ENHANCED KNOWLEDGE IN SCIENCES AND TECHNOLOGY
e-ISSN: 2773-6385

EKST

Vol. 6 No. 1 (2026) 118-124
https://publisher.uthm.edu.my/periodicals/index.php/ekst

Shortest Route for Electric Vehicle Routing Problem Using Branch and Cut Algorithm

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DOI: https://doi.org/10.30880/ekst.2026.06.01.015

Article Info

Received: 3 January 2026
Accepted: 5 June 2026
Available online: 9 July 2026

Keywords

Branch and Cut Algorithm, Electric Vehicle Routing Problem, Travelling Salesman Problem, EV Charging Station, Limited Battery Constraint

Abstract

Electric Vehicle (EV) route planning has become increasingly important due to the its limited battery capacity and their dependence on charging infrastructure. One of the main challenges in electric vehicle routing is determining the shortest possible route that is both connected and energy-feasible, especially when battery constraints are considered. This study addresses the Electric Vehicle Shortest Route Problem (EV-SRP) by formulating it as a range-constrained Travelling Salesman Problem (TSP), where conventional shortest-path methods may generate disconnected or infeasible routes due to the absence of explicit subtour and energy constraints. To solve this problem, the Branch and Cut (B&C) algorithm, an exact optimization method, is applied. The routing network is modelled using five strategically selected EV charging stations in subregion Johor, including highway rest areas, urban charging hubs, and commercial locations. The algorithm integrates linear programming relaxation, subtour elimination constraints, and battery-aware branching to ensure route connectivity and feasibility under a 150 km battery limit. Simulation results show that the Branch and Cut algorithm successfully generated a fully connected shortest EV tour with a total distance of 205.60 km. Due to the battery limitation, the model correctly identified the need for one optimal charging stop at Batu Pahat Mall, allowing the route to be completed feasibly. In conclusion, the findings demonstrate that the Branch and Cut algorithm is effective in producing optimized, connected, and energy-valid EV routes. This study highlights the importance of subtour elimination and battery feasibility enforcement in EV routing and provides a strong foundation for future research involving larger EV charging networks in Malaysia.

1. Introduction

The Electric Vehicle Shortest Route Problem (EV-SRP) is an extension of classical shortest path and vehicle routing studies, incorporating real-world constraints unique to electric mobility, particularly battery limitations and charging station dependency. Traditional shortest route research began with deterministic graph-based solutions such as Dorigo's algorithm, which guarantees optimality through exhaustive cost-based exploration on graphs with non-negative edge weights. However, despite its optimal guarantees, the algorithm suffers from scalability challenges when applied to large-scale networks due to its high computational complexity [1],[2]. To address these limitations, metaheuristic alternatives such as Ant Colony Optimization (ACO) were later introduced, mimicking pheromone-based indirect communication among agents to solve routing problems including

Travelling Salesman Problem (TSP) and Vehicle Routing Problem (VRP), offering faster convergence in complex search spaces [3],[4]. While metaheuristics significantly improve computational efficiency, these methods demonstrated improved solution speed but trade precision for approximation, often producing near-optimal rather than exact solutions [5],[6].

As the focus shifted toward sustainable transportation, the need to adapt routing models specifically for electric vehicles was first highlighted by [7] through the Green Vehicle Routing Problem, integrating environmental considerations and refuelling dependencies into routing frameworks [8],[1],[6]. These developments marked an important step toward EV-specific routing. Among exact algorithms, the Branch and Cut (B&C) algorithm, originally developed for solving large-scale symmetric TSP instances, integrates Linear Programming relaxation, branching trees, and cutting-plane constraints to remove invalid subtours while preserving feasible integer solutions [9]. Furthermore, [10] also highlighted the importance of local search and LP-guided pruning when improving exact route construction.

In the Malaysian context, national initiatives strongly support toward green transportation, aiming for Electric Vehicle to reach 20% of vehicle sales by 2025 and 50% by 2035. However, widespread adoption is hindered by high vehicle costs, grid stress due to increased electricity demand, and uneven charging station placement, where approximately 4000 stations remain concentrated in major western and southern urban regions including Johor [11],[12]. The lack of reliable charging access along intercity routes contributes to range anxiety, reinforcing the need for feasible shortest-route planning models that explicitly enforce connectivity and energy constraints [11],[12].

