

Research Article

Research on Intersection Frequent Overflow Control Strategy Based on Wide-Area Radar Data

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Overflow identification and control at urban road intersection is a derivative problem of oversaturation control. The existing cross-section detector uses the road cross-section occupation of vehicles to identify the overflow state; then, the downstream road condition is often ignored. At present, more and more advanced traffic detection technologies, such as vehicle-to-infrastructure and wide-area radar, can provide reliable data for accurate overflow identification. In this paper, a new method of overflow identification and control at intersections is proposed by using advanced wide-area radar detection data. As a detector for specific segment of road, the wide-area radar can detect the traffic flow data in a certain range of road and provide more data types. Therefore, the average speed and space occupancy of the effective detection road segment are selected as subindicators to establish the comprehensive identification index of overflow identification. Then, the overflow control strategy is developed considering the traffic demand of the overflow phase and the nonoverflow phase. It is proved that the method is more accurate and effective in overflow identification and control by using simulation experiment of field data.

1. Introduction

Intersections are important nodes of urban road networks. The multidimensional, complex, and time-varying characteristics of traffic demand often lead to multiple traffic states at intersections. Therefore, finding suitable control strategies for different traffic states is the key to achieve effective traffic control and alleviate traffic congestion.

At present, the identification and control of the oversaturated state of the key intersections in the urban road network is a key problem to be studied in the intersection control [1, 2], and the overflow caused by the queuing of the downstream intersection is also needed. However, due to the limitations of traditional detection techniques and types of detection data, the accuracy of traffic state recognition based on traditional traffic detection is not sufficient. The reason is that the traditional detection is mainly based on cross-sectional detection and the output data are mainly statistical data. Although these data can reflect the movement characteristics of traffic flows, the details are often ignored.

Recently, with the development of V2I technology [3–5] and wide-area radar technology [6, 7], the low-latency, high-precision, and traceable techniques provide new ideas for the recognition of intersection traffic conditions, especially in judging the truth or falseness of intersection overflow. Although these new technologies have been widely used in traffic control [8–10], traffic guidance [11, 12], and autonomous driving [13–15], no one has attempted to use them in the field of intersection overflow.

The segment within a certain range of the upstream intersection is regarded as the research object. The queuing of the downstream intersection will block the departure road section of the upstream intersection, leading to vehicles being not able to enter the departure road section, resulting in congestion or deadlock. The continuous consequence is to spread congestion to the surround road network. Therefore, the detection and identification of the traffic flow within the effective range are necessary. The issues mentioned above can be solved by finding the potential overflow trend and implementing control strategy.

In this way, the main content of this paper is to use wide-area radar detection to identify and control intersection overflow. The main contributions of this paper include the following:

An overflow detection method by using wide-area radar is installed at the departure road at intersection, which is the first time in this field. The comprehensive identification index of overflow detection is designed by using the average space occupancy rate and average speed of vehicles in the effective detection area as subindicators.

The traffic demand of nonoverflow phase and the rationality of control strategy are considered in this study, which was rarely involved before. Moreover, a kind of intersection overflow control method based on genetic algorithm is developed.

The proposed method is verified by the simulation of field data in the overflow identification, response of control strategy, and prevention of false triggering.

The remainder of this paper is organized as follows: Section 2 presents a literature review of related work. Section 3 introduces the details of the causes of overflow at intersections. Section 4 describes the effective detection area of wide-area radar detector and designs the overflow identification index and method in the effective detection area. Section 5 presents a genetic algorithm for the control of frequent overflow at intersections. Section 6 describes the simulation experiments and presents the experimental results. Section 7 concludes this paper and discusses future research.

2. Related Work

Overflow identification and control of urban road intersection is a derivative problem of oversaturation control, which can be traced back to the 1950s [16]. It can be regarded as a link between intersection control and trunk control. Therefore, it attracts many scholars to study, and the existing methods can be generally divided into two categories.

2.1. Theoretical Analysis of Overflow Identification and Control without considering the Detection Method. This kind of study analyzes the characteristics of the traffic flow parameters of the downstream section and the upstream intersection [17, 18], constructs the overflow queuing effect model [19–23], and realizes the overflow control by adjusting the capacity of the overflow phase of the intersection. The limitation is that it does not consider the detection method and the accuracy of detection data.

2.2. Overflow Control Based on Point Detector. The traditional cross-section detector is deployed at the departure road of the upstream intersection, and the vehicle-occupied detector [24–29] is used to design the identification method of queue overflow at the intersection. This type of detector is

a cross-sectional detector, and its data type and detection frequency are low.

2.3. Overflow Control Based on Internet of Vehicles Technology. By using the information interaction between vehicle and intersection signal control [30], the overflow trend can be identified by the all vehicles' position data, and the overflow prevention can be realized by combining vehicle speed control and signal control. This kind of advanced detection method requires the utilization of V2I and Internet of Vehicles.

The first two methods face difficulty to achieve good results in the overflow identification and control at intersections because they are limited by the traditional detection technology. The traditional cross-section detector uses the existing detection method for vehicle identification, and the detection data have the characteristics of coarse granularity and strong statistics. It ignores the complicated traffic flow details, and there are many cases of false triggering in applications. For example, some vehicles with abnormal behavior attached to the detection point may be misjudged as overflow (see Figure 1(a)) or as the state of overflow (see Figure 1(b)). The third method requires the utilization of V2I and Internet of Vehicles, which is not yet realized.

3. Intersection Overflow Cause Analysis

Traffic overflow is a phenomenon related to vehicle queues at signalized intersections, leading to traffic congestions and deadlocks in conflict zones because of such factors among others as road planning and design, traffic signal timing, and accidents.

