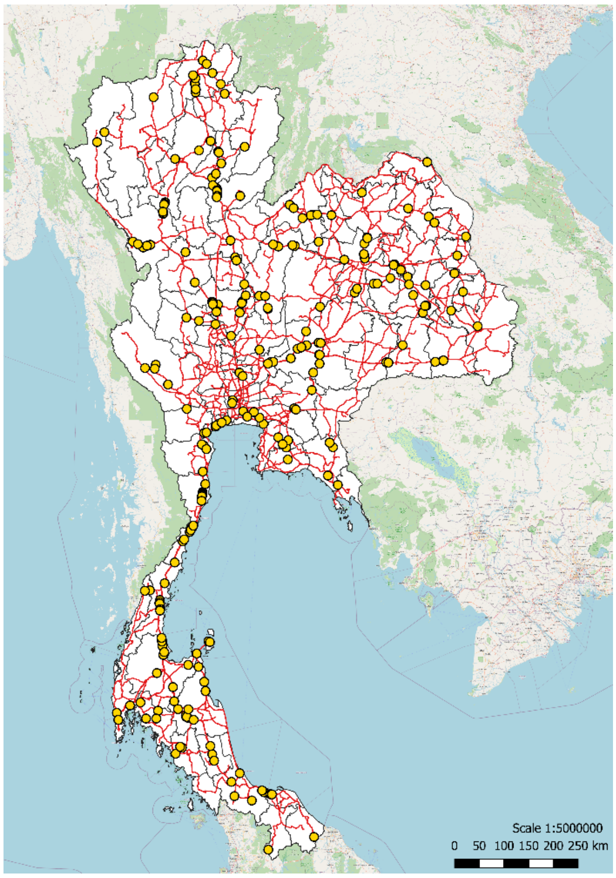

Figure 2. Interpolated charging locations under the assumption of 250-kilometer intervals.

2.2 Charging Demand Estimation

To facilitate spatial demand estimation, the study applied a uniform grid system across Thailand, dividing the country into cells measuring 10 × 10 kilometers. A charging demand score (CDS) was then calculated for each grid cell, representing the potential demand that could be served if a charging station were located at that position. The score was derived by aggregating the contributions of nearby candidate charging points, which were interpolated at 250-kilometer intervals along intercity bus routes. An exponential decay function was applied to weight each point's contribution based on its distance to the grid cell, assigning greater weight to those located closer. This approach supports the identification of high-priority locations for charging infrastructure deployment. The CDS for each grid cell was calculated using the following equation:

$$CDS_i = \sum_r P_j e^{-\alpha d_{i,j}} \quad (1)$$

In this equation, i and j denote the grid cell and the candidate charging point, respectively. The variable P represents the score assigned to each candidate charging point, which was arbitrarily set to 1. The term $d_{i,j}$ refers to the Euclidean distance between grid cell i and candidate charging point j, while α is the decay constant, also arbitrarily set to 0.1 in this study. The exponential decay function ensures that charging points closer to a given grid cell contribute more significantly to its score.

3. Results and Discussion

The CDS calculation results reveal several significant areas for charging infrastructure across Thailand. The scores are visualized using a grid-based heatmap, in which darker shades indicate greater charging demand, highlighting priority locations for station deployment.

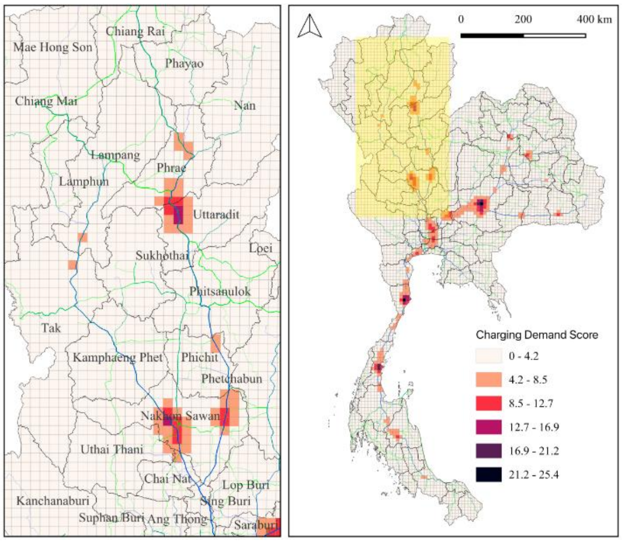

Figure 3. Charging demand in northern Thailand.

