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Article

A Study on Urban Traffic Congestion Pressure Based on CFD

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Abstract: With the rapid advancement of urbanization, the problem of traffic congestion in cities has become increasingly severe. Effectively managing traffic congestion is crucial for sustainable urban development. Previous studies have indicated that fluid dynamics theory can be applied to address flow problems in transportation, and this article aims at utilize CFD to solve congestion issues in urban road traffic. Firstly, a similarity analysis is conducted between fluids and traffic flow at the theoretical level. By converting parameters, the formula of fluid is derived into the formula of traffic flow, thus demonstrating the feasibility of using CFD in traffic flow research. On this basis, targeting recurrent congestion and non-recurrent congestion scenarios, 2D road fluid domains and constraints are constructed based on the common characteristics of each congestion type area. By using Fluent software to analyze the flow conditions under different congestion characteristics, use the smoothness of fluid motion to find out the problems causing traffic congestion and conduct analysis to reveal the microscopic mechanism behind congestion formation. For different types of congestion, in order to clarify the effectiveness of congestion mitigation measures, the geometric design of road intersections and diversion measures are discussed in depth. The traffic pressure is analyzed by adjusting the vehicle inlet angle at intersections or controlling the vehicle flow speed. Finally, the optimal design scheme is obtained by comparative analysis. The work of this article provides new ideas for optimizing urban road design and solving vehicle traffic congestion problems. The optimization measures can effectively reduce the accident rate and improve the efficiency of traffic flow.

Keywords: urban transportation; traffic congestion; CFD; traffic flow; geometric design

1. Introduction

With the acceleration of urbanization and the rapid development of urban road traffic systems, the problem of traffic congestion has become increasingly prominent. The frequency and duration of its occurrence increased significantly. Solving this problem is crucial to the normal operation of the city [1]. For urban roads, urban road intersections, as an important part of urban road systems, are the throats of urban road networks. Crossing pedestrians, motor vehicles and non-motor vehicles will produce many merging points, diverging points and conflict points. The three interact with each other, resulting in a significant reduction in road capacity. A large number of facts have proved that the congestion at urban road intersections is the most serious. The insufficient capacity of intersections often causes traffic congestion, and more than 80 % of delays are concentrated on intersections [2]. Unsignalized intersections, especially roundabouts and on-ramp merging areas, are more congested [3]. Therefore, alleviating congestion at unsignalized intersections is an important issue.

In the research on the congestion problem at unsignalized intersections, the commonly used methods in previous studies are to construct complex traffic flow models and develop advanced simulation platforms to explore and develop technologies such as connected automated vehicles (CAVs), vehicle-to-everything (V2X), and automated driving (AD) [4–8]. The core of these methods lies in the optimization of traffic flow through the integrated regulation of vehicle flow or regulation speed on the road network. However, in reality, when the entire road network is saturated with traffic during peak hours, or when the congested road section is unavoidable for vehicle commuting, these

studies cannot effectively solve the problems because it does not improve the capacity of the road network or road section.

However, the traffic congestion problem can be solved by using the dynamic properties of fluid flow in CFD. At present, there are many researches on the combination of fluid mechanics and transportation in solving the problems related to passenger flow. Many scholars have studied the passenger flow on the platform of urban rail transit station by using the theory of fluid mechanics [9–11] found that the movement of passenger flow is close to the 'quasi-one-dimensional' pipe flow from a relatively wide range to a narrow mouth, which means that there is a great similarity between passenger flow and fluid, and put forward the application of macroscopic fluid mechanics phenomenon in passenger flow movement. In fact, passenger flow and urban road traffic flow also have certain similarities. The study of urban road traffic flow can also be based on the theory of fluid mechanics. Lighthill and Whitham [12] used the concepts of fluid mechanics to liken traffic flow to a kind of fluid, taking long highway tunnels as their objects of study, and analyzed the patterns of traffic flow under high-density conditions, proposing a hydrodynamics simulation theory; Richards [13] also put forward a similar theory of traffic flow and gave a conservation of matter equation for describing the change of vehicle density with time and location. It is found that the change rate of vehicle density is equal to the negative value of the spatial derivative of traffic flow change. This first-order continuous medium model describing the vehicle flow is called LWR theory [14]. Newell [15,16] proposed a simplified motion wave theory, which uses the cumulative flow to express the conservation law and uses the cumulative curve to analyze traffic dynamics. On this basis, Huang et al. [17] present a distributed traffic detection and prediction solution by using a shock wave traffic model. Li [18] in the derivation of the continuity equation for the vehicle flow, transformed the law of mass conservation in the derivation of the continuity equation of fluid dynamics into the law of conservation of the traffic flow, that is, in a certain period, the difference between the traffic flow out of the control body and the traffic flow into the control body is equal to the traffic flow reduced by the change of the vehicle density in the control body. This analogy is based on the assumption of a continuous medium, which links the dynamic behavior of traffic flow with the principle of fluid dynamics. At present, there are some scholars [19–21] have already investigated the similarity between traffic flow and fluid by using fluid to simulate traffic flow. Although some scholars have combined fluid mechanics with traffic flow, the research literature is less and mostly at the theoretical level, without solving a specific problem. At the same time, some scholars have used CFD-related software to analyze traffic flow. Sun et al. [22] developed a CFD implementation methodology for modeling traffic problems such as queue/platoon distribution, shockwave propagation and prediction of system performance. It is proposed that the CFD can effectively insight into the formation and propagation of congestion, to facilitate the study of the influence of queue distribution on congestion formation. Hatem et al. [23] used the CFD method to simulate the traffic flow of specific sections of Army Canal Street. It is found that the unknown value of exit or entrance traffic flow can be estimated by collecting upstream and downstream data. In addition, CFD can intuitively identify the high and low areas of traffic flow on the road section according to the color contour map, to estimate the location and time of congestion. They concluded that CFD is beneficial for studying traffic congestion, but the report does not specify how to leverage CFD's advantages to alleviate congestion. Therefore, on this basis, this paper studies the typical urban congestion areas and proposes solutions. However, according to the occurrence characteristics of traffic congestion, it can be divided into two categories: recurrent congestion and non-recurrent congestion. Recurrent congestion is a long-term existence, usually due to insufficient road capacity, excessive traffic flow, unreasonable urban planning and other reasons, such as roundabouts and on-ramp merging areas. Non-recurrent congestion is temporary, usually caused by accidents, construction, emergencies or traffic peaks at specific times. Recurrent congestion often requires long-term planning and governance measures to solve. For Non-recurrent congestion, once the cause of congestion is eliminated, traffic flow will gradually return to normal. These two traffic congestion scenarios can be well visualized using CFD software.

