

Article

A Graph-Based Scheme Generation Method for Variable Traffic Organization in Parking Lots

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Abstract: To deal with the traffic congestion issues caused by the imbalance between supply and demand in parking lots, this study proposes a graph-based scheme generation method for variable traffic organization in parking lots. A graph-based methodological framework is developed to dynamically generate feasible traffic organization schemes and adapt the road networks of parking lots based on fluctuating demands. First, we design a parking lot-tailored enhanced primal approach by adding a directedness attribute while maintaining road continuity to ensure correspondence between generated graphs and traffic organization schemes. A graph generation algorithm is then designed to generate all feasible schemes in the scenario, deploying the depth-first search algorithm to check the connectivity of each graph and narrowing down feasible options based on domain knowledge. Finally, the initial parking space distribution and parking demand are used as inputs to calculate the total vehicle cruising time under each scheme, serving as the key indicator to select the optimal organization scheme. A single-level parking lot model is developed to verify the performance of our method under six initial parking space distributions. This model is built using the multi-agent simulation platform AnyLogic version 8.8.6, which enables the quick transformation of organization schemes by customizing the behavior of different agents. The results show that the optimal organization scheme generated by the proposed method can reduce vehicle cruising time by 15–46% compared to conventional traffic organization, varying according to parking space distributions. The significance of this study lies in its potential to mitigate traffic congestion in parking lots, thereby enhancing overall efficiency and user satisfaction. By dynamically adapting to fluctuating parking demands, this method provides a robust solution for urban planners and parking lot operators aiming to optimize traffic flow and reduce unnecessary delays.

Keywords: variable traffic organization; dynamic lane reversal; real-time adaptation; AnyLogic simulation



Citation: Cao, J.; Ling, H.; Li, T.; Wang, S.; Jiang, S.; Zhao, C. A Graph-Based Scheme Generation Method for Variable Traffic Organization in Parking Lots. *Sustainability* **2024**, *16*, 4778. <https://doi.org/10.3390/su16114778>

Academic Editor: Armando Carteni

Received: 21 April 2024

Revised: 29 May 2024

Accepted: 30 May 2024

Published: 4 June 2024



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1. Introduction

Parking infrastructure constitutes a pivotal element within urban transportation networks, exerting profound influences on regional parking behaviors across metropolitan landscapes [1]. Nevertheless, as urban development escalates alongside increases in population density, the costs associated with the construction of parking facilities continue to soar to unprecedented levels [2]. This escalation renders parking spaces increasingly scarce in more developed cities, exacerbating traffic congestion. In the year 2022, the ratio of automobiles to parking spaces was approximately 1:0.8 in major Chinese cities, whereas in smaller and medium-sized cities, this figure was approximately 1:0.5. Consequently, there exists a deficit of 80 million parking spaces [3]. Moreover, antiquated parking lot designs and inadequate directional signage contribute to significant vehicular circling, which in turn aggravates traffic congestion and escalates greenhouse gas emissions [4,5].

This scenario detrimentally impacts the operational efficiency of parking facilities and deteriorates the quality of the urban travel experience.

In response to these challenges, the optimization of existing parking infrastructure is increasingly recognized as a critical strategy for alleviating parking congestion. Recent advancements in connected autonomous vehicles (CAVs) and intelligent roadside devices have introduced novel and viable solutions to these issues. Research concerning CAVs within parking environments encompasses various dimensions, including the allocation of parking resources [6,7], management of parking operations [8,9], and dynamic scheduling of parking assets [10,11], which collectively enhance the efficiency of parking resource utilization from the perspective of the vehicle.

Simultaneously, the digital enhancement of roadside equipment augments the capacity for flexible traffic management within parking facilities, thus improving overall service efficiency. Among these technologies, sensory devices such as cameras, millimeter-wave radar, and lidar play integral roles in parking lot semantic modeling [12], risk assessment [13], vehicle positioning [14,15], and the precise monitoring and instantaneous response to both internal flow dynamics and external traffic conditions within the parking facility [16,17]. Furthermore, variable guidance devices are predominantly utilized to dynamically display traffic organization within parking lots [18]. As illustrated in Figure 1, the variable projection sign effectively projects the current lane directions onto the pavement and can adaptively modify lane flows in real time based on situational demands. The intelligent mobile road cone offers enhanced flexibility, being capable of relocating to various points to mitigate traffic conflicts within the scenario. Additionally, the variable guidance screen facilitates real-time adjustments in navigational information to align with the prevailing traffic management strategy.

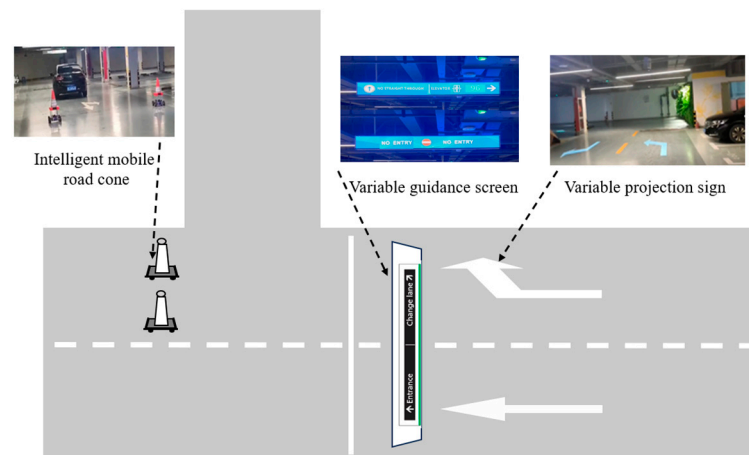


Figure 1. Layout of “variable traffic control devices” in a parking lot.

Consequently, the real-time planning and management of individual lanes and the broader regional road network within the parking facility become achievable. The organizational structure of the road network can be modified dynamically in accordance with evolving demands. This study proposes a method for generating and selecting variable traffic organization schemes based on the spatial and temporal distribution of vehicles and parking spaces. The objective is to identify optimal traffic management schemes for various parking lot scenarios, thereby enhancing parking space utilization and reducing vehicle detour durations.

The following are the contributions of our research:

- (1) **Development of a Graph-Based Methodological Framework:** The study introduces a novel graph-based framework for generating and dynamically adapting traffic organization schemes in parking lots. This framework utilizes a parking lot-tailored

enhanced primal approach and a graph generation algorithm to ensure efficient and feasible traffic management.

- (2) **Implementation and Verification Using Multi-Agent Simulation:** The research employs the AnyLogic multi-agent simulation platform to build a single-level parking lot model. This model tests the proposed method's performance under various initial parking space distributions, demonstrating the practical applicability and effectiveness of the approach.
- (3) **Significant Reduction in Vehicle Cruising Time:** The proposed method is able to significantly reduce the vehicle cruising time compared to conventional traffic or organization methods. This reduction highlights the method's potential to alleviate traffic congestion, improve overall parking lot efficiency, and enhance user satisfaction by dynamically adapting to changing parking demands.

2. Literature Review

2.1. Parking Management Strategies

The capacity of parking resources within established facilities is inherently finite, whereas parking demand exhibits substantial temporal fluctuations, diverging significantly between weekdays and weekends and varying across different times of day [19,20]. The conventional, static organization of the road network within these facilities fails to adequately address the dynamic interplay between the demand for and supply of parking, leading to a considerable volume of circulating parking traffic and consequent congestion [10]. Several scholarly works have investigated various parking management interventions, such as parking pricing schemes, intelligent parking systems, and park-and-ride solutions, aimed at enhancing parking space utilization or diminishing the time spent cruising for parking.

