Optimization Design of Expressway Entrance and Exit Based on Actual Traffic Flow Characteristics

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Abstract. The combination area of entrance and exit is the frequent bottleneck of urban expressway system. The running state of traffic flow in combination area is closely related to the key parameters including the acceleration and deceleration lane length, the interweaving area length, the sign identification, etc. And the analysis of traffic flow status can in turn guide the design of road engineering. Therefore, this paper proposes the geometric elements optimization model and design results of the expressway entrance and exit combination area based on the actual traffic flow characteristics and driver's driving characteristics. To verify the superiority of the optimization model, this paper takes a combination area of Jinzhai Expressway in Hefei City as an example, and after a large number of road traffic surveys, uses VISSIM to simulate and evaluate optimization effect based on proposed model and calculation results. The results show that the optimization model based on traffic flow characteristics is better at improving traffic flow status, especially during the peak period, the average delay of the research section decreased by 18.1%, and the average pass rate of the bottleneck increased by 13.6%.

1. Introduction

As an important part of the urban road transportation network, the expressway is of great significance in undertaking long-distance travel and mitigating traffic congestion. However, the actual running state of the traffic flow in combination area is complex and diverse, and the internal traffic efficiency is closely related to its geometric elements. Therefore, it is necessary to deeply consider the impact of the actual traffic flow state on the geometric element design of the urban expressway entrance and exit in order to reduce the delay of the vehicle at the bottleneck and improve the capacity of the expressway.

At this stage, experts and scholars from various countries have made in-depth researches on the design of the expressway geometric elements and the macroscopic characteristics of traffic flow. Weiss[1] used the delay theory to analyze the merging characteristics of the acceleration lane, and according to the running time on acceleration lane to obtain a reasonable acceleration lane length; Fitzpatrick and K Chrysler[2] studied the relationship between the deceleration lane length and driving speed, and found that the calculation speed used in the past specification was often higher than in actual driving process, which leads to the shortage of the actual deceleration lane length and proposed an improvement measure; Yang Xiaoguang[3] of Tongji University has summarized the existing minimum distance calculation method of the expressway entrance and exit into two methods: model calculation method and empirical calculation method. The traffic flow characteristics of the expressway entrance and exit, and the components of the four types of combination area are analysed in depth. Zhou Ru[4] and others have studied the influence of the interweaving area length and the interlaced flow rate on
traffic efficiency of the entrance and exit. Wang Yu[5] and Wang Yuansheng[6] researched the design of the key elements of the entrance through qualitative analysis of traffic flow characteristics.

Most of the studies on the design of expressway entrances and exits in the past were mainly based on simulation. With the maturity of data acquisition technology, more and more related researches are supported by measured data. However, such researches focus more on the qualitative analysis of traffic flow. There are few quantitative studies on the impact of actual traffic flow characteristics on the design of entrance and exit geometric elements. Based on existing researches, this paper provides a reference for the design and construction of urban expressway entrances and exits by analysing the actual observation data including the actual traffic flow characteristics and driver's driving characteristics.

2. Data collection and analysis
In order to study the actual traffic flow characteristics of the expressway, this paper uses the aerial photography technology to investigate the traffic flow at an entrance and exit of Huizhou Expressway in Hefei City. As shown in Figure 1, the diverging and merging area are respectively divided into five sections and the velocity distribution information is obtained by analysing the spatiotemporal trajectory. The flow from on-ramp and off-ramp is detected in diverging and merging area. The average speed and related statistical indicators in each sub-interval are shown in Table 1, Table 2 and Figure 2.

![Segmentation diagram of the survey intervals in the diverging and merging area.](image)

Table 1. Statistics of velocity distribution in each interval of the merging area.

| Area number | Average speed (km/h) | Adjacent interval speed difference | Adjacent interval relative speed difference |
|-------------|----------------------|-----------------------------------|-------------------------------------------|
| 1           | 47.92                | 1-2 Area: 1.93                   | 4.0%                                      |
| 2           | 49.85                | 2-3 Area: 8.21                   | 16.5%                                     |
| 3           | 58.06                | 3-4 Area: 5.2                    | 8.9%                                      |
| 4           | 52.86                | 4-5 Area: 5.33                   | 10.1%                                     |

Table 2. Statistics of velocity distribution in each interval of the diverging area.