In summary, this paper carries out research on urban road congestion using Fluent software of CFD. The specific content is as follows: Firstly, thinking from the typical phenomenon in fluid mechanics, by analyzing the similarity between urban road traffic flow and fluid, and deriving the calculation formula of traffic flow based on the calculation formula of fluid flow it proves that CFD

applies to the study of traffic flow. Secondly, according to the working conditions of the roundabout, on-ramp merging area, and the non-recurrent congestion sections, the characteristics of the geometric design are integrated. A typical section is designed for each working condition as the object of this study, and various geometric and numerical models are determined. Different schemes are designed for different types of typical road sections, and the results of the design parameters of different schemes are compared and analyzed. Finally, according to the obtained data and the actual situation of road construction, the optimal design scheme is obtained. This study provides suggestions and a theoretical basis for optimizing the design of roads and alleviating traffic congestion.

2. Method

The similarity analysis is carried out from three perspectives: fluid properties, motion types and basic concepts of fluid and traffic flow. Equate the traffic flow to a fluid, model the road geometry and use computational fluid dynamics methods for calculation.

2.1. Similarity Analysis

2.1.1. Fluid Properties Similarity Analysis

1. Deformability

Due to the driving of travel purposes, vehicles may frequently change lanes during driving, so that the traffic flow has strong mobility and is difficult to have a fixed shape.

2. Compressibility

According to the different road environments, traffic flow has compressibility. When the traffic flow is small and the surrounding environmental conditions are more favorable, the vehicle speed is fast and the safety distance between vehicles is large. The traffic flow can be compressed. When the traffic environment is poor, traffic flow is large, to reach the maximum capacity of the road, the density of the traffic will not happen again a big change. This time for the incompressible fluid.

3. Viscosity

When the traffic flow is large, due to the interaction between the individual vehicles, there will be obstacles, queuing, waiting and so on. The free choice between individuals has a greater interference. This interference is similar to the role of viscous fluids. The text continues here.

2.1.2. Motion type Similarity Analysis

4. Viscous fluid flow and ideal fluid flow

Due to the existence of a viscous effect between the traffic, the traffic will be regarded as viscous fluid flow.

5. Compressible and incompressible flow

As analyzed above, the traffic flow is divided into compressible and incompressible flow according to different road environments, and this paper studies the characteristics of traffic flow in traffic congestion, so the traffic flow is regarded as incompressible flow in the analysis.

6. One-dimensional, two-dimensional and three-dimensional flows

Traffic flow is three-dimensional motion in some sections, such as traveling up and down slopes. However, in most cases, the traffic flow is regarded as simple one- and two-dimensional motion.

7. Steady flow and unsteady flow

The flow of traffic generally belongs to the non-stationary movement. But in some special states, such as in the road capacity to reach the maximum, in a certain period, the road capacity will not occur again with the time variable. At this time, it is a steady flow. Therefore, in this paper, the traffic flow is regarded as a steady flow.

2.1.3. Basic Concepts Similarity Analysis

8. The system and control body of traffic flow

The traffic flow system is a collection of several vehicles, and it always contains these identified vehicles during the movement. The boundary of the system changes with the movement of traffic flow. The control volume refers to a certain area in the road, and the boundary of the area is called the control line. The shape of the control body is arbitrarily selected according to the movement and

boundary of the traffic flow. Once selected, the shape and position of the control body are fixed concerning the selected coordinate system.

9. Flow cross-section

In the study of traffic flow, the flow cross-section refers to the section perpendicular to the speed of traffic flow.

2.1.4. Feature Parameter Transformation

To effectively apply the theory of hydrodynamics in the study of traffic flow movement law, some physical characteristic parameters of the traffic flow are transformed into the corresponding hydrodynamic parameters, to better apply the idea of hydrodynamics to understand and derive. The specific correspondence is shown in Table 1.

Table 1. Properties parameter transformation between traffic flow and fluid

Physical properties	Fluid flow	Traffic flow
Continuum	Unidirectional incompressible fluid	Single-lane incompressible traffic flow
Discrete Element	Molecule	Vehicle
	Quality m	Density k
Variable	Velocity v	Velocity u
	Pressure P	Flow rate q
Momentum	mv	ku
Dynamic Equations	$P = cmt$	$q = ku$
Continuity Equation	$\frac{\partial m}{\partial t} + \frac{\partial(mv)}{\partial x} = 0$	$\frac{\partial k}{\partial t} + \frac{\partial(ku)}{\partial x} = 0$
Equations of Motion	$\frac{dv}{dt} + \frac{c^2}{m} \frac{\partial m}{\partial x} = 0$	$\frac{du}{dt} + k \left(\frac{du}{dk} \right)^2 \frac{\partial k}{\partial x} = 0$

By comparing the properties of traffic flow and fluid, it is found that the two have great similarities and can be transformed into each other in parameters. Based on this finding, the vehicle flow can be regarded as an equivalent model of fluid flow in theory. Therefore, only the fluid needs to be studied below.

2.2. Geometric Model

10. Model processing

To study the congestion characteristics of urban roads and eliminate the influence of gravity and other factors on the fluid, the 2D computational domain is used to represent the research section. The model designed by ANSYS Design Modeler is two-dimensional (no thickness). The specific model is constructed as follows :

For the roundabout, according to the observation, it is found that the area prone to congestion is the central island, which is the roundabout of the square. The diameter of the central island is generally in the range of 50m to 100m, mostly four lanes, with four entrances and exits respectively. The entrance angles are generally in the range of 25° to 35° and all meet the minimum length of the weaving segment. To study the general characteristics of the general roundabout, the diameter of the outer ring of the roundabout selected in this paper is 100 m, and the diameter of the inner ring is 65 m. It belongs to the conventional roundabout. There are four lanes in the ring. Each entrance and exit are a two-lane with a width of 7.5 m. Each entrance angle is 30° and the entrance and exit lanes are connected to the ring road with a radius of 15 m. The geometric model is shown in Figure 1 (a).

For the on-ramp merging area, according to the characteristics of road sections prone to congestion, the model is set to select the arterial road as a one-way three-lane road with a width of 11.25 m. The ramp is a single lane with a width of 4 m, the intersection entrance angle is 30°, and the connection is connected with a circular arc with a radius of 4 m. The geometric model is shown in Figure 1 (b).

For the non-recurrent congestion, in the normal urban road driving process, the outermost lane may cause more accidental traffic congestion due to parking, right turn, large traffic volume, adjacent to non-motorized lanes and other reasons. Therefore, this paper deducts a trapezoidal area on the right side of the road to simulate the accident area. The model road parameters are a one-way three-lane width of 11.25 m, the trapezoidal height of the accident area is 2.5 m, the top edge width is 6 m, and the bottom edge width is 18 m. The geometric model is shown in Figure 1 (c).

