Study on the Setting Conditions of High Density and Small Spacing Compound Interchange in Stereo-Compound Expressway

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Abstract—Due to the limited land space and insufficient design space, the high-density and small-spacing compound interchange needs to adopt the collector-distributor lane without meeting the minimum design spacing. This paper combines the configuration of the interchange section, and the setting requirements of the lanes’ number are refined. Then, it is analyzed the characteristics of lane change behavior in the collector-distributor lane, and the length of interweave section in different design speeds and forms is calibrated. On the basis, the service level of the interweaving area under different traffic needs and different interweaving area lengths is obtained. Finally, VISSIM simulation software is used to verify the calculation results. The results show that when the steering traffic is large, it is not recommended to use the single-in-single-out A and single-in-single-out B design, and single-in-double-out B design should be selected according to actual needs.

1. INTRODUCTION

The stereo-compound expressway is a kind of compound freeway form. With the limitation of the space, it is necessary to make full use of the stereoscopic space when it is impossible to use the conventional plane to widen the expressway. Considering that the stereo-compound expressway is generally constructed in a highly urbanized area with high degree of development, full land use and large traffic demand, the traffic volume of the main line and ramp is generally large. And the interchange is an important hub and node of the stereo-compound expressway, which has the structural form of multi-layer space and the traffic transfer function. According to the requirements of ‘Design Specification for Highway Alignment’ (JTG d20-2017) [1], the collector-distributor lane can be used between small spacing interchange. However, the number of collector-distributor lanes, the amount of traffic volume that can withstand, and the distance of the connecting length that can adapt to… all problems need to be
solved, especially in the design of the stereo-compound expressway, these requirements need to be refined.

There is only a few studies on the setting up of collector-distributor lane model in foreign countries, and many of them are based on the experience to establish the corresponding model of linear relationship, which is not convenient to be directly applied to design. For example, the corresponding relationship between interweave length and weaving traffic volume is given in "design essentials of expressway" in Japan [2], and five situations of setting collector distributor lane are put forward. In addition, the United States has also studied the setting of collector-distributor lanes [3] in the HCM, but the research content only focuses on the interweave section and ramp merging area [4], and has no research results on the weaving area of collector-distributor. The research in China mainly focuses on the capacity [5], traffic flow characteristics [6] and traffic behavior [7-8], while the study on the setting of the collector-distributor and its weaving length of is relatively simple.

To sum up, foreign related studies generally consider two aspects: one is to study the operation characteristics of vehicles in weaving area, obtain a series of data and conduct regression analysis; the other is to collect the number of traffic accidents [9-10] occurring within the scope of interchange, so as to establish the accident rate prediction model. At the same time, the domestic and foreign research on the setting of the collector-distributor lane is not specific enough, which is inconvenient to use.

2. COLLECTOR-DISTRIBUTOR LANE SETTING

When the clear distance between the two interchanges is insufficient, and the form of auxiliary lane connection cannot meet the demand on traffic flow interweaving, the collector-distributor lane connection should be adopted. For the composite interchange connected by collector-distributor lane, the collector-distributor lane is connected with the main line, and the ramp is connected with the collector-distributor lane. The collector distributor between interchanges usually extends to the outside of the two interchanges. All the entrances and exits on one side of the main line are merged into the collector distributor. Only a pair of entrances and exits of the collector distributor lane are left on the main line. The layout of entrances and exits meets the setting principle of "merging ramp entrances and reducing the number of mainline openings", so as to reduce the impact on the direct traffic flow of the main line. The separation zone is set between the collector-distributor lane and the main line to further reduce the impact on the direct traffic flow of the main line. Compared with the auxiliary lane, the land occupation is slightly increased.

2.1 Configuration of Weaving Section in Collector-distributor Lane

According to the design requirements of the cross section of the collector distributor, there are hard isolation facilities between the collector-distributor lane and the main line, and the collector-distributor lane is connected with the ramp at the entrance and exit. The section from on ramp to off ramp forms the weaving section.

According to the design requirements of weaving section, in practice, the design of composite interchange collector distributor adopts two types, A and B. Therefore, it only analyzes the two suggestions in analyzing the number of lanes.