| Area number | Average speed (km/h) | Adjacent interval speed difference | Adjacent interval Relative speed difference |
|-------------|----------------------|-----------------------------------|-------------------------------------------|
| 1           | 68.27                | 1-2 Area: 4.95                   | 7.8%                                      |
| 2           | 63.32                | 2-3 Area: 10.16                  | 16.1%                                     |
| 3           | 53.16                | 3-4 Area: 7.51                   | 14.1%                                     |
| 4           | 45.65                | 4-5 Area: 5.84                   | 12.8%                                     |
| 5           | 39.81                |                                   |                                            |
Figure 2. Velocity distribution in each interval of the diverging and merging area.

From the velocity distribution curves in Figure 2, it can be seen that the vehicle in merging area will accelerate to the approximate main road speed on acceleration lane for a period of time, and then the speed will decrease from the gradient segment into the main road. The speed difference is about 10%. The main reason may be that the driver in middle or high flow state needs to take into account the left rear vehicles and the change of road linearity. From the quantitative statistical analysis of the velocity distribution in diverging area, it can be seen that the vehicle has started to decelerate before it reaches the deceleration lane. The average speed from the outermost lane of the main road to the gradient section has been reduced by about 15%, and then the vehicle starts to enter the deceleration lane. Based on the velocity distribution difference analysis between each interval of the diverging and merging area, the geometric elements design optimization model of the combination area is constructed.

3. Optimization of geometric elements in the entrance and exit combination area

3.1. Acceleration lane length optimization in combination area

The acceleration lane includes a straight section and a gradient section, and it is segmented according to the actual speed characteristic difference, which is shown in Figure 3. The function of the acceleration area is to provide a certain transition length for the vehicles to achieve the speed required for merging. The length of the merging waiting area is calculated according to the accepted gap theory [1] [7] [8]. At this time, the merging vehicles’ speed has approached or reached the driving speed of the main road. The gradient area is located at the end of the acceleration area. During entering the main road by changing lane once, the speed is reduced but the fluctuation is small, which is relatively reduced by 10% by statistical analysis. It may be that the driver needs to observe the vehicles of the rear main road during the process of changing into the main road, and the driving is more cautious. Therefore, given reduction factor $a=0.9$, the acceleration lane length ($L_a$) optimization model is shown in equation (3.1).

$$L_a = (V_{a}^2 - V_{m}^2) / (25.92a) + \frac{1000V_{m}[\alpha^{(t-t')} - 1]}{Q_{m}} + aV_{a}t$$  (3.1)

where $V_a$ is ramp or auxiliary road design speed, $V_m$ is main road driving speed, $a$ is the average acceleration of the vehicle, generally takes 0.8-1.0m/s$^2$, $t$ is the driving time on the gradient area,
generally takes a changing-lane time of 3.0s, \( t_c \) is the gap threshold value that can be allowed, generally takes 3~4s and \( Q_m \) is the main road flow.

The calculation method usually uses the speed-flows power exponential model. Many scholars and experts in China have continuously optimized and improved the model, and obtained the speed-flow curve model adapted to China's expressway \( [9] \), which is shown in equation (3.2).

\[
V_n = \begin{cases} 
V_f e^{[-b(q - q_o)^{a}],} & q \geq q_o \\
V_f, & q < q_o 
\end{cases}
\]

(3.2)

where \( V_f \) is main road free flow speed, generally takes the main road design speed, \( q \) is flow turning point, generally takes 0.5 times the capacity and \( a, b \) are model parameters, the calibration values are respectively 2.0 and 1.0x10^{-6}.

3.2. Deceleration lane length optimization in combination area

The design of the deceleration lane length often adopts the "secondary deceleration theory" \( [10] \) \( [11] \). The existing researches hold that the speed of traffic flow on gradient section closes to the main road running speed \( [6] \) and take the average speed of the main road traffic as speed value. According to the above-mentioned measured data quantitative analysis, the running speed of the vehicles on gradient section has been reduced by about 15% relative to the main road vehicles' speed. Therefore, based on the analysis of the actual speed characteristics, the speed reduction factor \( \beta = 0.85 \) is given in the model.