Despite extensive EV routing advancements, limited studies focus on shortest route construction using B&C algorithm in intercity Malaysian charging networks, particularly under a TSP-based route-connectivity environment with a fixed travel range constraint of 150 km. Consistent with findings in recent studies [13], [14] the results of this research demonstrate that Branch and Cut can successfully generate a feasible and connected EV tour while satisfying strict battery constraints.

2. Methodology

The first step of the methodology is the collection of data that presents the information about the distance between all five nodes used for this study around one of Malaysia's states, Johor. All five nodes are represented by RnR Pagoh, ChargeSini near Muar Bypass, ChargEV Tangkak, ChargeSini near (The Summit Batu Pahat), and Gentari near (Batu Pahat Mall). For each node, it has been selected because their graphical location and provides an electric vehicle charging station.

Using the Branch and Cut algorithm, it is expected to solve the Electric Vehicle Routing Problem. It starts by building a Mixed Integer Linear Programming (MILP) model that includes all the important details such as the goal to minimize travel distance, and limits like battery capacity and charging requirements for electric vehicles.

2.1 Implementation of the Branch and Cut Algorithm

This research applies the Branch and Cut algorithm to solve the Electric Vehicle Routing Problem (EVRP) with the aim of minimizing travel distance while considering full electric vehicle specific constraints like limited battery range and charging station requirements. The methodology is initialized with the following step:

2.1.1 LP Relaxation

In this first step called Linear Programming (LP) relaxation, the objective is to convert the original Mixed Integer Linear Programming (MILP) model to an LP model by relaxing the binary constraints. This provides a starting point and a lower bound for the solution.

Original binary constraints:

$$x_{ij} \in \{0,1\} \qquad \nabla i, j \in N, i \in j \tag{1}$$

Relaxed to:

$$0 \leq x_{ij} \leq 1 \tag{2}$$

where value 1 refers to if the route goes directly from node *i* to node *j* while value 0 is otherwise.

2.1.2 Cut Generation

In this step, a cut generation step is needed to eliminate infeasible fractional solutions found in the LP relaxation by adding linear constraints (cuts) without removing any valid integer solutions. The constraints include subtour elimination constraints, energy limited range constraints and lastly depot recharge constraints.

Subtour Elimination Constraints:

$$\sum_{i\in S}^{n}\sum_{j\in S, j\neq 1}^{n} x_{ij} \leq |S| - 1 \quad (3)$$

$$\nabla S < C, 2 \leq |S| \leq |C| - 1 \quad (4)$$

C is the set of stop points in the network (all the locations that the EV must visit excluding the depot. S represents a potential subtour (a loop that happens within a subset of nodes, excluding the depot, and thus is invalid in routing problems [9].

Energy or Range Constraints:

$$d_j \geq d_i - e_{ij} - M\left(1 - e_{ij}\right) \quad (5)$$

where d_i represents the battery level at node i and e_{ij} represents energy consumed from i to *j.* This constraint ensures that the EV only travels along edges that are feasible. Battery modelling follows EV routing frameworks introduced in the Green Vehicle Routing Problem [7].

Depot Recharge Constraints:

$$d_i = Q \qquad \nabla i \in \{D\} \cup S \quad (6)$$

Q represents maximum battery capacity of the EV and D represents the depot node. This constraint ensures correct initialization of the energy model [7], [12]. The inclusion of battery feasibility constraints and charging decisions is essential in EV routing, as cumulative energy consumption may lead to infeasible routes even when individual road segments are within range limits [15].

2.1.3 Branching Process

The objective of this branching step is to handle the remaining fractional solutions by splitting the problem into subproblems with additional constraints, building a branching tree. In MILP, binary variables can be only either 0 or 1, not 0.6 or any other fractional value. If it shows any fractional value, create two subproblems to force whether to not take or include the path from i to *j.*

If:

$$x_{ij} = 0.6 \text{ (invalid in MILP)}$$

Then, we create two subproblems, and make either 0 or 1. This recursive splitting narrows the feasible area and directs the search toward valid integer solutions (0 or 1 for x_{ij}). This algorithmic framework follows the classical Branch and Cut methodology proposed by Padberg and Rinaldi [9].

