An Effective Berths-Based Approach to Calculate the Capacity of Drop-Off Exclusive Roadway

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Abstract. To accurately estimate the capacity of multi-lane drop-off exclusive roadway, a calculation approach based on effective berths is proposed. First, the study specifically analyzes different layout types of parking and through lanes and introduces the concept of effective berths of drop-off exclusive roadway. A calculation approach of the capacity of multi-lane drop-off exclusive roadway at airport terminal based on effective berth and spatiotemporal trajectory theory is proposed. The effective berth under a certain level of delay is determined via VISSIM simulation and the drop-off exclusive roadway in Jinan Yaoqiang Airport-China is taken as an example for case analysis. The results show that the accuracy of the proposed method is more than 95%. The proposed approach is more in line with the actual unload process of the drop-off vehicles than traditional methods and lays a theoretical foundation for service level evaluation and the management and guidance of drop-off vehicles.

Keywords: Traffic capacity · Effective berth · Drop-off exclusive roadway · Spatiotemporal trajectory theory · Airport terminal

1 Introduction

In recent years, due to the rapid growth of the number of passengers traveling by air and the limitation of airport land space, many cities are extending or constructing airports. In this context, how to rationally design the layout of landside facilities to improve the corresponding traffic capacity is one of the main problems to be resolved. As one of the airport's roadside facilities, the drop-off exclusive roadway refers to the road set up in front of the departure hall of the terminal building for vehicles to complete passage and short stops for passengers to disembark and unload luggage. There are flows of passengers and vehicles which intertwine on the staging area (i.e., the section outside the terminal). Especially for the peak period, the congestion and traffic disorder are widespread and seriously affect traffic efficiency of the airport's landside (i.e., the drop-off exclusive roadway). How to accurately estimate the traffic capacity of a drop-off

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exclusive roadway is a key issue for accurately evaluating its service level, effectively managing drop-off vehicles, which requires in-depth exploration.

At present, scholars have carried out a lot of studies on the calculation approach of the capacity of the drop-off exclusive roadway at the airport terminal, mainly focusing on theoretical and simulation methods. De Neufville and Odoni [1] defined the drop-off exclusive roadway and gave the empirical formula for calculating the length of the drop-off roadway in "Airport System: planning, design, and management". Zhang et al. [2] analyzed the characteristics of traffic flow on the drop-off exclusive roadway and proposed calculation methods of traffic indicators (including average vehicle stay time, average number of vehicles on the drop-off exclusive roadway, etc.) based on the queuing theory. Chen et al. [3] proposed a lane-changing behavior based on a deep learning approach to simulate the relationship between the speed and spacing of the lane-changing vehicle. Liu et al. [4] developed a model to control the demand scale of the drop-off exclusive roadway based on the multi-desk queuing theory with the capacity limitation (M/M/n/C/). Parizi and Braaksma [5] established a basic mathematical calculation model for the capacity of the drop-off exclusive roadway with a single parking lane, which ignores the deceleration behavior of vehicles parking and driving away. Zhang et al. [6–8] proposed formulas for calculating the capacity of two-lane drop-off exclusive roadway by considering the change of speed and the interaction between internal and external lanes. Zhang [9] analyzed the capacity of a three-lane drop-off exclusive roadway with double parking lanes. The introduction of connected and autonomous vehicles will reshape the transport system. Traffic flow, particularly the road capacity and free-flow speed could considerably be improved [10, 11]. Carrone et al. [12] investigated how the utilization of the road capacity degraded as a function of heterogeneity in congested motorways.

Javid et al. [13] proposed the conceptual model of the simulation analysis of the drop-off exclusive roadway, laid a theoretical foundation for the subsequent simulation system practice. Chang [14] developed a multi-lane parking simulation model with driver preferences in mind. ACRP and TRB [15] gave a method to estimate the required length of parking lane in "Airport Cooperative Research Program Report 40 (ACRP40)" and suggested VISSIM simulation could be used to estimate the capacity of drop-off exclusive roadway.

The above-mentioned works mostly focus on the two-lane drop-off exclusive roadway with one parking lane. Currently, the drop-off exclusive roadways lanes of most terminals are more than three. For multi-lane drop-off exclusive roadways with different layouts of lane functions, each has its operation regulation, and the utilization rate of parking lanes is also diverse. There are varying degrees of mutual interference between vehicles. The capacity of the drop-off exclusive roadway is not equal to the mere accumulation of the capacity of every single lane. Therefore, the existing capacity calculation methods are not applicable anymore.