2.2 Number of Collector-distributor Lanes

The geometric configuration of composite interchange connected by collector distributor can be divided into four types: single in and single out, single in and double out, double in and single out, double in and double out. Among them, there are two kinds of double-in-double-out (single lane or two lane connecting Lane), and two kinds of single-in-single-out (single lane ramp connecting to the main line of collector-distributor lane or widening of collector-distributor lane), a total of five geometric configurations. These geometric configurations are shown in Figure3.
### TABLE 1. SUGGESTION TABLE OF LANE NUMBER SETTING OF COLLECTOR DISTRIBUTOR

| Layout type       | Single-in-single-out | Single-in-double-out | Double-in-single-out | Double-in-double-out |
|-------------------|----------------------|----------------------|----------------------|----------------------|
| Lane number       | A        | B        | B        | A        | B        |
|                   | 3        | 2        | 3        | 3        | 3        |

The collector-distributor lane is not the main line of the stereo-compound expressway’s ground layer or stereoscopic layer, which is belongs to the ramp part. If there are too many lanes in the collector-distributor lane, it will give the driver an illusion of driving on the main line, and the excessive number of lanes will provide overtaking space for drivers, which will increase the accident risk.

### 3. WEAVING SECTION LENGTH OF COLLECTOR-DISTRIBUTOR LANE

#### 3.1 Driving Behavior of Collector-distributor Lane

In terms of the traffic flow characteristics of the collector-distributor lane, the composite interchange connected with it is along the main driving direction, the exit of the collector-distributor lane is connected with the entrance, and the weaving section is located in the collector-distributor lane. In the weaving section, only the traffic flow from the on ramp to the collector distributor, and the traffic flow from the off ramp through the collector-distributor lane. These two traffic flows constitute the total traffic flow of the collector distributor, and both of them belong to the interwoven traffic flow. All traffic flow in the collector-distributor lane is involved in weaving, so the weaving efficiency is high.

There is a certain difference between the lane changing of the collector-distributor lane and the auxiliary lane. Under normal circumstances, vehicles entering on the on ramp will no longer exit from the off ramp, unless the vehicles are running incorrectly. In calculating the minimum spacing, only the length requirements under normal driving conditions are considered. Therefore, the vehicle lane changing demand of the collector-distributor lane includes: vehicles on the on ramp drive into the collector-distributor lane through one or two lane changes, and the vehicles on the collector-distributor lane drive into the off ramp through one or two lane changes. The vehicle lane change figure is as follows.

![Figure 1. Schematic figure of vehicle lane change on collector-distributor lane](image)

It can be found that the vehicles in double-in-single-out A type can enter or leave the expressway after two lane changes. In other design forms, vehicles change one lane. Therefore, it is necessary to put forward the minimum distance between adjacent entrances and exits under different design forms.

#### 3.2 Calculation of Key Indicators

The design speed of the collector distributor is 40 km/h-80 km/h, and the design speed of the ramp connected with the collector distributor lane is also 40 km/h-80 km/h. When calculating the length of weaving section under lane change demand, the influence of acceleration and deceleration on the length is not needed to be considered.

According to the driving process characteristics of the driver, the minimum distance between the adjacent entrances and exits includes the driver's visual recognition distance to the signs $L_1$, waiting for lane change gap distance $L_2$, vehicle position adjustment distance $L_3$, lane change distance $L_4$, exit confirmation distance $L_5$, Length of confluence/ shunt wedge end marking $L_6$, $L_7$.

$$S = L_4 + L_3 + L_2 + L_1 + L_5 + L_6 + L_7$$
3.2.1 *Driver’s visual recognition distance to the signs* \( L_d \): The driver’s recognition distance to the sign refers to the distance that the driver starts to read the information after seeing the guide sign until the reading is completed, thinking and making the lane change decision.

\[
L_d = \frac{V(t_r + t_d)}{3.6}
\]  
(2)

Where \( V \) is ramp design speed; \( t_r \) is time required to read signs, generally 1-2s; \( t_d \) is time required for decision-making, generally 2-2.5s. In this paper, \( t_r \) and \( t_d \) are taken as 1s and 2s respectively.

3.2.2 *Waiting for lane change gap distance* \( L_w \): When the demand of lane changing is satisfied, the headway of vehicles approximately conforms to the negative exponential distribution.

\[
p(h \geq t) = e^{-\lambda (t - \tau)}, t \geq \tau
\]  
(3)

Where \( p(h \geq t) \) means probability of headway greater than or equal to \( T \) seconds; \( \lambda \) is the number of vehicles per lane per second (pcu/s/ln); \( \tau \) is minimum headway (s).

3.2.3 *Vehicle position adjustment distance* \( L_p \): When the driver waits for the lane change gap and decides to change lanes, the driver turns on the turn signal to indicate that the vehicle behind is about to change lanes. At the same time, drivers adjust the speed and position of the vehicle until the vehicle is parallel with the waiting lane change gap to be inserted, and is ready to use this gap to merge into the target lane. The distance traveled by the vehicle in the above process is the vehicle position adjustment distance.

\[
L_p = \frac{0.76V}{3.6} \times \frac{V_d}{V_v - 0.76V}
\]  
(4)

Where \( V \) is target lane speed (km/h), \( t_v \) is average waiting time for lane change (s)

3.2.4 *Lane change distance* \( L_c \): In this process, the longitudinal displacement of the vehicle mainly occurs, and the lateral displacement can be ignored.

\[
L_c = \frac{V}{3.6} t_c
\]  
(5)

Where \( t_c \) is the vehicle lane change time (s), the transverse speed of vehicle moving to the target lane is generally 1 m/s, when the design speed of Expressway reaches 80 km/h and the lane width is 3.75m, the time for vehicle to move to the target lane is 3.25s.

