Method for setting dedicated directional lanes on port collection and distribution highways based on OD data

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Abstract

Port collection and distribution highways are vital links connecting seaports to their inland hinterlands. However, growth in port throughput has caused a decline in the operational efficiency of port collection and distribution highways. This study proposes a method for setting up dedicated directional lanes on port collection and distribution highways based on origin-destination (OD) flow information. First, traffic simulation technology is utilized to develop a delay model for dedicated directional lanes. Then, a methodology for configuring dedicated directional lanes is introduced. Extensive testing of the proposed model was conducted using collection and distribution highways in the Port of Tianjin as a simulation scenario. The results show that the model leads to a significant improvement in operational efficiency along critical OD directions, reducing overall operational delays by more than 18.19%. This study provides insight and guidance for planning port collection and distribution highways.

Keywords: Directional Dedicated Lanes, Interweaving Zone, Weaving Section Lane Change Delay , Traffic Simulation.

1. Introduction

Since China's reform and opening up, its foreign trade has grown rapidly, leading to a rapid increase in the throughput of its coastal ports. Among the top 10 ports in the world,, China claims eight spots and maintains the largest port development scale globally. The rapid pace of port throughput development has resulted in a relatively low level of highway service quality, which serves as the primary transportation mode for port collection and distribution operations, often characterized by frequent traffic congestion. The proactive adoption of active traffic management measures, such as lane function control – specifically, the recent trend of setting up dedicated directional lanes – presents itself as a highly effective means of enhancing the traffic capacity of highways serving

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port collection and distribution operations, featuring low investment requirements and swift outcomes.

Currently, because of the limited implementation of directional lanes in a few pilot cities, research on the conditions for establishing such lanes is scarce. In the investigation of traffic conditions in directional lanes, the core objective is to minimize road delays. Directional lanes reduce weaving delays by restricting lane changes, except at designated points. However, the presence of slow-moving vehicles in these lanes can create moving bottlenecks, which in turn lead to increased following or trailing delays. Thus, balancing the reduction in weaving delays by managing potential mobile bottlenecks is crucial for effective application of directional lanes.

With the increasing traffic demand on highways, congestion, especially in merging areas, is becoming more frequent during peak hours. This instability can lead to bottlenecks and frequent congestions. Kita (1999) constructed a binary logit model to address acceptable gap analyses and solutions. Lertworawanich et al. (2003) proposed a new highway capacity model. Jiang (2003) introduced a model to calculate traffic delays and optimize vehicle operating costs in freeway merging zones using a Boltzmann simulated annealing neural network.

The merging zone capacity is often influenced by lane-changing behavior. Li et al. (2021) implemented an active refined lane-management method to reduce traffic delays. Gong et al. (2016) developed an optimization model to determine the optimal mandatory lane-changing locations for mitigating traffic flow impacts near exit ramps. Hayat et al. (2016) analyzed driver response times to lane-changing guidance messages and proposed measures to alleviate congestion.

Currently, the research on dedicated lanes mainly focuses on bus, truck, tidal, customs, and dedicated lanes; however, research on directional lanes and freight collection and evacuation corridors are lacking. This leads to insufficient theoretical basis and a perfect setup system, and there are several problems that need to be solved. In this study, directional lanes were implemented on a port collector-reliever highway with the aim of reducing lane-changing delays in the merging area and enhance the overall highway capacity.

Based on the shortcomings of existing research, the following issues need to be discussed:

(1) Construction of a model of the vehicle lane-changing delay in the intertwined area of a port collection and distribution highway, reflecting the current traffic operation status.

(2) Setting up of an optimization model for directional lanes in a port collection and distribution highway, as existing research lacks a model for directional lanes.

(3) Building a simulation model for directional lanes on port collection and distribution highways. Limited practical data in China poses challenges; however, simulations offer efficient solutions. Replicating real traffic conditions provides crucial data for directional lane analysis, thereby overcoming manpower and cost constraints.

The main contributions of this study are as follows.

(1) Research on basic conditions of directional lane settings. Based on the results of the road survey, possible forms of directional lane road section composition were obtained, and the road setting conditions of directional lanes in the ideal state were determined, including the road composition type of the directional lane section, number of lanes in the road section, relative positions of the start and end points and weaving zone, and traffic saturation degree of the road section.

(2) Interweaving modeling. An interweaving zone simulation model was established. Multiple linear regression was used to derive a delay calculation formula for the interweaving zone considering the number of lanes, interweaving distance, convergence ratio, and interweaving ratio as parameters. Significance testing verified the effectiveness of the formula for calculating channelized vehicle delays.

(3) Research on an optimized setting method for directional lanes. Using origin-destination (OD) data and basic setting conditions, we used the average delay of highway vehicles as an index. We calculated the average delay of the road section vehicles according to the interweaving zone delay model. The proportion of the road section vehicle delay reduction was used as the basis for this judgment. After setting the directional lanes, we obtained the proportion of the road section delay reduction. By combining this with genetic algorithm modeling, we determined the optimal directional lane-setting method. This process provides specific information, such as the length of the directional lanes, number of lanes, and location that can be used to solve the optimized setting method for directional lanes. The setup length, number of lanes, setup location, and other specific information are provided to form a complete setup program.

The remainder of this paper is organized as follows (as shown in Figure 1). The first part addresses the traffic characteristics of directional lanes, encompassing the setup mode, impact on traffic, and analysis of the start and end points of directional lanes. The second section focuses on constructing an interweaving area vehicle lane-changing delay model using the VISSIM simulation program. The variables were adjusted to obtain the model. In the third section, we describe the construction of the directional lane optimization model. This is achieved by converting OD traffic into interweaving zone traffic and utilizing the resultant interweaving zone delay to formulate an optimal directional lane setup scheme. The fourth section presents a case study using the Tianjin port collection and distribution corridor for the experimental investigation. Finally, conclusions and recommendations for future research are presented in the last section.