![Figure 4. Segmentation diagram of the deceleration lane.](image)

As shown in Figure 4, the deceleration lane length calculation is solved in sections according to above optimization ideas. The labels of the nodes are given in the figure, which are not described here again. The lane length \( (L_d) \) optimization model is shown in equation (3.3).

\[
L_d = \beta V_n (t_0 + t_f) - \frac{1}{2} a_1 t_1^{2} + \frac{1}{2} a_2 (V_n - a_1 t_1^{2} - V_a^{2}) / (2a_2)
\]

(3.3)

where \( a_1 \) is the first stage deceleration, generally takes 0.8-1.2m/s², \( a_2 \) is the second stage deceleration, generally takes 1.5~2.0 m/s², \( t_0 \) is the gradual section driving time, generally takes a lane-changing time of 3.0s, and \( t_f \) is the first stage deceleration time, generally takes 2.5~3.5s.

3.3. Interweaving area length optimization in combination area

The length of the interweaving area is related to many factors such as the flow, speed and interlacing ratio of the main and auxiliary roads. The interweaving strength \( W \) defined in the Specification for Design of Urban Expressway \( [12] \) and Code for Design of Urban Road Engineering \( [13] \) represents the complexity of interweaving. The calculation model is shown in equation (3.4).

\[
W = a(1+f)^{n} (Q/n)^{f} / (3.28L_e)^{f}
\]

(3.4)

where \( a, b, c, d \) are constant coefficient, \( n \) is the total number of one-way lanes in interweaving area, \( Q \) is total flow in interweaving area, \( L_e \) is interweaving area length, and \( f \) is interlacing ratio.

According to the three elements relationship of traffic flow, the average speed of the interweaving area is shown in equation (3.5).
\[ v = \frac{Q}{Q_{w} / V_{w} + Q_{nw} / V_{nw}} \]  

(3.5)

where \( V_{w} \) and \( V_{nw} \) respectively represent the average speed of interlaced flow and non-interlaced flow, which are shown in equation (3.6).

\[
\begin{align*}
V_{w} & = V_{\text{max}} + \frac{V_{\text{max}} - V_{\text{min}}}{1 + W} \\
V_{nw} & = V_{\text{min}} + \frac{V_{\text{max}} - V_{\text{min}}}{1 + W}
\end{align*}
\]

(3.6)

where \( V_{\text{max}} \) and \( V_{\text{min}} \) respectively represent the maximum and minimum driving speed.

Equations (3.7) is available from equations (3.4), (3.5) and (3.6).

\[
nK = \frac{Q_{w}}{V_{\text{min}} + \frac{V_{\text{max}} - V_{\text{min}}}{1 + W}} + \frac{Q_{nw}}{V_{\text{min}} + \frac{V_{\text{max}} - V_{\text{min}}}{1 + W}}
\]

(3.7)

If we have known the total flow rate, the interlacing ratio, the traffic density, and the number of lanes in interweaving area, we can calculate interweaving area length.

3.4. Sign identification length optimization in combination area

It can be known from the driving characteristics of the drivers that the process of identifying the traffic sign can be roughly divided into two stages. The first stage is to understand the traffic sign, that is, the perceptual reaction stage, and the second stage is to perform the corresponding lane-changing behaviour, that is, the behavioural reaction stage. The existing researches and related statistics at home and abroad generally suggest that the cognitive response time \( t_{1} \) often takes 3s. And the average speed of the main road traffic to achieve lateral shifting of the lane-changing is 1m/s. The actual traffic flow characteristics are analysed about the main road with the number of one-way lanes \( n \). The lane-changing times from the inside to the outside is successively decreased. The average lane-changing times in each lane are approximately \( n/2 \), and the sign identification length \( (L) \) is obtained according to the kinematics theory, which is shown in equation (3.8).

\[
L = \frac{v}{3.6} (3 + \frac{d}{v_{s} \cdot \frac{n}{2}})
\]

(3.8)

where \( v \) is vehicle driving speed, \( v_{s} \) is average speed of vehicles’ lateral movement when changing lanes, and \( d \) is the width of single lane.