2.1.4 Iteration

Continue iterating through subproblems (nodes in the search tree) using LP Relaxation, Cut Generation and Branching step by step until an optimal integer solution is found. For each iteration, it involved solving LP for subproblems, adding cuts when needed, doing a branching process if still fractional, and comparing the objective value.

2.1.5 Final Output

In this step, once the search tree exploration is complete, extract the final optimal path(s) and relevant EV routing details.
This includes:

- Selected arcs: $x_{ij} = 1$
- Total travel distance:

$$Z = \sum_{i \in N}^{N} \sum_{j \in N \neq 1}^{N} c_{ij} x_{ij} \quad (7)$$

- Battery level at each node: d_i
- Changing station visit (nodes where recharging occurred)

This is to provide the total minimized cost such as distance travel or energy consumption of the EV routes. This objective function is standard in TSP and EVRP optimization problems [2], [5].

3. Result and discussion

The algorithm was implemented in Python, following the methodology, using a graph model constructed from five real-world electric vehicle charging station locations. In this study, charging stations serve as the primary routing nodes, and road distances between them were derived from mapping data, forming a weighted network for optimization. The evaluation of results focuses on two key metrics: the ability of Branch and Cut algorithm to generate a connected and feasible EV tour without subtours, and the algorithm's capability to maintain feasibility under the EV maximum travel range of 150 km per charge.

3.1 Related Data

The data collected will be used to formulate the mathematical model, define the problem parameters, and simulate the case study scenarios. For this study, the focus area is selected within the state of Johor, Malaysia which is an urban and semi-urban area with an established road network and several known charging stations.

Table 1 Distance (km) between all five nodes in kilometres

	RnR Pagoh	**ChargeSini near Muar Bypass**	**ChargEV Tangkak**	**ChargeSini near (The Summit Batu Pahat)**	**Gentari near (Batu Pahat Mall)**
RnR Pagoh	*0*	*78.2*	*23.5*	*91.2*	*33.7*
ChargeSini near Muar Bypass	*53.9*	*0*	*77.4*	*37.4*	*51.3*
ChargEV Tangkak	*34.5*	*75.6*	*0*	*91.2*	*25.2*
ChargeSini near (The Summit Batu Pahat)	*68.3*	*33.9*	*91.8*	*0*	*84.2*
Gentari near (Batu Pahat Mall)	*29.7*	*51.2*	*24.0*	*87.1*	*0*

Table 1 represents the driving distances (in kilometers) between five selected EV charging station locations in Johor. These include stations located at RnR Pagoh, ChargEV Tangkak, ChargeSini near (Muar Bypass), ChargeSini near (The Summit Batu Pahat) and Gentari near (Batu Pahat Mall). Table 1 helps visualize how far each location is from the others and serves as the foundation for route planning and optimization in this study.

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3.2 Result of Branch and Cut Algorithm

After implementing the Branch and Cut algorithm in the electric vehicle shortest route optimization model, the solver successfully produced a single, fully connected EV tour that visits all five selected charging station locations exactly once before returning to the depot at RnR Pagoh.

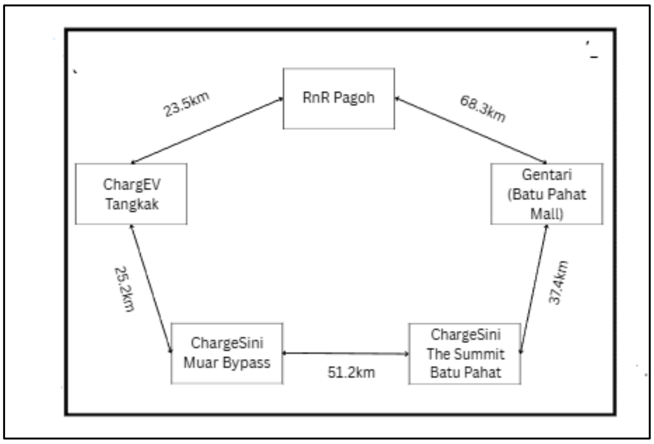

Fig. 1 Nodes in the Graph Model

Fig. 2 All charging station located in Google Map

Figure 1 above illustrates the shortest travel path between all five EV charging stations in Johor marked as nodes. Also, Figure 2 above illustrates the real-world location for all fives the EV charging station that had been node using black battery graphic. RnR Pagoh is set to be the starting point and expected to travel to all nodes and comeback to RnR Pagoh again within limited battery range. The optimal path starts from RnR Pagoh and begins its first travel to ChargEV Tangkak covering 23.5 km. Next, travel to ChargeSini Muar Bypass as long as 25.2 km and then continue 51.2 km to ChargeSini the Summit Batu Pahat. After that, travel to the last node, Gentari EV charging station near Batu Pahat Mall for 37.4km before travelling back to the depot along 68.3km. The total travel distance accumulated is 205.60 km.