This study starts from the differences in the layout of parking and through lanes of drop-off exclusive roadway at airport terminal, summarizes the lane function layout types, and proposes a calculation approach of the capacity of multi-lane drop-off exclusive roadway based on effective berth and spatiotemporal trajectory theory. Effective berth at each delay level under a certain level of delay is determined via VISSIM simulation, and a case study is conducted to verify the accuracy of the capacity calculation approach proposed in this study. The proposed approach is suitable for various numbers of lanes and lane function layout types and provides a new method for calculating the capacity of drop-off exclusive roadways.

2 Lane Function Layout Types of Drop-Off Exclusive Roadway

Drop-off exclusive roadways are composed of single or multi-lane groups. Each lane group includes one parking lane and one through lane at least. Drop-off vehicles make a short stop and drop off on the parking lane, and complete the process of entering and leaving the drop-off area on the through lane. Figure 1 is a schematic diagram of a double-width drop-off exclusive roadway.

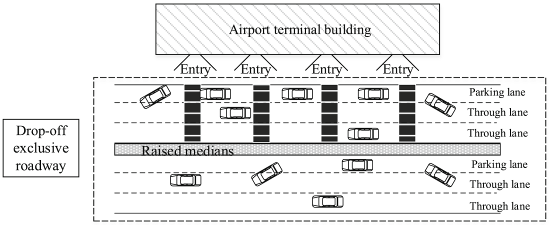
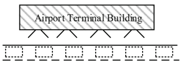
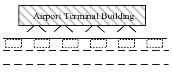
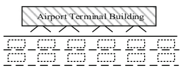
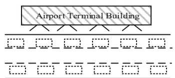
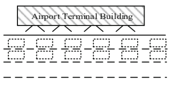
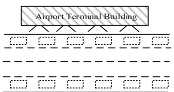
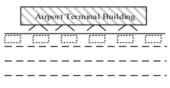
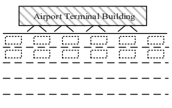
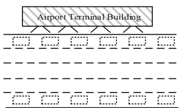


Fig. 1. The layout of the curbside area alone the drop-off exclusive roadway.

The drop-off exclusive roadway can be divided into double-lane, triple-lane, four-lane, and five-lane according to the number of lanes. Two and three-lane groups are used primarily at small or medium airports, and four and five-lane groups are used at large airports. The layout types of drop-off exclusive roadways are also diverse, which are summarized into 9 types, as shown in Table 1.

Table 1. Lane function layout types of drop-off exclusive roadway.

Number of lanes	Layout type		
Double-lane	 1P1T		
Triple-lane	 1P2T	 2P1T	 2P1T*
Four-lane	 2P2T	 2P2T*	 1P3T
Five-lane	 2P3T	 2P3T*	

Note: P stands for the parking lane; T represents the through lane; * represents the middle lane.

3 Calculation Approach of the Capacity of Multi-lane Drop-Off Exclusive Roadway Based on Effective Berths

3.1 The Theoretical Model Based on Time-Space Trajectory Theory

Parizi and Braaksma [5] have proposed a method for calculating the capacity of drop-off exclusive roadway based on time-space trajectory theory, which mainly considers the following assumptions:

1) Only for two-lane drop-off exclusive roadways.
2) Ignore drop-off vehicles' acceleration and deceleration behaviors.
3) Assuming that the driver has no preference when choosing a parking space.

As shown in Fig. 2, this method divides drop-off exclusive roadway into n linearly arranged parking spaces, and the capacity of drop-off exclusive roadway is the sum of the number of vehicles parked and departed on n parking spaces within a unit time.

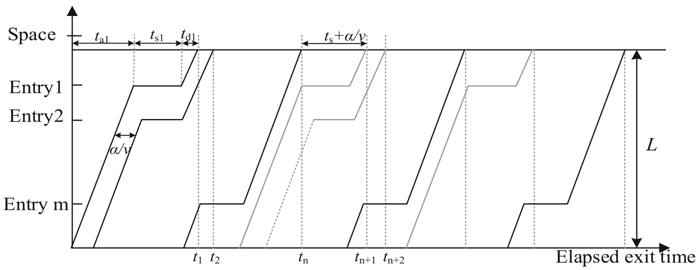


Fig. 2. Time-space diagram of vehicles in case with n entries [5].