Existing approaches often overlook real-time changes in parking demand and the dynamic adjustments needed for traffic flow within parking lots. Our study introduces a graph-based method to address this issue. Unlike conventional methods, our approach dynamically generates and adjusts traffic organization schemes according to changing demands.

2.1.1. Pricing Strategies in Parking Management

Progressive and dynamic pricing are primary strategies to balance parking supply and demand by adjusting costs. Progressive pricing increases hourly charges over time, optimizing revenue and societal welfare through tiered pricing structures [21]. Conversely, dynamic pricing adapts continuously in response to real-time changes in parking space occupancy. For instance, Saharan et al. [22] introduced a machine learning and game theory-based framework for dynamically pricing and allocating on-street parking slots. Similarly, Wang et al. [23] developed a hybrid model incorporating dynamic pricing and parking permits, demonstrating that this hybrid approach substantially enhances network travel efficiency compared to strategies solely based on parking fees.

2.1.2. Intelligent Parking Systems

Focused predominantly on expansive parking areas, intelligent parking systems aim to boost area-wide service efficiency through systematic management, typically encompassing real-time parking data acquisition, parking guidance, and parking reservation functionalities. The intelligent parking system is essential for the implementation of our variable traffic organization scheme, as the system provides necessary real-time data such as parking space availability, and the flow in and out of the parking lot.

To capture real-time parking availability data, some researchers introduced the MePark system, which utilizes parking meter transaction data coupled with limited sensor reports to predict real-time, citywide on-street parking availability at a granular level [24]. Other researchers established comprehensive citywide parking guidance systems (CPGS) that gather data from sensor-equipped parking lots, generate data for unsensored lots using recurrent Generative Adversarial Networks (GANs), and refine the data according to similar environmental conditions [25]. Subsequently, various algorithms have been employed to

devise routing strategies for parking guidance. Ćelić et al. [26] advocated a cooperative vehicular guidance approach to directing drivers to available parking spots, simulating four distinct parking demand scenarios. During the reservation phase, the optimization objectives typically encompass minimizing drivers' total monetary costs, maximizing parking resource utilization, and enhancing profitability for platform operators [27,28].

2.2. Dynamic Lane Reversal

Dynamic lane reversal [29], a traffic management strategy that modulates traffic flow by alternating the directional usage of specific roadway lanes, is particularly applicable in parking lots characterized by regular, time-variable traffic patterns, where additional lanes cannot be constructed or expanded. Reversible lanes are considered one of the most efficacious methods to augment peak-hour capacity on existing roadways.

Typically employed for the management and control of arterial roads and intersections within urban networks, dynamic lane reversal has seen extensive application. Levin et al. [30] proposed a max-pressure control strategy for autonomous intersection management that incorporates dynamic lane reversal. Li et al. [31] developed a dynamic lane reversal strategy predicated upon area-specific congestion levels. Zhao et al. [32] crafted a lane-centric optimization model that synergizes the control of reversible lanes with other traditional traffic management strategies.

The advent of connected and autonomous vehicles (CAVs) has significantly extended the application of dynamic lane reversal, enhancing its real-time flexibility and control. Chen et al. [33] devised a mixed-integer linear programming model for dynamic lane reversal tailored to environments with CAVs, aimed at identifying the most efficacious strategy. Zhou et al. [34] introduced a real-time dynamic reversible lane safety control model, analyzing key factors influencing the safety of reversible lanes, such as the parameters of no-entry and buffer zones in conflict areas. Their findings indicate that this approach effectively maintains the rate of traffic conflicts below 5%. Furthermore, Chu et al. [35] designed a dynamic lane reversal traffic scheduling management system that adjusts lanes in response to the travel demands of CAVs, significantly enhancing travel times for CAVs, as evidenced by simulation results.

By integrating dynamic lane reversal into our graph-based traffic organization method, we can further optimize traffic flow and reduce congestion in parking lots. This approach allows for flexible adaptation to real-time traffic demands, enhancing the overall efficiency and user experience in parking facilities.

3. Methodology

The salient aspects of the study concerning the generation and selection of variable traffic organization schemes within parking facilities are characterized as follows:

- The object of this study is a parking facility equipped with variable traffic control hardware. These devices are designed to dynamically modify the directional flow of internal roadways within the parking lot.
- The formulation of traffic organization schemes for the parking lot is contingent upon the real-time demands of both ingress and egress traffic flows, in conjunction with the spatial distribution of available parking spaces throughout the facility.
- Architecturally, the parking facility is constructed on a single level and features multiple access points, typically comprising two or more entrances.
- The efficacy of various traffic organization schemes is assessed through the aggregation of total parking or departure durations for all vehicles across designated temporal intervals, providing a measure of operational efficiency in response to the implemented traffic management protocols.

3.1. Graph Representation for Parking Lots

To facilitate a quantitative analysis of traffic organization methods within parking facilities, which often incorporate numerous internal road intersections, extensive road

segments, and complex road network topologies, it is imperative to abstract these physical elements into a mathematical model.

Graph structures are often used to describe complex traffic network structures. A graph is an abstract mathematical structure composed of nodes and edges that describes relationships between objects. Among them, nodes represent objects, entities or locations in the graph, usually represented by letters or numbers. For example, a node set can be represented as the following: $V = \{A, B, C, D\}$, where A, B, C, D are nodes in the graph. Edges are line segments connecting nodes in a graph and are used to represent the relationships between nodes. Edges can be directed or undirected, and can be represented by a pair of nodes. For example, (A, B) represents the undirected edge connecting node A and node B, and $(A \rightarrow B)$ represents the directed edge from node A to node B.

Contemporary graph-structure methods for analyzing traffic network structures are generally bifurcated into the primal approach and the dual approach, contingent upon the abstraction methodology applied to the real-world traffic network. These approaches are extensively discussed within the literature [36,37], serving as exemplars for delineating infrastructure components and their interdependencies, and for modeling real-world challenges to devise pragmatic solutions.

The selection of a modeling paradigm to represent the parking network exerts a foundational influence on the outcomes of the research. Notwithstanding, prevailing methodologies predominantly address the delineation of road networks, with scant attention accorded to parking network models. As illustrated in Figure 2, a hypothetical road traffic network graph is depicted using both the primal and dual approaches, and the numbers in the figure are the serial numbers of nodes.