4. Case study and simulation evaluate

4.1. Main evaluation indicators and calculation models

4.1.1. Average delay of the vehicles in combination area. At present, the common delay models in combination area of entrance and exit are logarithmic and exponential models [14]. The main variables in the model are relative merging ratio, diverging ratio, combination area length, etc. In order to cite these models as evaluation indicators for the convenience of calculation and analysis, the flow value is used to replace the merging ratio and diverging ratio, and the delay \( (d) \) of in-out type entrance and exit is shown in equation (4.1).

\[
d = L \cdot \exp(-7.62 + 0.59Q_{b} / 1000 + 3.32 \frac{Q}{Q_{b}} - 0.77L / 1000)
\]

(4.1)

where \( L \) is the length of combination area, that is the entrance and exit spacing, and \( Q_{b} \), \( Q_{m} \) respectively represent the flow of main road upstream and on-ramp.

4.1.2. Average pass rate of the vehicles in combination area. In this paper, the indicator “average pass rate of combination area” is used instead of the capacity to characterize the efficiency of combination
area. In other words, the combination area is regarded as a whole when researching, and the pass rate model ($\eta$) of in-out type entrance and exit is given in equation (4.2).

$$\eta = \frac{Q_{in} + Q_{out}}{Q_{in} + Q_{out}} \times 100\%$$  (4.2)

where $Q_{in}$, $Q_{out}$, $Q_{in}$, $Q_{out}$ respectively represent the flow of upstream, downstream of combination area, on-ramp and off-ramp.

4.1.3. Average speed of the vehicles in combination area. The average speed reflects the smoothness of the traffic flow. This indicator has been widely used in previous research in order to evaluate the influence factors and traffic efficiency of the expressway entrance and exit.

4.2. Case simulation and result evaluation

A certain entrance and exit combination area (Wang Jiang Road-South Second Ring Road Section) of Jin Zhai expressway, Hefei City is selected as the case analysis object, which is shown in Figure 5. After the field investigation, the road conditions of the research section are obtained (mainly including the main road lane allocation and the single lane width, each element length in the combination area), which are shown in Table 3, and the data are all obtained from the one-way road section survey.

Table 3. Summary of road condition survey parameters.

| Number of main road lane | Main road lane width (m) | Acceleration lane length (m) | Acceleration gradient length (m) | Interlacing area length (m) | Deceleration lane length (m) | Deceleration gradient length (m) |
|-------------------------|--------------------------|-----------------------------|---------------------------------|-----------------------------|-----------------------------|---------------------------------|
| 3                       | 3.75                     | 180                         | 50                              | 400                         | 115                         | 50                              |

Traffic surveys are conducted during peak and flat peak periods. The main survey contents include main road upstream traffic flow, on-ramp flow, off-ramp flow, which are shown in Table 4.

Table 4. Traffic flow survey of each section.

| Time    | Main road upstream flow (pcu /h) | On-ramp flow (pcu /h) | Off-ramp flow (pcu /h) |
|---------|----------------------------------|-----------------------|------------------------|
| flat peak | 1728                              | 620                   | 415                    |
| peak    | 4050                              | 945                   | 780                    |

The simulation results of the current situation by VISSIM are shown in Table 5.

Table 5. Summary of current situation simulation results.

| Time    | Average delay (s) | Driving time (s) | Average speed (km/h) | Downstream flow (pcu /h) | Average pass rate |
|---------|-------------------|------------------|-----------------------|--------------------------|-------------------|
| flat peak | 1.8               | 48.8             | 65                    | 1724                      | 91%               |
| peak    | 11.6              | 102.1            | 32                    | 2529                      | 66%               |

According to the geometric elements length optimization model of the combination area and the calculation results, the geometric element value is changed to optimize the combination area under the
current actual road traffic conditions. The optimization value of this case is shown in Table 6 (optimization length with an interval of five meters). Other simulation parameters are unchanged and simulation results are shown in Table 7.

Table 6. Geometric elements optimization value.

| Acceleration lane length | Acceleration gradient length | Interlacing area length | Deceleration lane length | Deceleration gradient length |
|--------------------------|------------------------------|-------------------------|--------------------------|-----------------------------|
| 165 m                    | 60 m                         | 430 m                   | 135 m                    | 55 m                        |

Table 7. Summary of optimization simulation results.

| Time     | Calculation delay(s) | Simulation delay(s) | Driving time(s) | Average speed(km/h) | Downstream flow(pcu /h) | Average pass rate |
|----------|-----------------------|---------------------|-----------------|---------------------|-------------------------|-------------------|
| flat peak| 1.5                   | 1.7                 | 43.35           | 72                  | 1785                    | 94%               |
| peak     | 9.5                   | 9.2                 | 91.2            | 35                  | 2936                    | 75%               |

From the results of the theoretical calculation delay and the actual simulation delay in Table 7, comparison error of the delay calculation formula and the actual simulation result is less than 10%. It is reasonable. To further illustrate the expected optimization effect, the results of the current status and the optimization scheme are compared and analysed, which are shown in Figure 6.