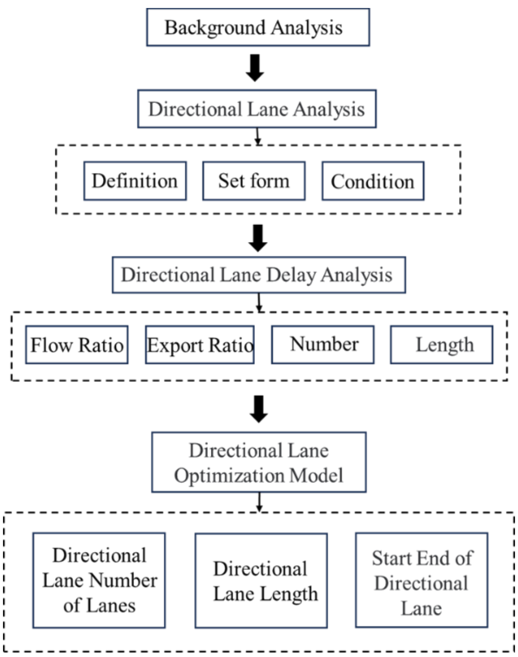


Figure 1: Flowchart of the Proposed Method

2. Literature Reviews

A dedicated lane provides a dedicated right of way for specific types of vehicles, such as buses, special vehicles, and vehicles with specific functions, and reduces the interweaving delay caused by lane changes by reducing the frequency of lane changes for vehicles. A directional lane is a type of dedicated lane provided for a specific flow direction or specific starting and ending points of vehicles. In the literature review section of this paper, first, the implementation of existing dedicated lanes is summarized, and then the literature on road delay and vehicle lane-change behavior is reviewed.

2.1 Study on dedicated lane setting

In the study of urban roads, the focus on the implementation of dedicated lanes is primarily public transport. Lim et al. (2012) evaluated road safety before and after the implementation of bus lanes, summarized the suitability conditions of central bus lanes, and proposed an optimization plan. Aakre and Aakre (2017) replaced intersections with appropriately sized roundabouts with bus-only lanes in the center of the road. This reduced the number of points of conflict between the bus and other vehicles to two, giving the bus higher priority. The experimental data showed that buses had the fewest delays, and delays for other vehicles were also reduced. Guler et al. (2012) proposed allowing ordinary vehicles to enter bus lanes at the bottleneck sections of the city and reducing congestion through a shared lane strategy.

In highway studies, the focus on the implementation of dedicated lanes is mainly on allowing vehicles with different functional types to operate separately. Roorda et al. (2010) conducted OD surveys on passenger and freight vehicles, analyzed the travel time before and after the establishment of dedicated lanes, and considered the travel time as a key indicator to assess the demand for dedicated lanes. Based on the policy of restricting trucks in the right lane of Louisiana, Korkut et al. (2010) adopted a multiple linear regression method to obtain the relationship between the collision and compliance rates, showing that restricting trucks in the right lane is conducive to traffic safety. Kobelo et al. (2008) studied the relationship between passenger-cargo separation management mode and vehicle collision by modeling traffic accidents in Florida, and the results showed that the passenger-cargo separation section had fewer collisions than the section with no restriction on truck lanes. Das et al. (2020) selected 16 locations in the Dallas-Fort Worth area to collect vehicle collision data and analyzed the data using a Bayesian empirical method. Machiani et al. (2021) explored the implications of adding an autonomous vehicle (AV) -exclusive lane to expressways, with the experimental results indicating that an AV-exclusive lane could potentially increase traffic flow and density by up to 14% and 24%, respectively. Wang et al. (2024) proposed an AV-exclusive lane design problem for road networks to reduce the total comprehensive cost by optimizing exclusive lane designs. The experimental results demonstrated that the implementation of AV-exclusive lane design schemes significantly improved the overall network performance, particularly in terms of total system travel time. Kim et al. (2023) advocated the establishment of zero-emission vehicle-exclusive lanes on expressways. Through a detailed benefit-cost analysis, they demonstrated that these lanes are not only environmentally beneficial but also economically viable, effectively promoting the development and adoption of zero-emission vehicles. The results show that setting up dedicated lanes for separate trucks can improve driving safety and implementing the management mode of separating passengers and cargo can bring higher cost benefits to urban roads.

2.2 Impact study on vehicle lane change

Many researchers have used different methods to study the highway capacity and lane-change behavior. In the context of highway capacity research, it has been proven that highway capacity is not a fixed value and changes with changes in traffic conditions (Brilon et al., 2007). Lorenz et al. (2001) proposed an improved capacity model that considers the probability of highway congestion under various conditions. The highway capacity was defined as a function of the probability of congestion caused by on-ramp vehicles. The model also incorporated the congestion process of the combined region and was validated using probabilistic methods.

In non-dedicated lane scenarios, delays caused by vehicle lane changes are important factors in reducing highway capacity. Lane change delays are caused by interference from other vehicles, driver skills, traffic signal control, and other factors that increase travel time. The modeling of vehicle lane-change behavior has been studied extensively. For example, Gipps (1986) proposed the classic GiPPS lane-change model and analyzed drivers' decision-making processes. Ruder (2002) introduced the highway lane-change assistant monito, which is a driver-assisted lane-change system. Existing research has also been refined by introducing parameters that affect vehicle lane changes. Moridpour et al. (2010) performed a statistical analysis of the lane-change behavior of highway vehicles, including traffic delays caused by accidents or congestion.

After the design of the dedicated lane, because the vehicle must follow a dedicated lane, the lane-change behavior and driving delays of vehicles is significantly reduced. In the design of a dedicated lane, the most important step is to calculate the vehicle delay before and after the dedicated lane is set, and minimizing the vehicle delay is the goal of the scheme design. However, owing to the many factors in the operation process, it is difficult to construct a delay model using only a theoretical scheme. Moreover, the wide variety of road vehicles available for collection and distribution makes it difficult to construct a delay model. Several simulation methods have been used to model road capacities and delays.

