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Discussion on the Design of Compound Interchange Interweaving Section of Expressway

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Abstract: The purpose of this article is to explore the design of compound interchange interweaving sections on expressways. During the research phase, based on the support of the literature research method, the classification and development of the interchange system, as well as the design forms of the compound interchange interweaving section, were analyzed. Subsequently, based on the case method, the design of the compound interchange interweaving section of the ShiWu and ShiBai expressways in Shiyan, Hubei Province, was discussed, and a design scheme and scheme comparison were proposed. It is hoped that this article can provide technical reference and ideas for China's road and bridge engineering teams, ensuring that the design results can not only guarantee the normal passage of traffic on the North Intersection Expressway but also ensure the straight-line traffic capacity of the main highway under the background of dislocation intersection, achieving smooth and safe transitions between different expressways.

Keywords: Expressway; Compound traffic interweaving section; Collector-distributor road; Auxiliary lane

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1. Introduction

The construction of the expressway interchange system aims to ensure smooth and unobstructed road traffic on expressways. In the context of continuous growth in traffic volume and accelerating urbanization in China, expressways are facing escalating pressure and challenges [1]. As a new design concept, the compound interchange interweaving system can effectively reduce the investment level of construction and the land occupation of highway construction while ensuring the smoothness and safety of expressways. It plays a more important role in alleviating congestion and improving expressway traffic capacity. Therefore, researching the design of compound interchange interweaving sections on expressways is a high-value research behavior that further leverages the advantages of this design form and promotes continuous improvement in China's expressway construction and service levels [2].

2. Classification and development of expressway interchange systems

2.1. Classification of expressway interchange systems

2.1.1. Interchange type

The principle of the interchange type system is to achieve non-interference of traffic flow between different roads through the interchange combination of bridges, tunnels, and other three-dimensional structures, promoting rapid vehicle passage on the roads. It is suitable for areas with high traffic volumes, such as important transportation hubs. This system can effectively avoid congestion and traffic accidents caused by plane intersections, but its design and construction costs are high, and the construction period is long [3].

2.1.2. Ramp-type interchange

Ramp-type interchanges achieve turning and switching between different roads by setting a series of curves and ramps. This system is characterized by its relatively simple design, lower construction difficulty, and larger land occupation. Typically, this system is mostly applied to highway entrances and exits and areas with lower traffic density. However, ramp-type interchanges may experience traffic convergence and congestion under high traffic volume conditions [4].

2.1.3. Hybrid interchange

The hybrid interchange system combines the characteristics of both the interchange and ramp types, creating a more flexible traffic flow conversion system through a combination of multi-level interchanges and ramps. This form is characterized by flexible design, diverse functions, and strong adaptability, allowing effective traffic diversion while also enabling adjustments and optimizations based on specific needs. Hybrid interchanges are suitable for large integrated transportation hubs with complex terrains and diversified transportation demands, balancing construction costs and traffic efficiency to some extent.

2.1.4. Compound interchange

The compound interchange system integrates various interchange modes, such as interchanges, ramps, and roundabouts, to form a complex traffic network structure, enabling the highway interchange system to have extremely high traffic capacity and diversified traffic conversion methods. The compound interchange system is highly suitable for areas with extremely high traffic volumes, such as the periphery of large cities and hub zones where multiple highways intersect [5].

2.2. Development history of expressway interchange systems

Currently, expressway interchange systems have undergone multiple generations of development. Early expressway interchange systems focused on simple ramp designs. In the 80s and 90s, as traffic volumes continued to expand globally, the interchange-type became the mainstream construction mode for interchange systems. This form ensured improved separation and safety at intersections while overcoming traffic volume and terrain limitations. With the development of road and bridge engineering technology, the hybrid interchange system emerged to effectively overcome the high construction costs and large land occupation constraints faced by the interchange-type system. This system not only achieved a good transition between highways and city roads but also integrated the advantages of interchange and ramp systems [6]. However, as time progressed, it was found that this system limited drivers' visibility, and the separation effect at intersections was not ideal. Based on the above background and considering the advantages and disadvantages of different systems, the compound interchange system was born. Compared to the hybrid interchange system, the compound interchange system is more flexible in spatial utilization, provides a broader field of vision for vehicle drivers, and can ensure traffic safety. Simultaneously, this system can further enhance the traffic capacity of expressways through improved ramp designs.