Zhang [6] distinguishes the speed of the through lane and the parking lane and takes into account that the vehicle will travel a certain distance on the parking lane and get a modified method, which is constructed as:

$$C = \frac{n(T - \frac{L - L_R}{v_L} - \frac{L_R}{v_R})}{t_s + n\frac{\alpha}{v_R}} \tag{1}$$

$$L_R = \frac{1.007L_E - 2.959}{2} \tag{2}$$

The capacity of the drop-off exclusive roadway is represented by C, where L is the length of the drop-off exclusive roadway; L_R is the driving distance of the vehicle in the parking lane; L_E is the farthest distance between parked vehicles and the entry; v_L represents the speed of the vehicle in the through lane; v_R represents the speed of the vehicle in parking lane; n is the number of parking spaces; T is time, usually, 3600 s; α denotes the average safe distance of vehicles driving in drop-off exclusive roadway; t_s is the time of vehicles parking in the parking lane.

The C obtained by Eq. (1) is the capacity of a two-lane drop-off exclusive roadway (1P1T) in ideal conditions. This calculation method lays the foundation for the calculation approach of the multi-lane drop-off exclusive roadway proposed in this study.

3.2 Concept of Effective Berths

Federal Transit Administration (FTA) [16] first introduced the concept of effective berth and use it to explore the difference between multiple on-line and off-line bus stops. Since then, effective berths have been used to study the transfer capacity of bus stops and the optimal design of bus stops [17]. This study introduces effective berths into the calculation of the capacity of the drop-off exclusive roadway at the airport terminal. The main reasons are as follows:

1) The lane function layout types of drop-off exclusive roadway are diverse, and the number of parking lanes and through lanes are different. The capacity of multiple lanes is not equivalent to the simple accumulation of the capacity of a single lane.
2) Because of the driver's preference, the further the parking lane is, the fewer vehicles are parked and the greater the gaps between parked vehicles are.
3) Vehicles that expect to park on the inner parking lane often need to cross the outer parking lane from the through lane to park, which often occupies the outer parking lane's time and space resources available for parking.
4) When a vehicle parking inner prepares to leave, the distance and enough time for the vehicle to pass need to be considered. Sometimes it is necessary to wait for the outer vehicle to leave before looking for a gap to drive away.

Therefore, the effective berth factor of drop-off exclusive roadway is defined as: under a certain delay level, the ratio of the number of vehicles served by the multi-lane drop-off exclusive roadway and the number of vehicles served by the standard drop-off exclusive roadway (1P1T) within a unit time, which can be seen in Eq. (3):

$$N_{ei} = Q_i / Q_1 \tag{3}$$

The effective berth factor of the drop-off exclusive roadway is represented by N_{ei}, where Q_1 is the number of vehicles served by the standard drop-off exclusive roadway with 1 parking lane and 1 through lane within a unit time; Q_i is the number of vehicles served by the multi-lane drop-off exclusive roadway within a unit time.

3.3 Calculation Approach of the Capacity of Drop-Off Exclusive Roadway

The formula for calculating the capacity based on effective berth is:

$$C_i = N_{ei} \frac{n\left(T - \frac{L - L_R}{v_L} - \frac{L_R}{v_R}\right)}{t_s + \frac{n\alpha}{v_R}} \tag{4}$$

For multi-carriageway drop-off exclusive roadway, the capacity is the sum of the capacity of the lane groups.

4 Determination of the Effective Berth Factors Based on Simulation

This section simulates 9 lane function layout types of the drop-off exclusive roadway via VISSIM. To analyze each type, the vehicle input of each type and the corresponding delay in the simulation are recorded, and then draw scatter diagrams of the simulation output data. Use Eq. (3) to calculate efficient berth factors for different types of lane arrangements on exclusive drop-off roadway under a certain level of delay.