Traffic overflows can be divided into two types: frequent and sporadic. The frequent overflow causes are, in their turn, to be primarily categorized as internal and external. Among the former are unreasonable road planning and design at signalized intersections, traffic signal timing (main phase sequence), and so on, as shown in Figure 2(a). The latter normally represents a mismatch between storage space and traffic demand related to the upstream and downstream intersections in the road network. It appears to be difficult to meet the overall traffic demand of vehicles, nonvehicles, and pedestrians when the mixed traffic is too intensive. Furthermore, there is another problem why coordinated control between the upstream and downstream intersections is presently lacking, as shown in Figure 2(b).

Sporadic overflow is mainly caused by emergencies at signalized intersections or roads, which are usually caused by traffic accidents or the passing of emergency vehicles (ambulance, fire trucks, etc.), as shown in Figures 3(a) and 3(b).

The frequent overflow caused by external causes is more likely to affect the normal operation of the signalized intersection and whole road network. Thus, this study focuses on identification and control strategy in the effective detection area in the neighborhood of a signalized intersection with frequent overflow.

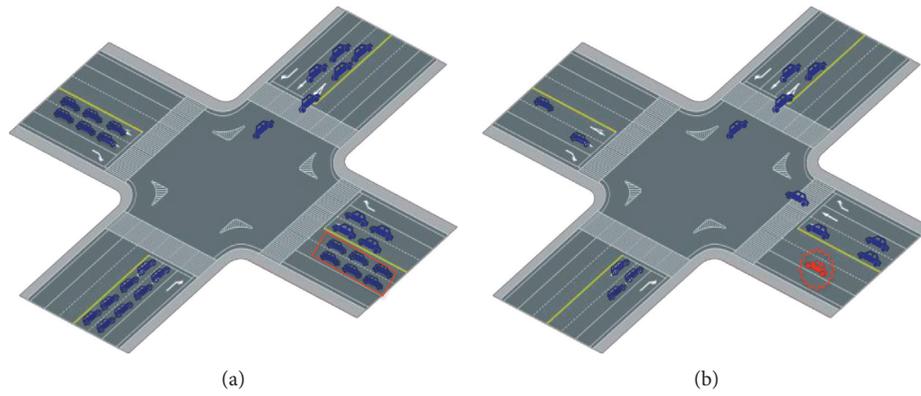


FIGURE 1: Overflow at intersections: (a) real situation of overflow at intersections and (b) false situation of overflow at intersections.

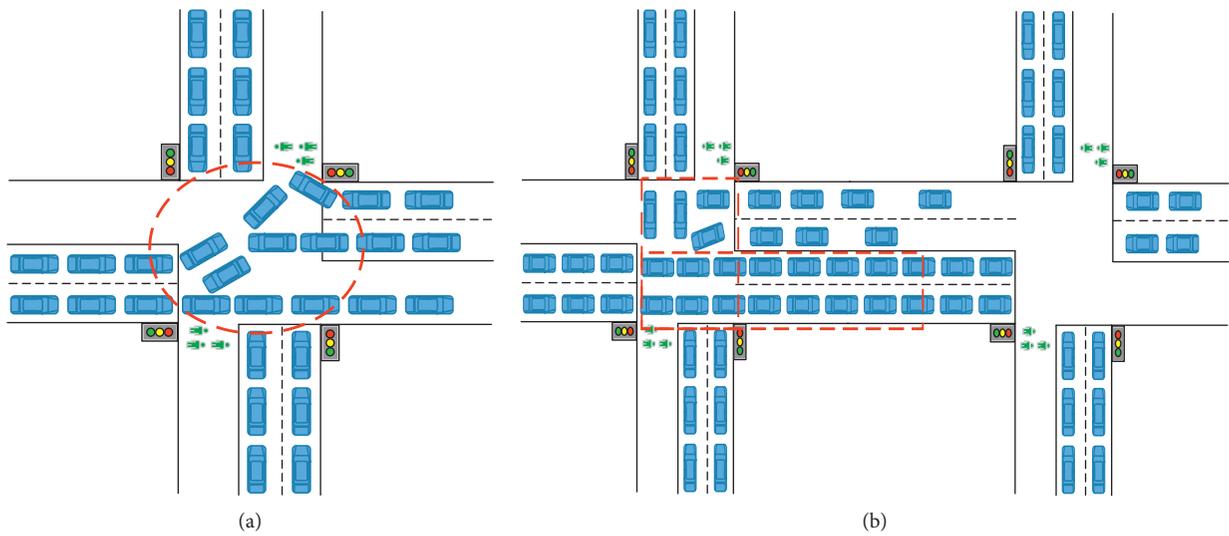


FIGURE 2: (a) Internal and (b) external causes of frequent overflow.

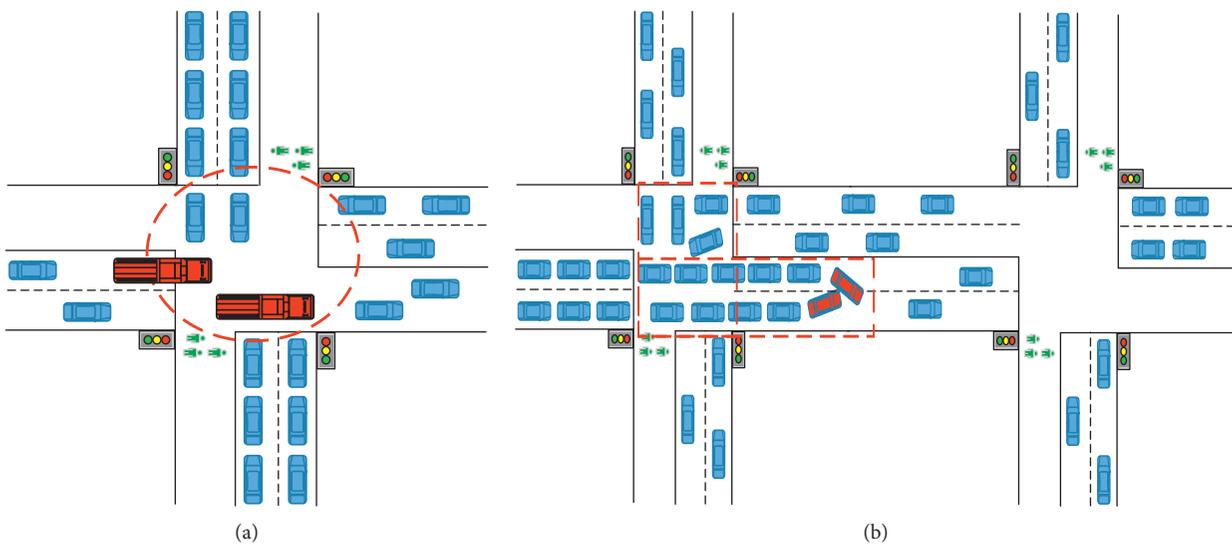


FIGURE 3: Causes of sporadic overflow (a) by special vehicle and (b) by traffic accidents.

