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# Traffic Flow Catastrophe Border Identification for Urban High-Density Area Based on Cusp Catastrophe Theory: A Case Study under Sudden Fire Disaster

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**Abstract:** For traffic management under sudden disasters in high-density areas, the first and foremost step is to prevent traffic congestion in the disaster-affected area by traffic flow management and control, so as to provide enough and flexible traffic capacity for emergency evacuation and emergency rescue. Catastrophe border identification is the foundation and the key to traffic congestion prediction under sudden disaster. This paper uses a mathematical model to study the regional traffic flow in the high-density area under sudden fire disaster based on the Cusp Catastrophe Theory (CCT). The catastrophe border is identified by fitting the CCT-based regional traffic flow model to explore the stable traffic flow changing to the instable state, as to provide a theoretical basis for traffic flow management and control in disaster-affected areas, and to prevent the traffic flow being caught into disorder and congestion. Based on VISSIM simulator data by building simulation scenarios with and without sudden fire disaster in a Sudoku traffic network, the catastrophe border is identified as 439 pcu/lane/h, 529 pcu/lane/h, 377 pcu/lane/h at 5 s, 10 s, 15 s data collection interval in a Sudoku traffic network respectively. The corresponding relative precision, which compares to the method of Capacity Assessment Approach (CAA), is 89.1%, 92.7% and 76.5% respectively. It means that 10 s data collection interval would be the suitable data collection interval in catastrophe border identification and regional traffic flow control in high-density area under sudden fire disaster.

**Keywords:** catastrophe border identification; traffic congestion; dynamic traffic management; risk management; cusp catastrophe theory; VISSIM

## 1. Introduction

With the rapid development of China's social economy and the accelerating urbanization process, population, buildings, wealth and other infrastructures are more highly concentrated in urban areas. Cities, especially urban centers, have gradually formed in a high-density state [1]. The high-density characteristics of spatial structure, population, buildings and wealth make the urban safety system more fragile, with more potential disaster, higher disaster risk, harder in identification of disaster sources, more complicated in disaster risk management, more serious in damage and loss, and so on [2].

With the characteristics of high density, high intensity and high complexity, these urban center areas present a situation of multiple disasters and secondary disasters coexisting and concurrent. These disasters include natural disasters and man-made disasters. They are traditional disasters or new types of disasters (such as virus infection, terrorist). These situations make disaster management more

difficult to control and withstand. In addition, the disaster is easier to propagate and diffuse in a high-density environment [3]. Under the disaster-formative environment and with the disaster-prone characteristics, the high-density urban area has become the core and critical area in urban disaster prevention and mitigation [4]. The research on the high-density urban central area disaster prevention and mitigation system has become the basic premise and difficult problem in ensuring urban security and keeping sustainable urban development [5].

Emergency traffic management and control plays an important role in the disaster prevention and mitigation, especially in urban high-density area under sudden disaster. Fast and effective emergency traffic management and control can significantly reduce the losses of life and property, and other losses caused by disaster. According to the statistical from government authorities, effective emergency traffic management and control can reduce the disaster losses to 6% of that without emergency traffic management and control under sudden disaster [6].

Furthermore, the concentration of facilities in high-density urban areas, strained traffic land, and frequent activities of residents make the contradiction between traffic demand and traffic supply more prominent. According to the statistics data from urban traffic authorities, in central areas of most large and medium-sized cities in China, 90% of the road network is saturated or supersaturated during the peak hours [7], and even the traffic congestion has become normalized within the urban centers in some cities [8,9]. Under such high-density area and crowded traffic circumstances, if a sudden disaster breaks out, the road traffic system which is supposed to play an emergency safe-guarder in urban disaster prevention, disaster mitigation and relief, may have adverse effects on disaster relief due to traffic congestion in the traffic route of emergency rescue.

In addition, when the traffic agents responding to urban sudden disasters, they often rely on administrative procedures or historical experiences, especially in organizing the emergency traffic safeguard measures, developing the traffic control strategies. Due to the characteristics of uncertainty, randomness, diversity and information incompleteness, a sudden disaster is hard to predict and control by traffic agents. Therefore, it is difficult to analyze and identify the traffic aggregation, propagation and distribution promptly and accurately under sudden disaster by traffic agents [10]. For traffic management under sudden disaster in high-density area, the first and foremost step is to prevent traffic congestion in the disaster-affected area by traffic flow management and control, as to provide enough and flexible traffic capacity for emergency evacuation and emergency rescue. Therefore, traffic flow's catastrophe border identification is the foundation and the key in regional traffic flow control under sudden disaster, which is the threshold to identify the state of traffic flow becoming unstable, disorder and congestion [11].

With the frequent occurrences of disasters all over the world, most countries have strengthened the theoretical and technical research on risk management, including disaster prevention planning, emergency resource allocation, and emergency evacuation. These researches mainly focus on large-scale natural disaster such as hurricane, earthquake. They used a highway or expressway network to simulate and evaluate the efficiency of emergency rescue, emergency evacuation and evacuation effectivity [10,12]. However, disasters in urban areas have become more frequent in recent years. These disasters demonstrated as happening in local positions, regional affected and required rapidly emergency response, such as sudden fire disaster, gas explosion, and road subsidence during metro construction. Due to the spatial-temporal uncertainty and multiplicities of urban small-scale disaster, the literature focusing on traffic flow analysis in urban high-density areas under sudden disasters is limited [13]. In addition, it is not conducive to make a scientific and effective emergency traffic management and control strategy to guarantee the disaster prevention, mitigation and relief work under sudden disaster in urban high-density areas.

Most urban high-density areas in China are in the old town of inner cities, the electrical and gas systems are older, degradation and prone to trigger sudden fire disaster. The reported sudden fire disasters were mainly caused by the ageing electrical and gas systems in the old towns of inner cities. Furthermore, with the aim of understanding the aggregation, propagation and distribution of traffic

flow in urban high-density area under sudden fire disaster, providing a theoretical basis method for traffic agents to manage and control regional traffic flow in disaster-affected area, and preventing the regional traffic flow being caught into disorder and congestion, This paper attempts to identify the catastrophe border of traffic flow in urban high-density area under sudden fire disaster. This study focuses on:

(1) Using catastrophe theory to analysis the traffic flow characteristics in urban high-density area under sudden fire disaster, modeling a regional traffic flow model based on Cusp Catastrophe Theory (CCT) to describe the changing of traffic flow and to identify the catastrophe border of traffic flow.

(2) For the aim of regional traffic flow control, using VISSIM simulator data with different data collection intervals to identify the catastrophe border, and analysis the suitable data collection interval for adaptive and automatic traffic control in sudden fire disaster.

The rest of the paper is organized as follows: Section 2 introduces the state-of-the-art research under fire disaster. Section 3 presents the proposed methods for analyzing traffic flow under sudden fire disaster. Simulation and calibration are presented in Sections 4 and 5 concludes the paper with contributions and limitations, as well as the perspectives on future work.