4.1 Basic Assumptions and Parameter Settings

When calculating effective berth factors, in addition to limiting a certain level of delay, it is also necessary to ensure that the traffic of drop-off exclusive roadways is comparable. This simulation ensures that the main boundary conditions of all drop-off exclusive roadways are the same, that is, vehicles have the same operating characteristics. The VISSIM simulation is based on the following assumptions:

1) Vehicles on exclusive roadways are all cars of the same size and parameters.
2) The drop-off vehicle's arrival obeys the same negative exponential distribution.
3) The parking time of vehicles on obeys the same distribution.
4) The length and width of each lane are identical.
5) Ignore the pedestrian and vehicle interference caused by the pedestrian crossing.

The simulation parameters used in the simulation are listed in Table 2:

Table 2. Parameters used in the simulation.

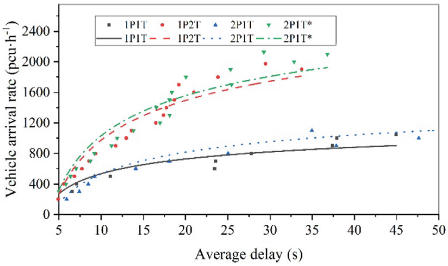
Simulation parameter	Value
Expected speed of vehicles on through lanes	30 km/h
Expected speed of vehicles on parking lanes	5.5 km/h
Parking time distribution	Empirical distribution (6~225 s)
Vehicle type	100% cars
Length of drop-off exclusive roadway	270 m
Lane width	3.5 m
The standard number of parking spaces of a parking lane	40
Length of per parking spaces	6 m
Priority rules	Vehicles on the through lane first

4.2 Simulation Results Analysis

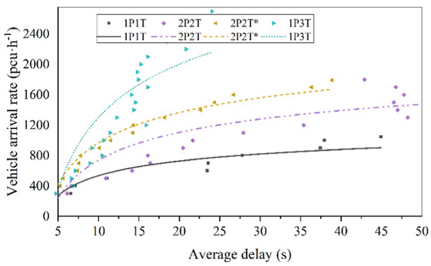
The simulation software VISSIM is used to establish the operation simulation systems to analyze the drop-off exclusive roadways. Delay measurements are set in 9 sub-models, and the attributes of results are output. Delay is equal to the actual travel time on the drop-off exclusive roadway minus the theoretical (ideal) travel time.

Set the initial value of the traffic flow on the drop-off exclusive roadway to start the simulation, and record the vehicle inputs and delays for each simulation. In the first stage, the vehicle input is added by 100 pcu/h in turn, and the average delay of the vehicle is recorded after each simulation. After that, add the vehicle input until the simulation gives a capacity limit warning that "the vehicle cannot be input completely". On the basis of the input of vehicles before the warning appears, add the vehicle input 10 pcu/h in turn, until the capacity limit warning appears again. Then, the vehicle input is added by 1 pcu/h in turn until the warning appears again, which means the traffic volume of the drop-off exclusive roadway in the simulation system has reached its peak and the drop-off exclusive roadway has reached its capacity.

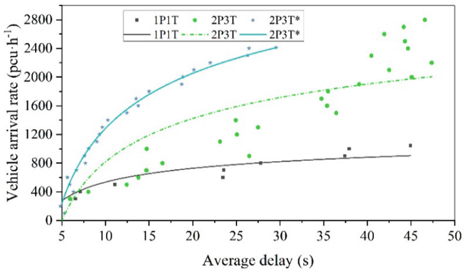
From the simulation results, we found that the capacity of drop-off exclusive roadway was not directly proportional to the number of parking lanes, but was related to the number of through lanes and the layout of lane functions. Select the two-lane drop-off exclusive roadway (1P1T) as the base type, analyze the simulation results of the three-lane, four-lane, and five-lane drop-off exclusive roadway respectively. Take the average delay as the x-axis, and the vehicle arrival rate (vehicle input) as the y-axis, then draw the data scatter diagram of each lane group, as shown in Fig. 3.



(a) three-lane drop-off exclusive roadway



(b) four-lane drop-off exclusive roadway



(c) five-lane drop-off exclusive roadway

Fig. 3. Comparative analysis of simulation results of each lane group.