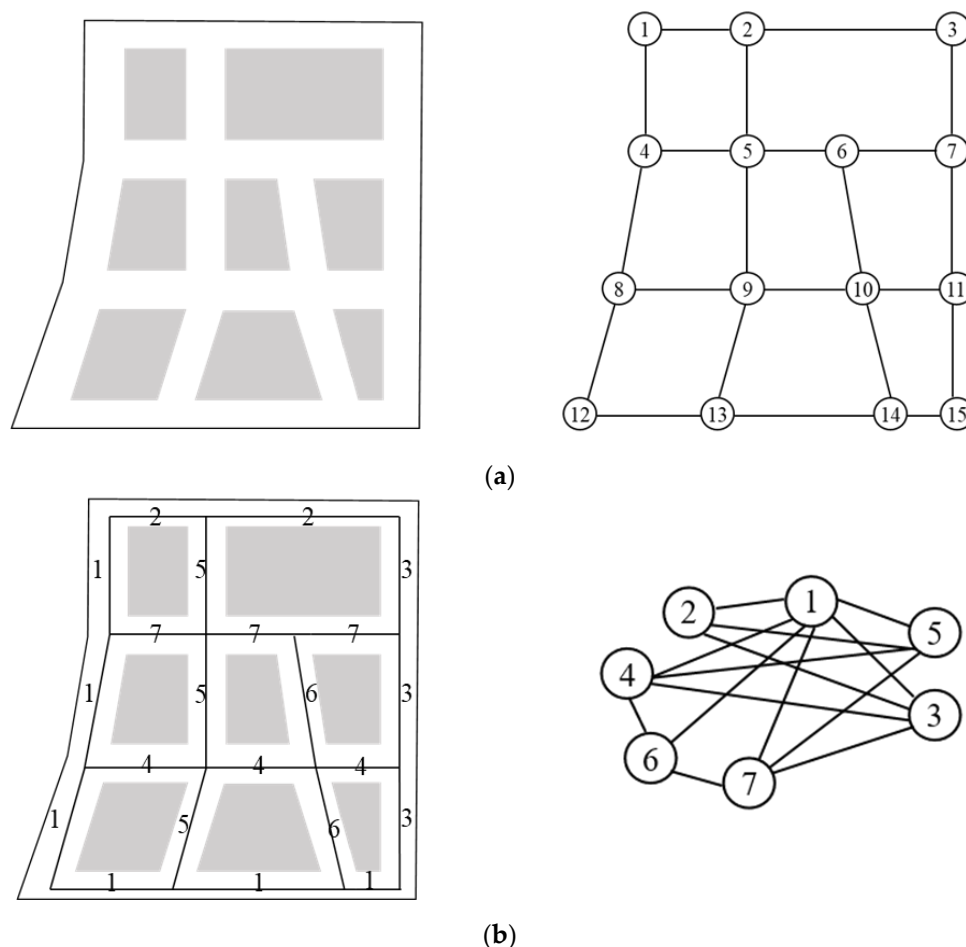


Figure 2. Primal and dual approach applied to fictitious road networks; (a) abstract by primal approach; (b) abstract by dual approach.

(a) **Primal Approach:** This method represents physical elements of a transportation network, such as intersections (nodes), roads, and junctions, as a graph. In this graph, intersections become nodes, and roads between them become edges. This helps in analyzing the network's layout, road capacity, traffic flow, congestion, and other practical parameters.

(b) **Dual Approach:** This method represents roads and bus routes (line facilities) as points (vertices) on the graph. The connections between these roads or routes, such as shared intersections or transfer points, become lines (edges). This approach is useful for analyzing optimal paths, maximum flows, minimum cuts, and other characteristics of the traffic network.

However, within the context of parking lot variable traffic organization, both aforementioned methodologies manifest limitations. While the primal approach preserves a direct correspondence between nodes and edges, as well as intersections and road segments, disparities in coherence and articulation relationships may arise, potentially fragmenting a continuous road into multiple segments or positioning nodes in road segments that do not comply with the conditions for variability. This can result in a model of heightened complexity, thus amplifying the intricacies involved in analysis and computation. Conversely, although the dual approach simplifies the abstraction of the underground garage into a less complex model, it engenders a loss of critical information pertaining to the parking lot's structure, including the connectivity of roads, the spatial layout, and the quantity of parking spaces, rendering it unsuitable for this specific scenario.

In response to these challenges, we propose an enhanced primal approach tailored for application in parking lots. This revised approach incorporates three additional constraints relative to the traditional primal model:

- **Equivalence:** Ensures a one-to-one correspondence between the abstract graph and the actual road network, precluding the addition or deletion of existing road structures.
- **Continuity:** Each edge within the graph corresponds to a contiguous road segment, thereby avoiding the placement of isolated nodes that could disrupt the continuity of the road.
- **Directedness:** The graph is structured as a directed network, with each edge assigned a specific direction and weight, indicative of the permissible traffic flow direction.

The nodes and edges in the graph, as formulated using the enhanced primal approach, possess distinctive spatial and traffic-related attributes:

1. Nodes

Spatial characteristics: These are representative of intersections, corners, and entry or exit points within the parking lot, strategically segmenting the roadway to facilitate the implementation of divergent traffic organization directions.

Traffic characteristics: Nodes typically signify the ingress or egress points of the parking lot or demarcate specific parking zones. When designating parking zones, nodes are attributed with the number of remaining and occupied parking spaces.

2. Edges

Spatial characteristics: Edges correspond to sections of the roadway amenable to directional changes. Variations in traffic organization schemes are manifested in the graph through configurations of directed edges.

Traffic characteristics: Each edge is defined by a clear direction and an associated weight, which delineates the current directional flow of traffic on that roadway segment and the theoretical passage time. Notably, the passage time may vary depending on the flow direction of the same road segment.

The graph, as generated through the enhanced primal approach, not only enhances the coherence and articulation relationship of the roadway network, but also preserves the integral structure of the road. It ensures that each pair of adjacent edges at a node within the graph can feasibly support traffic organization in differing directions. Consequently, this refined primal approach constitutes the most appropriate method for abstracting models in the generation and selection of variable traffic organization schemes within

parking facilities, affording a robust framework for addressing the complexities inherent in managing parking lot traffic flows.

3.2. Algorithm Design

During peak periods within a parking facility, the adherence to a fixed traffic organization pattern frequently precipitates unidirectional traffic congestion and suboptimal utilization of alternate lanes. This inefficiency typically stems from the varied distribution of parking spaces and the asymmetric demands for entry and exit. In light of these challenges, it becomes imperative for parking lot managers to consider the real-time status of parking spaces and adaptively adjust the traffic organization strategy to minimize the overall detour distance and duration for all vehicles, thereby augmenting the operational efficiency of the parking facility.

In this section, we delineate the detailed procedural steps involved in the generation and selection of variable traffic organization schemes, which are summarized as follows:

3.2.1. Rough Set Generation

Initially, any parking lot is abstracted into a directed graph $G_0 = (V, E)$ as outlined in Section 3.1, where m represents the number of nodes and n denotes the number of edges within the graph. Each edge in this graph symbolizes a two-lane roadway capable of supporting in-degree, out-degree, and bi-directional traffic flows, thus generating a total of 3^n potential traffic organization combinations, represented as S_1 .

It is evident that certain configurations within S_1 may not comply with essential road design criteria. Primarily, it is crucial to ensure that connectivity is maintained across the parking lot, meaning any parking zone must be accessible from any other zone and entry point. To ascertain this connectivity, a depth-first search (DFS) algorithm is employed to evaluate each graph and eliminate those that fail to meet the criteria. The process involves the following steps:

1. Initialize a Boolean array $visited[V]$ and set all elements to false, indicating that no nodes have been visited yet.
2. For each node $v \in V$, perform DFS(v).
 - i. If $visited[v]$ is false, mark $visited[v]$ as true, indicating that node v has been visited.
 - ii. For each unvisited neighbor node $u \in Adj(v)$ of v (where $Adj(v)$ denotes the set of neighbor nodes of node v), perform DFS(u).
3. Check if all elements of the visited array are true. If all are true, every node in the graph is reachable to all other nodes.