3.2.5 *Exit confirmation distance* \( L_e \): After entering the outermost lane of the main line of the expressway, the vehicle shall maintain free flow operation and confirm the safe distance of exit. This paper takes the confirmation time as 2.5s, then the confirmed exit distance is:

\[
L_e = \frac{V}{3.6} t_e
\]  
(6)

3.2.6 *Length of confluence/ shunt wedge end marking* \( L_n \), \( L_s \): In practical application, transition markings are set at the junction between the interchange entrance and the main line, and lane change is prohibited at the transition markings. Referring to some design projects, the length of the marking transition section at the wedge end of the collector distributor lane is obtained as follows:

| TABLE 2. LENGTH OF WEDGE-SHAPED END MARKING LINE |
|-----------------|---|---|---|
| Design speed of collector-distributor Lane (km/h) | 80 | 60 | 40 |
| Length of confluence wedge end marking (m) | 90 | 71 | 48 |
| Length of shunt wedge end marking (m) | 81 | 63 | 44 |
3.3 Weaving Section Length Calculation
According to the requirements of 2 lane change for double in and single out A’s vehicles and 1 lane change requirement for other design, the weaving section length of collector-distributor lane with design speeds of 80, 60 and 40 km/h is calculated. By rounding the calculated value, the recommended length corresponding to each design form can be obtained under different ramp design speeds.

TABLE 3. DISTANCE BETWEEN ENTRANCES AND EXITS OF COLLECTOR-DISTRIBUTOR LANE UNDER DIFFERENT DESIGN FORMS

| Number of lane changes | Design speed | Calculated value | Rounding value | Applicable design form           |
|------------------------|--------------|------------------|----------------|----------------------------------|
|                        | 80           | 465              | 470            | Single-in-single-out A/B         |
|                        | 60           | 338              | 350            | Single-in-double-out B          |
|                        | 40           | 216              | 220            | Double-in-double-out B          |

4. VERIFICATION OF THE LENGTH OF DISTRIBUTION LANES UNDER DIFFERENT TRAFFIC DEMAND
In order to verify whether the efficiency of the collector-distributor lane can meet the requirements of the service level under different traffic demands and weaving section length, it is necessary to adopt the weaving area capacity calculation method to refine the traffic volume that the collector-distributor weaving area can adapt to.

4.1 Capacity Analysis Index
The traffic flow in weaving section is divided into weaving flow and no-weaving traffic flow. In the figure below, the flow from the collector's road to the off ramp must pass through the on ramp to the collector's flow. The traffic flow in these two directions is weaving traffic flow, and the other two directions are no-weaving traffic flow. Then, the traffic flow in each direction is shown as (7)-(9).

Weaving flow rate
\[ Q_w = Q_{WR} + Q_{FR} \]  \hspace{1cm} (7)

No-weaving flow rate
\[ Q_{NW} = Q_{NR} + Q_{NR} \]  \hspace{1cm} (8)

Total flow rate of weaving section
\[ Q = Q_w + Q_{NW} \]  \hspace{1cm} (9)

Figure 2. Schematic diagram of weaving traffic flow

4.2 Capacity Analysis
In the analysis of service level, V/C value is taken as the main evaluation index to determine the service level. The specific calculation method of service level is as follows:

\[ v/C = Q/C_w \]  \hspace{1cm} (10)

\[ C_w = C_{inl} \times N \]  \hspace{1cm} (11)

\[ C_{inl} = C_J - 495.6 \times \ln(1 + QR) - \ln(1 + DR) + 0.05 \times L_w - 60.38 \times N \]  \hspace{1cm} (12)

\[ DR = Q_{FR} / Q_{NR} \]  \hspace{1cm} (13)
Where: $C_w$ is capacity of weaving section (pcu/h); $N$ is number of lanes in weaving section; $DR$ is outflow flow ratio; $C_r$ is reference capacity of one lane in main line (pcu/h/ln); $C_{wr}$ is reference capacity of one lane in weaving section (pcu/h/ln).

