

A Tabu Search Approach for Capacitated Vehicle Routing with Pickup and Delivery in Motorcycle-Based Urban Logistics under Traffic and Weather Constraints

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ABSTRACT

Motorcycle-based couriers play an essential role in urban logistics due to their flexibility and efficiency in congested environments. However, limited vehicle capacity combined with simultaneous delivery and pickup activities makes route planning a complex optimization problem. This study addresses the Capacitated Vehicle Routing Problem with Pickup and Delivery (CVRPPD) for motorcycle couriers by incorporating traffic congestion and weather conditions into the travel cost model. A Tabu Search metaheuristic is proposed to optimize routing decisions while simultaneously determining the optimal number of vehicles under a dynamic load constraint. The objective function is formulated using a lexicographic approach, prioritizing the minimization of the number of vehicles followed by the minimization of total travel cost, which is influenced by distance, traffic level, and weather condition. Computational experiments were conducted on a dataset consisting of one depot and 50 customers, with a maximum vehicle capacity of 30 kg. The simulation results demonstrate that the proposed approach consistently identifies an optimal solution using five motorcycles, which corresponds to the theoretical lower bound derived from total pickup demand. All customers are served exactly once without violating capacity constraints, and the maximum vehicle load reaches the allowable limit of 30 kg. The total travel cost obtained is 1316.262, indicating efficient route construction under dynamic environmental conditions. These results confirm that Tabu Search is an effective and robust approach for solving CVRPPD in motorcycle-based urban logistics, particularly when realistic operational factors such as traffic congestion and weather variability are considered.



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INTRODUCTION

The rapid growth of urban logistics services in recent years has been driven by the expansion of electronic commerce and the increasing demand for fast and flexible goods distribution [1], [2]. Within this context, motorcycle couriers have become one of the most widely adopted transportation modes due to their ability to navigate congested urban areas, lower operational costs, and higher mobility compared to larger vehicles [3], [4]. Nevertheless,

the use of motorcycles for distribution purposes is inherently constrained by limited carrying capacity, which implies that suboptimal route planning may lead to increased distribution costs and a decline in service quality [5].

Route planning problems in logistics are generally formulated as the Vehicle Routing Problem (VRP), which has been extensively studied in the field of combinatorial optimization [6], [7]. One VRP variant that is particularly relevant to modern distribution systems is the Capacitated Vehicle Routing Problem with Pickup and Delivery (CVRPPD), where vehicles are required to perform delivery and pickup operations simultaneously [8], [9]. This characteristic substantially increases problem complexity, as vehicle loads become dynamic and vary along the route. In motorcycle courier operations, such dynamics are especially critical, since even minor capacity violations can render a solution operationally infeasible.

In addition to capacity constraints and pickup-delivery dynamics, environmental factors such as traffic congestion and weather conditions play a significant role in distribution performance [10]. In practical settings, the shortest-distance route does not necessarily result in the lowest travel time or travel cost, particularly when vehicles operate under heavy congestion or adverse weather conditions [11]. However, most existing CVRPPD studies still model travel cost primarily based on distance, which limits their ability to accurately represent real-world operational conditions, especially in motorcycle-based urban distribution systems [12], [13].

From a computational perspective, CVRPPD is classified as an NP-hard problem, making exact solution approaches impractical for medium- to large-scale instances within reasonable computational time [14], [15]. Consequently, metaheuristic methods have been widely adopted due to their capability to generate near-optimal solutions with improved computational efficiency. Among these methods, the Tabu Search algorithm has been shown to be effective in solving various VRP variants by employing adaptive memory structures that help avoid local optima and enable systematic exploration of the solution space.

This study focuses on the application of a Tabu Search algorithm to solve the CVRPPD for motorcycle couriers with limited vehicle capacity. The proposed model explicitly accounts for dynamic vehicle loads along the route and integrates distance, traffic congestion, and weather conditions into the travel cost function. Furthermore, the number of vehicles is not predefined but is optimally determined by the algorithm using a lexicographic objective approach, in which the minimization of fleet size is prioritized before minimizing total travel cost.