4. Identification of Overflow within an Effective Detection Area of Intersection

Wide-area radar traffic detection is an advanced technology developed in recent years and applied first to speed and section flow detection. With enhancement for data volume and precision in intelligent traffic signal control, a wide-area radar has been favored by scholars and users for its long detection distance, large coverage area, multiple tracking targets (vehicles), and abundant data types. In this study, the wide-area radar detector was used to detect frequent overflow at urban signalized intersections, which enabled us to propose a comprehensive identification index for overflow detection.

4.1. Wide-Area Radar Detection Design for Overflow Scene. Considering the requirements of overflow detection as well as the wide-area radar detector settings, the detection process was designed, as shown in Figure 4(a).

Here, it is important to note the following: (i) the detector is installed on the traffic signal pole, and a detection direction is towards the exit from the intersection. (ii) The number of detectors installed is denoted by N , which is greater than one and less than four and depends on a direction of frequent overflow at this signalized intersection. (iii) L_z denotes the vertical effective distance of the wide-area radar detector range, yielding $L_z \geq \max(L_C + L_{E,Z})$; L_h is the transverse effective distance that meets the condition $L_H \geq L_{E,H}$. L_z should be greater than the sum of maximum side length of the conflict area and vertical side length of the effective detection area, namely, $\max(L_C) + L_{E,Z}$. L_H should be greater than the width of all lanes $L_{E,H} = \sum_{i=1}^n l_i$, $n \geq 1$, at the signalized intersection. (iv) Wide-area radar detectors provide two types of data, namely, raw data (including target number, length, location (XPos and YPos), and speed (XSpeed and YSpeed)) and processing data (area occupancy ratio and regional average speed light), as shown in Figure 4(b).

4.2. Analysis of Traffic Flow Characteristics within the Effective Detection Area. The occurrence of overflow leads to a change of traffic flow characteristics, so the analysis of these changes can provide a basis for overflow detection. Depending on how comprehensive the wide-area radar detection data and requirements to frequent overflow identification are, the basic graph and shock wave can be used to analyze the traffic flow characteristics within the effective detection area such as in Figure 3(b). As shown in Figures 5(a) and 5(b), if the average speed and density within the effective detection area appear to be without overflow within noncongested area F, there is no shock wave (i.e., only forward wave is present). Figures 5(c) and 5(d) present the situation when the average speed and density within the effective detection area appear to indicate an overflow in the overflow area. In congestion area G, shock waves are being generated and queues obviously arise.

4.3. Comprehensive Identification Index for Overflow Detection. Based on the analysis of traffic flow characteristics above, the average space occupancy $O_{\bar{D}}$ and average speed of vehicles $V_{\bar{D}}$ in the effective detection area have been chosen to serve as subindices in order to form the comprehensive identification index PI:

$$PI = w_1 \cdot O_{\bar{D}} + w_2 \cdot V_{\bar{D}}, \quad (1)$$

where $w_i \in (0, 1)$, $i = 1, 2$, are index weights normalized to unity $\sum_{i=1}^n w_i = 1$, and $O_{\bar{D}} = \bar{L} \cdot \rho \cdot L_w / L_{E,Z}$, where \bar{L} is the average vehicle length and L_w is the unit length of calculating traffic density.

Traditionally, the weights of subindexes in the performance index PI are usually adjusted by the artificial experience method. In order to describe characteristics of traffic flow parameters in traffic overflow scenarios, the distance entropy [31] of translation correction is to be used to determine the weights in equation (1). Thus, (i) the distance entropy is used to calculate the weights of the subindexes and finally PI; (ii) when the subindexes are fixed or the magnitude of changes is very small, the distance entropy is equal to zero after normalization and standardization. The data translation correction method is to be used to deal with these indicators to ensure the contribution of all the subindexes.

The method design is the following. The design subindexes matrix reads $A = [O_{\bar{D}}, V_{\bar{D}}]$. Upon letting $O_{\bar{D}} = a_1$ and $V_{\bar{D}} = a_2$, it is easy to get the information decision matrix $A = [a_i]_m$, where a_i is the index observation value, $i = 1, 2, 3, \dots, m$, $m \geq 2$. The procedure of calculations is as follows.

Step 1. Normalization processing is to be applied to $A = [a_i]_m$; then, standard information matrix $R = [r_i]_m$ is to be obtained. According to the method of normalization processing, for bigger and better subindexes [32],

$$r_i = \frac{a_i - \min(a_i)}{\max(a_i) - \min(a_i)}, \quad (2)$$

whereas, for smaller and better subindexes,

$$r_i = \frac{\max(a_i) - a_i}{\max(a_i) - \min(a_i)}. \quad (3)$$

The optimal unit value r_i^* ($i = 1, 2, 3, \dots, m$, $m \geq 2$) is to be chosen, which corresponds to the best index:

$$r_i^* = \begin{cases} \max_{1 \leq i \leq m} \{r_i\}, & i \text{ Benefit Properties,} \\ \min_{1 \leq i \leq m} \{r_i\}, & i \text{ Cost Properties,} \end{cases} \quad \forall i. \quad (4)$$