As illustrated in Figure 3, the spatial distribution of CDS highlights several high-priority areas for charging infrastructure deployment. Notably, elevated CDS values are concentrated along major intercity corridors in Thailand's northern, northeastern, and southern regions. In northern Thailand, provinces such as Nakhon Sawan and Uttaradit, situated along key transportation corridors, exhibit notably high CDS values. Additionally, moderate demand levels are observed in neighboring provinces, including Phichit, Tak, Phrae, and Lamphun, indicating their potential as secondary hubs for future charging station development.

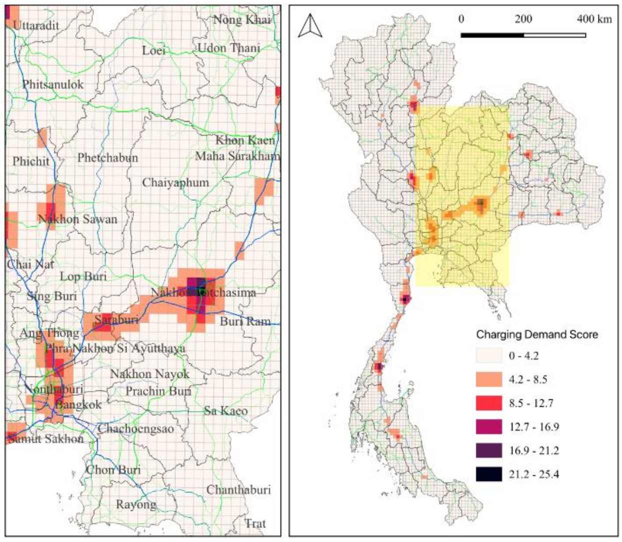

Figure 4. Charging demand in the northeastern Thailand.

Figure 4 illustrates the spatial distribution of high-demand areas for charging infrastructure, particularly within Thailand's central and northeastern regions. Notably, Bangkok, the capital and a central hub for public transportation, exhibited a high concentration of demand. Surrounding provinces such as Nonthaburi and Phra Nakhon Si Ayutthaya also demonstrated elevated demand levels. Furthermore, Saraburi, a key gateway to the northeastern region, was identified as a high-demand area. Nakhon Ratchasima recorded the highest CDS among all provinces, indicating a significant need for charging station deployment.

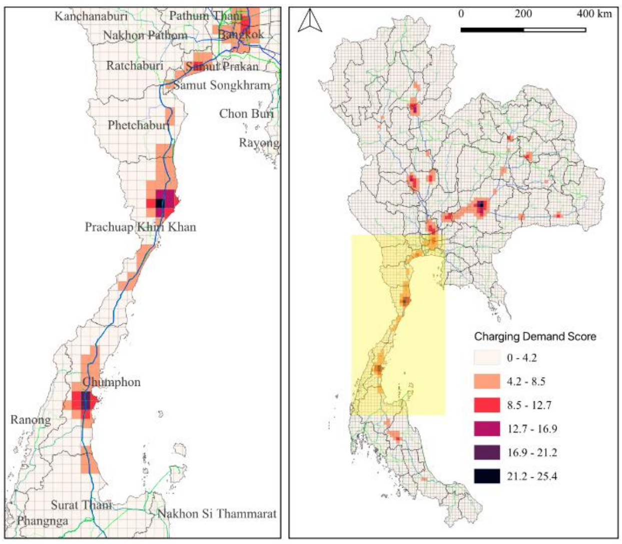

Figure 5. Charging demand in southern Thailand.