The main contribution of this research lies in the development of a more realistic CVRPPD model for motorcycle couriers by simultaneously considering environmental factors and optimal fleet size determination. Simulation results demonstrate that the proposed Tabu Search approach is capable of producing feasible solutions that satisfy all capacity and customer coverage constraints while achieving the theoretical minimum number of vehicles. Therefore, this study is expected to contribute both methodologically and practically to the design of efficient and adaptive urban distribution systems under dynamic operating conditions.

METHODS

Problem Description

This study addresses the *Capacitated Vehicle Routing Problem with Pickup and Delivery* (CVRPPD) in a motorcycle-based distribution system. The system consists of a single depot acting as the starting and ending point of all routes and a set of customers, each with specific delivery and pickup demands. Each customer must be served exactly once by a single

vehicle, and all vehicles are required to return to the depot after completing their routes.

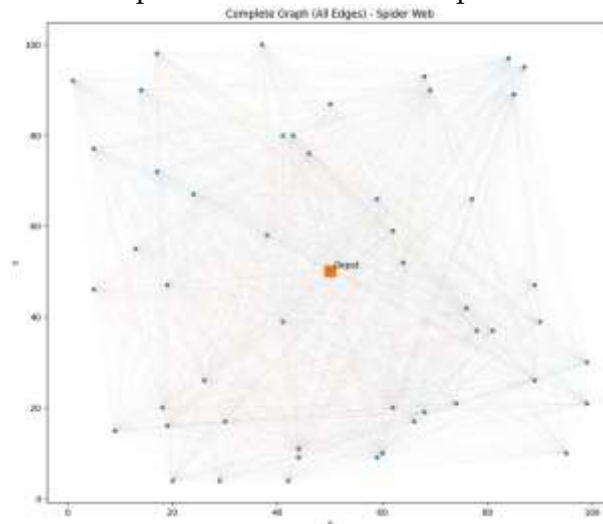


Figure 1. Complete Graph

The vehicles used in this study are motorcycles with a limited maximum capacity of 30 kg. This capacity limitation requires careful route planning to ensure that vehicle loads do not exceed the allowable limit at any point along the route. The problem complexity is further increased by the simultaneous delivery and pickup operations, which cause vehicle loads to vary dynamically during the distribution process.

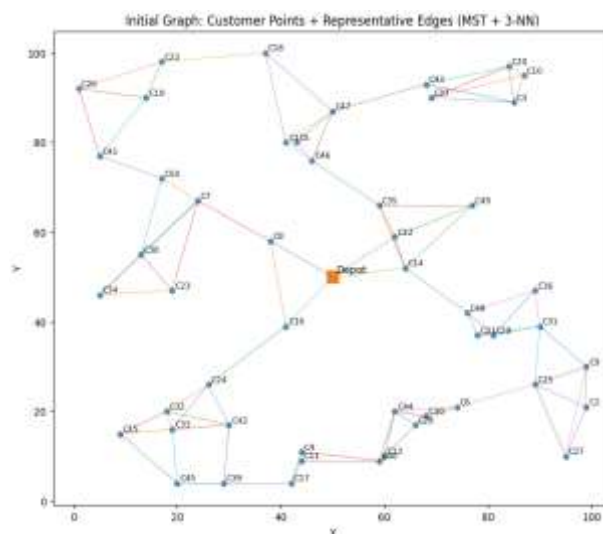


Figure 2. Costumer points + Representative Edges

Mathematical Formulation of CVRPPD

The CVRPPD is modeled as a complete directed graph $G=(V,A)$, where $V=\{0,1,2,\dots,n\}$ represents the set of nodes consisting of one depot (node 0) and n customers, and A denotes the set of directed arcs connecting each pair of nodes.

Each customer $i \in V \setminus \{0\}$ has a delivery demand d_i and a pickup demand p_i . Each vehicle has a maximum capacity Q . A route is considered feasible if it starts and ends at the depot, serves a subset of customers, and satisfies the vehicle capacity constraint throughout the route.