## 2. Literature Review

In the area of sudden fire disaster, researcher mainly focused on the evacuation problem over the last decade. Zheng [14] investigated the dynamics of pedestrian evacuation with the influence of the fire spreading. A numerical model based on cellular automaton was proposed by Yuan [15] to simulate the human behavior termed as flow with the stream, in emergency evacuation from a large smoke-filled compartment. Evacuation features from a terrace classroom were investigated by Xi [16] through simulations using both the models and experiments. A modified particle swarm optimization algorithm was proposed by Li [17] to investigate the dynamic of pedestrian evacuation from a fire occurred in a public building—a supermarket with multiple exits and configurations of counters. Sahin [18] proposed an approach which combines a multi-agent model with fuzzy logic to handle multiple behavior features of human-beings to simulate individual and group behavior during finding the safety egress. Delcea [19] used agent-based simulator to analyze the evacuation processes under the surrounding that a sudden fire happening in a classroom with two exits. In traffic networks, the studies mainly focused on sudden fire disasters happening in tunnels. Sýkora [20] designed a simple and realistic model to calculate the hazards and influences of sudden fire disasters occurring in tunnel. An optimal smoke control strategy was developed and evaluated for an urban traffic link tunnel fire in Beijing center business district by Hua [21], and using critical velocity, minimal smoke spreading area and available safe evacuation time to evaluate the performance of proposed model. Caliendo [22] presented a model to simulate the effects of sudden fire disasters due to different vehicle types in a bi-directional road tunnel. A set of full-scale experiments was conducted by Yu [23] to study thermal and smoke control strategies using transverse ventilation system in a sloping urban traffic link tunnel. The results showed that the slower spread velocity of the smoke, the better effective of control strategy. Experimental studies on the smoke spread characteristics in a titled tunnel were carried out with a reduced-scale tunnel model by Li [24].

On the topic of fire disasters, the studied scenes are mainly within the building and urban traffic link tunnel. The research contexts are mainly distributed in dynamic diffusion mechanisms of fire, emergency evacuation models, and traffic behaviors under fire disasters. However, the studies on traffic flow characteristics in the traffic network under sudden fire disasters are limited in the state-of-the-art research literatures. Traffic flow characteristics analysis is the foremost step in emergency traffic organization, such as evacuation route optimization, emergency vehicle dispatching, and traffic management and control in disaster-affected area. Therefore, this paper tries to analyze the traffic flow characteristics in urban high-density area under sudden fire disasters.

In traffic flow analysis, the traditional traffic flow theory using the relationship between traffic flow parameters to explain the traffic flow characteristics is intuitive and easy to understand. However, if the

road segment being saturated or supersaturated, it is difficult to describe the traffic flow characteristics accurately based on traditional traffic flow theory [11]. In urban high-density area, traffic aggregation and evacuation makes the traffic network congested under sudden fire disasters. The traffic flow characteristics are not suitable to describe by the normal two-dimensional relationship based on traditional traffic flow theory under this situation [25]. The catastrophe theory has the advantage in describing the mutation behavior of a system in natural or human society, such as biological variation, cell division, human behavior, congestion in public area. The processes of transition can be linear or nonlinear. It is widely used to recognize and predict the behavior of a complex system, especially in analysis the catastrophe changing from continuous changing status to discontinuous changing status with internal state variables [26–28]. In the area of traffic flow analysis, Dendrinou [29] used a two-dimensional catastrophe model to describe the relationship between traffic volume and VC ratio. Then, Navin [30] proposed a three-dimensional cusp catastrophe model in 1986, and analyzed the traffic flow characteristics based on cusp catastrophe using the volume, speed and density of traffic flow as internal state variables. Forbes and Hall [31] used the cusp catastrophe theory to analyze the traffic flow characteristics of Queen Elizabeth Avenue in Ontario during peak hours, and confirmed that using the relationship between volume, speed and density based on traditional traffic flow theory, cannot describe the traffic flow characteristics exactly, when the traffic network is in the saturated or supersaturated status.

In the area of traffic flow management and control under sudden disasters, there is growing demand for a computer-based simulation tool to evaluate the plans or strategies of traffic flow management and control under different scenarios, due to the lack of field data and experiences under different scenes and different sudden disasters. It is an important supportive tool in decision-making and choosing the optimal solution. Elmitiny [32] used the VISSIM traffic simulation tool to evaluate and to study the effect of evacuation plans and strategies with nine evacuation scenarios under the potential threats and attacks of public transit stations. The total network delay for each scenario was compared by using VISSIM simulator. Bahaaldin [33] used traffic micro-simulation software VISSIM to identify the locations where traffic incidents can significantly increase durations during a no-notice evacuation, so as to guide the operation engineers to focus on traffic incident management resources during evacuations. Liang [34] used VISSIM to simulate hurricane evacuation traffic in New Orleans, as to better understand evacuation behavior of mass evacuation in urban areas. Fabianova [35] used VISSIM to design and evaluation traffic control model, as to minimize traffic congestion in the traffic network. Chen [36] used VISSIM to set up different control strategies to evaluate the performance of the proposed algorithm, as to alleviate traffic congestion in freeway network of Shanghai. From the literatures, microscopic traffic flow simulations (such as VISSIM, CORSIM, TransModeler) are widely used in model calibration and validation, design plan and control strategies evaluation under different scenarios. Based on the flexibility of scenarios design and responsibility of traffic flow simulation, this paper used the VISSIM simulator to calibrate and validate the proposed model under sudden fire disasters.

### 3. CCT-Based Traffic Flow Model

#### 3.1. Cusp Catastrophe Theory

In mathematics, catastrophe theory is a branch of bifurcation theory in the study of dynamical systems, which studies and classifies phenomena characterized by sudden shifts in behavior arising from small changes in circumstances. Small changes in certain parameters of a nonlinear system can cause equilibria to appear or disappear, or to change from attracting to repelling and vice versa, leading to large and sudden changes of the behavior of the system [37]. Catastrophe theory provides a mathematical framework that deals with discontinuous transition between the states of a system, and describes how small, continuous changes in control parameters can have sudden, discontinuous effects on dependent variables. As a powerful mathematical tool in studying the evolution of systematic order,

catastrophe theory can better explain and predict sudden phenomena in nature and society [38–40]. Catastrophic change emphasizes the meaning of discontinuities or mutational changes in the process of changing. In most high-density urban centers, the traffic flow is always within a stable and unstable equilibrium boundary during the peak hours. With a sudden fire disaster, the traffic flow status in high-density urban central area will be catastrophically changing and the traffic flow status will be transiting. The continuous steady traffic flow status will be interrupted and lead to qualitative changes.

In the case of sudden fire disasters, the traffic flow in the disaster affected-area can be managed and controlled by intelligent transportation systems (such as adaptive traffic signal control system, advance route guidance system) or human beings with insulated fences. Through controlling the inflow and outflow in the boundary of disaster-affected area and managing the speed within the disaster-affected area, the density or occupancy of regional traffic flow can be estimated and manage by the relationship of traffic flow characteristics with the intelligent transportation systems. From the perspective of catastrophe theory, as the behavior of catastrophe models can become extremely complex when the number of behavioral and control parameters is increased [40]. The cusp catastrophe is the simplest and most often applied catastrophe model to describe the catastrophe characteristics and discontinuous behavior with two control variables and one state variable. When traffic is congested, two control variables already allow for the prediction of quite intricate transitional behavior [11]. Therefore, the relationship of flow–speed–occupancy can correspond to the variables in the cusp catastrophe model. The potential function that goes with the cusp model of catastrophe theory is Equation (1), when one explores what happens to a fold bifurcation if a second parameter  $y$  is added to the control space. Varying the parameters, one finds that there is now a curve of points in  $(y, z)$  space where stability is lost, where the stable solution will suddenly jump to an alternate outcome [37].

$$U(x, y, z) = x^4 + yx^2 + zx \tag{1}$$

where:  $x$  is the internal state variable of the system;  $y$  and  $z$  are the external control variables.