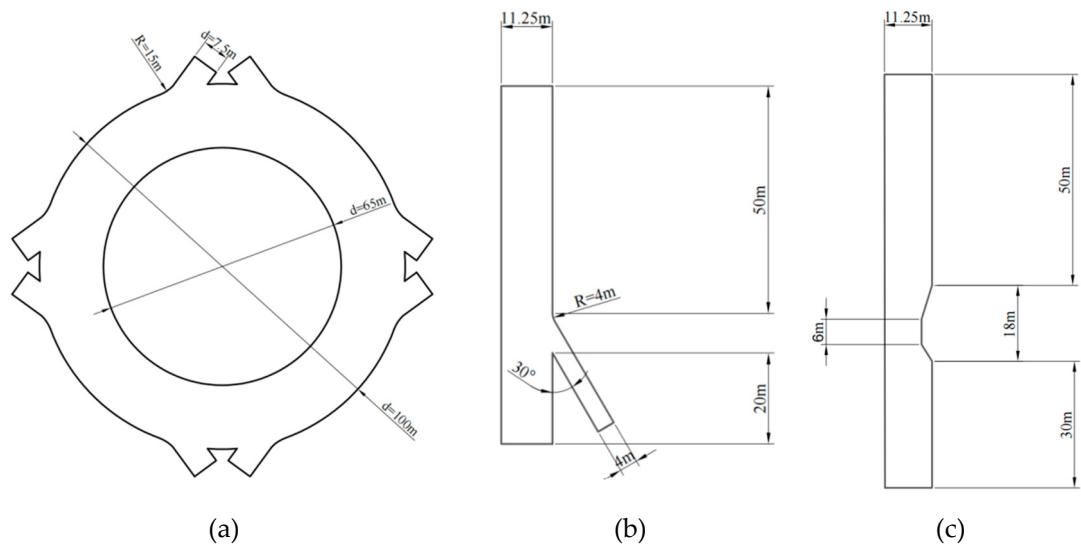


Figure 1. Geometrical model diagram

11. Mesh control strategy

To improve the calculation accuracy, the boundary region is refined. The maximum and minimum values of the mesh element mass are in the range of 0 ~ 1. The mesh quality of each model is shown in Table 2. The grid division diagram and boundary condition setting are shown in Figure 2.

Table 2. The proportion of grid quality of each model

Mesh quality	<0.3	0.3~0.4	0.4~0.5	0.5~0.6	0.6~0.7	0.7~0.8	0.8~0.9	0.9~1.0
Roundabout	0.000%	0.107%	1.712%	0.194%	0.854%	1.238%	4.537%	91.358%
On-ramp merging area	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.004%	99.996%
Non-recurrent congestion	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	100%

The above data indicates that the meshing is of good quality and meets the meshing criteria.

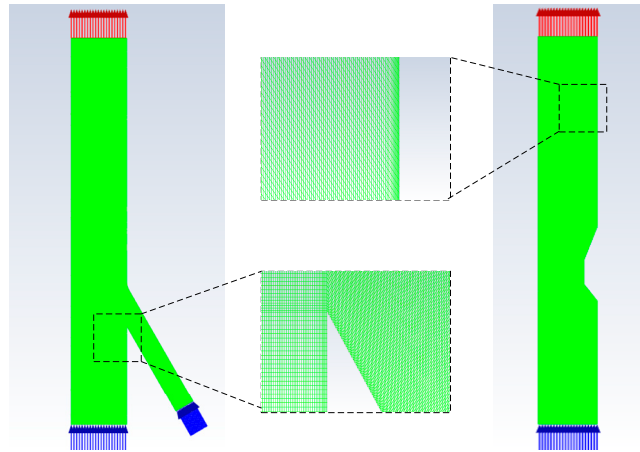


Figure 2. Mesh division and boundary condition setting of each model.

12. Parameter setting

In this paper, the simulation experiment is carried out by Fluent software. The solution type is configured to be based on pressure. The speed format is set to absolute, and the steady-state solution is solved. The solution method is set to SIMPLEC. The boundary conditions are set to select the standard (2eqn) model. The wall function is used to select the standard wall function. The flow phase material is water-liquid, and the inlet boundary conditions are set as the velocity inlet. For the roundabout, the speed of each entrance is set to 30km/h. For on-ramp merging area, the arterial road entrance speed is 60km/h, and the ramp entrance speed is 30km/h; especially, for non-recurrent congestion, the entrance speeds are set to 20km/h, 30km/h, 40km/h, 50km/h, and 60km/h, respectively. The outlet condition is the pressure outlet, the initial gauge pressure is 0, and the backflow is suppressed. The wall is set to a static wall with standard roughness.

2.3. Control Equations

1. Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (1)$$

where ρ is the density, t is the time, u and v are the components of the velocity vector in the x and y directions.

Since the simulation chooses a steady state environment where the density does not vary with time, equation (1) can be expressed as:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (2)$$

2. Turbulent kinetic energy equation:

The turbulent viscosity governing equations in this study are calculated using the standard $k - \varepsilon$ (2 eqn) model as follows.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + G_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (4)$$

Where G_k is the generation term for turbulent energy k due to the mean velocity gradient, G_b is the generation term for turbulent energy k due to buoyancy, and Y_M represents the contribution

of pulsation expansion in compressible turbulence, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are empirical constants, $C_{3\varepsilon}=0$ when the main flow direction is perpendicular to the direction of gravity, and the default constants $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_\mu=0.09$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$.

When the flow is unpressurised and no user-defined source terms are considered, $G_b=0$, $Y_M=0$, $S_k=0$, $S_\varepsilon=0$. At this time, the standard $k-\varepsilon$ model becomes:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \quad (5)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_{1\varepsilon} \varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (6)$$

2.4. Analysis of Fluid Properties

In order to verify the consistency between the simulation in Fluent and the actual operation of urban roads, Fluent software was used to analyze the congestion area of the roundabout, and the species transport model was selected to ensure that the traffic flow at each entrance can be transmitted to each exit. The simulation output results are shown in Figure 3.

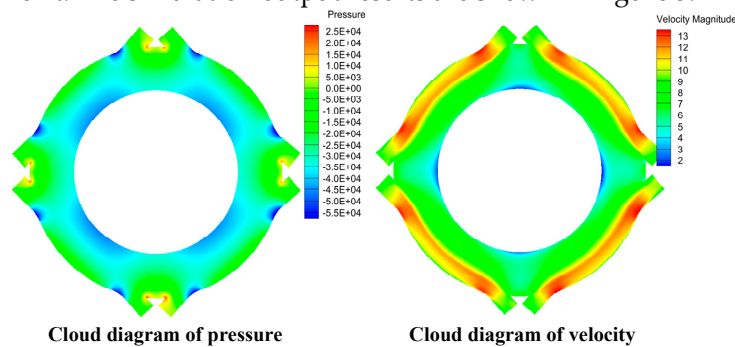


Figure 3. Pressure cloud and velocity cloud at ring intersection.