The initial vehicle load for a given route is defined as the total delivery demand of all customers assigned to that route:

$$L_0 = \sum_{i \in R} d_i$$

After serving customer i at step t , the vehicle load is updated using the dynamic load equation:

$$L_{t+1} = L_t - d_i + p_i$$

subject to the following capacity constraint:

$$0 \leq L_t \leq Q \quad \forall t$$

The objective of the CVRPPD is to determine a set of routes that serve all customers exactly once, satisfy all capacity constraints, and minimize the number of vehicles and the total travel cost.

Travel Cost Model

In this study, the travel cost between two nodes is not determined solely by distance but also incorporates traffic congestion and weather conditions. For each directed arc from node i to node j , three attributes are defined: distance $dist_{ij}$, traffic level $traf_{ij}$, and weather condition $weat_{ij}$.

The travel cost is computed using the following cost function:

$$c_{ij} = dist_{ij} \times (1 + \alpha(traf_{ij} - 1) + \beta(weat_{ij} - 1))$$

where α and β are weighting parameters that control the influence of traffic congestion and weather conditions on the travel cost. This formulation allows the cost to increase proportionally with worsening traffic and weather, thereby providing a more realistic representation of operational conditions in urban motorcycle-based logistics.

Objective Function

The objective function is designed using a lexicographic optimization approach with two hierarchical priorities. The primary objective is to minimize the number of vehicles used in the distribution system, while the secondary objective is to minimize the total travel cost.

To implement this approach computationally, the objective function is expressed as:

$$\min F = \lambda \cdot K + \sum_{(i,j) \in A} c_{ij}$$

where K denotes the number of vehicles used, c_{ij} represents the travel cost between nodes i and j , and λ is a sufficiently large penalty constant that ensures vehicle minimization is always prioritized over travel cost minimization.

Tabu Search Algorithm

The Tabu Search algorithm is employed as a metaheuristic approach to solve the CVRPPD efficiently. A solution at iteration k is represented as $S^{(k)} = \{R_1, R_2, \dots, R_K\}$, where each R_m denotes a route served by a single vehicle that starts and ends at the depot.

The quality of a solution is evaluated using the objective function defined previously:

$$f(S) = \lambda \cdot K(S) + \sum_{m=1}^{K(S)} \sum_{(i,j) \in R_m} c_{ij}$$

Neighborhood solutions are generated by applying local search operators, including customer relocation between routes, customer swaps across routes, and route sequence modifications. Only solutions that satisfy the dynamic capacity constraints are considered feasible.

To prevent cycling and repetitive search patterns, a tabu list is used to store recently applied moves for a fixed number of iterations, known as the tabu tenure. A tabu move may

still be accepted if it satisfies the aspiration criterion, meaning that it produces a solution with a better objective value than the best solution found so far. Formally, a tabu solution S' is accepted if:

$$f(S') < f(S^*)$$

where S^* denotes the current global best solution.

The search process starts from an initial feasible solution generated using a greedy heuristic and iteratively explores the neighborhood until a termination condition is met, such as reaching the maximum number of iterations or exceeding the predefined computational time limit.

Intensification, Diversification, and Evaluation Metrics

To enhance solution quality, intensification is performed by focusing the search around promising regions of the solution space, particularly by attempting to eliminate routes with a small number of customers to reduce the fleet size. Diversification is applied when the search stagnates by introducing controlled perturbations to explore new regions of the solution space.

The performance of the proposed approach is evaluated using several metrics, including the number of vehicles, total travel cost, feasibility with respect to capacity constraints, customer coverage, and convergence behavior throughout the search process. These metrics are used to assess the effectiveness and robustness of the Tabu Search algorithm in solving the CVRPPD under dynamic operational conditions.

RESULTS AND DISCUSSION

Dataset Description and Simulation Settings

The computational experiments were conducted on a dataset consisting of one depot and 50 customers, each characterized by delivery and pickup demands. The total delivery demand across all customers is 66 kg, while the total pickup demand reaches 149 kg. The distribution system employs motorcycle couriers with a maximum vehicle capacity of 30 kg, making capacity constraints a critical factor in route construction.