Step 2. The distances between r_i and optimal unit value r_i^* are to be calculated:

$$d_i = |r_i - r_i^*|, \quad i = 1, 2, 3, \dots, m, m \geq 2. \quad (5)$$

Step 3. The index probabilities are to be calculated:

$$p_i = \frac{(d_i + u_i)}{\sum_{i=1}^m (d_i + u_i)}, \quad i = 1, 2, 3, \dots, m, m \geq 2. \quad (6)$$

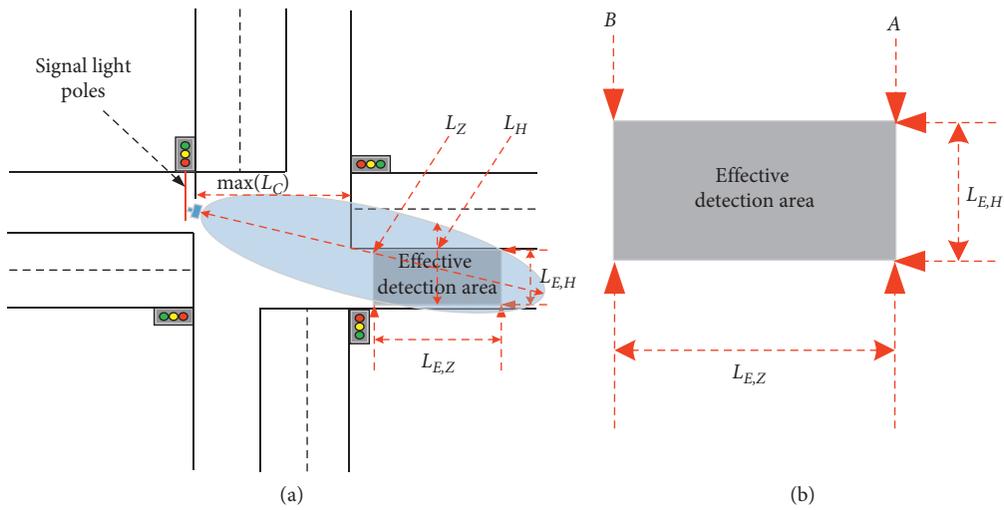


FIGURE 4: Wide-area radar detection settings: (a) the location of wide-area radar detector and (b) effective detection area.

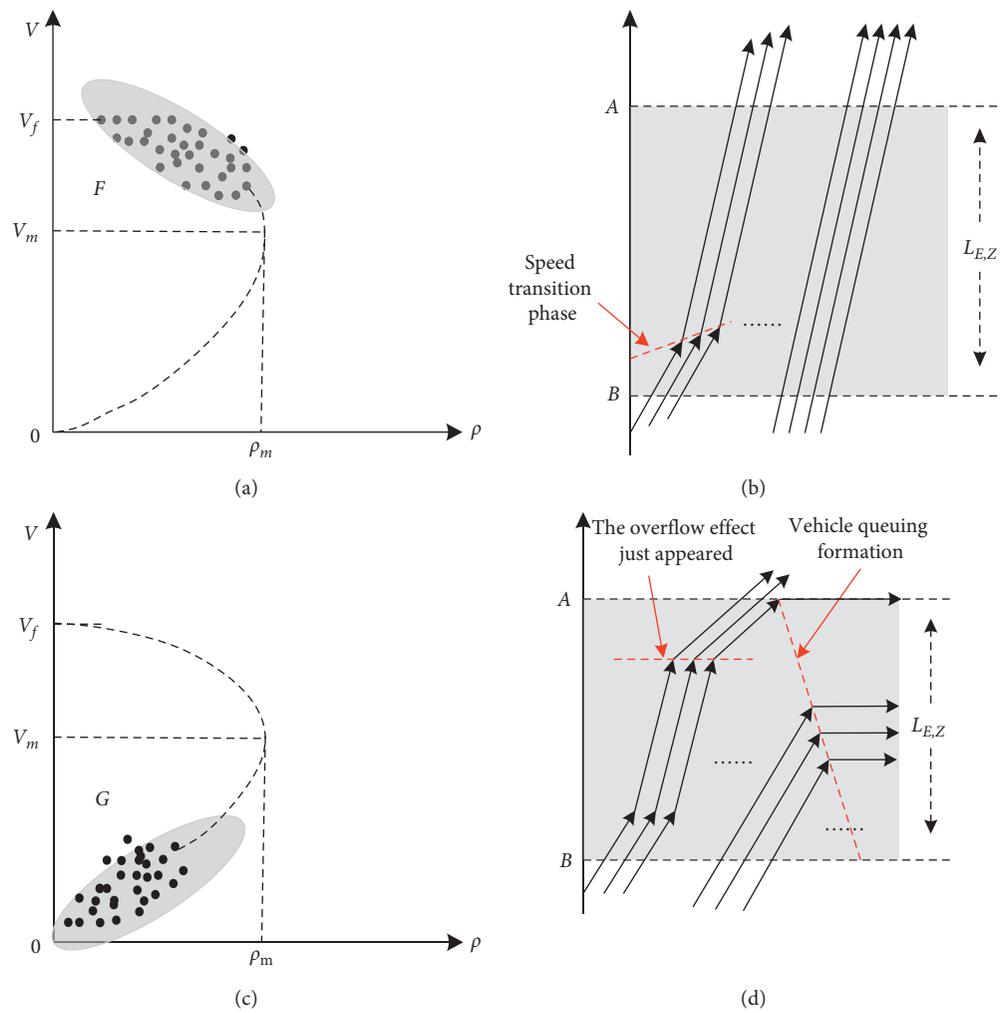


FIGURE 5: Effective detection of changes in traffic flow characteristics. (a) Fundamental diagram of normal traffic flow. (b) Normal traffic shock wave. (c) Fundamental diagram of traffic overflow. (d) Overflow traffic shock wave.

If $d_i > 0$, there is no need to revise p_i , and $u_i = 0$. When $d_i = 0$, the subindex does not affect p_i , and in order to ensure the availability of all the index data, the translation correction of p_i is needed to be applied. In this case u_i is the constant yielding $u_i > 0$.