When  $x$  satisfying  $\frac{dU}{dx} = 0$ , the system is in equilibrium. That is, the states for which the derivative of formula (1) is zero as formula (2). The entire panel of formula (1) is associated with only one, or three points on the cusp surface in Figure 1 [40,41].

$$4x^3 + 2yx + z = 0 \tag{2}$$

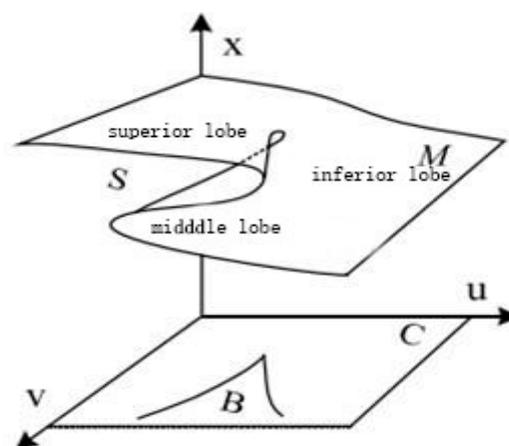


Figure 1. Cusp catastrophe equilibrium surface.

As shown in Figure 1, the critical equilibrium surface is divided into upper, middle and lower parts. The upper and lower parts represent stable regions. In the middle part, the state of the system jumps and becomes unstable. The middle lobe is composed of folding regions, and the folding area can

be projected to the bifurcation set. The bifurcation set is shown as B section in Figure 1. When  $(u, v)$  outside the bifurcation set, the changing of the control variables will lead a continual change in the system status. However, when the point enters the bifurcation set, a sudden jump of the state variable occurs. Therefore, the critical value of mutation corresponds to a discriminant equal to zero [42].

Due to sudden fire disasters, the traffic flow will present as an aggregation characteristic in disaster-affected area. As with evacuation, the traffic flow will concentrate to the road segments and intersections. Because of traffic congestion, the vehicle speed decreases sharply. This phenomenon is consistent with the characteristics of the cusp catastrophe theory. Therefore, this paper focuses on using the cusp catastrophe theory to describe the catastrophe change of traffic flow under sudden fire disasters. Before the sudden fire disasters happen, the traffic network is in a stable state of high speed and low occupancy, which corresponds to the upper leaf of Figure 1 based on cusp catastrophe theory. Under the sudden fire disaster, the capacity of traffic network is decreasing, and the traffic network is changing to the state of low speed and high occupancy, which corresponds to the lower leaf of Figure 1 based on cusp catastrophe theory. It is considered that there is a sudden transition between two states with a catastrophe border. Therefore, a regional traffic flow model is proposed to identify the catastrophe border based on formula (2).

### 3.2. CCT-Based Traffic Flow Model under Sudden Fire Disaster

Two critical issues need to be considered in constructing the regional traffic flow model based on cusp catastrophe theory: (1) the selection of traffic flow parameters and (2) the corresponding relationship between traffic flow parameters and variables in the cusp model of catastrophe theory.

#### (1) Traffic flow parameters selection.

When a sudden fire disaster happens, the range of affected traffic flow includes not only the location where fire disaster happened, but also the adjacent road segments and intersections. It is a regional affection to the traffic network. Therefore, the parameters of regional traffic flow are suitable to describe the status and degree of affection and changing for a disaster-affected traffic network. The cusp catastrophe model has three variables, state variables  $x$  and control variables  $y$  and  $z$ . Considering the possibility of traffic data collection and analysis under sudden fire disasters, the regional average volume, occupancy and speed of traffic flow are selected to describe the characteristics of traffic flow in the sudden fire disaster-affected area.

#### (2) Relationship between traffic flow parameters and variables in the cusp model of catastrophe theory.

To matchup the relationship between traffic flow parameters and variables in the cusp model of catastrophe theory, the most important thing is to determine the traffic flow parameter corresponding to the state variables. In reality, the most intuitive and visible indicator of traffic state is speed, so the regional average speed is chosen as the state variable. Furthermore, from the perspective of traffic flow theory, the catastrophic change of speed may be caused by a slow change of traffic flow occupancy or traffic flow volume. Therefore, it is feasible to select the regional average speed  $v$  as the state variable  $x$ . Then, the remaining parameters are regional average flow  $q$  and regional average occupancy  $o$ , corresponding to the control variables  $y$  and  $z$  in the cusp model of catastrophe theory.

To form a CCT-based model with traffic flow parameters, we assume that there are three conversion relations between traffic flow parameters and cusp model variables. We make the hypothesis that:

$$x = a \cdot v \tag{3}$$

$$y = b \cdot q \tag{4}$$

$$z = c \cdot o \tag{5}$$

where:  $a, b, c$  is the conversion coefficients of regional average speed  $v$ , volume  $q$  and occupancy  $o$  of traffic flow, respectively.

Putting formula (3)–(5) into formula (1), formula (1) can be rewritten as:

$$E(v, q, o) = a^4 \cdot v^4 + b \cdot q \cdot a^2 \cdot v^2 + c \cdot o \cdot a \cdot v \tag{6}$$

Based on cusp catastrophe theory, if the state of traffic flow  $v$  satisfies  $\frac{dE}{dv} = 0$ , the traffic flow is in equilibrium. The derivative of formula (6) is zero.

$$4a^4 \cdot v^3 + 2b \cdot a^2 \cdot q \cdot v + c \cdot a \cdot o = 0 \tag{7}$$

where  $\beta = 4a^4 / (c \cdot a) = 4a^3 / c$ ,  $\gamma = 2b \cdot a^2 / (c \cdot a) = 2ba / c$ . Formula (7) can be updated and simplified as:

$$\beta \cdot v^3 + \gamma \cdot q \cdot v + o = 0 \tag{8}$$

The parameters  $a, b, c, \beta, \gamma$  can be estimated by using maximum likelihood procedures.

According to the catastrophe dynamics method, if the state of traffic flow  $v$  satisfies  $\frac{d^2E}{dv^2} = 0$ , the traffic flow is also in equilibrium, but in edge of discontinues changing. The second derivative of formula (6) is also zero.

$$3\beta \cdot v^2 + \gamma \cdot q = 0 \tag{9}$$

Then, catastrophe border can be identified in the singularity set of the equilibrium surface. The solution formula of the equilibrium surface for singularity set is:

$$\begin{cases} \beta \cdot v^3 + \gamma \cdot q \cdot v + o = 0 \\ 3\beta \cdot v^2 + \gamma \cdot q = 0 \end{cases} \tag{10}$$