Travel costs between nodes were computed by integrating distance, traffic congestion, and weather conditions. The weighting parameters for traffic and weather were set to $\alpha=0.1$ and $\beta=0.1$, respectively. The Tabu Search algorithm was executed with a computational time limit of approximately 120 seconds, during which the algorithm iteratively explored the solution space while recording performance metrics at each iteration.

Table 1. Dataset Characteristics and Simulation Parameters

No	Component	Information
1	Number of depots: 1	1
2	Number of customers: 50	50
3	Total delivery requests: 66 kg	66 kg
4	Total pickup requests: 149 kg	149 kg
5	Vehicle type: Motorcycle	Motorcycle
6	Maximum vehicle capacity (Q): 30 kg	30 kg
7	Vehicle load model: Dynamic load (delivery-pickup)	Dynamic load (delivery-pickup)
8	Graph structure: Complete directed graph	Complete directed graph
9	Traffic parameters: Scale 1-5	Scale 1-5

10	Weather parameters: Scale 1-5	Scale 1-5
11	Travel cost model: Distance + traffic + weather	Distance + traffic + weather
12	Traffic weight (α): 0.1	0.1
13	Weather weight (β): 0.1	0.1
14	Optimization method: Tabu Search	Tabu Search
15	Objective function approach: Lexicographic (min vehicles, then min cost)	Lexicographic (min vehicles, then min cost)
16	Initial number of vehicles: Variable (determined by the algorithm)	Variable (algorithm determined)
17	Simulation time limit: ± 120 seconds	± 120 seconds
18	Capacity feasibility status: All routes are feasible	All feasible routes
19	Customer service status: 100% of customers served	100% of customers served
20	Optimal number of vehicles (result): 5 vehicles	5 vehicles

Optimization of Fleet Size

One of the primary objectives of this study is the determination of the optimal number of vehicles without specifying the fleet size a priori. The simulation results show that the Tabu Search algorithm consistently identifies a solution using five motorcycles. This result is not only empirically optimal but also aligns with the theoretical lower bound derived from the total pickup demand, which can be expressed as:

$$\left\lceil \frac{149}{30} \right\rceil = 5$$

Throughout the search process, the best fleet size remained at five vehicles, indicating that no feasible solution exists with fewer vehicles under the given capacity constraints. This finding confirms that the proposed approach successfully reaches the global optimum in terms of fleet size minimization.

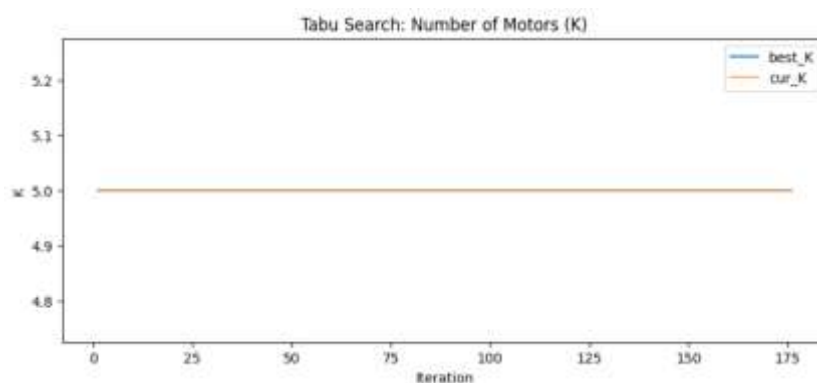


Figure 3. Convergence of the number of vehicles during the Tabu Search process

Analysis of Travel Cost and Route Quality

After achieving the optimal fleet size, the Tabu Search algorithm focused on minimizing the total travel cost. The final solution resulted in a total travel cost of 1316.262, which reflects the aggregated cost of all routes considering distance, traffic congestion, and weather conditions.