Step 4. The distance entropies are to be calculated:

$$e_i = -\frac{1}{\ln n} \sum_{i=1}^m p_i \ln p_i, \quad \forall i. \quad (7)$$

Step 5. The entropy weights are to be calculated:

$$w_i = \frac{1 - e_i}{m - \sum_{i=1}^m e_i}, \quad \forall i, \quad (8)$$

where $\sum_{i=1}^m w_i = 1, 0 < w_i < 1$.

Step 6. The comprehensive identification index for overflow detection PI is to be calculated:

$$PI = \sum_{i=1}^m w_i p_i, \quad \forall i. \quad (9)$$

The following final expression can be derived from equations (1) and (9):

$$PI = w_1 \cdot O_{\overline{D}} + w_2 \cdot V_{\overline{D}} = \sum_{i=1}^m w_i p_i, \quad \forall i. \quad (10)$$

5. Control Strategy of Frequent Overflow at Intersection

A signalized intersection is the smallest unit of an urban traffic signal control system and is characterized by volatility, randomness, and uncertainty. For the sake of safety and efficiency, signal control strategies are to be based on both the theory of reasonable allocation of road rights and theory of conflicts. Therefore, traffic demand of a nonoverflow phase and rationality of the control strategy should be considered while designing a control strategy of the frequent overflow. The overflow control strategy structure is presented in Figure 6.

Step 1. The comprehensive identification index for overflow detection PI is to be calculated. It is to be determined whether it reaches the overflow condition. If no, calculations are to be continued; otherwise, transition to Step 2 is to be undertaken.

Step 2. Objective function J and constraint condition D are to be defined (the nonoverflow phase traffic demand):

$$\begin{aligned} J &= \min(PI(t)) \\ \text{s.t. } D &= [D_j]_m, \quad j = 1, 2, 3, \dots, m, m \geq 4. \end{aligned} \quad (11)$$

Step 3. The control strategy designed to match nonoverflow phase traffic demand is to be set:

$$CS = [CS_i]_n, \quad i = 1, 2, 3, \dots, n, n \geq 4. \quad (12)$$

Note: the global impact of the signalized intersection and the traffic demand of the nonoverflow phase should be considered when the frequent overflow occurs. Generally speaking, the control strategies to be designed according to the demand include delay, change, jump, insertion, and reverse phases, as shown in Figure 7:

Figure 7(a) shows that when the overflow occurs in the specific phase, the green time of the nonoverflow phase should be extended to restraint the vehicles entering the intersection.

Figure 7(b) shows the change phase. The phase change strategy is that the overflow phase should be closed when overflow occurs, while the next phase has fewer vehicles, so it is not easy to accumulate vehicles to raise the overflow. Then, the phase changes to the next phase to achieve the purpose of alleviating the overflow to the overflow control.

Figure 7(c) shows the jump phase. The skip phase strategy is to ignore the green signal of the overflow phase, and the green time of this phase will not be displayed. Then the phase will stop immediately, and the vehicle in the next phase is easy to enter the overflow phase to increase the overflow. When the vehicle flow in the next phase is small, the next phase can be skipped, and the phase will not increase the overflow.

Figure 7(d) shows the insertion phase. Insertion phase strategy is to add a specific phase for overflow phase in the normal phase sequence of intersection. When the overflow occurs, the added phase between the current phase and the next phase can gradually loosen the overflow phase.

Figure 7(e) shows the reverse phase. The reverse phase strategy is to change the execution order of phase in a cycle. When the phase overflows, the phase will stop immediately; the most independent phase will be executed first to decrease vehicles aggregation at the intersection.

Step 4. Determine whether the switching conditions are met and, accordingly, successive operating. The specific strategies are as follows:

$$D_j \longrightarrow CS_i \{ \min(PI(t)) \} + \varepsilon, \quad \text{Switch to Policy } n, m = n, \quad (13)$$

where $\varepsilon > 0$ is the lag factor.

Step 5. The following genetic algorithm is to be used for optimization:

- The objective function is considered as $J = \min(PI(t))$
- The constraint condition reads $D = [D(k)], k = 1, 2, 3, 4$

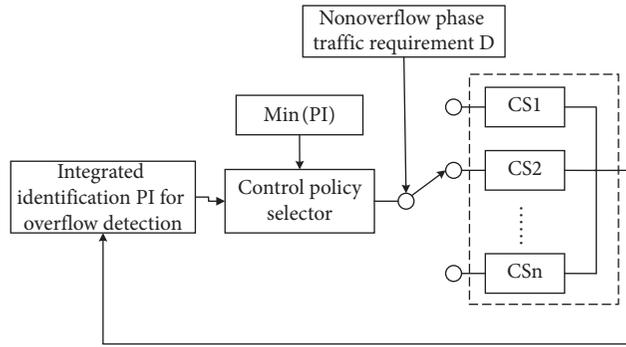


FIGURE 6: Overflow control strategy structure.