From Figure 3, the pressure at the entrance and exit of the ring intersection is higher, this is because the vehicle entering the ring has a conflict point with the vehicle leaving the ring, resulting in the deceleration of the vehicle. When the traffic flow is large, it will cause congestion, which is consistent with the actual results. The minimum speed in the intersection is 4.32km/h, and the maximum pressure is 26451.9Pa. According to the pressure cloud diagram and the velocity cloud diagram, the pressure of the inner ring road is slightly lower than that of the outer ring road, and the velocity of the inner ring road is also slightly smaller than that of the outer ring road, which is consistent with the actual situation. Therefore, Fluent can be used to study some urban road traffic flow.

When using Fluent software to calculate the established model, due to the local stress concentration caused by the geometric shape of the model, there is a certain error in the local data, especially the influence on the speed is too large, so in the later model simulation, the pressure is used as the index of traffic congestion degree.

3. Design and Analysis

3.1. Recurrent Congestion

The current methods of solving the problem of recurrent traffic congestion all suffer from the problems of the large amount of work and high cost of money. For roundabouts, a large number of literature have proved that the geometric shape of the roundabout is the main determinant of the capacity and performance of the roundabout [24–28], for the traffic congestion problem at the

roundabout, most scholars choose to transform the roundabout, and the solutions can be summarized into three types [29]: 1) Remove the roundabout to a level crossing; 2) Adopting traffic signals to control the vehicles entering the roundabout; 3) Geometric transformation (import approach, division of special lanes). However, for the on-ramp merging area, most scholars' studies are focused on-ramp traffic flow characteristics research, ramp coordination control, expressway intersection area capacity research, etc. Through the establishment of a model to detect and control the traffic flow in real-time, so that the vehicle to replace the optimal route or control the vehicle to enter the waiting for the congestion to dissipate [30–33]. Therefore, this paper starts from the mechanism of traffic congestion, and deeply explores the causes of traffic congestion, especially for the traffic flow characteristics at intersections, with the lowest resource input to achieve effective mitigation of traffic congestion at intersections..

3.1.1. Roundabout

It can be observed from the pressure cloud diagram in Figure 3 that the peak pressure is at the entrance of the roundabout, which indicates that the inflow of the entrance traffic flow may hinder the normal driving of the vehicles in the ring. To weaken this effect, the influence of different angles of road entrance at the roundabout on the congestion pressure at the intersection will be studied. The road entrance angles are set to 15°, 20°, 25°, 30°, 35°, 40° and 45° respectively, and detailed traffic flow simulation analysis is carried out for each angle configuration. In order to better analyze the pressure characteristics at each location of the roundabout, four key monitoring points are selected as shown in Figure 4: point A is located at the center of the intersection entrance, point B corresponds to the projected position of the midpoint of the entrance on the inner ring road, point C is located on the side of the inner ring road close to the outer ring road, and point D is close to the inner ring road. The pressure cloud diagram of each inlet angle is shown in Figure 5. It can be seen from Table 3 that the pressure values at each point correspond to the entrance angle of each road.

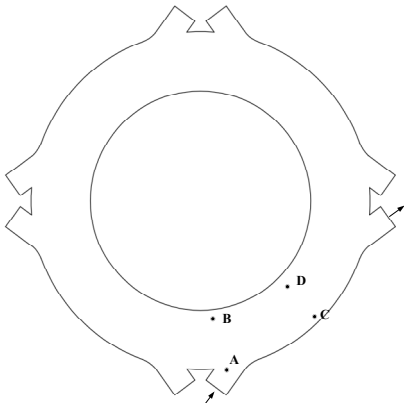


Figure 4. The key points for roundabout

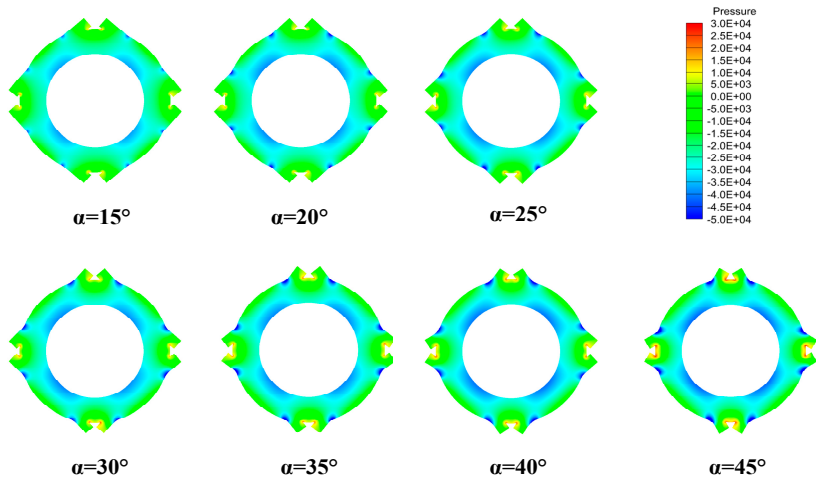


Figure 4. Pressure cloud for each inlet angle at the roundabout

Table 2. The proportion of grid quality of each model

Angle	15	20	25	30	35	40	45
A	-12032	-11938	-11847	-11283	-11017	-10567	-9794
B	-25896	-27108	-27714	-29913	-29087	-28326	-29956
C	-13067	-13418	-12588	-12194	-12229	-12031	-11566
D	-35945	-37327	-37606	-38781	-39618	-38849	-39982
MAX	27992	28179	28811	29442	30173	31285	33493

The internal pressure of the roundabout is an important index to measure the degree of traffic congestion. According to Figure 6, it can be observed that with the decrease of the entrance angle, the overall pressure inside the intersection shows a downward trend. Especially when the inlet angle is reduced from 45° to 35°, the reduction of the maximum pressure is particularly significant. Therefore, in order to effectively alleviate the congestion of the roundabout, it is recommended to set the entrance angle below 35°. However, it must also be taken into account that a smaller entrance angle means that more land area is required to construct the entrance road. For example, when the inlet angle is further reduced from 20° to 15°, the maximum pressure value is reduced by only 0.7%, which is the smallest change in all observed intervals, and according to the observation, the pressure reduction is gradually reduced with the decrease of the angle. Therefore, on the premise of taking into account the economic cost and local road land conditions, To effectively alleviate traffic congestion, it is recommended to set the entrance angle between 20° and 35°.

In addition, Figure 6 also reveals the pressure change trend of lane points A and C in the outer ring and lane points B and D in the inner ring. For points A and C, as the inlet angle increases, the pressure value also increases. When it increases from 15° to 45°, the pressure changes by 19.7% and 11.5%, respectively. On the contrary, for points B and D, the pressure decreases with the increase of the inlet angle. Similarly, from 15° to 45°, the pressure changes by 13.6% and 10.1%, respectively. These data indicate that when the inner ring lane of the roundabout is subjected to greater traffic pressure, an appropriate increase in the entrance angle may help relieve the pressure, although the effect may not be significant. On the contrary, when the traffic pressure of the outer ring lane and the entry/exit points is high, appropriately reducing the entrance angle will more effectively improve the congestion situation in the intersection.