Tanaka et al. (2017) created a vehicle control algorithm for the interweaving zone of urban expressways and built a microtraffic simulation model to calculate vehicle delays and conflict points in the interweaving zone. Cho et al. (2017) used VISSIM to analyze the average delays of vehicles inside a roundabout for small intersections and proposed efficient planning and design criteria. Yun et al. (2013) designed intersections using VISSIM software and verified the traffic flow performance. Subsequently, the average delay of vehicles under different traffic volumes was analyzed, and the critical traffic volume for setting the stop sign or yield sign was proposed, with minimum delay as the optimal goal.

Researchers have studied methods for establishing dedicated lanes. However, current dedicated lanes are mostly set in the scenario of passenger and cargo separation of urban traffic buses and expressways, and the scene setting for freight collection and distribution channels has not been reported. At the same time, most current dedicated lanes are set up to provide a special right of way for specific vehicles, and there is a lack of dedicated lanes for vehicles with specific starting and ending points (OD). At the same time, scholars have conducted extensive research on lane change behavior and models related to highway capacity change, but there is a lack of research on the construction of models for vehicle lane change delay using simulation methods. In addition, unlike ordinary roads, the flow characteristics of the collection and distribution channels are more obvious; most vehicles start from different starting points, and most vehicles converge at the port. In this case, the collection and distribution channels must be designed as directional special channels to reduce vehicle delays.

Therefore, a simulation-based delay modeling method for directional lane design is proposed in this study. In this method, simulation software was used to model the vehicle delay in the interweaving area under complex conditions to obtain the directional-dedicated lane-setting method under the condition of minimum delay. In addition, according to the characteristics of vehicle flow details in the collection and distribution channels, a directional lane-setting method suitable for this scenario was established, which reduced the lane-change delay between vehicles and improved the traffic capacity of the channel.

3. Methods

3.1 Framework of the proposed method

This study focuses on the setup of directional dedicated lanes for the collector-scheduler freight corridor, and the flow of the method is shown in Figure 1. The method comprises three parts: analysis of the directional lanes, acquisition of the vehicle-switching delay model in the interweaving area, and setup of the optimization model for the directional lanes.

3.2 Directional Lane Analysis

3.2.1 Purpose of Directional Lanes

A directional lane refers to a dedicated lane designated for vehicles traveling in specific locations or directions as predetermined by the road layout. Vehicles heading toward other destinations or directions are not permitted to enter the lane.

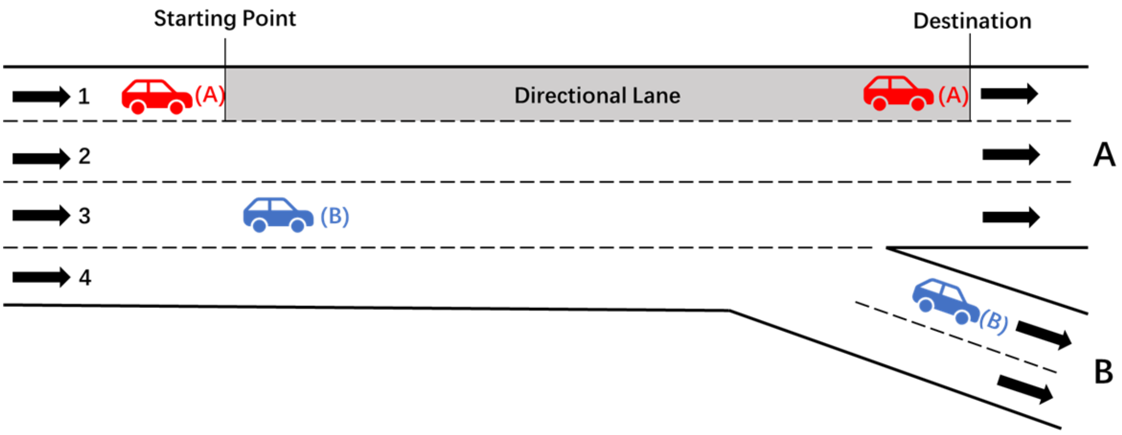


Figure 2: Schematic of directional lane

As shown in Figure 2, the road entrance has four lanes and the exit has two directions: A and B. The directional lane was set in Lane 1, with its endpoint located at exit A, downstream of the A and B exit split points. In this case, the prescribed direction for the lane is direction A, meaning that only vehicles heading in direction A can use this dedicated lane. Vehicles heading in direction B are not permitted to enter this lane. For example, the red vehicle in Figure 2.1 has its target direction A and can reach its destination by entering the directional lane. However, the blue vehicle, which is heading in direction B, can only use other lanes (Lanes 2, 3, or 4) to reach its destination, excluding the directional lane.

From the definition of a directional lane, it is clear that lane changes between the directional lane and adjacent lanes are prohibited in the section from the start to the endpoint of the directional lane. Specifically, vehicles in other lanes are not allowed to change to the directional lane and vehicles in the directional lane are not allowed to change out of it.

The installation of directional lanes is used to alleviate the problem of lane changing on major urban roadways (for example, bridges, tunnels, expressways, and intersections) and thus improve the efficiency of the roadway in the event of convergence or divergence of vehicles in a particular lane. Directional lanes can prevent vehicles from changing lanes at will. Interweaving driving and slower passenger and freight vehicles are prohibited from entering the directional lanes, and the speed of traffic is faster than that of mixed lanes.

3.2.2 Directional Lane Setting Mode

In existing research and practical applications, directional lanes are typically classified into inner and outer directional lanes based on their position on the road.