The singularity set of the equilibrium surface is two creases in the folded part of the equilibrium surface. By eliminating the state variable  $v$  and satisfying formula (10), the bifurcation set of the stability of the traffic flow state can be obtained as follows:

$$8\gamma^3 q^3 + 27\beta^2 o^2 = 0 \tag{11}$$

Based on formula (12), the discriminant of traffic state is formed as follows:

$$\Delta = 8\gamma^3 q^3 + 27\beta^2 o^2 \tag{12}$$

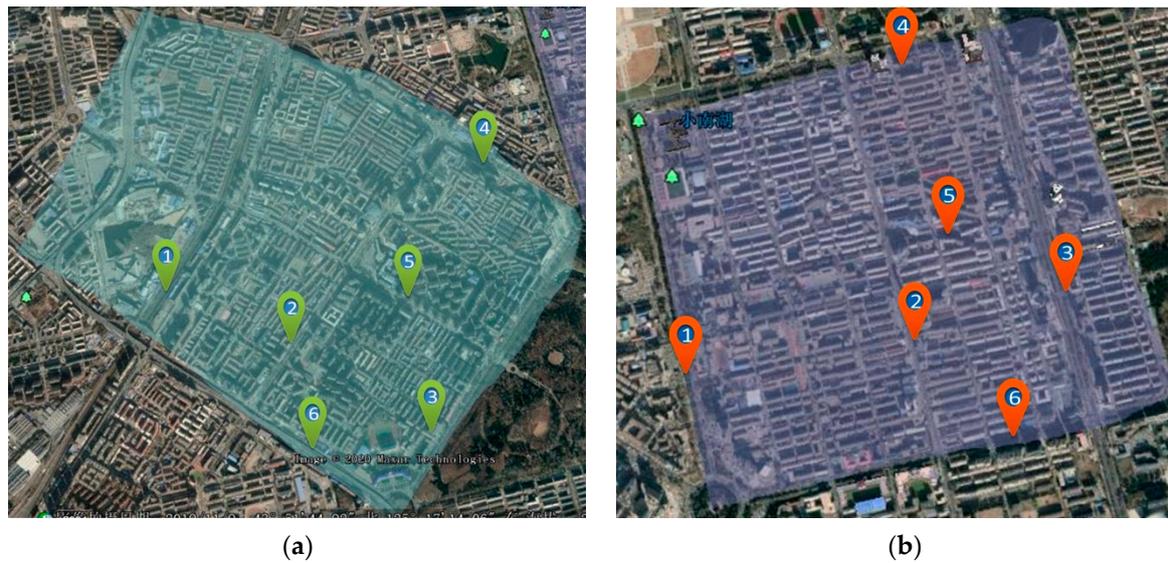
Based on cusp catastrophe theory, if  $\Delta > 0$ , the traffic flow is in a stable state, including the traffic states with high speed and low occupancy, low speed and high occupancy. If  $\Delta < 0$ , the traffic flow is in an unstable state, and the traffic is congested, spilling out from the intersection and disorder. If  $\Delta = 0$ , the traffic flow is in the border between stable and instable state. The corresponding traffic flow parameters—regional average speed  $v$ , regional average flow  $q$  and regional average occupancy  $o$ —can be identified as the catastrophe border.

In urban traffic networks, if the traffic flow is high speed and low occupancy, the traffic flow is in a stable state. When perturbed, the system will remain relatively unaffected. However, in urban high-density area under sudden disasters, the traffic network is saturated or supersaturated. The traffic flow is low speed and high occupancy. The traffic flow is in an unstable state. Only a small perturbation is needed to drive the system toward a different state. The possible equilibrium of traffic flow in high-density areas can be defined and collected by a computer-based micro-simulation model under different scenarios, such as with or without sudden disasters in the traffic network. The transition processes from stable to unstable traffic flow and can be formed in a three-dimensional panel to display the continuous changes and discontinuous transition before, during and after sudden disasters in high-density areas. Then, the catastrophe border can be identified by finding out the discontinuous transition boundary.

## 4. Simulation and Calibration

### 4.1. Simulation Scenarios and Data Collection

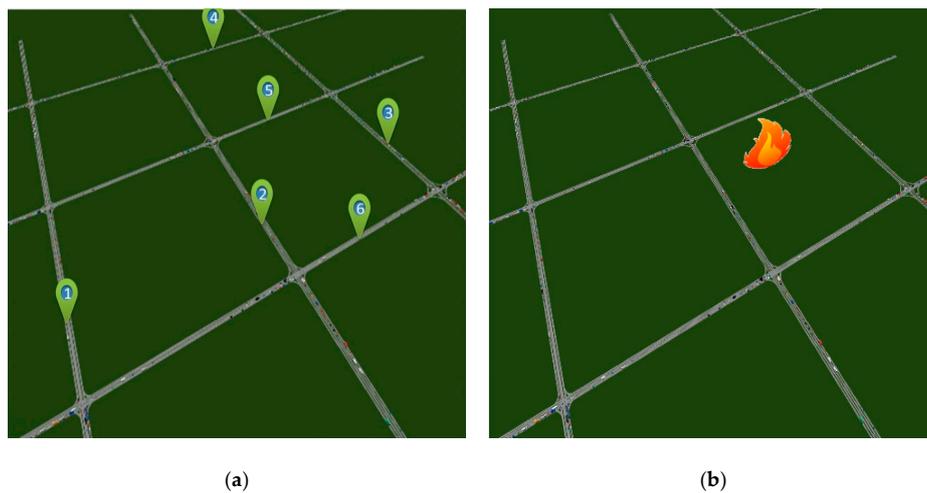
The microscopic traffic flow simulator VISSIM 8.0 (PTV Group, Karlsruhe, Germany) was used for building the proposed model. The model primarily consisted of Hongqi District Center (HDC) and Guilin District Center (GDC) in Changchun, China. They are all in the old town of inner cities, with a high density of buildings, population and other urban infrastructure, and with a grid traffic network, as shown in Figure 2.



**Figure 2.** Backgrounds urban high-density areas of model building in simulator. (a) Hongqi district center in Changchun; (b) Guilin district center in Changchun.

The distance between arterial streets in these district centers is about 500–700 m. The lane number is four-lanes-bidirectional in these district centers. The speed limit in these district centers is 60 km/h. The average vehicle speed is below 20 km/h during peak hours. The average vehicle speed is about 35 km/h during off-peak hours. The traffic composition in these district centers is: cars account for 75%–85%, the public transit buses account for 8%–12%, other vehicles including vans and trucks account for 5%–15%. The design capacity of the road segments in these district centers is about 1200 pcu/h/lane. Because of the discontinuous traffic flow caused by intersection, the real capacity of road segment is below 800 pcu/h/lane. To simplify to model building in the VISSIM simulator, a Sudoku traffic network based on the scenes of HDC and GDC was coded in VISSIM as links and connectors, as shown in Figure 3.

In the Sudoku traffic network, the traffic network is setting as: (1) the links between the intersections are setting as 600 m. (2) Each arterial road in the traffic network is setting as 2400 m and including three intersections. (3) Each road segment in the traffic network has two lanes, the inside lane is a straightforward lane and the outside lane is a straight and right-turn lane based on the traffic channelization in HDC and GDC. The traffic composition is setting as: cars account for 80%, buses account for 10% and trucks account for 10%. The expected vehicle speed is setting as 45 km/h. The traffic model simulated peak-hour traffic flow state and a sudden fire disaster occurring in these state during the peak hour in urban high-density area. Traffic volume data were categorized in two groups. Traffic volumes at the edge of the traffic network were used to input traffic to the network. The input traffic is setting as 800 pcu/lane/h. The traffic data at the center of the network were used to calibrate the network.



**Figure 3.** Snapshot of Sudoku traffic network in simulator. (a) Scenario without sudden fire disasters. (b) Scenario with sudden fire disasters.

To validate the model building in the simulation, peak-hours traffic volume and travel time data were collected on the traffic networks of HDC and GDC. The field data of travel volume and travel time obtained from the local traffic agent were collected by loop detectors and video-based intelligent monitoring and recording system. The recording, uploading and statistical interval of field data is 5 min. With several iterations and model running were completed in the VISSIM simulator without sudden fire disasters, the average traffic volumes and travel times of specially assigned locations and links in the Sudoku traffic network were output. The output data interval also was set as 5 min. Then the simulated data of traffic volume and travel time and actual data of traffic volume and travel time are compared in Tables 1 and 2, respectively.