| TABLE 4. SERVICE LEVEL ANALYSIS RESULTS |
|-----------------------------------------|
| **Lanes** | 2 | 3 |
| Weaving flow ratio | 0.6 |  
| Design speed | 60km/h |  
| Length / m | PHV | 800 | 1000 | 1200 | 1400 | 1600 | 800 | 1000 | 1200 | 1400 | 1600 |  
| 350-1000 | Los 2 | Los 3 | Los 4 | Los 5 | Los 2 | Los 3 |  
| Design speed | 80km/h |  
| 350-1000 | Los 2 | Los 3 | Los 4 | Los 5 | Los 2 | Los 3 |  
| Weaving flow ratio | 0.8 |  
| Design speed | 60km/h |  
| 350-400 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 400-600 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 600-800 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 800-1000 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| Design speed | 80km/h |  
| 350-400 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 400-600 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 600-800 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 800-1000 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| Weaving flow ratio | 1.0 |  
| Design speed | 60km/h |  
| 350-600 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 600-1000 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| Design speed | 80km/h |  
| 350-600 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  
| 600-1000 | Los 2 | Los 3 | Los 4 | Los 5 | Los 6 | Los 2 | Los 3 | Los 4 | Los 3 |  

It can be seen from the results that when the design speed of the collector-distributor is 80 km/h, all conditions meet the design requirements of Los 4 [11]. When the design speed is 60 km/h, some cases cannot meet the service Los 4. In these cases, the method of increasing the number of lanes or increasing the design speed can be used to ensure the traffic capacity of the weaving section.

5. SIMULATION ANALYSIS

The JiHe Expressway Reconstruction and Expansion Project plans to build a stereo-compound expressway including an upper-layer-stereoscopic passage and the lower-layer-floor passage. For the design of small spacing composite interchange, there are design conditions for connecting He’Ao-ShuiHe and XiuFeng-BanLan interchange. Therefore, combined with the design documents, the simulation modeling is carried out for the collector-distributor lane.

There are many design forms of collector-distributor lane. VISSIM software is used to establish road models under these design forms. The traffic volume at Los 4 and the predicted traffic volume of the JiHe expressway are taken as the inputs, and the average delay and the queue length of the weaving section are taken as the indexes to analyze the traffic flow.
5.1 Predicted Traffic Volume

In the environment of traffic volume prediction of the main line and ramp, the length of collector distributor lane is designed with the minimum spacing of main line design speed of 100km/h and collector-distributor lane of 80km/h. The simulation results show that: under the same traffic volume, the average delay of single-in-single-out A and double-in-single-out B is the highest, and the queue length of single-in-double-out B is the largest. It is worth noting that under the predicted traffic volume, the average delay and queue length are not too high, which is acceptable for the operation of expressway. However, if there is certain design space, it is not recommended to use single-in-single-out A, double-in-single-out B, and single-in-double-out B.
5.2 Traffic volume at Los 4

Considering that the Los 4 needs to analyze the traffic operation under different length of the collector-distributor lane, taking the 400m, 600m and 1000m collector distributor as the typical length, the road network model is established to analyze the traffic operation.

The simulation results show that the average delay and queue length of single in single out A and B are significantly higher than those in other design cases. For the queue length, the index of single in and single out A and B are significantly longer than other design conditions and typical design lengths in the 400m collector-distributor lane. Compared with the queue length of each typical length, the queue length of 400m collector distributor is higher than 600m and 1000m. In addition, the queue length does not decrease with the increase of design length. Under the design of single-in-double-out B, double-in-single-out B, and double-in-double-out B, the queue length of 600m is lower than 400m and 1000m.

In terms of average delay of road network, the average delay of single-in-single-out A and B is significantly higher than that of other design types. Among the five design types, the average delay of single-in-double-out B is the lowest.
To sum up, under the maximum service traffic volume operation under Los 4, it is not recommended to use the design methods of single-in-single-out A and B, but the way of adding lane’s number can be used to alleviate congestion.

6. CONCLUSION
Basing on the actual stereo-compound expressway project, the setting requirements of high-density and small-spacing composite interchange collector-distributor lane are refined. The research conclusions include the following aspects:

(1) According to the design consistency, continuity, lane balance and other conditions, the number of collector distributor lanes is refined. Combined with driving behavior characteristics, dynamic principle, and lane changing theory, the key indicators affecting the weaving length of lane changing are calculated, and the exit and entrance spacing on the collector-distributor lane under different ramp design speeds and design forms are obtained.

(2) VISSIM software is used to simulate the Los 4 and predict traffic volume of the project. The results show that, the design methods of single-in-single-out A and B, and double-in-single-out B are not recommended under the large service traffic volume of the stereo-compound expressway.

(3) Since the JiHe Expressway, which this paper relies on, is responsible for the functions of transit traffic and distribution passageway, a part of the vehicles are the local, and the drivers are familiar with the road environment. Therefore, in applications of expressway with transit traffic as the main function, it is necessary to consider the driving characteristics and refine the key indicators.

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