Upon completion of the phase, we have identified and delineated the feasible rough set S_2 , which comprises graphs that fulfill the connectivity criteria.

3.2.2. Domain Knowledge Pruning

Beyond the elementary connectivity requirement, the design of traffic organization schemes for parking lots must also conform to industry standards and engineering practices. To this end, it becomes imperative to refine the set S_2 utilizing domain-specific knowledge, thereby aligning with engineering specifications and narrowing the feasible set range. This refinement process incorporates several common domain knowledge constraints which include:

1. The entrance direction constraints

Each entrance is subject to three potential organizational modes—double entry, double exit, and a combination of one entry and one exit, corresponding to the dual-lane road flow at these ingress points. Distinct program categories ought to be delineated based on the various combinations of entrance and exit flows.

2. Peripheral arterial road constraints

Establishing fixed bidirectional traffic on the main thoroughfares that connect internal parking zones and bear the primary traffic flow within the parking facility. This configuration is instrumental in enhancing the circulation efficiency of vehicles within the lot.

3. Special structure constraints

Given the unique distribution characteristics of parking zones or the diverse functional requirements within the parking facility, it is essential to integrate specific structural constraints into the graph. Such configurations may include ridge layouts, circular layouts, radial layouts, and grid layouts.

These three constraints represent standard steps applicable to any parking facility configuration. In real-world applications, further considerations should include factors such as the allocation of accessible parking spaces, fire zones, charging stations, pedestrian pathways, elevator lobbies, and other relevant variables. The pruning of the rough set S_2 based on domain knowledge not only renders the solution space more rational but also significantly reduces the computational burden associated with the generation and selection of solutions. The ensemble of graphs that emerges from the domain knowledge-based pruning process is subsequently denoted as S_3 .

3.2.3. Optimal Strategy Selection

Following the aforementioned procedural phases, the resultant set S_3 encapsulates all viable solutions pertinent to parking facilities. Subsequent refinements of the solutions within S_3 are undertaken to ascertain the most efficacious strategy. It is crucial to note that during periods of low demand, where the influx and egress of vehicles are relatively balanced, traditional traffic management schemas are generally adequate to maintain fluid vehicular movement within the facility. Therefore, variable traffic organization schemes are only deployed during rush hours; in the selection of the optimal strategy, a distinction is made between peak entry and peak exit periods.

During peak entry periods, when the number of entering vehicles approximates the remaining parking spaces within the facility, drivers are inclined to follow the system-recommended route and opt for the nearest available parking space upon entering the parking lot, according to the findings of researchers such as Han et al. [38]. Eventually, all vacant parking spaces within the parking lot will be occupied. The total parking time for vehicles is computed for each traffic organization strategy, and the strategy with the shortest duration is selected as the optimal strategy.

1. Set the peak hour threshold

The concepts of peak entry and exit periods are primarily qualitative. To transition these into a framework amenable to quantitative analysis, set the threshold value θ . When the calculated value exceeds the threshold, it is identified as a peak entry or exit period:

$$\frac{Q_{in/out}}{Q_{in} + Q_{out}} \geq \theta, \quad (1)$$

where:

Q_{in} —hourly traffic volume of parking lot entry, which is predicted by historical data or collected in real time by sensing devices;

Q_{out} —hourly traffic volume of parking lot exit, which is predicted by historical data or collected in real time by sensing devices.

2. Compute the weights of the edges.

For graph $G_i = (V, E)$ in S_3 , edge $e_{ab} \in E$, take the travel time of a vehicle passing through the roadway represented by e_{ab} as the weight of e_{ab} :

$$W_{ab} = L_{ab} / (V_0 * r), \quad (2)$$

where:

W_{ab} —the edge weight of two neighboring nodes a to b of graph G_i ;

L_{ab} —the actual road length of the corresponding section of e_{ab} ;

V_0 —the design speed of the parking lot;

r —the number of road strips from a to b.

3. Compute node attributes.

For graph $G_i = (V, E)$ in S_3 , when node $v \in V$ denotes a parking zone, it possesses attributes indicating the remaining and occupied parking space quantities:

$$O_v = \sum_{i=1}^n \frac{1}{K_i} O_i, \quad (3)$$

$$I_v = \sum_{i=1}^n \frac{1}{K_i} I_i, \quad (4)$$

where:

O_v and I_v —number of occupied and remaining parking spaces at node v ;

O_i ($i = 1 \dots n$)—number of spaces occupied by the i -th parking zone adjacent to node v ;

I_i ($i = 1 \dots n$)—number of spaces remaining by the i -th parking zone adjacent to node v ;

K_i ($i = 1 \dots n$)—number of nodes adjacent to the i -th parking zone.

4. Compute the shortest entry or exit path.

The Dijkstra algorithm is used to calculate the shortest path between nodes, which takes into account the phenomenon of congestion and develops the balance function based on distance and time. The calculation results represent the optimal paths that can be chosen by vehicles entering and leaving the parking lot under the current traffic organization strategy.

For graph $G_i = (V, E)$ in S_3 , $Dst[v]$ denotes the shortest path distance of node v , which is initialized to infinity; W_{uv} is the edge weight from two neighboring nodes u to v ; V_d denotes the collection of nodes that have already been visited, the algorithm includes the following steps:

- Initialize $Dst[start] = 0$ and $Dst[v] = \infty$ ($v \neq start$);
- Select the shortest path node $v \in V$ such that $Dst[u]$ is minimized and $u \notin V_d$;
- Update the distances of neighboring nodes. For each neighboring node $v \in Adj(u)$, which denotes the set of nodes neighboring u , compute the new distance: $Dst_{new} = Dst[u] + W_{uv}$, if $Dst_{new} < Dst[v]$, then update $Dst[v] = Dst_{new}$;
- Calculate the balance function value: $B_{value} = \alpha * Dst[v] + \beta * T_{uv}$, where α and β are the weight parameters of the balance function and T_{uv} denotes the time from node u to node v ;
- Consider the balance function value when selecting the next node, i.e., select the node that minimizes the B_{value} as the next shortest path node.

5. Select the optimal strategy.

Taking peak entry period as an example, for graph G_i in S_3 , calculate the time used by each vehicle to drive from the entrance node to the parking zone node, and add them up to obtain the total entrance time T_i . Comparing T_i for all the graphs in S_3 , and taking the minimum value of the corresponding graph G' as the optimal traffic organization strategy under the peak entry period:

$$T_i = \sum_{v=1}^n I_v * D_v, \quad (5)$$

$$G' = \min(T_i, i = 1 \dots m), \quad (6)$$

where:

I_v —number of remaining parking spaces at node v ;

D_v —shortest path elapsed time from the entrance to node v ;

T_i —total entrance time of graph G_i ;

G' —graph corresponding to the optimal traffic organization strategy.

4. Experiments

4.1. Experiment Settings

We undertook a series of experiments employing a single-level parking lot model characterized with a grid layout, featuring two entrances and dual-lane internal roads. The parking facility extends 128 m in length and 57 m in width, providing a total of 334 parking spaces. We indicate the number of parking spaces in each parking area in Figure 3. Alongside the four parking zones situated along the periphery, the central area of the lot comprises nine grid-like distributed parking zones. The layout is systematically structured with internal roads forming a grid pattern, inclusive of four cross intersections and eight T-shaped intersections (Figure 3).