**Table 1.** Comparison of actual and simulated traffic volumes.

Location	HDC	GDC	Sudoku Simulated Volume (veh/h)	Compare to HDC		Compare to GDC	
	Actual Volume (veh/h)	Actual Volume (veh/h)		Difference	Error (%)	Difference	Error (%)
1	1583	1613	1674	91	5.44	61	3.64
2	1784	1573	1711	−73	4.27	138	8.07
3	1671	1771	1732	61	3.52	−39	2.25
4	1569	1505	1525	−44	2.89	20	1.31
5	1407	1313	1449	42	2.90	136	9.39
6	1607	1689	1804	197	10.92	115	6.37

**Table 2.** Comparison of actual and simulated travel times.

Link	HDC	GDC	Sudoku Simulated Travel Time(s)	Compare to HDC		Compare to GDC	
	Actual Travel Time(s)	Actual Travel Time(s)		Difference	Error (%)	Difference	Error (%)
1	665	806	737	71	9.70	−69	9.38
2	661	711	798	136	17.09	87	10.93
3	742	758	876	134	15.33	118	13.43
4	713	732	816	103	12.58	83	10.23
5	757	819	782	25	3.18	−37	4.79
6	727	731	628	−99	15.69	−103	16.33

The difference in traffic volume between simulated network of Sudoku and the real network of HDC is less than 10.92%. The difference in traffic volume between simulated network of Sudoku and the real network of GDC is less than 9.39%. The difference in average travel time between simulated network of Sudoku and the real network of HDC is less than 15.69%. The difference in average

travel time between simulated network of Sudoku and the real network of GDC is less than 16.33%. According to the study of Brockfeld, Kuhne and Wagner, an error of 15% to 25% cannot be suppressed in microscopic models [43]. Because the differences between model outputs and field data are within the acceptable ranges, the simulation model is considered to adequately represent the traffic congestion in urban high-density areas.

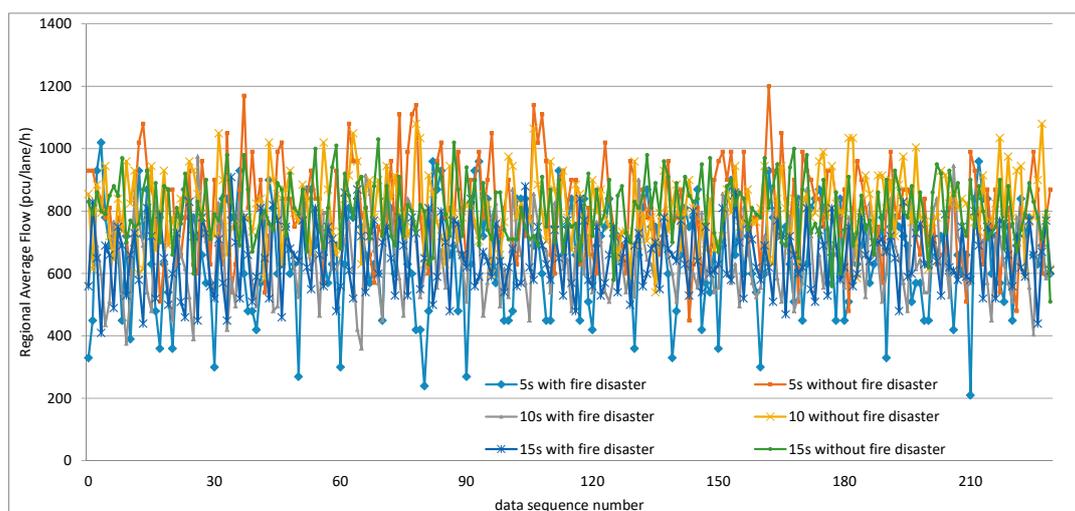
To simulate traffic flow under sudden fire disasters, the VISSIM COM and VC++ were programmed to restrict the capacity, speed, vehicle routes based on the temporal and spatial distribution influence model under traffic accident in the urban traffic network [44–49]. Other parameters such as headway and driver behavior were left to the default VISSIM values.

#### 4.2. Data Processing and Analysis

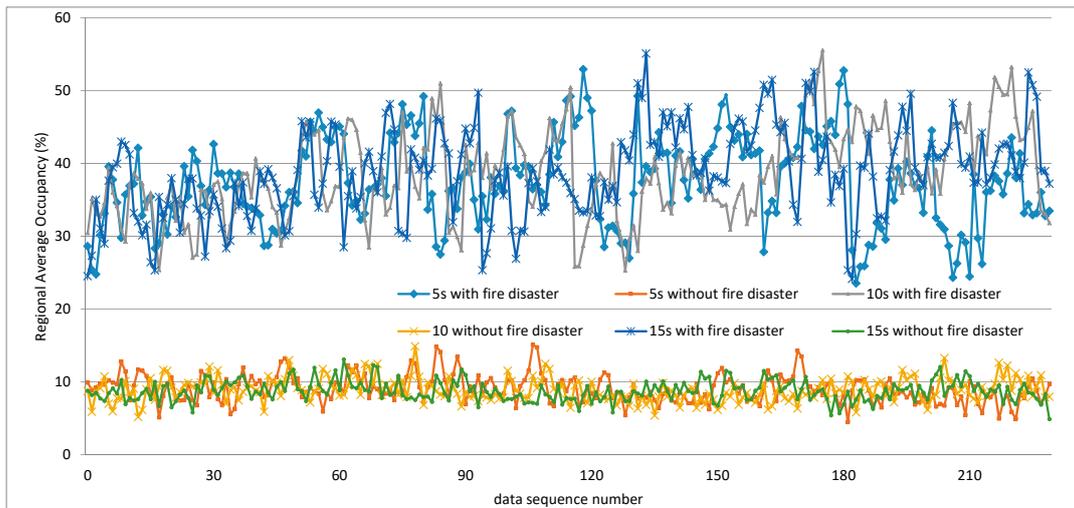
Microscopic simulation models contain many parameters that describe traffic flow characteristics. The proposed model of this paper was calibrated by regional average traffic flow speed, volume, and occupancy. Travel time detectors were set in the entrance and exit of each arterial to collect average travel time of traffic flow passing through the arterial. The arterial average speed is obtained by the distance of travel time detectors dividing the average travel times of each arterial. The regional average speed is defined as the mean value of arterial average speed in the network. Traffic flow detectors were set in the middle of road segment between two intersections to collect traffic volume and occupancy. The regional average flow and regional average occupancy are defined as the mean value of traffic volume and occupancy collected by traffic flow detectors in the network respectively.

Different time interval of traffic data will show out different accuracy and performance in regional traffic flow managing and controlling. In this paper, traffic data was collected at 5 s intervals, 10 s interval and 15 s interval with and without sudden fire disasters in the simulation network respectively as to identify the catastrophe border of traffic flow. Because of VISSIM's stochastic nature, multiple runs must be conducted for each parameter set to reduce the stochastic variability. The required number of runs was determined by running the model 10 times initially, then calculating the minimum sample size on the basis of the traffic data output mean values and standard deviation, assuming a Student *t*-distribution [32].