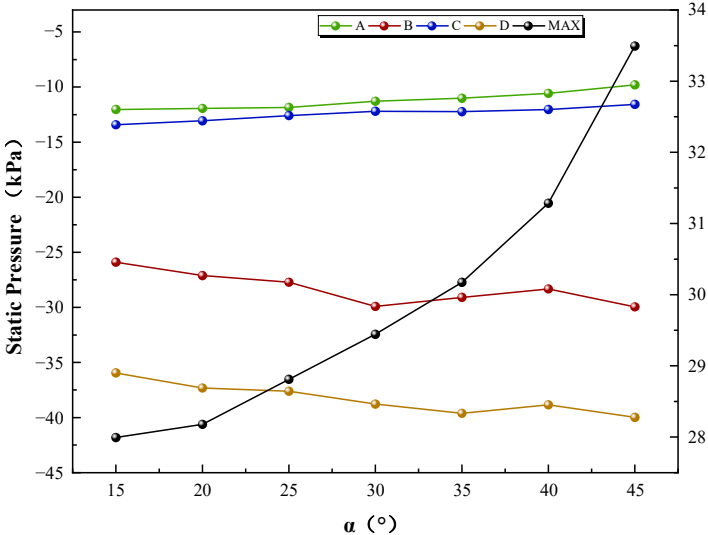


Figure 6. Relationship between inlet angle and pressure at the roundabout.

3.1.2. On-Ramp Merging Area

Analyze the congestion area at the ramp merge confluence. There are two design modes of the intersection ramp confluence road, one is the parallel ramp and the other is a direct ramp. Among them, the parallel design is regarded as a special case of the road intersection angle of 0°, which is studied together with the direct ramp. In order to study the influence of road entrance angle on the congestion pressure at the ramp merge, this paper establishes models with different entrance angles. The road entrance angles are set to 0° (parallel ramp), 15°, 30°, 45°, and 60°. And two key monitoring

points A and B shown in Figure 7 are selected for auxiliary analysis. The pressure cloud diagram of each entrance angle is shown in Figure 8. In addition, the pressure values at each point corresponding to each road inlet angle can be seen in Table 4.



Figure 7. The key points for on-ramp merging area

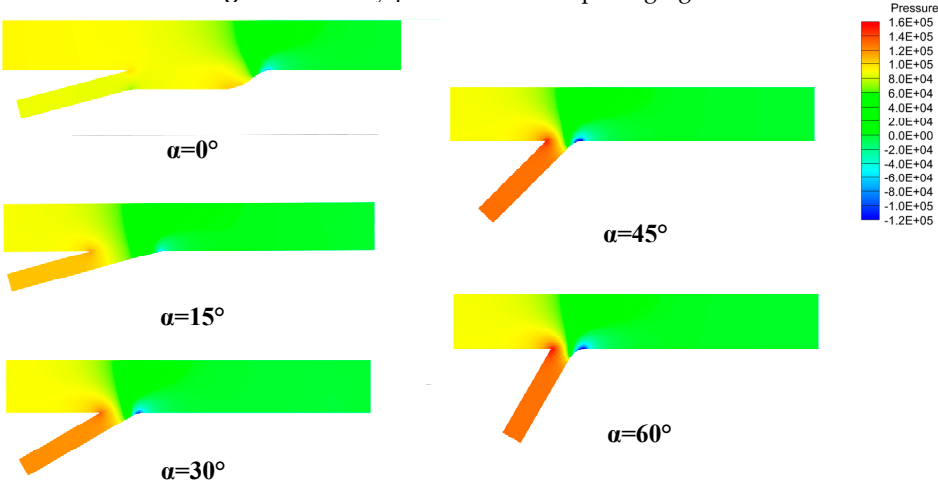


Figure 8. Pressure cloud for each inlet angle at the on-ramp merging area

Table 4. The key point pressure value of each inlet angle at the on-ramp merging area

Angle	0°(parallel ramp)	15°	30°	45°	60°
A	91912	96281	97346	98038	106239
B	95156	112889	116622	128963	129311
MAX	111555	124041	134750	150407	152261

According to Figure 9, with the decrease of the entrance angle, the traffic pressure of the road shows a downward trend. Specifically, when the entrance angle is adjusted from 60° to the parallel ramp, the traffic pressure at point A is reduced by 13.5%, the traffic pressure at point B is reduced by 26.5%, and the overall maximum pressure value is reduced by 26.8%. Therefore, to effectively alleviate traffic congestion, it is recommended to use a smaller ramp confluence angle as much as possible when conditions permit, and a parallel ramp entrance design is recommended. This design can extend the weaving section of the vehicle and provide more space for the vehicle to accelerate or decelerate, thereby reducing congestion and traffic accidents.

However, when the actual conditions limit the implementation of parallel ramp entrances, consideration should also be given to minimizing the confluence angle of the ramp. In the chart, the pressure change of point A is only 9.4% in the angle range of 15° to 60°, and within the subset of this range, from 15° to 45°, the pressure change is only 1.8%, indicating that point A is less sensitive to angle change within this specific range. The pressure changes of point B at 15° to 30°, 45° and 60° are 3.3%, 12.5% and 12.7%, respectively, showing a high sensitivity to angle changes. This shows that adjusting the confluence angle of the ramp has a limited impact on the traffic pressure of the arterial road, but it has a significant impact on the pressure of the ramp itself. Therefore, it is concluded that for specific confluence intersections, if the ramp pressure is high, the confluence angle of the ramp should be reduced to relieve the pressure. On the contrary, if the arterial road pressure is high, it should be considered to be transformed into a parallel ramp entrance to effectively reduce traffic pressure.

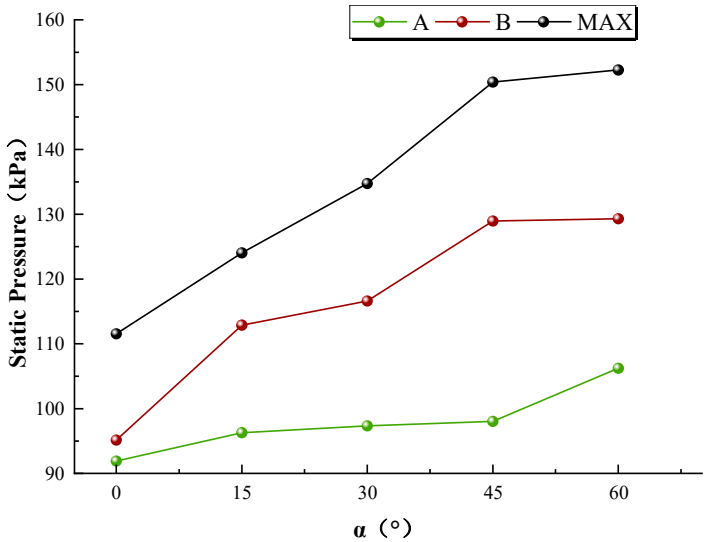


Figure 9. Relationship between inlet angle and pressure at the on-ramp merging area

3.2. Non-Recurrent Congestion

Non-recurrent congestion refers to short-term traffic congestion caused by unexpected events or special circumstances. These situations may include accidents, bad weather, temporary road closures or large-scale events. In reality, the common cause of non-recurrent congestion in urban roads is traffic accidents, thus this paper only analyses this type.