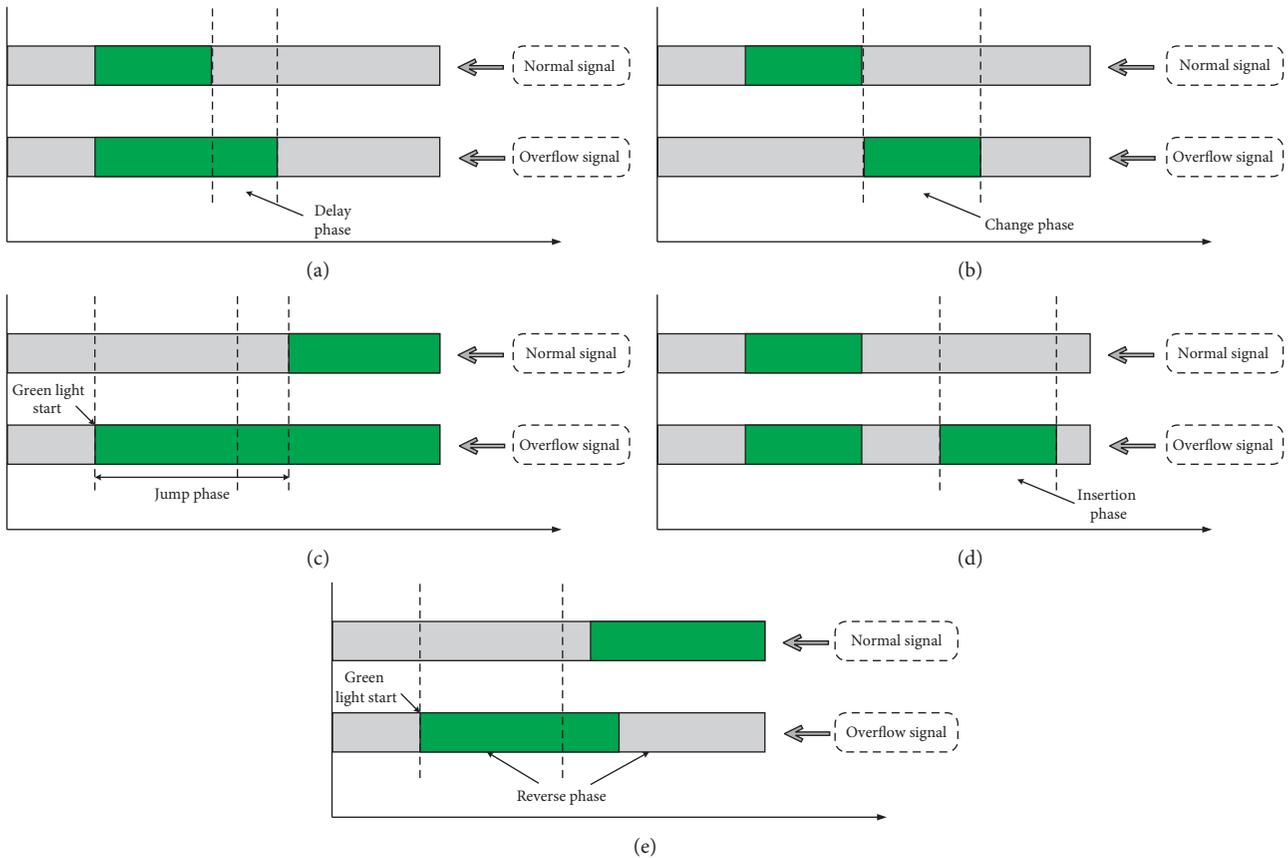


FIGURE 7: Overflow control strategy structure. (a) Delay phase. (b) Change phase. (c) Jump phase. (d) Insertion phase. (e) Reverse phase.

(c) The fitting function is chosen as $F = 1/J = 1/\min(\text{PI}(t)) = 1/\min[\sum_{i=1}^m w_i p_i(t)]$

(d) Design includes population size, crossover probability, mutation probability, and optimization algebra

6. Experiment and Analysis

6.1. *Experimental Design.* In order to verify feasibility of the algorithm proposed in this paper, the traffic data of the intersection of Siping Road and Shengli Street in Weifang were chosen for consideration.

It is important to note the following:

The intersection of Siping Road and Shengli Street is located in the core of Weifang. The traffic around the intersection is complex and serves large-scale enterprises, universities, and so on. The traffic demand is large, and peaks are obvious in the morning and in the evening. According to the statistics, there is a frequent overflow at the intersection. Therefore, its usage as the simulation object is representative.

Traffic data were gathered by means of a wide-area radar detector for detecting overflow at intersections. The detection frequency is 10 ms and the minimum statistical data unit is 5 s.