The inside lane is near the centerline of the road or the side of the central divider. In China and most countries with right-side traffic rules (such as the United States and Germany), the inside lane is generally used for vehicles going straight or passing fast, which are less affected by vehicles entering and leaving the main road, thus helping to maintain high speed and continuity. In addition, on multilane roads, the inside lane is often used as a passing lane, allowing high-speed vehicles to overtake slower vehicles ahead.

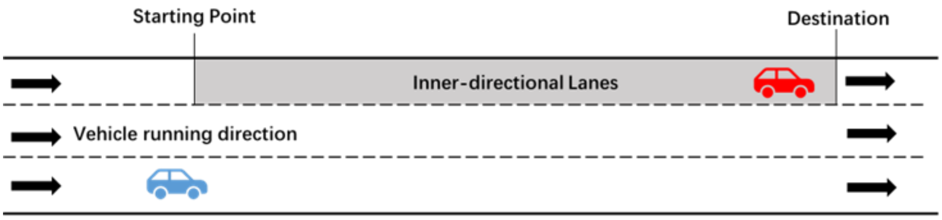


Figure 3: Inner-directional lanes

Characteristics of inner-directional lanes: These lanes are relatively independent, unaffected by the merging or divergence of the outermost lane, and experience less lateral interference between lanes.

The outer lane is located at the edge of the road, away from the centerline. This type of lane mainly serves vehicles that must enter or leave the main road, such as vehicles preparing to enter a ramp or turn. In the outside lane, vehicles may slow down, speed up, or change lanes frequently; therefore, they are often designed considering this dynamically changing demand. In countries that implement left-side traffic rules (such as the United Kingdom and Japan), the outside lane also bears a similar function, but its specific layout adapts to the habit of driving on the left.

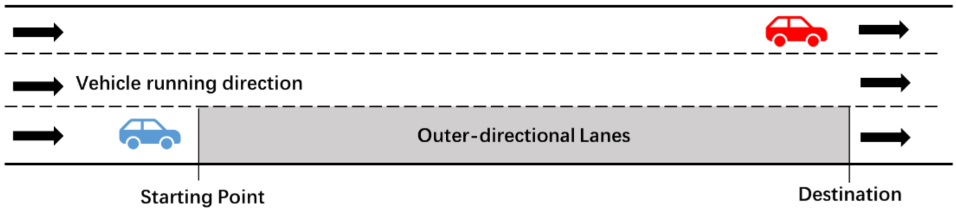


Figure 4: Outer-directional lanes

Characteristics of outer-directional lanes: They are relatively less independent and more susceptible to influences, such as buses stopping at stations, taxis stopping at the roadside, and pedestrians entering or exiting the roadside. The safety of the outer directional lanes was lower owing to these factors. In the context of collection and evacuation corridors, outer directional lanes are prone to intersecting ramp lanes, making them more easily affected by lane-changing behaviors.

This means that vehicles drive on the right side, with the inside lane on the left side of the road and the outside lane on the right side. Due to the fact that in inboard directional lanes, the delay generated by vehicle lane changing in the interweaving area is smaller, which is more in line with the operational characteristics of the collector and distributor freight corridors. The inboard directional lanes are selected as the setup method of directional lanes in this study.

3.2.3 Impact of Directional Lanes on Traffic

Based on the definition of directional lanes, it can be observed that the traffic flow within a directional lane operates independently of other lanes. First, the traffic within the directional lane is unaffected by lane changes, weaving, or other behaviors from adjacent lanes, as shown in Figure 5, ensuring a more stable traffic flow within the lane and improving the overall efficiency. Second, because the traffic flow in the directional lane is influenced only by the longitudinal movement of vehicles within the same lane and not by lateral interference; the overall travel speed is higher, and the passage efficiency is greater, particularly during peak hours. Third, because lane changes are prohibited within directional lanes, the likelihood of traffic accidents is reduced, thereby enhancing vehicle safety.

However, since lane changes are not allowed, vehicles within the directional lane are primarily influenced by the vehicles in front or behind, and generally do not experience lateral interference. When traffic flows smoothly and the leading vehicle operates at a low speed or encounters a breakdown, the following vehicles in the directional lane are affected. Because lane changes are prohibited, these vehicles cannot pursue optimal travel conditions, which can negatively impact the travel satisfaction of road users.

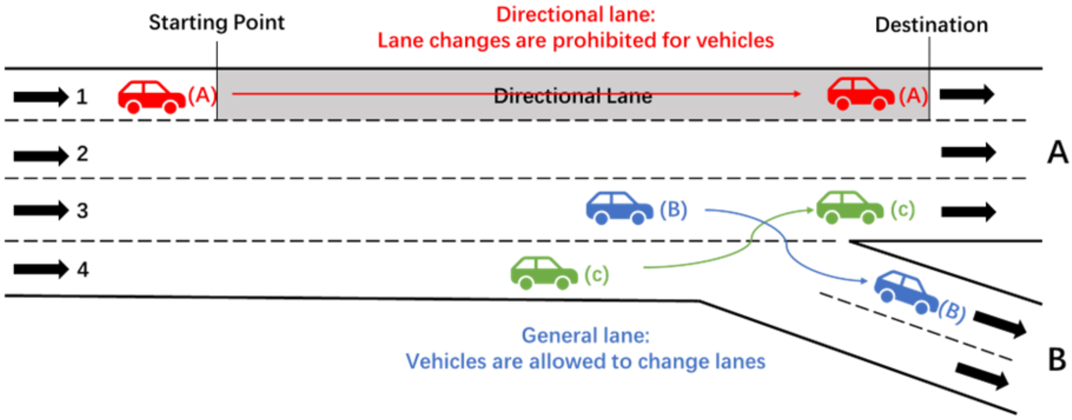


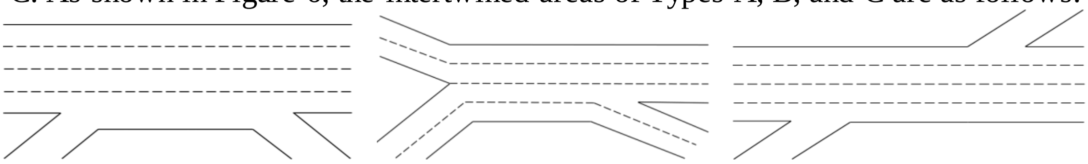
Figure 5: Impact of directional lanes on traffic