Figure 5 highlights the spatial distribution of charging demand in the southern regions of Thailand. A notable concentration of high demand is observed in Samut Prakan. Further south, Prachuap Khiri Khan and Chumphon also exhibit significantly high demand levels. These two provinces display a widespread distribution of demand, which can be attributed to a primary transportation corridor that serves as the main connection between upper Thailand and the southern region.

Figures 3 and 4 highlight areas in Thailand's upper central and northeastern regions with notable variations in charging demand. Specifically, Figure 3 shows that Nakhon Sawan and Uttaradit possess high CDS values, likely due to their roles as junctions on major transportation corridors between Bangkok and the northern provinces. Additionally, Figure 4 illustrates that Nakhon Ratchasima and Saraburi exhibit substantial charging demand, serving as critical nodes for the northeast-bound transport flow.

Figure 5 shows a different distribution pattern in the southern region. While high CDS values are concentrated in Samut Prakan and certain coastal corridors, significant demand is also observed in Prachuap Khiri Khan and Chumphon. These provinces lie along the long-distance route connecting the central to the southern part of Thailand. Due to route length and operational constraints, BEBs would likely require midway charging opportunities. Therefore, placing charging stations in these locations could enable long-haul BEB operations, reduce service interruptions, and support regional electrification goals.

The figures collectively identify several provinces with significantly high demand for charging infrastructure. However, to effectively promote the adoption of BEBs within the public transport sector, it is essential to integrate trip demand data with charging demand areas. For example, as illustrated in Figure 3, the Bangkok–Chiang Mai corridor, passing through Nakhon Sawan, Tak, and Lampang (represented by the left blue line), covers approximately 687 kilometers and accommodates many daily trips. To support BEB operations on this route, charging infrastructure should be strategically located, with the first charging point in Nakhon Sawan and a second in Tak. Although Tak exhibits only moderately high demand, installing a charging station is necessary to ensure route continuity. Conversely, as shown in Figure 5, routes leading to provinces in the southern region that record a low volume of daily trips may not warrant the transition to electric buses. Installing charging stations in high-demand provinces such as Prachuap Khiri Khan and Chumphon may not be cost-effective due to insufficient service frequency. This study goes a step further than many previous approaches by focusing on the actual routes that intercity buses take. As a result, it offers a clearer picture of where charging infrastructure is needed and makes the methodology more useful for real-world planning. To support practical implementation, the CDS outputs could be integrated with additional planning criteria such as budget constraints, proximity to existing infrastructure, and energy grid accessibility. This would enable policy makers to prioritize locations not only based on spatial demand but also on feasibility and cost-effectiveness, making the approach more scalable and adaptable to real-world policy environments.

4. Conclusion

This study proposes a spatial planning framework to support the deployment of BEB charging infrastructure across Thailand's intercity transportation network. By combining route-level data with a grid-based spatial model, the analysis introduces a CDS to quantify the relative need for charging infrastructure at different locations. The CDS was derived using an exponential decay function that simulates how demand potential decreases with distance, thereby reflecting the operational constraints of BEBs, particularly their limited driving range between charges. The results indicate that high-demand areas are concentrated along major intercity corridors in the northern, northeastern, and southern regions. Notable provinces such as Nakhon Sawan, Uttaradit, Nakhon Ratchasima, and Chumphon emerged as key locations where strategic deployment of charging infrastructure could facilitate the transition to electric intercity transport. These findings underscore the importance of aligning infrastructure planning with vehicle capabilities and spatial travel patterns. While the CDS provides a useful spatial signal for identifying high-demand locations, this study does not incorporate constraints such as electrical grid capacity, land availability, zoning regulations, or economic feasibility. These factors are critical for determining whether a proposed site is suitable for real-world deployment. Future work should integrate these considerations, including co-location opportunities with existing fuel stations or maintenance hubs, to improve the practicality and cost-effectiveness of infrastructure planning. Additionally, the current analysis does not consider service frequency, passenger load, or operational scheduling constraints, which play a vital role in determining actual charging demand. Incorporating these factors, along with case study validation, feedback from transport operators, and seasonal or future route variation, would help bridge the gap between theoretical demand modeling and operational implementation.

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