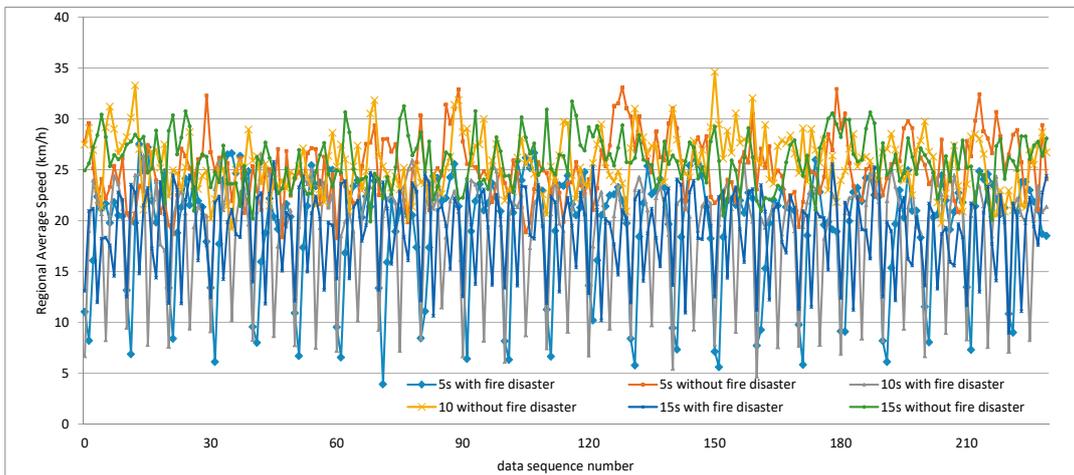
After 10 iterations were completed, 230 groups of regional traffic flow parameters in each scenario and each collecting interval were calculated and extracted as sample datasets for further analysis. The datasets used for further analysis are shown in Figures 4–6.



**Figure 4.** Dataset of regional average flow in different collecting time intervals with and without sudden fire disasters.



**Figure 5.** Dataset of regional average occupancy in different collecting time intervals with and without sudden fire disasters.



**Figure 6.** Dataset of regional average speed in different collecting time intervals with and without sudden fire disasters.

The process of catastrophe border identification for urban high-density area under sudden fire disasters based on simulation datasets can describe as following step.

Step 1: Data normalization processing.

To highlight the characteristics of traffic flow data and identify the sudden jump of catastrophe border more easily, the sample datasets are performed normalization processing. The normalization processing method is as follows:

$$X = \text{speed} - \text{speed at capacity} \tag{13}$$

$$Y = (\text{flow} - \text{capacity}) / 100 \tag{14}$$

$$Z = \text{occupancy} - \text{maximum occupancy at maximum flow} \tag{15}$$

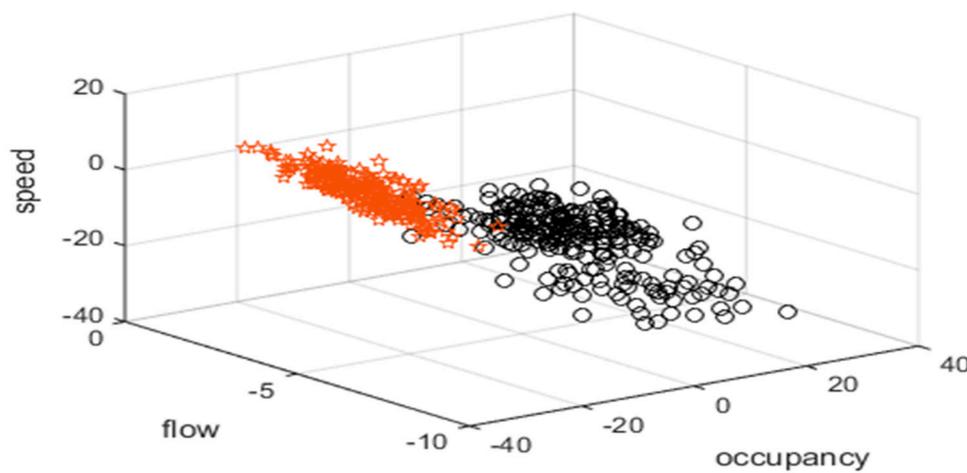
The capacity in the formula is the statistical capacity, and the maximum flow is collected in each interval based on the extracted data from simulation model by multi-running the simulator. The critical value extracted from simulation in different time intervals is shown as Table 3.

**Table 3.** Critical value in normalization processing in different time intervals.

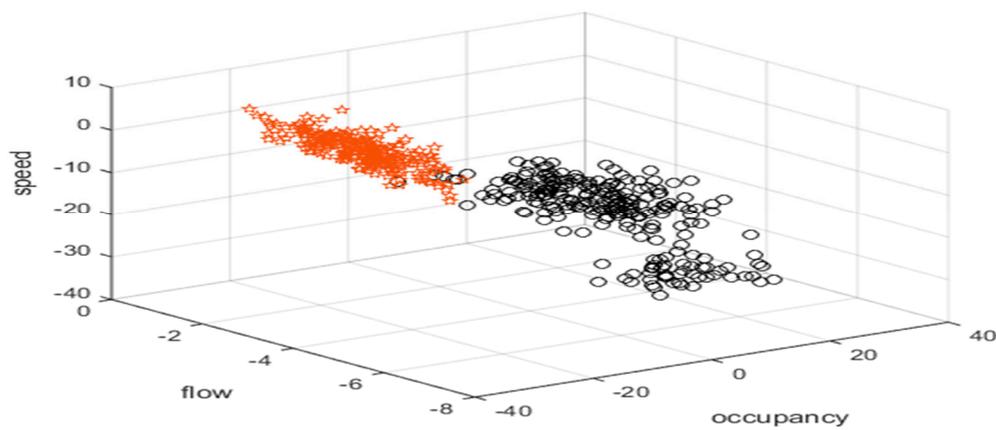
Data Collection Interval (s)	Critical Speed (km/h)	Capacity (pcu/h)	Maximum Occupancy (%)
5	25.2375	1200	30.175
10	27.4333	1080	27.49167
15	24.62913	1030	27.34583

Step 2: Data displayed in three-dimensional panel.

After normalization processing, the traffic flow parameters in different traffic conditions can be converted into the corresponding variables in the cusp model of catastrophe theory, respectively. Then, three datasets of traffic flow data after normalization processing are displayed in a three-dimensional panel to indicate the transition from stable state to instable state of traffic flow, as shown in Figures 7–9. In Figures 7–9, the red pentagon in the figures represents the traffic flow data without a sudden fire disaster situation, and the black circle represents the traffic flow data with sudden fire disasters.



**Figure 7.** Distribution of traffic flow data at 5 s interval with and without sudden fire disasters.



**Figure 8.** Distribution of traffic flow data at 10 s interval with and without sudden fire disasters.

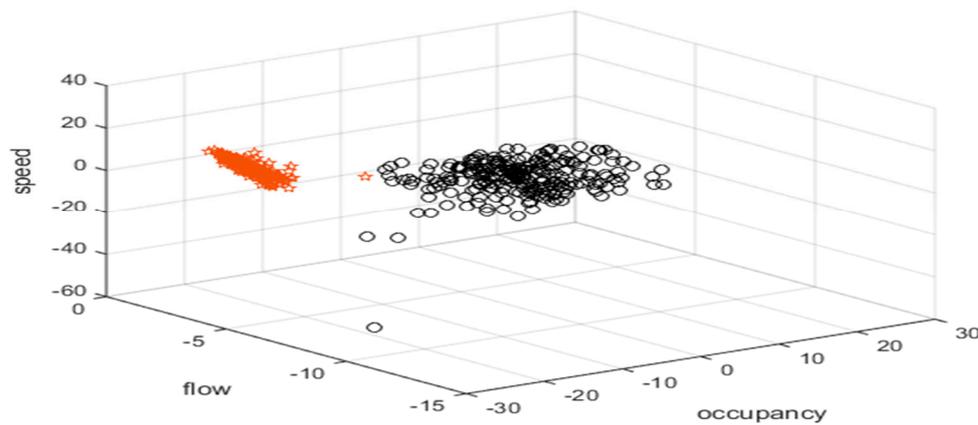


Figure 9. Distribution of traffic flow data at 15 s interval with and without sudden fire disasters.