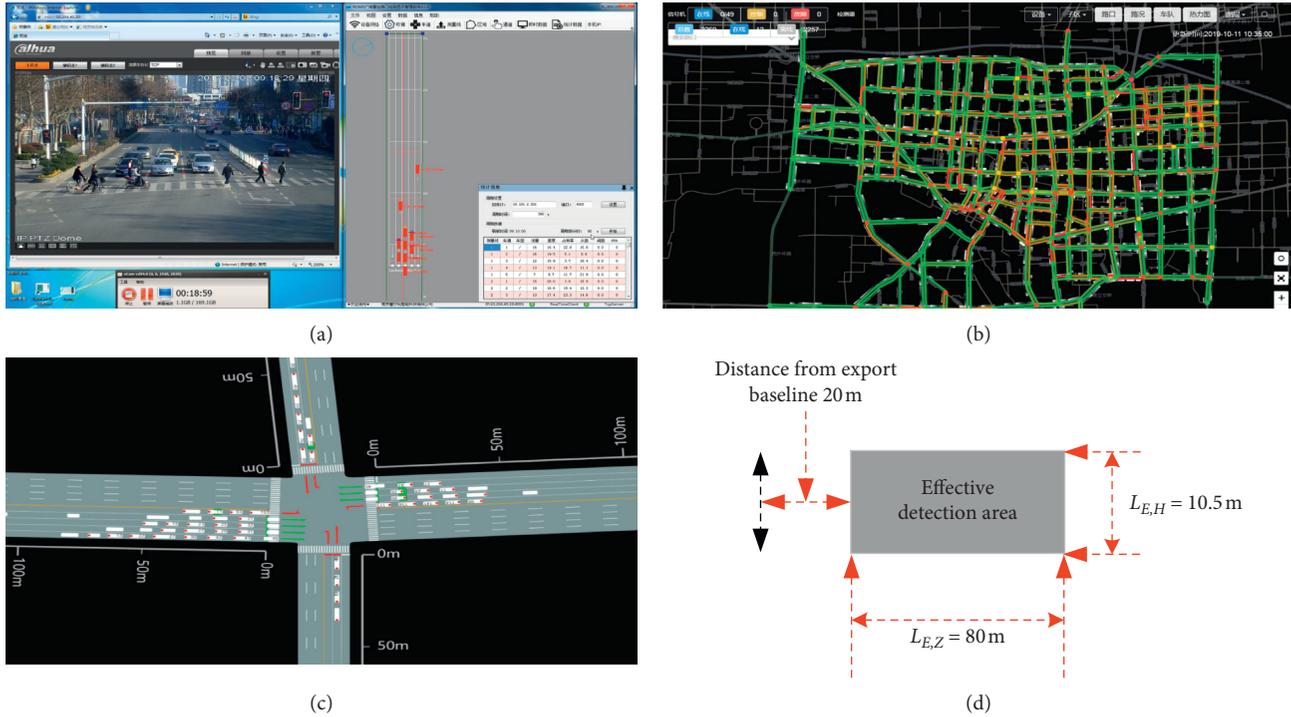


FIGURE 8: Intersection of Siping Road and Shengli Street in Weifang. (a) Wide-area radar detector setup software. (b) Middle- and microsimulation platform. (c) Signalized intersection. (d) Effective overflow detection area.

The effective detection area is shown in Figure 8(d).

The simulation uses the proprietary micro- and medium-scale simulation software aimed for development of the control strategy, effective detection area settings, and radar data generation of traffic demand (original data of the wide-area radar, including target number, length, location (XPos, YPos), and speed (XSpeed, YSpeed)), as shown in Figure 8(a).

The queue along Shengli Street from the west to the east leads to overflow at the signalized intersection as shown in Figures 8(b) and 8(c).

The overflow control strategy set for the signalized intersection reads $CS = [CS_i]_p$, $i = 1, 2, 3, \dots, n$, $n = 4$, including delay phase, change phase, jump phase, and insertion phase, as shown in Figures 7(a)–7(d). The reverse phase has a great influence on the traffic flow of the intersection, so it is not used in the experimental simulation.

There are 10 lanes in entrance and exit of east-west direction and 4 lanes in entrance and exit north-south direction at the intersection. Turn left 2 lane and straight 3 lanes in east-west direction. Turn left 2 lanes and straight 2 lanes in the north-south. The lane width is 4 m.

The original signal control timing was provided by Weifang traffic police department. $C = 156$ s, $p_1 = 45$ s (straight of east and west), $p_2 = 45$ s (straight of south and north), $p_3 = 30$ s (turn left of east and west), $p_4 =$

22 s (turn left of south and north), and $L = 12$ s (total lost time).

6.2. Experimental Data Analysis. When an overflow occurs at the signalized intersection, the average speed and average density data of the effective detection area belong to the constrained area, and the vehicles interact with each other, produce shock waves, and form a queue of vehicles. Comprehensive identification index PI serves as the overflow occurrence indicator, and the control strategy selector chooses the matching control strategy according to the traffic demand of the signalized intersection and nonoverflow phase. As shown in Figure 9, Figures 9(a)–9(f) show the change in traffic flow characteristics in the effective detection area after overflow control strategy has been visually implemented. Among these figures, Figure 9(f) presents overflow elimination and recovery of normal operation of the signalized intersection.

The total delay time and the average number of stop cycles of all vehicles at intersections are selected as analysis parameters. As shown in Figure 10, it can be seen that serious overflow occurred at the intersection when the simulation runs at the 2000th second. Figures 10(a) and 10(b) show that the total delay time and the average number of stop cycles at intersections will be maintained at a higher level without control strategy after overflow; when overflow control strategy is adopted, the overflow situation at intersections is alleviated at the 700th second according to simulation, and the overflow phenomenon is eliminated eventually.