3. Design forms of compound interchange interweaving sections on expressways

When there is a need for traffic conversion between newly built and existing expressways, establishing a single intersection point cross full-hub interchange is the most ideal form. However, during the actual design phase, there are often limitations due to existing features, topography, or narrow available corridors. When planning and design stages do not allow for the establishment of a single intersection point cross full-hub interchange, displaced intersection often becomes the most economical and reasonable design form. In this context, compound interchange interweaving sections can be designed in three forms based on differentiated compound methods: auxiliary lanes connecting to form an integrated road segment, collector-distributor roads connecting to form a separated road segment, and interweaving separation lanes connecting to form a completely separated road segment [7].

3.1. Auxiliary lanes connecting to form an integrated road segment

In this design form, when the length of the shared road segment is greater than 3km, or the volume of interweaving traffic and turning traffic is less than the connection between adjacent interchanges, the existing main expressway line can be widened and expanded, and auxiliary lanes can be constructed to meet the needs of turning and straight traffic on the shared road.

3.2. Collector-distributor roads connecting to form a separated road segment

In this design form, when the length of the shared road segment is less than or equal to 3km, or even if auxiliary lanes are set up in the integrated road segment mode, but the traffic demand cannot be met, independent collector-distributor roads can be set up outside the straight lanes of the main expressway line to directly connect the main entrance and exit. This design can reduce the difficulty of adjacent exits on the main expressway line, maintain the continuity of two straight lanes, and effectively transfer the interweaving traffic volume on the main expressway line to the collector-distributor roads.

3.3. Interweaving separation lanes connecting to form a completely separated road segment

This design form is suitable for situations where the length of the shared road segment is too short. Even if the form of collector-distributor roads connecting to form a separated road segment is adopted, it still cannot meet the length requirement of the interweaving section. This design involves adding interweaving separation lanes for each turn, using connecting ramps to directly separate the interweaving traffic flows of different directions, fundamentally avoiding conflict points caused by interweaving traffic flows and reducing the negative impact on straight traffic safety [8].

4. Research on the design of complex interchange interweaving sections of expressways

4.1. Overview of the expressway

This article takes the complex interchange project of Shiwu Middle Expressway in Shiyan City, Hubei Province as an example to explore the design process of the complex interchange interweaving section. During the operation of this section of the highway, the Shiwu Middle Expressway and the Shiwu North Expressway both need to interconnect with the Shitian Expressway in Baoxia Town. Due to the constraints brought by the terrain of this node, the distribution of large-scale structures such as bridges and tunnels on the Shitian Expressway, and the corridor of the main highway, there is a displaced intersecting common section between the Shiwu North Expressway and the Shiwu Middle Expressway in Baoxia Town. In the design phase of the complex interchange interweaving section, it is required to ensure that the main direction of the two highways is always in normal operation, minimize the construction volume of the complex interchange interweaving section, save economic costs, and form a safe, reasonable, and economical interconnection method. Based on traffic volume predictions, the distribution of traffic volume in different directions at this engineering node is obtained, as shown in **Figure 1**.

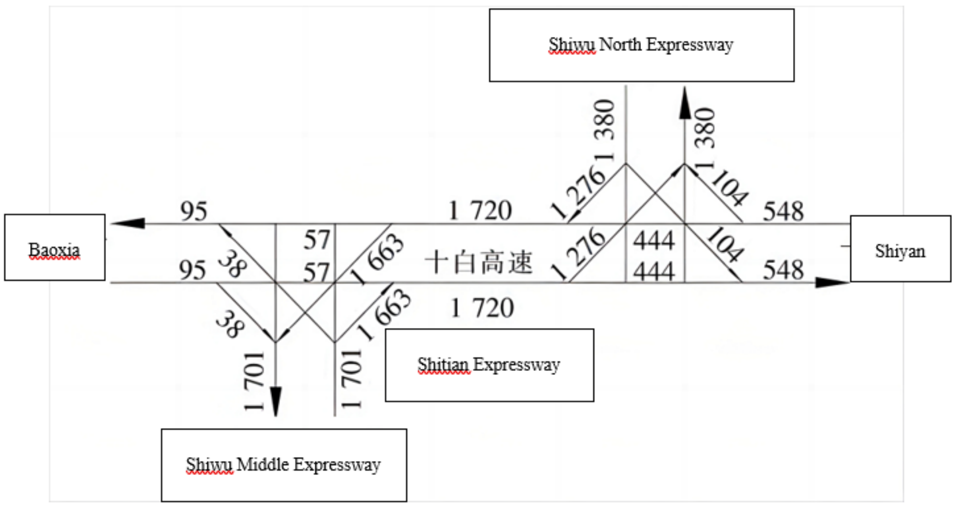

Figure 1. Distribution of traffic volume in different directions at the engineering node

As shown in **Figure 1**, the main traffic volume at this node is concentrated in the direction of Shiwu North Expressway → Baoxia, with a traffic volume of 1276 pcu/h calculated based on the long-term traffic forecast for 2042. The secondary traffic volume is focused on the direction of Shiwu North Expressway → Shiyan, with a traffic volume of 104 pcu/h.