Drop-off exclusive roadways have an upper limit of their capacity. According to the model of vehicle arrival rate and delay given by Zhang et al. [18], combined with the changing trend of the curve in Fig. 3, it can be concluded that when the vehicle arrival rate reaches the upper limit of the load-bearing capacity of the drop-off exclusive roadway, the average delay is about 25 s. The arrival rate-delay curves intersect at some points on the delay interval (5, 10), and use the new methodology proposed by Wang et al. [19]

to calibrate. Use Eq. (3) to calculate the effective berth factors for various lane groups when the average delay is 25 s, as shown in Table 3.

Table 3. Effective berth factors of each type.

IDX	Qty of lane	Lane function layout	Qty of P	Qty of T	Effective berth factor
1	Double-lane	1P1T	1	1	1.00
2	Triple-lane	1P2T	1	2	2.08
3		2P1T	2	1	1.14
4		2P1T*	2	1	2.17
5	Four-lane	2P2T	1	3	1.53
6		2P2T*	2	2	1.88
7		1P3T	2	2	2.76
8	Five-lane	2P3T	2	3	2.01
9		2P3T*	2	3	2.88

5 Case Analysis

To verify the accuracy of the calculation approach of the capacity of multi-lane drop-off exclusive roadway, this study takes Jinan Yaoqiang International Airport-China as a case to analyze the capacity of drop-off exclusive roadway.

The drop-off exclusive roadway at Jinan Yaoqiang Airport adopts the type of lane function layout of 1 parking lane and 2 through lanes arranged in sequence (1P2T), the effective berth factor found in Table 4 is 2.08. Use Eq. (4) to calculate the capacity of the drop-off exclusive roadway at Jinan Yaoqiang Airport. The values of specific parameters are shown in Table 4, which are determined based on survey results.

Table 4. Values of parameters in calculating drop-off exclusive roadway capacity.

Parameter	L/m	N_{ei}	n	t_s/s	L_R/m	v_L /km·h^{-1}	v_R /km·h^{-1}	α/m
Value	270	2.08	37	61.2	30	30	10	6

Substitute the above parameters into Eq. (4), the capacity of the inner drop-off exclusive roadway is 1942 pcu/h. According to the actual survey results, due to the driver's preference, the ratio of traffic volume between the inner and outer roadways is about 2:1, so the capacity of the drop-off exclusive roadway is as follows:

$$C = C_{inner} + C_{outer} = (1 + 0.5)C_{inner} = 1.5 \times 1942 = 2913\,\text{pcu/h} \tag{5}$$

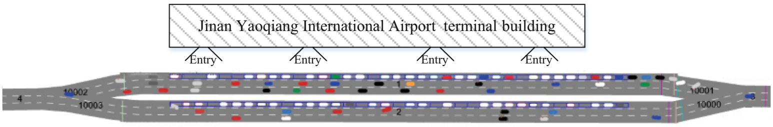


Fig. 4. VISSIM simulation model of Jinan Yaoqiang Airport drop-off exclusive roadway.

Then simulates this drop-off exclusive roadway via VISSIM, as shown in Fig. 4. When the capacity limit warning appears, the maximum input is 3049 pcu/h. Compared with the calculated capacity (2913 pcu/h), the relative error is 4.3%. The results verify the accuracy of the effective berth-based calculation approach of the capacity of the drop-off exclusive roadway at the airport terminal.

6 Conclusions

In this study, the capacity of drop-off exclusive roadway at airport terminal is studied, and an approach for calculating the capacity for multiple lane numbers and different lane function layout types is proposed. The lane function layout types of drop-off exclusive roadway are sorted out, the concept of effective berth is introduced, and the capacity calculation approach of multi-lane drop-off exclusive roadway based on effective berth is proposed. VISSIM simulation is used to determine the effective berth factors under different delay levels, and a case study at the terminal of Jinan Yaoqiang Airport is carried out. The results show that the accuracy of the calculation approach for the capacity based on effective berth is as high as 96%. Compared to traditional methods, the proposed approach for calculating capacity is more consistent with the parking characteristics of vehicles on drop-off exclusive roadways.

However, the drop-off area in front of the airport terminal is very complex. The proposed methodology ignores the influence of pedestrian and vehicle interference and the arrival distribution, which may affect the accuracy of the capacity calculation. Therefore, the mutual interference, conflicts between pedestrians and vehicles [20–22], and the arrival distribution [23] should be considered in future studies. Furthermore, drop-off exclusive roadway performance under mixed connected and regular vehicle environments is also a meaningful direction to explore [24].

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