The non-recurrent congestion studied in this paper can be regarded as the narrowing of the road. The continuity equation shows that there is an inverse relationship between the cross-sectional area of the fluid passing through the pipeline and the flow rate under the condition of constant mass flow. When the cross-sectional area decreases, the fluid must be accelerated to maintain a constant flow rate. This acceleration leads to an increase in flow velocity. Bernoulli's law shows that the increase in fluid velocity will lead to a decrease in pressure. Therefore, when the fluid passes through the details in the flow tube, the flow rate becomes larger and the pressure becomes smaller. The dynamic pressure represents the pressure effect generated by the fluid flow. The dynamic pressure arises due to the fact that when an object is moving in a fluid, the surface fluid directly opposite to the direction of the fluid movement is completely obstructed and its kinetic energy is converted into pressure energy, increasing pressure. According to the observation, the dynamic pressure cloud diagram is consistent with the actual traffic pressure, so the non-recurrent congestion uses the dynamic pressure as the pressure index.

When dealing with non-recurrent congestion, an effective mitigation strategy is to deploy diversion measures in the upstream area of the accident site to implement early traffic guidance and speed regulation. In order to deeply analyze the traffic pressure characteristics of each key area, this study selected two key detection points A and B as shown in Figure 10 to assist the analysis. The velocity and pressure contours of each inlet are shown in Figure 11. From Table 5, it can be seen that the key point pressure value and the maximum pressure correspond to the inlet velocity of each road.



Figure 10. The key points for non-recurrent congestion

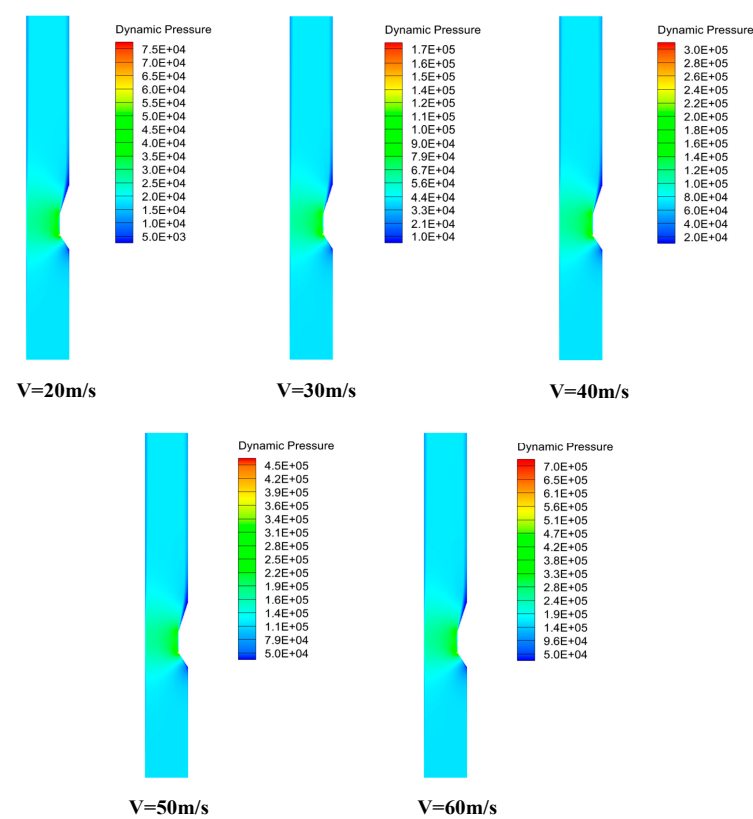


Figure 11. Pressure cloud for each entrance speed at non-recurrent congestion

Table 5. The key point speed value of each entrance speed at non-recurrent congestion

Velocity	20km/h	30km/h	40km/h	50km/h	60km/h
A	18105	40718	72365	113045	162757
B	31945	71839	127713	199577	287447
MAX	80171	181325	322934	504728	726482

According to Figure 12, with the increase of inlet setting speed, the pressure value of each point is on the rise, especially the change of maximum pressure value is more significant. However, in practice, higher speed means that more vehicles pass through the accident section. Therefore, under actual road conditions, the pressure value at higher speed should be theoretically lower than the experimental data. Although the pressure value of the key points increases with the increasing speed, the increase of the pressure value is different at the same speed range. It is concluded that the lower the speed required at the traffic control, the pressure value at the accident will decrease accordingly, but the magnitude of this decrease will gradually decrease. In addition, when the speed is low and the traffic volume is large, it may cause long-distance congestion in the rear of the accident. Therefore, the vehicle speed should be adjusted according to the actual traffic flow to avoid long-term traffic congestion.

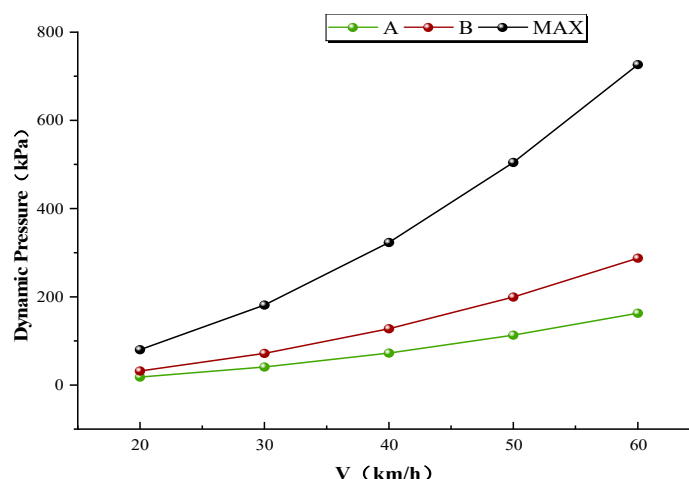


Figure 12. Relationship between inlet speed and pressure at non-recurrent congestion

3.3. Results and Discussion

For the roundabout, compared with the original 30° entrance angle, setting the entrance angle to 20° can alleviate traffic congestion and reduce the amount of work. For the on-ramp merging area, the optimal scheme is to convert the 30° direct ramp into the parallel ramp. Although the engineering scale is relatively large, it has an obvious effect on alleviating traffic pressure. For non-recurrent congestion, the optimal solution is to control the vehicle speed to 30km/h, which can not only enable drivers to make accurate lane change judgments, avoid more serious accident congestion caused by excessive vehicle speed, but also avoid excessive queuing caused by too slow vehicle speed.