3.2.4 Basic conditions for the installation of directional lanes

Directional lanes should be set up to meet the following conditions:
(1) Road conditions: When setting up directional lanes, roads without intersections are avoided. The road should have no fewer than three unidirectional lanes with four or more preferred lanes. The starting point for the directional lanes should be set behind the interweaving area or in a section without interweaving. The ends of the directional lanes were placed at the ends of the weave area.
(2) In terms of traffic flow, setting the saturation degree of traffic flow to 0.8 of the road to set up directional lanes can enhance traffic efficiency.
(3) In terms of traffic flow, the saturation degree of traffic flow reaches 0.8 of the road to set up directional lanes can improve its efficiency; after the saturation degree reaches 0.9, improving the effect. This shows that the road section capacity is increased after setting up the directional lanes compared to that before.

3.3 Interweaving zone delay formula acquisition

Vehicle lane-changing behavior within the interweaving zone can interfere with other vehicles, leading to increased operational delays. Before investigating the interweaving zone vehicle lane-changing delay model, it is crucial to correctly select and describe the significant factors affecting the interweaving operations. These factors include the length and width of the interweaving zone, type of construction, total number of travel lanes, interweaving ratio, proportion of vehicle types within the zone, amount of traffic within the interweaving zone, and total traffic volume. Observations at the survey site revealed that the key factors influencing interweaving delays were the interweaving flow ratio, convergence ratio, length of the interweaving zone, and number of lanes.
Interweaving zones can be categorized into the following three types: Types A, B, and C. As shown in Figure 6, the intertwined areas of Types A, B, and C are as follows:



(a) type A (b) type B (c) type C
Figure 6: Type of intertwined area

In Type A weaving zones, all vehicles on the ramp weave, and most auxiliary lanes are occupied by weaving vehicles. The outer lanes of the freeway are shared by weaving and non-weaving vehicles. Type-B weaving zones are more flexible, with lanes adjacent to through-lanes occupied by weaving vehicles. Furthermore, adjacent lanes are utilized to some extent. In Type C interweaving zones, interweaving vehicles can still fully occupy the "through lane" and take up a large portion of the adjacent lanes. Existing collector/distributor interweaving zones are typically structured as Type A interweaving zones.

Owing to limited investigation locations and data availability, a simulation-based approach was used to obtain delay data for ramp interchanges under different scenarios. The VISSIM simulation software was utilized for this purpose.

Based on the characteristics of the collector and distributor freight corridors, a simulation model of the Type A interweaving zone was developed, and a delay formula was calculated. The parameters included the interweaving flow ratio, sink-out ratio, length of the interweaving zone, and number of lanes. A single-factor analysis of the influencing factors was conducted to determine their impact on the delay.

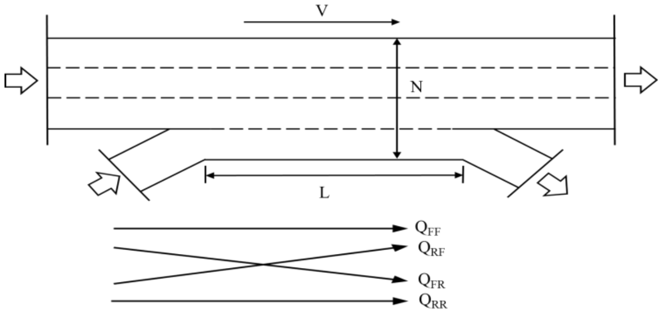


Figure 7: Simulation schematic

The vehicle delay in the interweaving zone was considered as the dependent variable, and the exit ramp traffic volume, ground road traffic volume, length of the interweaving zone, and frequency of mandatory lane changes were considered as the independent variables for the multiple linear regression analysis. The formulae for the interweaving flow ratio and convergence ratio are given in Equations 1 and 2, respectively.

$$R_{interleaving} = (Q_{FF} + Q_{RF} + Q_{FR})/(Q_{FF} + Q_{RF} + Q_{FR} + Q_{RR}) \quad (1)$$

$$R_{\text{exit}} = (Q_{RR} + Q_{FR})/(Q_{FF} + Q_{RF} + Q_{FR} + Q_{RR}) \quad (2)$$

Here, $R_{interleaving}$ is the interwoven flow rate and R_{exit} represents the exit ratio. The exit rate refers to the ratio of the flow of vehicles exiting the highway off-ramp to the total vehicle flow on the highway. Q_{FF} represents a straight-to-straight flow, Q_{FR} represents the straight-through-to-ramp flow, Q_{RF} represents the ramp-through-to-straight flow, and Q_{RR} represents the ramp-through-to-ramp flow.

The results of the analysis are presented in Table 1, which shows that the significance of each adjusted model parameter falls within the valid range. This indicates that the independent variables selected in this study effectively contributed to the dependent variable. Additionally, there was no multicollinearity among the independent variables.

Table 1: Experimental results on vehicle lane change delays

Variant	*Ratio*	*Significance*
Interweaving flow rate($R_{interleaving}$)	25.263	0.009
Exit ratio(R_{exit})	15.687	0.028
Length of interweaving zone(L)	-0.223	0.004
lane number(N)	1.475	0.001

The positive coefficients of the interweaving flow ratio, sink ratio, and number of lanes in the model indicate that the vehicle delay increases as these factors increase. Conversely, vehicle delay decreases with an increase in the length of the interweaving area. It can be found that interweaving flow ratio, sink ratio, and number of lanes are positively correlated with interweaving delay in the interweaving zone, and the length of interweaving zone is negatively correlated with interweaving delay in the interweaving zone. Among them, the interweaving flow ratio, sink ratio, and number of lanes had the most significant effects on the model. Therefore, the delay in each interweaving zone can be expressed by Equation 3:

$$d = q(25.263R_{interleaving} + 15.687R_{exit} - 0.223L + 1.475N) \quad (3)$$

Here, d represents the vehicle lane change delays in interweaving zone.