Figure 6. Comparison of the optimization and current status results in the flat and peak period.

Table 8. Statistical analysis of the optimization results in the flat and peak period.

| Time     | Average delay difference (s) | Average delay reduction percentage | Average speed difference (km/h) | Average speed increase percentage | Pass rate difference (%) | Pass rate increase percentage |
|----------|------------------------------|-----------------------------------|---------------------------------|----------------------------------|--------------------------|-------------------------------|
| flat peak| 0.3                          | 16.7%                             | 7                               | 10.8%                            | 3                        | 3.3%                          |
| peak     | 2.1                          | 18.1%                             | 3                               | 9.4%                             | 9                        | 13.6%                         |

It can be seen from the simulation comparison analysis in Table 8 that the results of the geometric elements optimization design of combination area are better than current traffic state, whether it is the peak period or the flat peak period. The results also indicate that the quantitatively researches of actual traffic flow characteristics are important to guide road engineering design.

5. Conclusion
This paper analyses the measured data based on the actual traffic flow characteristics and the driver's driving characteristics. The geometric elements of the urban expressway entrance and exit combination area are optimized. Then combine with the actual case to simulate and evaluate the optimization effect. It is shown that the optimization model and calculation results of the geometric elements in the expressway combination area based on the actual traffic flow characteristics are more superior than existing researches and specification design effect. Based on the model and optimization results
proposed in this paper, for the already completed or space-constrained situation, we can continue to study in following two aspects and obtain a more perfect theoretical system of the expressway combination area optimization design.

(1) Explore the optimal ratio of the length of each geometric element to the total length of the space when the distance between the entrance and exit of the expressway is limited;

(2) In order to better coordinate the expressway traffic organization, based on the qualitative and quantitative analysis of the actual traffic flow characteristics, consider corresponding control strategy to achieve reasonable guidance and traffic organization of the traffic flow at the bottleneck.

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References
[1] Weiss, D. E. B. H. (1971) Merging from an acceleration lane. Transportation Science, 5(2): 161-168.
[2] Fitzpatrick K, Chrysler S T, Brewer M. (2012) Deceleration Lengths for Exit Terminals. Journal of Transportation Engineering, 138(6): 768-775.
[3] Wang J, Yang X.G. (2010) Minimum Length between Entrance and Exit of Expressway. Urban Transport of China Vol.8, No.3.
[4] Zhou R, Liang X, Mao B.H. (2012) Simulation of Interlaced Flow Rate and Interleave Length of Urban Expressway Entrance and Exit. Traffic information and security.
[5] Wang Yu. (2013) Research on the values of key design elements for the exit and entrance on expressway.
[6] Wang Y.S. (2004) Study on traffic characteristics of urban expressway entrance and exit with auxiliary lanes.
[7] Li W.Q. (2017) Calculation method of parallel-type acceleration lane length of urban expressway. Journal of Traffic and Transportation Engineering.
[8] Shao C.Q. (2008) Research on Model of Computing Acceleration Lane Length and Analysis of Its Influence Factors. Journal of Beijing University of Technology, 34(1): 72-75.
[9] Shao C.Q, Zhao L. (2006) Study of Speed-Flow Relationships Model on Urban Individual Freeway Lanes. Road Traffic & Safety, 6(6): 8-10.
[10] Dai Z. (2006) Research On Safety Design of Main and Side Road Exits in Urban Expressway.
[11] Ning H.J. (2011) Study on the Minimum Spacing of the Entrance and Exit of Urban Expressway.
[12] Ministry of Housing and Urban-Rural Development of the People’s Republic of China. (CJJ129-2009) Specification for design of urban expressway. China Building Industry Press, Beijing.
[13] Ministry of Housing and Urban-Rural Development of the People’s Republic of China. (CJJ37-2012) Code for Design of Urban Road Engineering. China Building Industry Press, Beijing.
[14] Wang H. (2007) Study on Traffic Characteristics of Urban Expressway and Interweaving Area.