4.2. Design principles

To design the complex interchange interweaving section for the case study project, it is necessary to follow the principles of traffic flow optimization, safety enhancement, and streamline simplification and intuition. Firstly, the design phase should prioritize the optimization and management of traffic flow, reasonably arranging the number and width of lanes to ensure they meet the traffic demand during peak hours. The length of the interweaving section should be precisely calculated to ensure sufficient space for vehicles to adjust their speed during lane changes and merging. Furthermore, due to the high complexity of the complex interchange, which may increase the burden on drivers while driving, the design should simplify traffic streamlines as much as possible, making them more intuitive and easy to understand and reducing unnecessary interweaving points [9].

4.3. Design scheme for complex interchange interweaving section under short-distance misaligned intersection conditions

4.3.1. Design features

The complex interchange system at the misaligned intersection node of the Shiwu Expressway has several distinct features. Firstly, the adjacent interchanges have a short spacing, with a center distance of only about 2.1 km, and the regional traffic density is relatively low. The design speed of the Shitian Expressway (the crossed highway) reaches 80 km/h, indicating a high road grade. Secondly, both the Shiwu Middle Expressway and the Shitian Expressway ramps adopt two-lane exits and entrances. After eliminating the influence of variable speed lanes and auxiliary lanes, the net distance between the interchanges is almost zero, and the vehicles entering and exiting the interweaving section between the interchanges have only a short length, which will affect the safety and traffic capacity of the straight-running traffic on the Shitian and Shiwu Expressways. Thirdly, due to the influence of the terrain and features at the engineering node, the interchange ramps have very limited space for arrangement, which restricts the layout of the complex interchange scheme. Based on the analysis of the above characteristics, the design needs to consider whether the length of the shared road provided by the scheme can meet the length requirement of the interweaving section.

4.3.2. Alternative solutions

Based on the analysis of the characteristics of the engineering node, this project proposes three design forms for the complex interchange interweaving section under short-distance misaligned intersection conditions:

(1) Setting auxiliary lane

This solution utilizes the existing roadbed and bridges of the Shitian Expressway to widen the road, adding an extra lane to the main line of the shared section of the Shibai Expressway. During the construction phase, the existing pile-slab wall of the Shibai Expressway will be directly utilized for support.

(2) Setting collecting-distributing lane

The construction of a separated collecting-distributing lane will be added outside the Shitian Expressway, which will then merge into the entrance and exit of the Shitian Expressway. The effective transfer of interweaving traffic flow will be achieved through the collecting-distributing lane and three connecting ramps. This solution includes two sub-solutions. Solution A is the westward solution, which sets up a 485m-long interweaving section to effectively solve the interweaving conflict problem of the Shitian Expressway (north intersecting expressway).

Solution B is the eastward scheme, which tilts the center of the intersection point towards the east. Based on ensuring high horizontal and vertical alignment indicators, it increases the length of the interweaving section of the collecting-distributing lane, extending it to 895m. This ensures that, with minimal differences in engineering scale, the normal traffic capacity of the main line of the Shitian Expressway is maintained by merging the collecting-distributing lane into the entrance and exit. Simultaneously, by increasing the spacing between the collecting-distributing lane and the ramp entrance and exit, the impact of traffic flow turning on the main line of the Shiwu Expressway is effectively reduced.

(3) Setting interweaving separation lanes

This solution involves setting up collecting-distributing lanes in the originally crowded corridor while also installing longer branch ramps on the outer side to achieve the separation of collecting-distributing lanes and turning traffic. This scheme will significantly increase the scale of the project. According to investigations, the recent traffic volume participating in interweaving and turning at this engineering node is 444 pcu/h (Shiyan→Wuxi). By implementing the separation of collecting-distributing lanes and reserving conditions for interweaving separation lanes, more room for traffic volume growth is reserved for the long term [10].