Optimal path: RnR Pagoh > ChargEV Tangkak > ChargeSini Muar Bypass > ChargeSini (the Summit Batu Pahat) > Gentari (Batu Pahat Mall) > RnR Pagoh

3.3 Battery Limited Range

Table 2 Battery balance after travelling from each node

	RnR Pagoh	ChargEV Tangkak	ChargeSini Muar Bypass	ChargeSini (The Summit Batu Pahat)	Gentari (Batu Pahat Mall)	RnR Pagoh
Battery Usage (km)	0	23.5	25.2	51.2	37.4	68.3

Penerbit UTHM

Battery Balance (km)	150	126.5	101.3	50.1	12.7	81.7
Charging Needed	No	No	No	Aware	Yes	No

From Table 3.2, the final tour distance generated from the optimization was 205.60 km, which is greater than the vehicle's maximum battery travel range of 150 km per charge. Since the total travel distance of the tour is longer than the electric vehicle maximum range of 150 km, the battery charge gradually decreases as the vehicle moves from one station to the next. When the EV reached the Gentari charging station at Batu Pahat Mall, the battery level had dropped significantly and was no longer enough to support the next journey back to RnR Pagoh, which required 68.3 km. This situation is called a feasibility violation because the vehicle cannot continue driving without recharging.

To solve this, the model inserted one charging stop at Batu Pahat Mall, restoring the battery back to full capacity so that the remaining trip could be completed successfully. After charging, the EV had enough energy to travel the 68.3 km back to the starting point, proving that the route is feasible only when a charging stop is included at the right moment. From a practical perspective, this result suggests that EV users should actively monitor their battery level after reaching ChargeSini the Summit and consider recharging at nearby stations before continuing the journey, as earlier travel segments may significantly reduce battery capacity even if individual distances appear manageable.

4. Conclusion

This study successfully fulfils the objectives to implement and evaluate the performance of the Branch and Cut algorithm in solving the Electric Vehicle-Shortest Route Problem in Johor by successfully generating an optimal, connected electric vehicle tour that visits all selected charging stations exactly once before returning to the depot at RnR Pagoh throughout 205.60 km. By observing the results we gained, we can conclude that Branch and Cut algorithm is correct and reliable for solving routing problems that require both optimization and feasibility enforcement. Even though, a feasibility issue occurred during the tour when the electric vehicle's battery level was no longer sufficient to continue the next road segment, despite individual distances being within normal range limits. The Branch and Cut algorithm framework resolved this by inserting one charging stop at Gentari Batu Pahat Mall, allowing the tour to complete successfully. The algorithm's ability to remove subtours during the cut phase further ensured that no disconnected loops existed in the final solution, strengthening its suitability for energy-constrained Travelling Salesman Problem-based EV routing.

Overall, the findings of this study support the use of the Branch and Cut algorithm as an exact optimization approach for EV route planning under range and charging constraints, especially within a manageable regional scope such as Johor. This research contributes practical insights into electric vehicle routing behaviour, demonstrates the feasibility of structured travel between multiple charging nodes, highlights the importance of subtour elimination and energy feasibility checks, and establishes a strong foundation for future studies involving larger and more complex EV charging networks in Malaysia.

Acknowledgement

The authors would also like to thank the Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia for providing the facilities and financial support for this research.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Haris Ikhwan Rostam; Muhamad Ghazali Kamardan;* ***data collection:*** *Muhammad Haris Ikhwan Rostam;* ***analysis and interpretation of results:*** *Muhammad Haris Ikhwan Rostam;* ***draft manuscript preparation:*** *Muhammad Haris Ikhwan Rostam, Muhamad Ghazali Kamardan. All authors reviewed the results and approved the final version of the manuscript.*

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