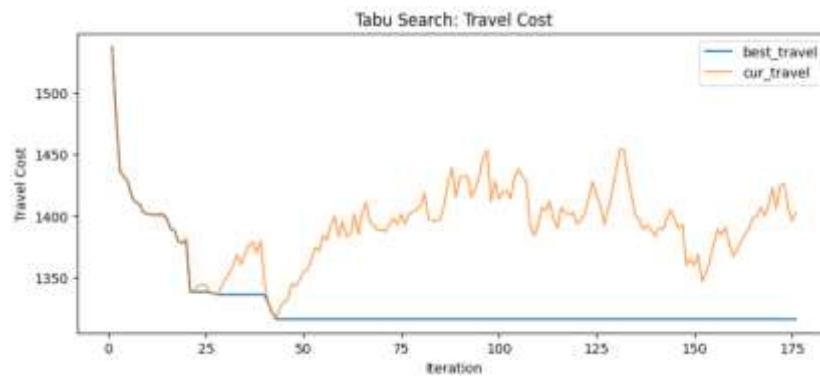


Figure 4. Convergence of travel costs during the Tabu Search process

An analysis of route-level costs reveals variability among the five routes. The minimum route cost is 187.287, while the maximum route cost reaches 330.851, with a standard deviation of 50.548. This variation indicates that the algorithm does not merely balance the number of customers per route but also adapts route construction based on environmental conditions. Routes with shorter distances but severe traffic or weather conditions may incur higher costs than longer routes under more favorable conditions.

Table 2. Summary of Simulation Travel Costs

No	Metrik Biaya	Nilai
1	Total biaya perjalanan	1,316,262
2	Biaya rute minimum	187,287
3	Biaya rute maksimum	330,851
4	Simpangan baku biaya rute	50,548

Dynamic Load Feasibility and Capacity Utilization

All routes generated by the Tabu Search algorithm satisfy the vehicle capacity constraints. The average initial vehicle load, defined as the total delivery demand assigned to each route, is 13.2 kg. As vehicles traverse their routes, the load dynamically changes due to delivery and pickup activities.

The simulation results show that the maximum vehicle load encountered across all routes is exactly 30 kg, which corresponds to the maximum allowable capacity. Importantly, no capacity violations were observed at any stage of the routes, and all intermediate loads remained within the feasible range. This outcome demonstrates that the dynamic load model has been correctly implemented and that the resulting routes are operationally feasible for motorcycle couriers.

Table 3. Vehicle Load Statistics on All Routes

No	Vehicle Load Metric	Value
1	Average initial vehicle load	13,2 kg
2	Maximum vehicle load	30 kg
3	Feasible capacity status	Feasible

Customer Coverage Validation

Customer coverage is a fundamental requirement in CVRPPD. The final solution successfully serves all 50 customers exactly once, with no missing or duplicated services. The customer coverage indicator (*CoverageOK*) is satisfied, and the number of uniquely served customers matches the total number of customers in the dataset.

Moreover, the total served delivery demand equals 66 kg, and the total served pickup demand equals 149 kg, which are fully consistent with the initial dataset. These results confirm

that the proposed approach guarantees full-service coverage while maintaining feasibility with respect to all problem constraints.

Convergence Behavior of the Tabu Search Algorithm

The convergence behavior of the Tabu Search algorithm was analyzed based on the recorded iteration history. During the early iterations, the algorithm exhibits a rapid reduction in travel cost as it explores diverse regions of the solution space. Any initial capacity penalties that occurred during the exploration phase were quickly eliminated, resulting in zero penalty values for the remainder of the search.

The fleet size remains stable at five vehicles throughout the simulation, indicating that the algorithm quickly converges to the optimal fleet size and subsequently performs intensification to improve route quality. In the later stages of the search, improvements in travel cost become marginal, suggesting that the algorithm has converged to a near-optimal solution.