4.3.3. Comparative analysis of solutions

Comprehensive analysis shows that Solution (1), which involves setting up auxiliary lanes, has certain characteristics. After verifying the data, it is found that the traffic volumes of Shiwu Expressway and Shibai Expressway are 1276 pcu/h and 2240 pcu/h, respectively, and the turning traffic volume and interweaving traffic volume are 501 pcu/h and 1720 pcu/h, respectively. The interweaving area belongs to the main line segment of the Shitian Expressway. Therefore, referring to relevant specifications, the design speed should not be less than 70% of the main line design speed. The minimum interweaving section length can be calculated based on a design speed of 60 km/h for the interweaving traffic demand, resulting in a minimum interweaving section length of 600 m. However, under the influence of a large merging traffic volume in the shared road segment of the two expressways, the actual interweaving section length of 860 m provided by the project may lead to a decrease in the traffic capacity of the interweaving area. Therefore, although Solution (1) can save construction costs and has a high utilization rate of existing projects, the short distance of the shared segment and the huge interweaving traffic volume will inevitably bring negative impacts on the traffic capacity and safety of the main traffic flows of the two intersecting expressways.

Solution A under Solution (2) can solve the interweaving conflict problem of the Shitian Expressway (the crossed expressway), but it does not address the interference caused by interweaving conflicts on the main direction in the context of setting up collecting-distributing lanes on the Shiwu Expressway. Solution B can reduce the impact of turning traffic on straight traffic flow by appropriately increasing the distance between the exit and entrance of the connecting ramps of the collecting-distributing lanes, improving functionality while achieving economic savings.

Although Solution (3) can ensure highly smooth traffic flow organization and meet the rapidly growing demand for long-term turning traffic volume on the highway, it requires a larger scale of branch ramp engineering and special design to meet immediate needs. Additionally, there may be future road widening requirements, resulting in greater variability and overall higher costs. **Table 1.** compares the characteristics of three schemes combined with MALTB simulation, including dimensions such as traffic volume processing, safety, economy, and scalability.

Table 1. Comparison results of different schemes

Comparison Dimension	Scheme (1) Auxiliary Lane	Scheme (2) Option A	Scheme (2) Option B	Scheme (3) Independent Ramp
Traffic Volume Handling	-ShiWu Expressway: 1276 pcu/h -ShiBai Expressway: 2240 pcu/h -Weaving traffic volume: 1720 pcu/h	-Resolves weaving conflicts on ShiTian Expressway. -Turning traffic on ShiWu Expressway still interferes with the main flow.	-Increases distance between ramp exits/entrances to ≥ 300m, reducing turning traffic interference.	-Uses branch ramps to divert turning traffic (diversion ratio ≥ 40%), accommodating long-term growth needs.
Safety	-High risk: 5 additional conflict points in weaving zones, increasing accident probability by 35%.	-Reduces conflict points by 3 on ShiTian Expressway, but interference remains on ShiWu Expressway.	-Reduces conflict points by 60%, lowers risk of lane interference through optimized spacing.	-Fewest conflict points (only 2), physical isolation belt installed to reduce accident rates.
Economy	-Low initial investment, but high maintenance costs during operation due to increased accident repair frequency in weaving zones.	-Balanced cost and benefit, improved operational efficiency on ShiTian Expressway offsets some costs.	-Achieves optimal overall efficiency (cost savings of 15%, traffic efficiency improved by 18%).	-High initial investment, but long-term operational costs are reduced due to a 30% decrease in maintenance fees resulting from fewer accidents.- High initial investment, but long-term operational costs are reduced due to a 30% decrease in maintenance fees resulting from fewer accidents.
Scalability	-No reserved space, future expansion requires demolition and reconstruction.	-ShiTian Expressway is scalable, but development is restricted by the collector-distributor lanes on ShiWu Expressway.	-Collector-distributor lanes reserve 20% width allowance to support mid-term expansion.	-Fully independent system, supports multi-directional expansion (reserved expansion space for 5 lanes).

Based on comprehensive analysis, Option B of Scheme (2), which involves adding collector-distributor lanes, highly meets the requirements of the project case. It not only has a moderate scale but also demonstrates strong economic efficiency. This option can effectively reduce conflict points, support mid-term expansion, and ensure smooth organization of traffic flow. Ultimately, the engineering team selected Solution B under Solution (2).

5. Conclusion

In summary, this article analyzes the classification, development history, and design forms of interweaving sections in highway interchange systems. Taking the design of the complex interchange interweaving section of the Shiwu and Shibai Expressways in Shiyan, Hubei as an example, it explores specific scheme designs and selections for different design options. Relevant engineering teams can draw inspiration from this article to enhance their understanding of highway interchange systems, clarify design ideas and key points under different working conditions, and ultimately design cost-effective and functionally satisfactory complex interchange systems that meet the safety, economic, and efficient construction goals of highways.

Disclosure statement

The author declares no conflict of interest.

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