4. Conclusion

Based on the similarity between fluid dynamics and urban traffic flow, this paper verifies the fluid dynamics characteristics of traffic flow through the continuum medium hypothesis and then adopts CFD theory to model and simulate urban traffic flow. The main conclusions are as follows :

(1) CFD applies to the study of traffic flow. On the theoretical level, through the similarity analysis of traffic flow and fluid and the transformation of eigenvalue parameters, the theoretical basis of CFD applied to traffic flow is established. The output results in the simulation are the same as the actual traffic flow, which verifies the applicability of CFD theory in traffic flow research.

(2) For recurrent congestion, reducing the intersection angle of the road can effectively improve the traffic pressure. For the roundabout, when conditions permit, changing the inlet angle from 45 degrees to 15 degrees reduces the pressure at the inlet by 19.2%, and the maximum pressure value in the ring can be reduced by 16.4%; For the on-ramp merging area, when conditions permit, the ramp is changed from a direct ramp with an entrance angle of 60° to a parallel ramp. The traffic pressure on the main road is reduced by 13.5%, the ramp is reduced by 26.5%, and the maximum pressure value in the road is reduced by 26.7%. The setting of the entrance angle of the intersection has a great influence on the traffic flow pressure. To obtain higher traffic capacity, it should be considered in the design and transformation of the intersection.

(3) For non-recurrent congestion, deceleration guidance upstream is conducive to the smooth passage of vehicles through the accident section. In the range of 20km/h to 60km/h, the accident section shows a significant change in pressure. The smaller the speed of traffic control, the lower the pressure of the accident section. In reality, a long queue may be formed, but it will reduce the probability of accidents. The vehicle speed should be properly controlled according to the actual traffic flow to obtain higher capacity.

In summary, this study provides valuable CFD-based information on how different road conditions affect road traffic flow pressure, thus helping traffic engineers make better urban road design decisions.

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References

1. Zeng, J.; Qian, Y.; Wang, B.; Wang, T.; Wei, X. The impact of traffic crashes on urban network traffic flow. *Sustainability* **2019**, *11*, 3956. <https://doi.org/10.3390/su11143956>
2. Su, C. Optimization and evaluation of urban road roundabouts. Master's Thesis, Fujian Agriculture and Forestry University, Fujian, China, 2016. https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLy3j3003PUilqaxJnqanxwx-1iCg2GH8OTFO6x9ssvXIUQfRI6FfqVzpSqWrUvI28mh2KABVEO8NP_ML3spp_Jd3IgM035GK1UgPUG7Tmb_qdbVyZl_rvvqs5WduPjnYgXTMSjK158yxehydZ6CMD-aKWxtVD_Pxdb0=&uniplatform=NZKPT
3. Sun, X.; Ma, W.; Huang, W. Comparative study on the capacity of a signalised roundabout. *IET Intelligent Transport Systems* **2016**, *10*, 175-185. <https://doi.org/10.1049/iet-its.2014.0310>
4. Wang, J.; Zhao, X.; Yin, G. Multi-objective optimal cooperative driving for connected and automated vehicles at non-signalised intersection. *IET Intelligent Transport Systems* **2019**, *13*, 79-89. <https://doi.org/10.1049/iet-its.2018.5100>
5. Zheng, Z. Research on cooperative control strategy of unsignalized intersection for intelligent connected vehicles. Master's Thesis, Shandong Jiaotong University, Shandong, China, 2023. https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLy3h8GSEH1K-n3ArRo_FEJZZXkU3mgu1dYNH_v4UPdTXwa7DVpnNBZkCZVDqtY04TxfODcyJD6hHsIxsOUkQjgPALn6YQhCqoqJfSNfIL17zevCwwHJFTYsbuwwgc78BzoiwbT1fjOBydX32mHGK7547cDAM8brbojec=&uniplatform=NZKPT
6. Zhou, A.; Peeta, S.; Yang, M.; Wang, J. Cooperative signal-free intersection control using virtual platooning and traffic flow regulation. *Transportation research part C: emerging technologies* **2022**, *138*, 103610. <https://doi.org/10.1016/j.trc.2022.103610>
7. Baldi, S.; Michailidis, I.; Ntampasi, V.; Kosmatopoulos, E.; Papamichail, I.; Papageorgiou, M. A simulation-based traffic signal control for congested urban traffic networks. *Transportation Science* **2019**, *53*, 6-20. <https://doi.org/10.1287/trsc.2017.0754>
8. Ma Q.; Zhang S.; Zhou Q. Development of a conflict-free unsignalized intersection organization method for multiple connected and autonomous vehicles. *PLOS ONE* **2021**, *16*: e0249170. <https://doi.org/10.1371/journal.pone.0249170>
9. Wang, Q. Research on subway passenger flow model based on fluid mechanics theory. Master's Thesis, Dalian Jiaotong University, Liaoning, China, 2018. https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLy3iAvJLFO6sBAijuEMFjRfBf5rW9KHZcpmpHE9KB9OvuP5i6eD5goVdi7l6x7QEThGZ9j1R3zKE_fee8xJ4JG_Qx6cKf7lBlkxoLuZZEXel7Rfs3URIGMmjQCKtnh4Na56agZuFNFQCrHdaUyOdGpBs9HZH8rBirV4=&uniplatform=NZKPT
10. Henderson, L. F. On the fluid mechanics of human crowd motion. *Transportation research* **1974**, *8*, 509-515. [https://doi.org/10.1016/0041-1647\(74\)90027-6](https://doi.org/10.1016/0041-1647(74)90027-6)
11. Roger, L. H. A continuum theory for the flow of pedestrians. *Transportation Research Part B: Methodological* **2002**, *36*, 507-535. [https://doi.org/10.1016/S0191-2615\(01\)00015-7](https://doi.org/10.1016/S0191-2615(01)00015-7)
12. Lighthill, M. J.; Whitham, G. B. On kinematic waves I. Flood movement in long rivers. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* **1955**, *229*, 281-316. <https://doi.org/10.1098/rspa.1955.0088>
13. Richards, P. I. Shock waves on the highway. *Operations Research* **1956**, *4*, 42-51. <https://doi.org/10.1287/opre.4.1.42>
14. Ren, F.; Liu, X.; Rong, J.; et al. *Traffic Engineering*, 2ed ed.; China Communications Press: Beijing, China, 2008; pp. 124.
15. Newell, G. F. A simplified theory of kinematic waves in highway traffic, part I: General theory. *Transportation Research Part B: Methodological* **1993**, *27*, 281-287. [https://doi.org/10.1016/0191-2615\(93\)90038-C](https://doi.org/10.1016/0191-2615(93)90038-C)
16. Newell, G. F. A simplified theory of kinematic waves in highway traffic, part II: Queueing at freeway bottlenecks. *Transportation Research Part B: Methodological* **1993**, *27*, 289-303. [https://doi.org/10.1016/0191-2615\(93\)90039-D](https://doi.org/10.1016/0191-2615(93)90039-D)
17. Huang, D.; Shere, S.; Ahn, S. Dynamic highway congestion detection and prediction based on shock waves, dynamic highway congestion detection and prediction based on shock waves. *Proceedings of the Seventh ACM International Workshop on Vehicular InterNetworking (VANET '10)*, ACM, New York, USA, 2010, pp. 11-20. <https://doi.org/10.1145/1860058.1860061>
18. Li R. Research on passenger flow model at subway platform based on fluid mechanics theory. Master's Thesis, Beijing Jiaotong University, Beijing, China, 2012. <https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLy3g2IvzZ3POxSYSBbRu3z3AmX7oS2a3S4JnaFlX>