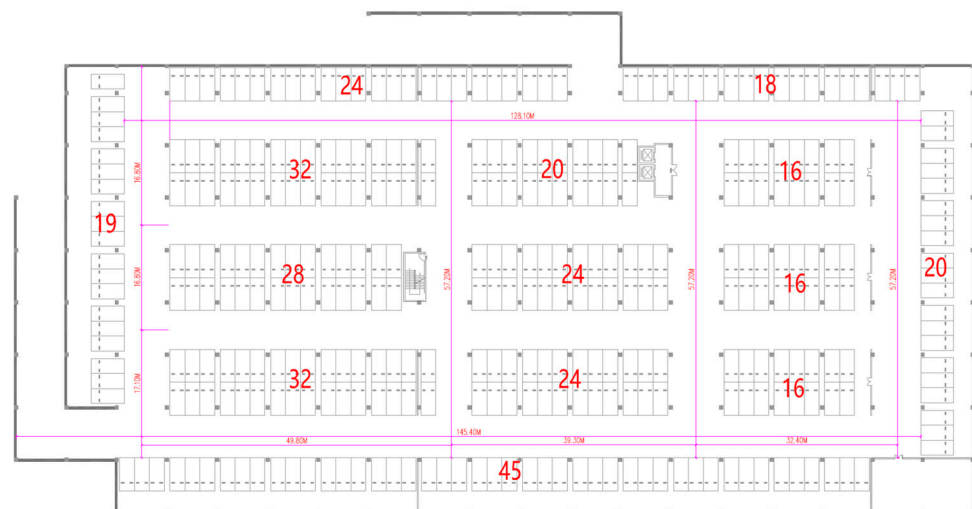


Figure 3. Parking lot model structure used for experiments.

The development of this model is underpinned by both practical and theoretical considerations. From a practical perspective, a single-level parking lot with dual entrances represents a prevalent configuration within urban traffic systems. Thus, the analysis and optimization of such a structure yield findings of significant relevance and applicability to real-world contexts. On the theoretical front, the chosen model's moderate complexity is particularly conducive to algorithmic scrutiny and simulation, offering a stark contrast to the intricate traffic networks typical of larger, multi-level parking facilities. Furthermore, the grid-like road architecture enhances the model's scalability, enabling modifications through the addition or subtraction of grid sections to suit varying structural requirements of parking facilities. This adaptability renders the model highly beneficial for ongoing and future research projects.

To ascertain the diversity and efficacy of the solutions generated under various parking space distribution scenarios, we established six distinct sets of initial parking configurations. These configurations are visually represented using heatmaps to depict the occupancy and distribution of parking spaces within the lot, where a bluer hue indicates a higher availability of parking spaces in a given zone, and a more orange hue denotes greater occupancy. Sets A through F depict unique scenarios of parking space distribution, strategically concentrated in the upper, middle, and lower regions of the parking lot to differentiate between peak entry and peak exit conditions (Figure 4).

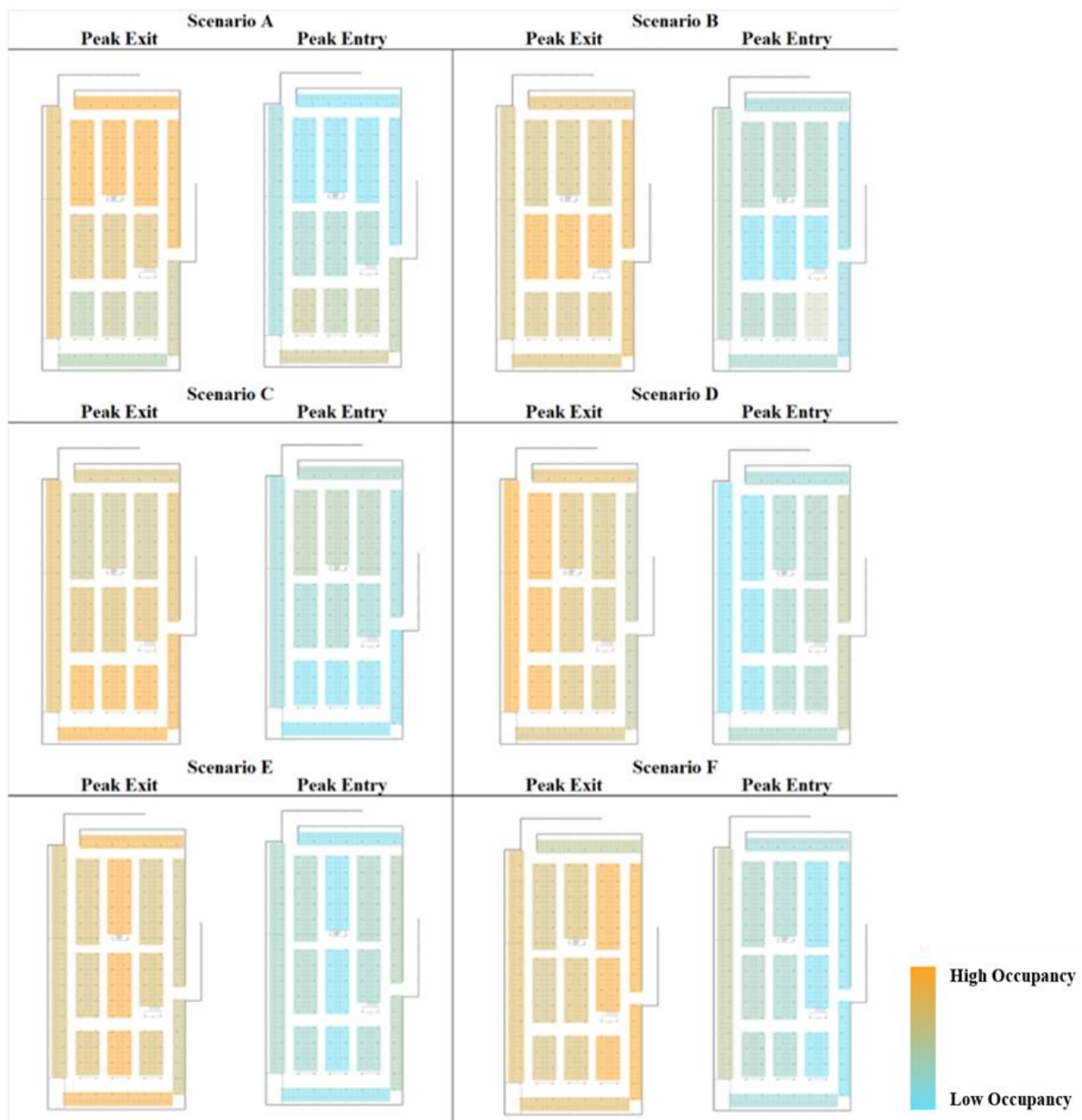


Figure 4. Heat map of initial parking space distribution (peak exit: high occupancy of parking spaces and high flow of leaving the parking lot; peak entries: low occupancy of parking spaces and high flow into parking lots).

4.2. Theoretical Calculation and Simulation

The network topology graph of the model, crafted using the enhanced primal approach, is depicted in Figure 5, where the numbers in the figure are the serial numbers of nodes. This representation preserves a precise one-to-one correspondence between each edge and its corresponding road segment, without modifying the original road infrastructure, thereby fulfilling the requirement of equivalence. Furthermore, the model avoids the insertion of additional nodes within central road sections or at corner bends, maintaining continuity. Each pathway is represented as bidirectional within the graph, adhering to the directional requirement, ensuring that all pathways are navigable under typical traffic configurations.