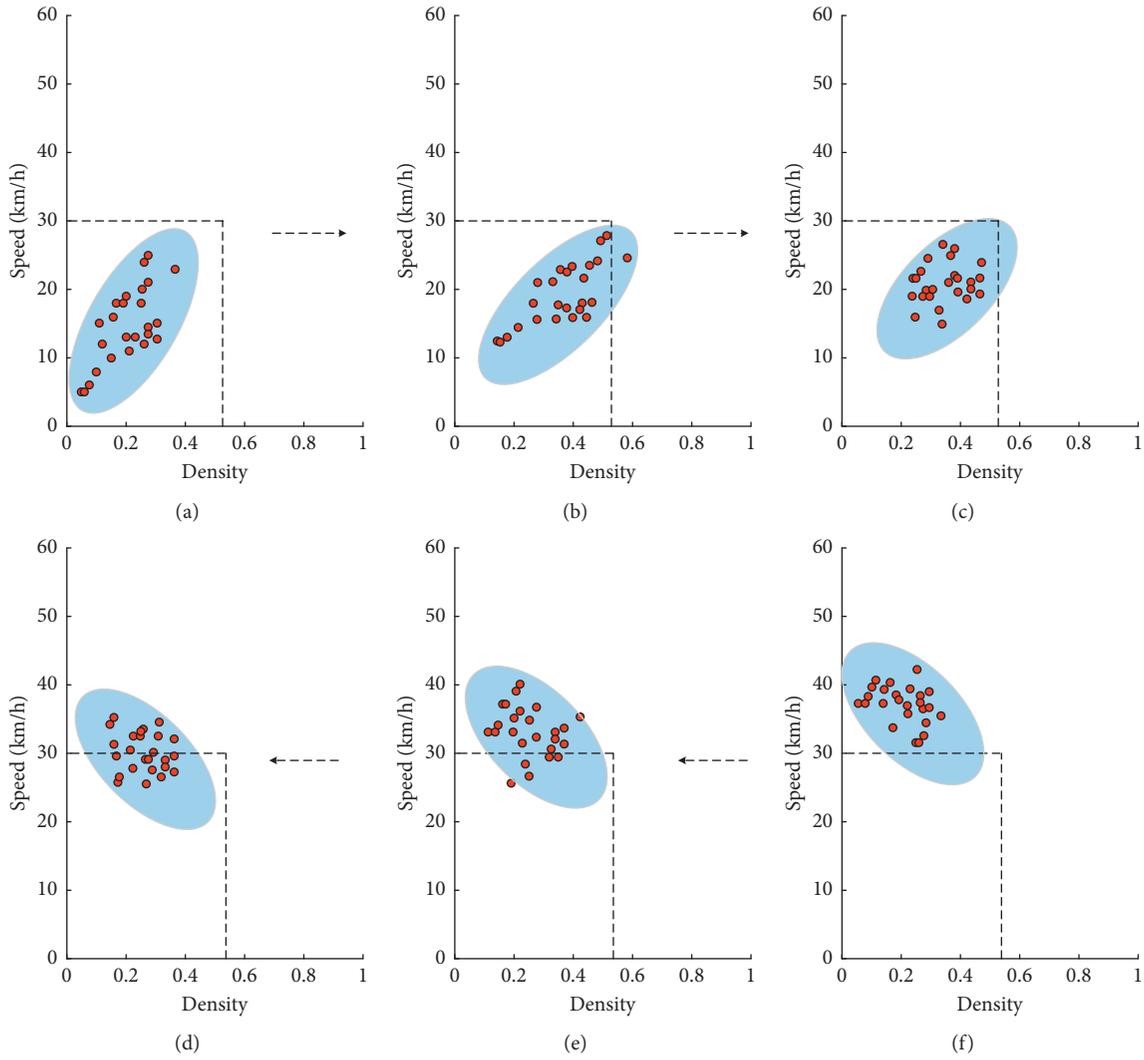


FIGURE 9: Effective detection of regional traffic flow: the fundamental diagram before and after the frequent overflow control has been applied.

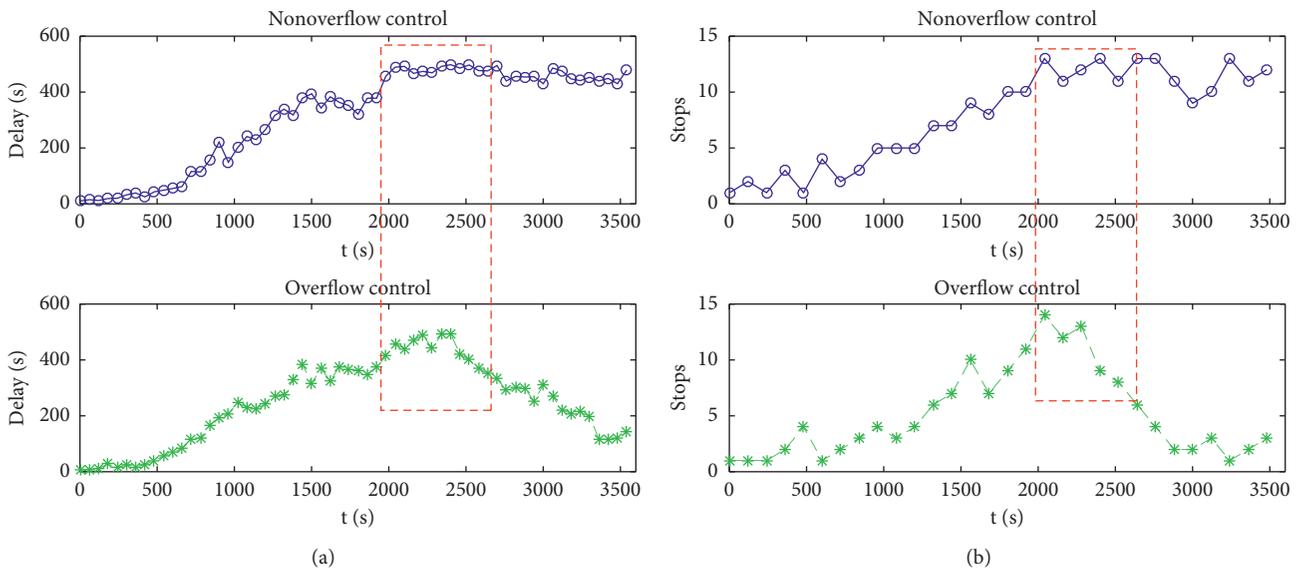


FIGURE 10: Analysis of overflow control at the intersection of Siping Road and Shengli Street in Weifang. (a) Total delay time at the intersection. (b) Cycle average of stops at the intersection.

7. Conclusion

For the frequent overflow at signalized intersections, due to abundant detection data provided by a wide-area radar, comprehensive identification index PI of overflow detection is developed. Average speed and space occupancy in the effective detection area serve as its subindexes whose weights are to be calculated by the distance entropy weight method with translation correction. Based on an objective function, the overflow control strategy set is designed to comprehensively consider the traffic demand of signalized intersections and nonoverflow phases. This paper presents the control strategy, effective detection area settings, radar data generation, and traffic demand generation by using the proprietary micro- and medium-scale simulation platform. Finally, the traffic flow characteristics of the effective detection area are analyzed and simulated, using the detection data of the actual signalized intersection. The results show that the proposed method can accurately detect the occurrence of overflow and eliminate overflow situations.

The contributions of this paper mainly include the following: (1) the overflow detection using wide-area radar detector is proposed for the first time; (2) the traffic demand and the rationality of control strategy of nonoverflow phase of intersection are considered comprehensively, and the method of frequent overflow control based on genetic algorithm is designed; (3) the proposed method is verified by the field data.

In this paper, the proposed method is based on the complete detection data of wide-area radar, but the detector often works abnormally in reality, so it is necessary to further study the overflow data completion and identification in the case of incomplete detection. Secondly, the identification and control of key intersection overflow in trunk coordinated control will be studied.

Data Availability

The data in this paper are provided by Weifang traffic police detachment in Shandong Province. The data are the real traffic data of Weifang city.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Li-li Zhang and Qi Zhao contributed equally to this work. Li-li Zhang and Qi Zhao contributed to conceptualization and methodology; Li Wang collected the resources and supervised the paper; Li-li Zhang contributed to writing the original draft; and Qi Zhao contributed to writing the paper and reviewed and edited it.

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