In Figures 7–9, it can be clearly seen that after conversion, the traffic flow data of regional average flow, occupancy and speed without sudden fire disaster situation are distributed in a small area, relatively concentrated, and located on the positive half axis of speed. In general, the traffic status without sudden fire disasters is in a high-speed stable state. The regional average flow, occupancy and speed of traffic flow under sudden fire disasters are more discretization comparing to those without sudden fire disasters. Before sudden fire disasters happened, the traffic network was in a state of high speed and low occupancy (as shown by the red pentagon in Figures 7–9). During the sudden fire disaster, the traffic flow changes to low speed and high occupancy (as shown by the black circles in Figures 7–9). It can be seen from Figures 7–9, the dispersion degree and distribution of the point before and after the sudden fire disaster is different. The traffic data under sudden fire disasters are shown to be relatively scattered. The traffic flow is low speed and high occupancy. The traffic data without sudden fire disasters are relatively centralized. The traffic flow is relatively high speed and low occupancy. From the distribution shown in Figures 7–9, as the traffic data collection interval increase, the traffic data are more centralized and scatter ranged, the gap is more clear between with sudden fire disasters and without sudden fire disasters. According to the catastrophe theory, there is a catastrophe border to make the catastrophe change occur. Therefore, the catastrophe border can be identified by catastrophe fitting with the transformed data.

Step 3: CCT-based transformed data fitting.

The datasets of transformed data in different time intervals are fitted by using the potential function that goes with the cusp model of catastrophe theory as formula (8). The fitting panels are shown in Figures 10–12.

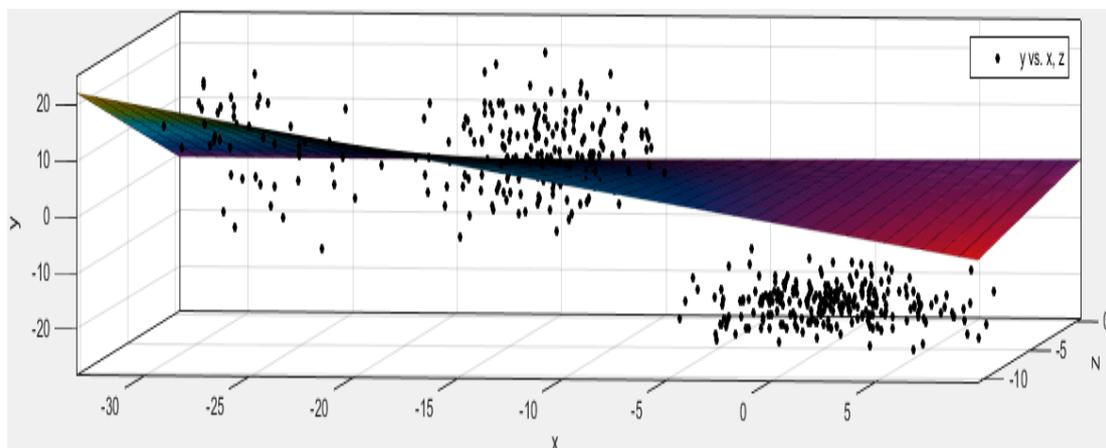


Figure 10. Fitting chart of traffic flow data at 5 s interval.

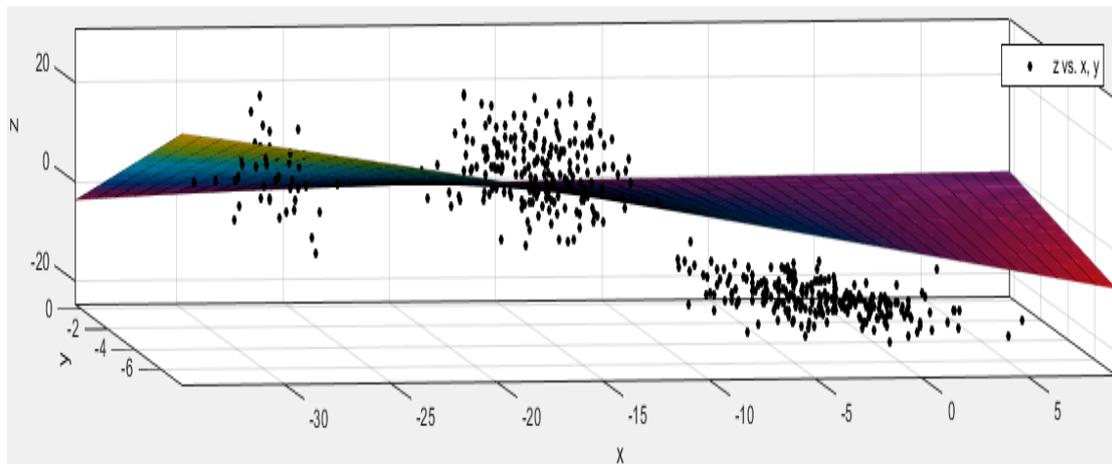


Figure 11. Fitting chart of traffic flow data at 10 s interval.

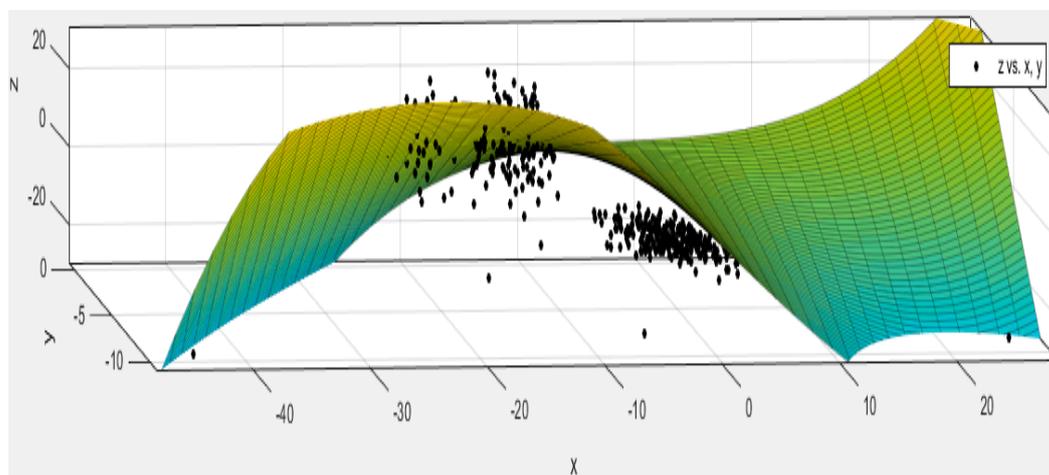


Figure 12. Fitting chart of traffic flow data at 15 s interval.

In Figures 10–12, the X-axis is the value of regional average speed. The Y-axis is the value of regional average flow. The Z-axis is the value of regional average occupancy. The catastrophe border can be seen from the figures.

The parameters of formula (8) in different time intervals are obtained by fitting the datasets of transformed data, as shown in Table 4.

Table 4. Parameters of CCT-based regional traffic flow model in different time intervals.