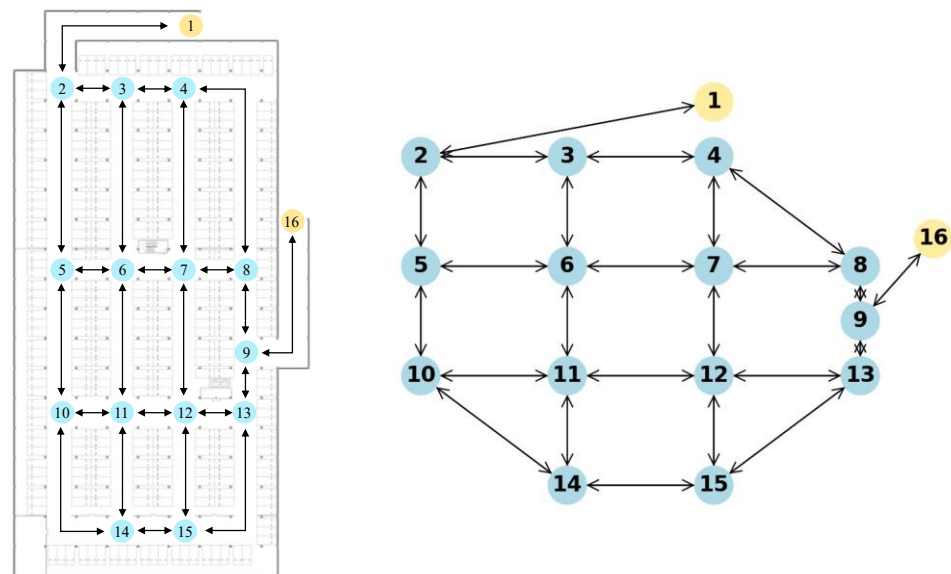


Figure 5. Graph generated by the improved primal approach.

The graph comprises 16 nodes and 24 edges, designated as g_0 (16,24). Node 1, marked in yellow within the graph, serves as the northern entrance, while node 16, also highlighted in yellow, denotes the eastern entrance. After validating connectivity through DFS, a feasible rough set of traffic organization schemes is established.

Subsequent to this phase, the rough set is further refined based on domain-specific knowledge. The entrance direction constraints and peripheral arterial road constraint are considered in this case. The configuration at nodes 1 and 16 is designed to support a combination of one-way and two-way traffic, divided into four specific scenarios:

1. α_1 : Node 1 sets unidirectional entry, Node 16 supports both entry and exit;
2. α_2 : Node 1 sets unidirectional exit, Node 16 supports both entry and exit;
3. β_1 : Node 16 sets unidirectional entry, Node 1 supports both entry and exit;
4. β_2 : Node 16 sets unidirectional exit, Node 1 supports both entry and exit.

The edge sets $E_1 = \{(2,3), (3,4), (4,8)\}$, $E_2 = \{(5,6), (6,7), (7,8)\}$, $E_3 = \{(10,11), (11,12), (12,13)\}$, and $E_4 = \{(10,14), (14,15), (15,13)\}$ represent four peripheral arterial roads within the graph g_0 . The directional orientation of these edges is consistently maintained to ensure connectivity across the network.

Upon delineating the feasible set, optimal schemes are selected as outlined in Section 3.2.3. The peak hour threshold θ is set at 0.8, and the ratios of entrance to exit volumes are adjusted to 1:4 or 4:1 based on this threshold. The design speed V_0 within the parking lot is assumed to be 20 km/h. The evaluation and selection of the most effective schemes are conducted under initial parking space distribution scenarios A through F, utilizing Python version 3.9.19 for all numerical experiments.

To substantiate the theoretical calculations and approximate operational data reflective of real-world scenarios, we developed a simulation model utilizing the multi-agent-based simulation software, AnyLogic version 8.8.6. This platform was selected for its capabilities that surpass those of VISSIM in certain aspects; specifically, AnyLogic version 8.8.6 conceptualizes traffic components such as vehicles, roads, intersections, and parking zones as intelligent agents. This approach facilitates the customization of each agent's behavioral rules using Java, allowing for adaptations that cater to the experimental requirements, such as the dynamic adjustment of parking space distributions and road directions.

Figure 6 depicts the parking lot simulation model under a conventional two-way traffic organization strategy:

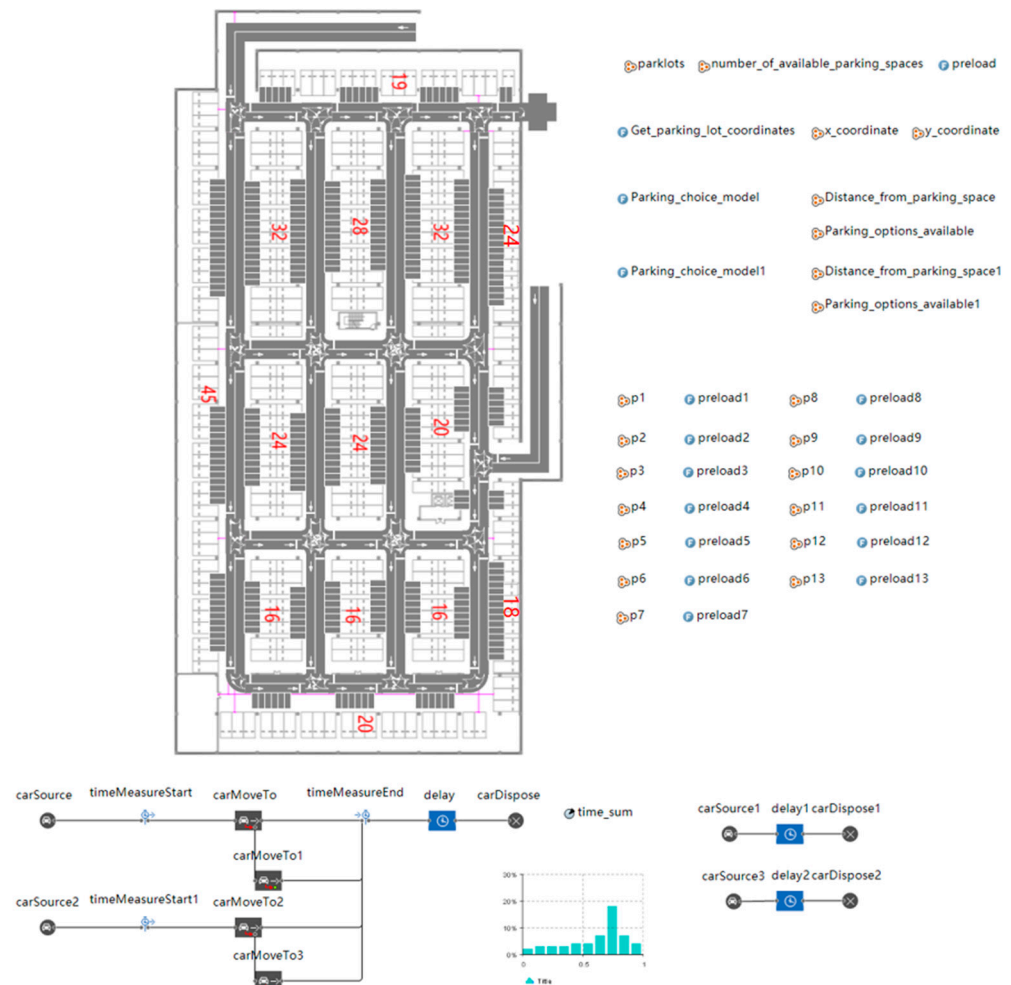


Figure 6. Anylogic simulation model.