- CdHhJIDnBSgJR6DS-DncD1z8VPJtjM4xwdNyyW9HDGHYNba0laa2Gk4ENS6r1l2XDU-gZfGXB4khhEwhIc4OlvO1exu66SuMwdok7npPapklAwHwRA8PQuNWyc=&uniplatform=NZKPTLi, J.; Wang, F.; He, Y.; *Traffic Engineering*. 1st ed; Peking University Press: Beijing, China, 2010; pp. 85-87
19. Li, J.; Xiong, L.; Peng, S. Dynamic model of mixed traffic flow. *Journal of Wuhan University of Technology (Traffic Science and Engineering)* **2006**, *02*, 362-364. <https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLyT3g7OrQjA75e4l2fvTs83mQ7-4ZXyQR0VgLYCeKzpj70gx28beGQALYtvGvuPJKbpb223bi-tXP2WoSFQjxfhEJmckEmCQ1-O7AegKoiVde8YPqouBEz4c5JqzRjGmhiA3uW-2g8l1clyv0NfcDKBdOR&uniplatform=NZKPT>
 20. Xiong, L.; Wang, Y.; Li, J. Theory, model and application of traffic flow dynamics. *Journal of Harbin Institute of Technology* **2006**, *05*, 732-734. https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLyT3iiYYBxJ75Zgh1ZqINajDcOel81lIUipdzymgazDhG8klw1j2Hp45up4e58noIWzZejOW_lSrUUKBNJxxbv0rmkQj95s6FBwuvfV0ua758GJ8uLu1LiWuPQFpHT5626SgaUyJd06fBcBsYdsuA8Qjiq&uniplatform=NZKPT
 21. Xiong, L.; Liu, H. Calibration of the relationship model between mixed traffic flow parameters. *Journal of Wuhan University of Technology (Transportation Science and Engineering)* **2008**, *03*, 561-564. https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLyT3iXC0f3XRtlOmgIzZ8fOMv8V-YyF6ekvmhcQuIyOoma1oE8BbNEAY-KrAASRNTrMDMYAt3IzY3LFpLc8ZxopBtP2_yOKIE60TD4ZZLADvrV6AwnsHwFV3mpAHR-XlhOmK3muLhikdURu2PSI6KcNRpP&uniplatform=NZKPT
 22. Sun, D.; Lv, J.; Waller, S. T. In-depth analysis of traffic congestion using computational fluid dynamics (CFD) modeling method. *Journal of Modern Transportation* **2011**, *19*, 58-67. <https://doi.org/10.1007/BF03325741>
 23. Hatem, M. K.; Qasim, G. J. Simulation Traffic Flow in Urban Arterial Streets Using CFD (Army Canal Street as a Case Study). In *IOP Conference Series: Materials Science and Engineering* **2021**, *1105*, 012105. <https://doi.org/10.1088/1755-1315/692/4/042102>
 24. Tian, Z. Z.; Troutbeck, R.; Kyte, M.; Brilon, W.; Vandehey, M. A. R. K.; Kittelson, W.; Robinson, B. A further investigation on critical gap and follow-up time. In *Proceedings of the 4th International Symposium on Highway Capacity*, Maui/Hawaii, Transportation Research Circular E-C018 2000; pp. 409-421. <http://worldcat.org/issn/00978515>
 25. Murphy, T. The Turbo Roundabout: A First in North America. In *Proceedings of the 2015 Conference of the Transportation Association of Canada 2015*, Charlottetown, PE, Canada, 27-30 September 2015 <https://www.tac-atc.ca/en/knowledge-centre/technical-resources-search/conference-papers/the-turbo-roundabout-a-first-in-north-america/>
 26. Vasconcelos, L., Seco, Á., & Silva, A. B. Comparison of procedures to estimate critical headways at roundabouts. *Promet-Traffic&Transportation* **2013**, *25*, 43-53. <http://hdl.handle.net/10400.19/1603>
 27. Ma, W., Liu, Y., Head, L., & Yang, X. Integrated optimization of lane markings and timings for signalized roundabouts. *Transportation research part C: emerging technologies* **2013**, *36*, 307-323. <https://doi.org/10.1016/j.trc.2013.08.013>
 28. Mauro, R.; Cattani, M. Functional and economic evaluations for choosing road intersection layout. *PROMET-Traffic&Transportation* **2012**, *24*, 441-448. <https://doi.org/10.7307/ptt.v24i5.1180>
 29. Gao X.; Zhu R.; Jin W. Reconstruction design of urban road roundabout. *Traffic Technologies* **2009**, *S2*, 133-136. https://kns.cnki.net/kcms2/article/abstract?v=hFA5SNLyT3iU0gdS5pTj8q8L9h9LEL_XRq2rI_XRrN0zCGjHfVMJfoGIGFeFmAv2Jk_spPSDijspJKCUEPb2TEhDj1DEv-i6E9WLZdjHrmiLGnanfBycvga3UUD3CECX&uniplatform=NZKPT&language=CHS
 30. Zhao, J.; Ma, W.; Xu, H. Increasing the capacity of the intersection downstream of the freeway off-ramp using presignals. *Computer-Aided Civil and Infrastructure Engineering* **2017**, *32*, 674-690. <https://doi.org/10.1111/mice.12281>
 31. Zhao, J.; Liu, Y. Integrated signal optimization and non-traditional lane assignment for urban freeway off-ramp congestion mitigation. *Transportation Research Part C: Emerging Technologies* **2016**, *73*, 219-238. <https://doi.org/10.1016/j.trc.2016.11.003>
 32. Liu, Z.; Wu, Y.; Cao, S.; Zhu, L.; Shen, G. A ramp metering method based on congestion status in the urban freeway. *IEEE Access* **2020**, *8*, 76823-76831. <https://doi.org/10.1109/ACCESS.2020.2990646>
 33. Shaw, L. On optimal ramp control of traffic jam queues. *IEEE Transactions on Automatic Control* **1972**, *17*, 630-637. <https://doi.org/10.1109/TAC.1972.1100093>

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