3.4 Acquisition of interweaving data

The OD data from the OD database were converted into interweaving data for the interweaving area between each OD, and the interweaving amount and interweaving ratio of each interweaving area were calculated. Considering one direction as an example, the number of ODs between the destination and endpoint is acquired and denoted as V_{ij}.

In the construction of the schematic of the highway, there are a total of n-2 interweaving zones for the n start and end points of the highway, as shown in Figure 8.

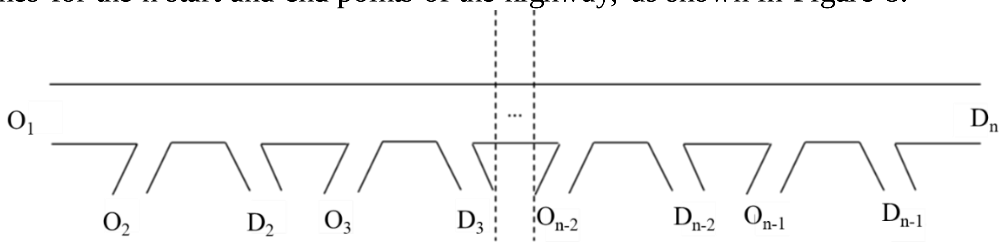


Figure 8: Schematic of the port collection and distribution highway

In conjunction with the OD data, the OD flow data in the initial database were expanded and corrected using Equation 4:

$$Q_{ijk} = V_{ijk} \cdot \alpha_k \cdot S_k \cdot W_k \cdot M_k \quad (4)$$

where Q_{ijk} denotes the number of trips of the k-th model from zone i to zone j, V_{ijk} denotes the sample size of the OD survey of the k-th model from zone i to zone j, α_k denotes the day/night ratio of the kth model, S_k denotes the inverse of the sampling rate, W_k denotes the weekly coefficient of inhomogeneity, and M_k denotes the monthly coefficient of inhomogeneity.

The formula for the weekly unaveraged coefficient W_k is shown in Equation 5:

$$W_k = \frac{\bar{N}}{N} \quad (5)$$

The weekly coefficient of variation measures the fluctuation between the daily traffic volume at a survey point and the weekly average. This metric helps to identify abnormal traffic flows, optimize traffic management, and improve traffic volume prediction models. Here, $\bar{N}$ denotes the weekly average daily traffic volume at the survey site and N denotes the observed daily traffic volume at the survey site.

The formula for calculating the monthly unaveraged coefficient M_k is shown in Equation 6:

$$M_k = \frac{\bar{N}_j}{\bar{N}_{mj}} \tag{6}$$

where $\bar{N}_j$ denotes the monthly average daily traffic volume at the survey site and $\bar{N}_{mj}$ denotes the observed monthly traffic volume at the survey site.

3.5 Establishment of directional lane optimization model for minimizing vehicle lane change delay in interweaving zone

Considering the interweaving zone vehicle transfer delay of the collector and evacuation highway as an index, when setting up directional lanes, it is necessary to compare the average vehicle transfer delay in the interweaving zone before and after setting up directional lanes. If the comparison shows that the average vehicle transfer delay in the interweaving zone of the collector and evacuation highway is less after setting up directional lanes than that before, it indicates that setting up directional lanes is feasible in this road section.

Therefore, the average vehicle change delay in the intertwined area of the collector and distributor corridors can be calculated using Equations 7 and 8:

$$delay_i = 25.263R_{interleaving} + 15.687R_{remittance} - 0.223L + 1.475N \tag{7}$$

$$Z_n = [\sum_{a=1}^{n}(delay_a \times q_a)] / \sum_{a=1}^{n} q_a \tag{8}$$

Here, Z_n represents the average delay of the original marshaling lanes without directional lanes.

Therefore, when directional lanes exist in some intertwining zones, the average vehicle lane-change delay in the intertwining zones of the collector and distributor corridors can be obtained from Equations 9 and 10:

$$delay_i' = 25.263R_{interleaving(directional\ lane)} + 15.687R_{remittance(directional\ lane)} - 0.223L + 1.475N_{(directional\ lane)} \tag{9}$$

$$Z_n' = [\sum_{a=1}^{n}(delay_i' \times q_a')] / \sum_{a=1}^{n} q_a \tag{10}$$

Here, $Z_n^{'}$ represents the average vehicle lane-changing delay in the intertwined zone of the collector and distributor corridors under the setting of directional lanes in certain road sections.

The formula for the overall vehicle delay reduction ratio is obtained as shown in Equation 11:

$$\varphi(Z_s) = \frac{Z_n - Z_n'}{Z_n'} \tag{11}$$

Using $\varphi(Z_s)$ as the optimization objective parameter, directional lanes are set for $\varphi(Z_s) > 0$.