In the simulation model, the lengths of roads are proportionally designed to align with the layout presented in Figure 3. Custom controls within the simulation environment enable the modification of road orientations, enhancing the flexibility of traffic management schemes. During runtime, inputting the graph matrix from S_3 generates the corresponding road network, thus facilitating the simulation of diverse traffic organization schemes. Vehicle behavior within the simulation is directed by controls such as “CarSource”, which designates the destination point for each vehicle. Adhering to the shortest path algorithm detailed in Section 3.2.3, vehicles systematically execute their parking or exit maneuvers.

For evaluation, the total time required for vehicles to enter or exit serves as the primary metric to assess the efficacy of different traffic organization schemes. The “Delay” control is employed to log the cruising time for each vehicle, which, upon the conclusion of the simulation, aggregates to reflect the cumulative cruising duration for all vehicles within the current scenario.

4.3. Results and Discussion

Statistical analyses were executed on the variable schemes across six initial parking space distributions, which were further delineated into four distinct strategies: α_1 , α_2 , β_1 , and β_2 . Focusing on scenario A during the peak entry period as a representative case, it was observed that parked vehicles predominantly occupied the lower part of the parking lot, with decreased occupancy rates noted towards the upper regions. During the peak entry period, the entrances were managed according to the α_1 or β_1 strategy. Figures illustrating the distribution of entry and exit times under these two regimes, including box plots and bar plots of the shortest and average entry and exit times, are displayed in Figure 7.

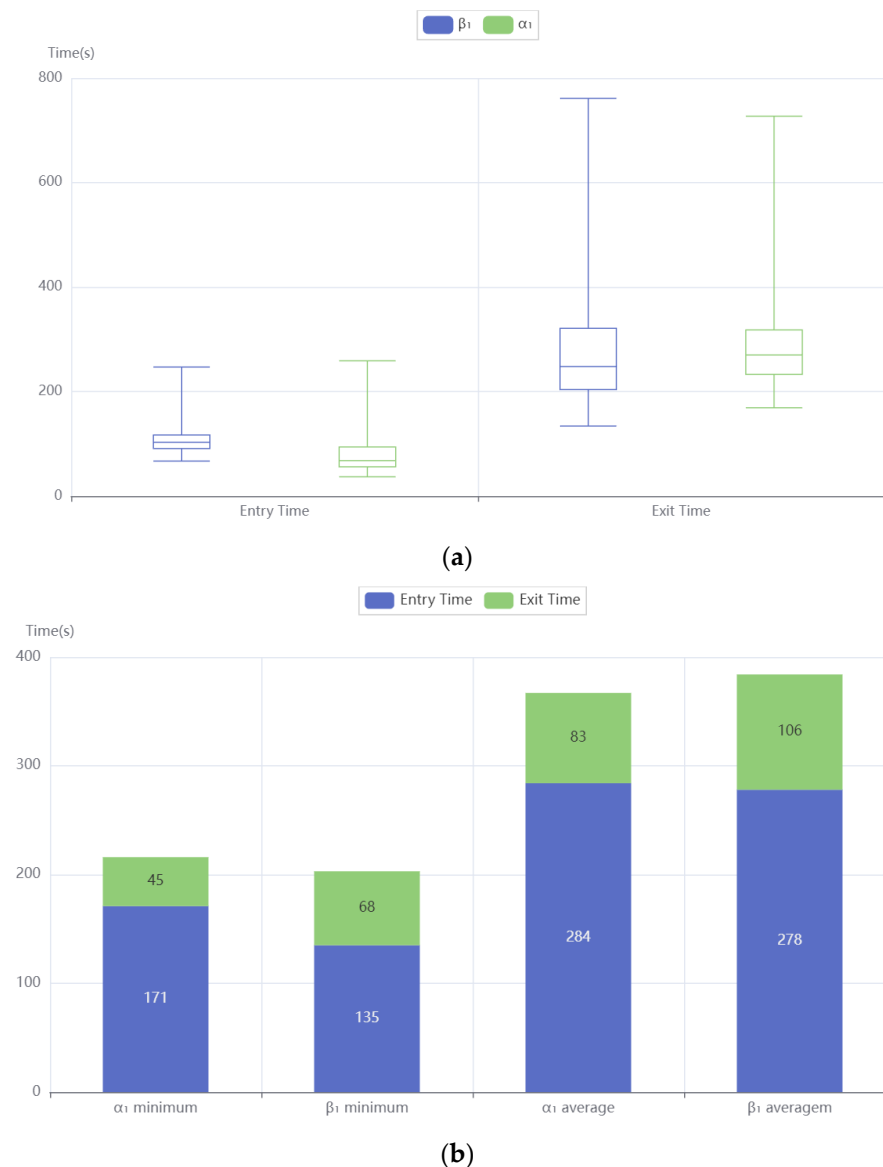


Figure 7. Statistical analysis of schemes in scenario A; (a) box plot of cruising time during peak entry period in scenario A; (b) bar plot of minimum and average time during peak entry period in scenario A.

As depicted in Figure 7a, the box plot for the α_1 configuration demonstrates a notably tighter interquartile range, shorter whiskers, and a more concentrated distribution of data points within this range, suggesting reduced variability among the measured times. Conversely, the box plot corresponding to the β_1 configuration reveals a broader spread between the minimum and maximum entry times, albeit with a narrower interquartile range for exit times. The whiskers extending from the box in both directions are shorter, indicating a lower degree of dispersion and fluctuation within the data.

Illustrated in Figure 7b, the minimum and average exit times for the α_1 strategy are comparatively shorter, with the minimum entry time recorded at 171 s. The β_1 strategy, however, exhibits superior performance regarding entry times, registering a minimum entry time of 135 s. When contrasted with traditional traffic organization schemes, the total cruising times for vehicles under the β_1 and α_1 strategies are reduced by 30.2% and 44.9%, respectively. This significant reduction in time spent by vehicles maneuvering within the lot markedly enhances the operational efficiency of the parking facility, showcasing the effectiveness of the implemented variable traffic organization schemes.

The superior traffic organization scheme scenario A, employing strategy α_1 , is depicted in Figure 8, where the numbers in the figure are the serial numbers of nodes. Relative to traditional traffic management methods, the simulation results indicate that the total cruising time for vehicles is reduced by 29.2% under strategy α_1 and by 46.6% under strategy β_1 . These findings corroborate the outcomes of the numerical experiments, affirming the effectiveness of the proposed method.