Data Collection Interval (s)	$\beta$	$\gamma$
5	−0.0001511	−0.0621
10	−0.0005264	−1.059
15	−0.001583	−0.2745

Putting the parameters into formula (10), the catastrophe border of regional average occupancy and regional average flow can be identified by the solution of formula (10), as shown in Table 5.

**Table 5.** Catastrophe border identification at different time intervals.

Data Collection Interval (s)	Catastrophe Border	
	Regional Average Occupancy $\rho$ (%)	Regional Average Flow $q$ (pcu/lane/h)
5	20	439
10	20	529
15	20	377

From Table 5, the catastrophe border is 439 pcu/lane/h, 529 pcu/lane/h, 377 pcu/lane/h in the 5 s, 10 s, 15 s traffic data collection interval, respectively. That is to say, for the aim of prevent traffic congestion and disorder under sudden fire disasters, the traffic flow should not exceed 439 pcu/lane/h, 529 pcu/lane/h, 377 pcu/lane/h within the disaster-affected area in the 5 s, 10 s, 15 s traffic data collection interval, respectively.

Chen and You [50] analyzed the traffic flow characteristics under sudden fire disasters in road segment used a Capacity Assessment Approach (CAA) based on VISSIM simulator data. The study results showed that the remaining capacity of the road after the fire is 61.611%. It can be concluded that if the traffic flow is 800 pcu/lane/h in traffic network in normal traffic condition, the capacity of traffic flow will remain about 493 pcu/lane/h under sudden fire disasters. If the volume of traffic flow exceed this value, the traffic network will be caught in congestion and disorder. This value can be considered as the catastrophe border of traffic network under sudden disasters. So the model ability at different data collection interval based on cusp catastrophe theory can be seen in Table 6.

**Table 6.** Model at different data collection intervals based on cusp catastrophe theory.

Data Collection Interval	Catastrophe Border based on CCT (pcu/lane/h)	Catastrophe Border based on CAA (pcu/lane/h)	Relative Precision (%)
5 s	439		89.1
10 s	529	493	92.7
15 s	377		76.5

In Table 2, the relative accuracy of catastrophe border identification at 5 s interval and 10 s interval are 89.1% and 92.7% compare to the method of capacity assessment approach (CAA) respectively, which shows that the study in this article based on cusp catastrophe theory can describe the traffic flow characteristics effectively at fine granularity data collection interval. However, the catastrophe border identification error at 15 s interval is larger, which is more than 20%. The cause of the larger error may be traffic flow parameters in coarse granularity cannot catch the traffic flow changing accurately in the simulation, and traffic flow mutation happening under sudden fire disasters always at smaller data collection interval.

In the area of risk management, it gradually reaches a basic consensus that emergency traffic flow management and control can effectively reduce emergency response time and improve security in disaster relief and mitigation. Traffic flow catastrophe border identification can help engineers, planners, and emergency managers identify the approximate time or position it would take for traffic flow to manage or control in disaster-affected area. In addition, advanced traffic signal control systems can have tremendous impact on the movement of traffic flow in urban high-density areas under sudden disasters, facilitates emergency evacuation and response in disaster relief and mitigation [51,52]. However, most of these studies have not considered the systematic integration of traffic data collection intervals when optimizing control target and signal timing [52]. The present simulation-based study tries to provide a technical understanding regarding which the data collection interval provides better results in identifying the catastrophe border. This traffic data collection interval is also suitable for integrating into advanced traffic control system in optimizing control targets and signal timing for disaster relief and mitigation, to match the changing of traffic flow in the network.

This paper provides the approach to identify the catastrophe border of traffic flow in urban high-density area under sudden fire disasters. However, the method and model of the present study still have many limitations. The first limitation is that model building in the simulation did not consider the traffic signal control in the intersection. Different types of signal control have different abilities to alleviate traffic congestion and disorder in high-density area under sudden disasters. The present study cannot explore catastrophe border under different types of signal timing or control model, such as fixed-time, actuated control, adaptive control and isolated signal control, arterial coordination control, or regional coordination control. The second limitation is that the present study only considers vehicle traffic flow in the network. However, under sudden disasters, pedestrian evacuation will influence the vehicle traffic flow significantly and dramatically reduce the road capacity. A third limitation is that the position of sudden fire disasters in the model building is fixed. The location of sudden fire disasters in the network will affect traffic flow's spatial-temporal distribution in the processes of aggregation, propagation. The fourth limitation is that the scenario in the model building is single and simple. Urban high-density areas are faced with numerous natural and human-caused, whether accidental or purposeful, disasters that have the potential to cause significant and large-scale devastation [51]. Besides the disaster itself, the traffic network always along with traffic incident during the emergency evacuation. For further studies, such problems and factors should be considered and added when model building in the simulation and calibration.

## 5. Conclusions

In this paper, we use the method of cusp catastrophe theory to model the regional traffic flow in high-density areas under sudden fire disasters. The mathematical modeling method is proposed to study the changing process of traffic flow from the stable state to instable state based on cusp catastrophe theory to improve the understanding of traffic flow aggregation, propagation and distribution characteristics in disaster affected area under sudden fire disasters. This paper explores the catastrophe border of regional traffic flow as to provide a theoretical basis for traffic agents to manage and control regional traffic flow in disaster-affected area, to prevent the regional traffic flow being caught into disorder and congestion. Finally, we use the microcosmic traffic flow simulator VISSIM to simulate and collect the traffic data in high-density area under sudden fire disasters. Throughout the data normalization and analysis, the catastrophe border is identified as 439 pcu/lane/h, 529 pcu/lane/h, 377 pcu/lane/h at 5 s, 10 s, 15 s data collection interval respectively. The relative precision, which compares to the method of capacity assessment approach, is 89.1%, 92.7% and 76.5% respectively. It means that 10 s data collection interval may be the most suitable data collection interval in catastrophe border identification and regional traffic flow control in high-density area under sudden fire disasters. The low accuracy at 15 s data collection interval may infer that the stable state of traffic flow catastrophe changing to instable state may be happen in short time, coarse granularity data collection interval cannot capture the transformation process accurately.

However, there are some topics remain to be studied, further research work includes: (1) The aggregation, propagation mechanism of regional traffic flow under sudden disasters and their influence factors should be identified and analyzed. The changing of spatial-temporal distribution during the sudden disaster should be considered in the mathematical model. (2) In high-density areas of urban central, the types of land uses, traffic networks, and transportation patterns are different. In this paper, we just consider the vehicle stream in a simple Sudoku traffic network. Pedestrian flow and its disturbances to traffic flow should be considered and analyzed in a real traffic network. (3) At present, only the simulator-based tests are performed, the field traffic data in high-density area before, during and after sudden fire disasters should be carried out in the future. (4) The identified catastrophe border should be applied into traffic signal timing optimization, explores different types of signal timing (e.g., fixed-time, actuated control, adaptive control) or control model (e.g., isolated signal control, arterial coordination control, regional coordination control) impacting on the catastrophe border identification.

In addition, how to match the signal timing with different traffic flow catastrophe borders should be simulated and calibrated to prevent the unstable state and disorder of traffic flow timely and effectively.

**Author Contributions:** Conceived and designed the experiments: C.L., D.W. Performed the experiments: B.G., Y.Y. Analyzed the data: C.L., Y.Y. Contributed reagents/materials/analysis tools: C.L., Y.Y., D.W., B.G. Wrote the paper: C.L., Y.Y., D.W. All authors have read and agreed to the published version of the manuscript.

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