Therefore, the directional lane design process is shown in Figure 9:

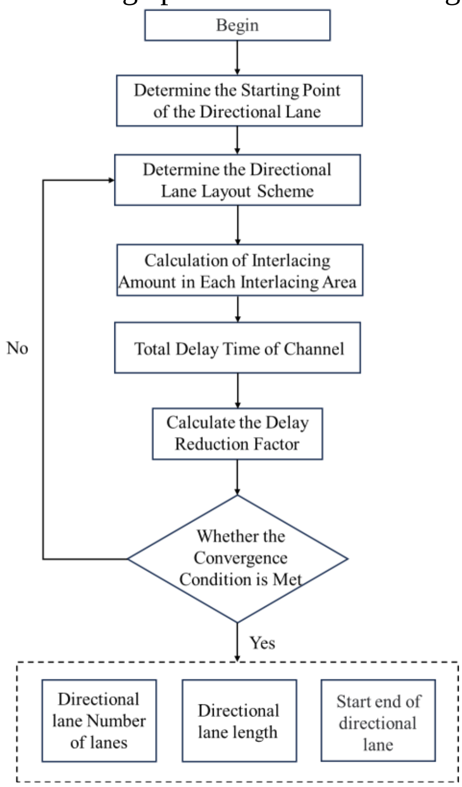


Figure 9: directional lane setup process

4. Case Study

4.1 Data description

Considering the Tianjin port collection and evacuation freight transportation highway project as an example, as shown in Figure 7, the collection and evacuation freight transportation highway has eight ramps, and the collection and evacuation freight transportation highway intersections of the peripheral roads, from east to west, are Tianjin Harbor, Beigang Road, Haibin Avenue, New North Road, Harbor City Boulerard, Qinbin Expressway, Changshen Expressway, and Beijing-Tianjin-Tanggu Expressway.

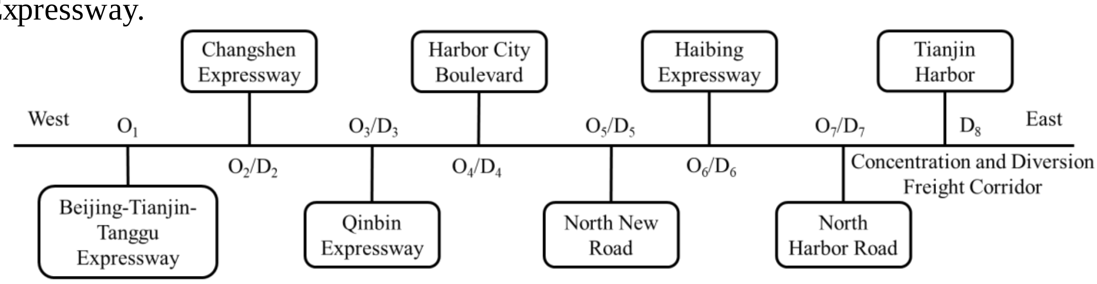


Figure 10: Tianjin Port collection and distribution highway

It was checked whether the Tianjin Port collection and transportation freight corridor meets the directional lane requirements. The corridor has 8-12 lane highways/expressways with a mainline speed of 80 km/h and >3 unidirectional lanes, each > 3.25m wide. Assuming a stable traffic flow at the exits and an actual capacity >

design capacity, we decided to implement directional lanes. We formulated OD database for containerized port collection and distribution highway networks using bottleneck sections, OD survey, toll data, traffic entry and exit data, categorization, and feature mining. The database includes 15 pairs of ODs from eight points. We used a neighbouring road network with the same OD traffic data as those of the benchmark, and the previous Tianjin Port direction as the upward direction to create the initial OD table (Table 2).

Tianjin Port, Qinbin Expressway - Seaside Avenue, Qinbin Expressway - Beigang Road, Qinbin Expressway, Tianjin Port, Gangcheng Avenue, Seaside Avenue, Gangcheng Avenue–Beigang Road, Gangcheng Avenue–Tianjin Port, Xinbei Road–Seaside Avenue, Xinbei Road–Beigang Road, and Xinbei Road–Tianjin Port, with a total of 15 pairs of OD.

TABLE 2:Initial od flow table

OD Flow	*Haibing Expressway*	*North harbor Road*	*Tianjin harbor*	*Total Flow*	*Total Flow in 12 Hour*
Beijing-Tianjin	534	825	3492	4851	58206
Changshen	386	597	2529	3513	42150
Qinbing	113	175	743	1031	12377
Harbor city	164	253	1073	1490	17876
New North	63	97	412	574	6882

4.2 Optimization calculations

(1) We calculated the traffic density for the section "Beijing-Tianjin-Tangshan Expressway-Tianjin Port." Considering the entire road section as an interweaving zone, average speed of all vehicles in the zone as the design speed of 80 km/h for Tianjin Port's collector and distributor freight corridor, number of lanes as eight in both directions, and correcting the daily traffic volume data using the time inhomogeneity coefficient, we obtained a traffic flow density of 30.52 pcu/km/lane.

(2) We converted the OD data of the "Beijing-Tianjin-Tangguang Expressway-Tianjin Port" road section into the interweaving data of each interweaving zone and obtained the interweaving ratio and sink ratio data of each interweaving zone without directional lanes. The map information was combined with the length of the interweaving zone with eight lanes in both directions (that is, one-way lanes were four lanes). Then, we calculated the average delay of vehicles in each interweaving area to obtain the average delay of vehicles in the whole section of the "Beijing-Tianjin-Tanggu Expressway-Tianjin Port," as 31.06s/pcu.

(3) A delay optimization model of port collection and distribution highways was constructed. First, we obtain the vehicle delay of the port collection and distribution highway without directional lanes and set the starting point of the directional lanes at the first road section where traffic control is needed, that is, at the entrance of the Beijing-Tianjin-Tanggu Expressway. In the experiment, a node was randomly selected as the end of the directional lanes, and one of the lanes from the Beijing-Tianjin-Tanggu Expressway to this road section was designated as a directional lane. The interweaving data and delay of each interweaving area were recalculated to obtain the average delay of vehicles on the entire collection and distribution highway.

According to the experimental results, under the 12th iteration, the average vehicle delay is 25.05s when the directional lane section is set at "Gangcheng Avenue - Beigang Road", and $\varphi(Zs)$ is 0.2399 and meets the maximum value. At this time, $\varphi(Zs)$ is 0.2399 and is the maximum value that satisfies the end condition of iteration. Thus, the directional OD lane is set as the section of "Gangcheng Avenue - Beigang Road".