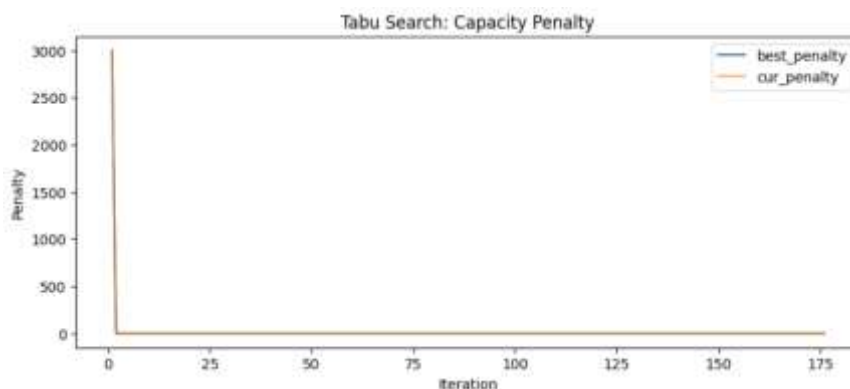


Figure 5. Capacity penalty behavior during Tabu Search iterations

Discussion

The overall results demonstrate that the proposed Tabu Search approach is highly effective in solving the CVRPPD for motorcycle couriers under dynamic operational conditions. The algorithm successfully determines the optimal fleet size while constructing feasible routes that respect dynamic capacity constraints and ensure complete customer coverage.

The integration of traffic congestion and weather conditions into the travel cost model contributes to more realistic routing decisions compared to distance-only approaches. Additionally, the lexicographic objective function enables a clear prioritization of fleet size minimization without compromising route efficiency.

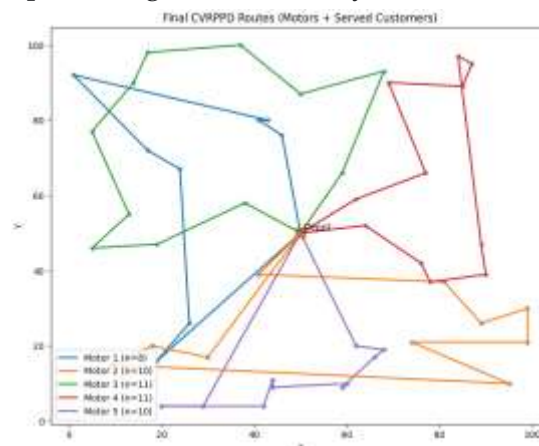


Figure 6. Visualization of the final route of CVRPPD with 5 vehicles

These findings highlight the robustness and practical applicability of the proposed method for urban motorcycle-based distribution systems, particularly in environments characterized by uncertainty and variability in traffic and weather conditions.

CONCLUSION

This study investigates the Capacitated Vehicle Routing Problem with Pickup and Delivery (CVRPPD) in a motorcycle-based distribution system by incorporating dynamic vehicle loads and environmental factors into the routing process. A Tabu Search metaheuristic was proposed to optimize routing decisions while simultaneously determining the optimal fleet size under strict capacity constraints.

Simulation results demonstrate that the proposed approach consistently identifies an optimal solution using five motorcycles, which corresponds to the theoretical lower bound derived from the total pickup demand and vehicle capacity. All customers are served exactly once without any violations of capacity constraints, and the maximum vehicle load reaches the allowable limit of 30 kg, confirming the correctness of the dynamic load modeling.

The integration of distance, traffic congestion, and weather conditions into the travel cost function results in a total travel cost of 1316.262 and enables more realistic routing decisions compared to distance-based models. The convergence behavior of the Tabu Search algorithm indicates stable and efficient performance, with rapid improvements during the early iterations and gradual intensification toward the best solution.

Overall, the findings confirm that Tabu Search is an effective and robust method for solving CVRPPD in motorcycle-based urban logistics, particularly under dynamic and uncertain operational conditions. The proposed model provides practical insights for improving the efficiency of urban distribution systems while maintaining feasibility and full customer coverage.

Future research may extend this work by incorporating additional real-world constraints such as time windows, heterogeneous vehicle capacities, or real-time traffic and weather data. Furthermore, comparative studies with other metaheuristic or hybrid optimization methods could provide a deeper understanding of the relative performance of the proposed approach.

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