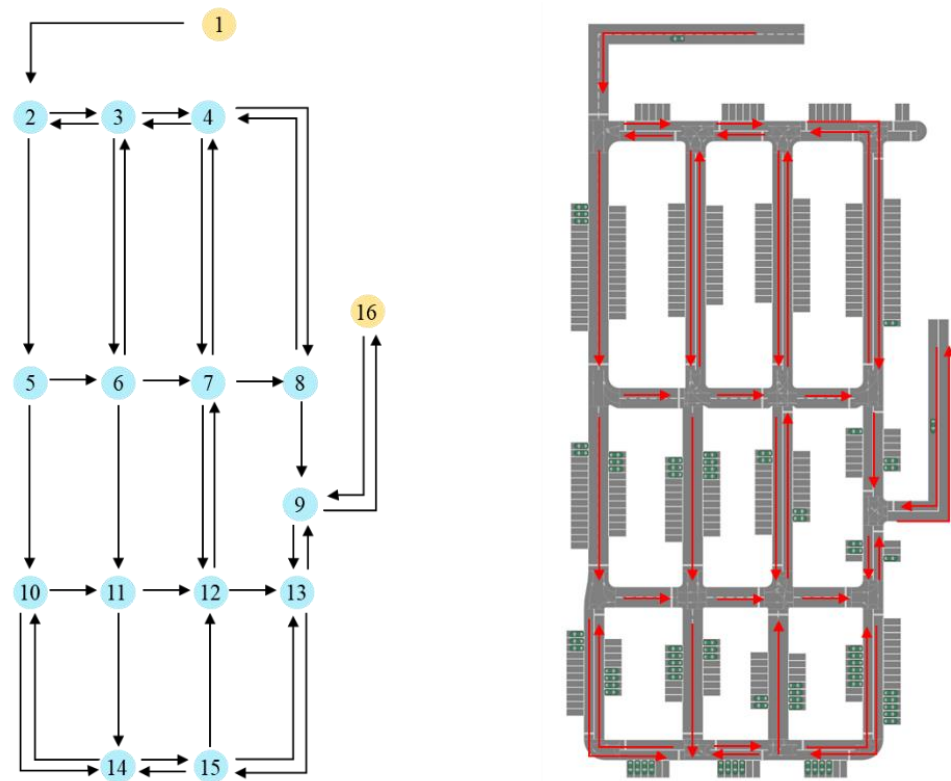


Figure 8. Optimal strategy graph and simulation model in scenario A.

Further analysis is conducted across other scenarios in a manner analogous to scenario A. The theoretical calculation results for scenarios A–F are shown in Table 1. The simulation results of scenario A–F are shown in Table 2.

Table 1. Theoretical calculation results for scenario A–F.

Scenario Type	Original Time (s)	α_1/α_2 Minimum Time (s)	Efficiency Improve	β_1/β_2 Minimum Time (s)	Efficiency Improve
A	245	171	30.2%	135	44.9%
B	235	185	21.3%	133	43.4%
C	239	193	19.2%	137	42.7%
D	257	176	31.5%	144	44.0%
E	250	183	26.8%	141	43.6%
F	230	188	18.3%	130	43.5%

Note: The original time refers to the cruising time of vehicles under the conventional traffic organization scheme where all roads are two-way roads.

The compiled data illustrate that, irrespective of the initial parking space distributions, the implementation of variable traffic organization schemes consistently diminishes the cruising time for vehicles within the parking facility by up to 46%. Specifically, in the parking lot utilized for this experiment with unidirectional access at entrance 16, particularly under strategy β_1 and β_2 , proves to be significantly more effective—reducing vehicle cruising time by an average of 43%. Conversely, strategy α_1 and α_2 yield an average reduction

in cruising time of 24%. This disparity is attributable to the superior accessibility offered by entrance 16, which facilitates shorter detours to various parking zones. The variance in efficiency between the entrance management schemes underscores the effectiveness of domain knowledge in feasible schemes simplification.

Table 2. Simulation results for scenario A–F.

Scenario Type	Original Time (s)	α_1/α_2 Minimum Time (s)	Efficiency Improve	β_1/β_2 Minimum Time (s)	Efficiency Improve
A	809	573	29.2%	432	46.6%
B	761	623	18.1%	446	41.4%
C	779	612	21.4%	437	43.9%
D	816	582	28.7%	467	42.8%
E	825	614	25.6%	475	42.4%
F	745	622	16.5%	430	42.3%

Note: The original time refers to the cruising time of vehicles under the conventional traffic organization scheme where all roads are two-way roads.

Moreover, the degree of efficiency improvement varies considerably across different scenarios. Scenario F shows the least improvement, with only 18.3%/16.5% enhancement in cruising time reduction. In contrast, the implementation of variable traffic organization schemes in scenario A is the most effective, achieving improvements of 30.2%/29.2% as per theoretical calculations and simulations, respectively. These results validate the algorithm's responsiveness to diverse parking space distribution scenarios, enabling it to identify different optimal solutions contingent upon specific spatial occupancy configurations. This nuanced sensitivity ensures that the overall service efficiency of the parking facility is maximized, tailored to the spatial layout of occupied parking spaces.

5. Conclusions

This paper proposes a common and effective method to generate the optimal scheme for traffic organization during peak periods, according to the road structure and initial space distributions in the parking lot. First, combining the primal approach's mapping of traffic elements with the dual approach's conceptualization of road connectivity relationships, an enhanced primal approach is designed to abstract the road structure and characterize organization schemes as a basis for further analysis.

In the generation of feasible schemes, the DFS algorithm is used to check the connectivity of each graph to ensure that every parking zone represented by the nodes can be reached or departed from. Then, the planned direction of the parking lot entrances and peripheral arterial roads are specified based on domain knowledge, which simplifies the feasible schemes while satisfying engineering standards. The optimal scheme is then selected based on the total vehicle cruising time indicator under the assumption that vehicles will follow the suggested route to enter or exit the parking zones. Each optimal scheme respectively corresponds to a certain kind of initial parking space distribution.

In the simulation experiments based on AnyLogic version 8.8.6, we developed a single-level parking lot model characterized by a grid layout, whose modest size simplifies the computational complexity, and the grid-like zone layout retains the convenience of adapting to other structures. It is found that the optimal scheme under two entrance organization strategies, respectively, reduces vehicle cruising time by an average of 43% and 24%, underscoring the effectiveness of domain knowledge in simplifying feasible schemes. Meanwhile, the effect of the optimal scheme under different initial parking space distributions verifies the algorithm's spatial sensitivity; for example, the best optimized scenario A reduces cruising time by 30.2%/29.2%, while this figure is only 18.3%/16.5% in scenario F.

In this study, we made a preliminary exploration of the generation method for variable traffic organization in parking lots. For future research, improving the precision of vehicle

cruising behavior models is crucial, as drivers may not always follow suggested routes. Advanced algorithms like genetic algorithms and ant colony optimization could help manage the increased complexity in larger parking lots. Integrating real-time data from intelligent parking systems (IPS) and connected autonomous vehicles (CAVs) can enhance adaptability and responsiveness. Collaborating with city planners and integrating with smart city infrastructure could optimize both parking lots and their urban interactions. Additionally, quantifying environmental benefits, such as reduced emissions from decreased cruising time, could support broader sustainability goals. Addressing these areas will lead to more robust, scalable, and efficient traffic organization solutions for various parking contexts.

Author Contributions: Conceptualization, C.Z.; methodology, J.C., H.L. and C.Z.; software, T.L. and J.C.; validation, S.J. and T.L.; formal analysis, C.Z.; investigation, J.C. and S.W.; resources, S.J.; data curation, J.C., H.L. and T.L.; writing—original draft preparation, J.C. and H.L.; writing—review and editing, J.C., S.W. and C.Z.; visualization, H.L. and T.L.; supervision, C.Z.; project administration, C.Z.; funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52102383.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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