4.3 Simulation Verification

To describe the effect of the directional lane setting more intuitively, traffic simulation modeling of the directional lanes was conducted using VISSIM. VISSIM is a microscopic multimodal traffic flow simulation software developed by the PTV Group. It was designed to model complex road networks and simulate traffic scenarios in a highly detailed and realistic manner.

VISSIM can simulate various aspects of traffic systems, including vehicle movement, public transportation, pedestrians, and cyclists. It offers powerful tools for traffic flow analysis, route optimization, traffic signal management, and emission calculations. Users can customize VISSIM models to suit specific traffic conditions or operational goals, and the software supports advanced visualization capabilities to present simulation results in an easy-to-understand format. In addition, VISSIM provides interfaces for integration with other software systems and remote control of simulations, making it a versatile tool for traffic planning, management, and research.

To verify the validity of the calibration model, traffic speed and other indicators were analyzed, ensuring a deviation within 5% between the simulation and measured values, thus validating the model. For the road section setup, no directional OD was initially set for the road section, and a simulation length of 600 s was used to obtain the average delay of the highway without directional lanes. The vehicle delay data obtained is 32.67s, within a 5% error from the vehicle delay data obtained using the interweaving zone delay model of 31.06 s, proving the model validity.

According to the modeling and solution in Section 2, the directional lane was set in the section of "Gangcheng Avenue–Beigang Road". In the simulation model, the innermost lane of the "Gangcheng Avenue - Beigang Road" section was set as the directional lane with a simulation length of 6000 s. The simulation generated various types of delay data for analysis. The highway delay data obtained from the simulation experiment were 26.73 s, with an error of 6.285% compared to the delay data obtained from the directional lane delay model. This slight error is attributed to delays generated in other road sections in addition to the weaving area. Nonetheless, the small error confirms the effectiveness of the directional lane delay model and demonstrates the feasibility of using VISSIM software for simulation validation.

Furthermore, Table 3 indicates a reduction in delay by 18.19% when setting "Gangcheng Avenue - Beigang Road" as a directional lane compared to no directional lanes, suggesting improved traffic operation in the collector and distributor corridor. Thus, the directional lane-setting method based on OD data proposed in this paper is effective in enhancing the traffic operation of port collection and distribution highways.

TABLE 3: Simulation results

Whether to install directional lanes	*Average delay(s)*	*Reduced ratio*
No	32.67	18.19%
Yes	26.73	

4.4 optimization results

In this section, the directional lane-setting method proposed in the previous section is verified and analyzed on specific roads. Through the directional lane optimization model, the average delay of highway vehicles was used as an indicator to optimize the reduction in vehicle delay. Various directional lane-setting schemes were determined and verified using a simulation software. It is concluded that setting the section "Hongkong City Avenue - Beigang Road" as a directional lane can maximize the reduction of vehicle delay. Additionally, the model shows that setting the section "Gangcheng Avenue - Beigang Road" as a directional lane can minimize the delay of vehicles, demonstrating the feasibility of the proposed model.

5. Conclusion and Future Work

5.1. Conclusion

This study addresses the challenges associated with lag in the construction of port collection and distribution highway systems. This highlights the inadequate infrastructure capacity of road transportation, which dominates port collection and distribution modes, making it difficult to cope with the rapid growth in port collection and distribution volumes. Furthermore, it identifies a gap between the development of large-scale container ports and outdated port collection and distribution highway networks, which hinder synergistic development. To address this, this study proposes enhancing the capacity of port collector and distributor freight corridors by implementing dedicated directional lane methods for functional lane control. A method based on OD data was introduced to establish directionally dedicated lanes by leveraging an optimization model for lane delays in port collector-reliever freight corridors. The main results of this study are as follows:

(1) Investigation of the fundamental conditions for setting directional lanes: This involves analyzing current road surveys to determine the potential forms of directional lane road sections in port collection and distribution highways. It identified the ideal setup conditions for directional lanes, including the composition type of road sections, number of lanes, relative positioning of the start and end points within the interweaving zone, and traffic saturation of the road sections.

(2) Modeling of interweaving zone delays: A simulation model for interweaving zones on port collection and distribution highways was developed. A multiple linear regression method was employed to derive a calculation formula for interweaving zone delays, considering parameters such as the number of lanes, interweaving distance, convergence ratio, and interweaving ratio. A significance verification confirmed the effectiveness of the formula for solving channelized vehicle delays.

(3) Investigation of optimized directional lane-setting methods: Utilizing OD data and adhering to basic setting conditions in port collection and distribution highways, the average delay of vehicles in road sections was calculated based on the interweaving delay model. It determines the proportion of reduction in road section vehicle delay as a criterion for judgment, and assesses the reduction in delay after implementing directional lanes. Combining these findings with genetic algorithm modeling facilitates the identification of optimal directional lane-setting methods.

5.2. Prospect

This study focused on researching the setup method for directional lanes in port collection and distribution highways, and some preliminary research results were obtained. However, because of limited personal abilities and objective conditions, there are issues to be addressed. Subsequent research can be considered from the following aspects:

(1) In this study, the basic conditions for directional lane setting included road structure, section composition, saturation, and other setting conditions. The analysis only considered unilateral and bilateral setups of directional lanes without exploring the possibility of setting up directional lanes for all lanes in a road section. Subsequent studies should consider establishing full-section directional lanes for special sections.

(2) When studying the delay calculation in the interweaving area, only some of the influencing factors were considered, and the influence of other factors on the delay was not considered. Future research should adopt a more comprehensive approach that considers a wider range of factors.

(3) This study adopted the single-parameter analysis method when analyzing the setting conditions, failing to analyze the setting parameters in a unified way. Subsequent research may consider introducing parameter weights when analyzing the parameters to ensure a more comprehensive analysis.

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