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Research Article

Space-Time Resource Integrated Optimization Method for Time-of-Day Division at Intersection Based on Multidimensional Traffic Flows

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Based on the change trends of traffic flow in different controlled directions at an intersection, the space-time resource integrated optimization method for TOD (time-of-day) division based on multidimensional traffic-flow data is proposed in this paper. By analyzing the traffic-flow data of 8, 4, 2, and 1 dimensions commonly used at the intersection, the dynamic Fisher algorithm is used to complete the time segment division of the traffic-flow sequence of different dimensions. On this basis, the preliminary TOD division is completed, and the phase timing and lane-use assignment corresponding to the preliminary time periods are optimized. Then, the adjacent time periods are merged and tested to complete the final result of the TOD division. In order to verify the effectiveness of the proposed method, the schemes based on traffic-flow data of different dimensions are carried out by using the data at an actual intersection in Wuhu City, and the total and average vehicle delays of different schemes throughout the day are evaluated by VISSIM. The results show that the more dimensions of traffic flow data are adopted, the more refined the TOD division scheme is, and the less the total delay and average delay at intersections throughout the day are. In particular, the TOD division scheme after further optimizing the lane-use assignment can further reduce the total and average vehicle delay throughout the day. It shows that the method using multidimensional traffic-flow data at an intersection to carry out the integrated optimization of TOD division, lane-use assignment, and phase timing has good applicability.

1. Introduction

Urban traffic signal optimization plays an important role in alleviating traffic congestion and improving the traffic capacity of road networks. The time-of-day (TOD) division of signal control schemes is an important part of signal timing optimization and can effectively adapt signal timing schemes to changes in traffic flow [1–3]. Research has shown that optimized TOD division and phase timing that matches the traffic flow can significantly improve intersection capacity and reduce vehicle delays [4–9].

TOD control involves dividing 24 h into several time periods according to changes in traffic flow at an intersection using different signal control schemes for different traffic time periods [10]. In practice, traffic engineers divide a day into several time periods according to the general trends in total traffic flow at intersections, such as a peak period, flat peak period, and low peak period. However, this empirical division makes it difficult to obtain optimal solutions [11]. In terms of theoretical research, most current research focuses on cluster analysis algorithms, in order to find optimal TOD breakpoints. For example, Wang [12] designed the TOD division method based on the C-means clustering algorithm and is verified by actual data. Su and Dong [13] put forward the study of TOD based on Isomap and K-means clustering algorithm, the results indicated that the Isomap and K-means algorithm outperformed the traditional artificial method. Xiu et al. [14] analyzed the macroscopic and microscopic variation of traffic flow deeply and proposed a multiperiods quadratic division based on the dynamic Fisher clustering algorithm. Guo and Zhang [15] presented an advanced cluster analysis aimed at identifying TOD breakpoints for coordinated, semiactuated modes when it is necessary for multiple intersection operations to be considered simultaneously. Although the above studies have achieved certain results by using different clustering algorithms in finding TOD breakpoints, it is uncertain whether the results of TOD division are conducive to reducing traffic delays and other indicators because they have not been evaluated for traffic benefits. Since the TOD division should serve to better improve traffic benefit, in recent years, more studies have conducted in-depth research on the TOD division method with traffic benefit evaluation. For example, Park et al. [16] proposed a genetic algorithm-based clustering, which was evaluated through the performance of an actual timing plan under a microscopic simulation program, SIMTRAFFIC. Li et al. [17] proposed a TOD division method by using dynamic recurrence order clustering, the results showed that, compared with the traditional K-means method, the average delay and queue length of the intersection were reduced by the proposed method in the peak periods. Yu et al. [18] improved the traditional fuzzy c-means clustering (FCM) algorithm and proposed a new method to divide the traffic signal control periods; compared with the traditional scheme, the improved FCM algorithm can effectively reduce the average delay of vehicles. Cao et al. [19] proposed a method for the automatic division of time periods of intersection based on Fisher-ordered clustering, and the simulation results showed that the method effectively reduces the average vehicle delay. In order to improve the precision of TOD breakpoints, Bie et al. [20] proposed a method to determine the numbers of transition cycles under different timing plan transition conditions; the results showed that, compared with the traditional method, the proposed method produces a reasonable number of time intervals and reduces total vehicle delay by 8.9%. Ratrout [21] introduced a subtractive algorithm-based K-means technique to determine the optimum number of TODs; SimTraffic was used to evaluate the performance of the selected number of clusters with respect to total delays, total stops, fuel used, and CO emissions. Smith et al. [11] proposed the data-driven methodology for signal timing plan; the results of a case study demonstrated that, compared to currently used techniques, the methodology provided benefits when considering performance measures such as delay. Although the above studies demonstrate the effectiveness of the TOD division method through the traffic benefit evaluation, the results of TOD division are all based on the total traffic-flow data at the intersection, and the change trends of traffic flow of different phase are ignored, which leads to the TOD division results may not be able to meet the needs of phase timing optimization. In order to solve the above problems, some studies began to use multidimensional traffic-flow data to carry out the TOD division research. For example, Xu et al. [22] developed a double-order optimization model of TOD control segmented point division, the dimensions of the traditional traffic-flow data were increased, and the classic model was reconstructed in the first-order optimization. Dai et al. [23] calculated the cycle time by considering the difference of traffic flow direction at the intersection, studied the TOD division method at the intersection, and provided a basis for a multiperiods timing scheme. Zhao et al. [24] selected the flow of each phase as the clustering data, improved the classical NJW (Ng-Jordan-Weiss) algorithm in spectral clustering, and used SimTraffic to perform simulation evaluation on the results of TOD division under different cluster numbers, so as to select the best number of clusters and finally obtained the results of TOD division under the given number of clusters. Chen et al. [25] took the intersection phase flow as clustering data and finally conducted clustering by reducing the dimension and systematically compared the influence of K-means, hierarchical clustering, and Fisher clustering methods on TOD division. The results show that Fisher ordinal clustering outperforms k-means and hierarchical clustering in terms of performance measures. The above studies further verify the effectiveness of using multidimensional traffic-flow data such as phase flow to carry out TOD division. However, on the one hand, the TOD division results obtained by using traffic-flow data clustering of different dimensions are not compared and analyzed, and the influence of multidimensional traffic-flow data clustering on TOD division results is not illustrated. On the other hand, TOD division is closely related to signal phase timing and lane-use assignment optimization (such as setting variable lanes at different time periods). In the process of TOD division, most studies have not fully considered signal phase optimization. For example, [21, 22, 25] all adopted Synchro software to optimize the timing scheme but did not mention the phase optimization. In addition, hardly has literature considered the lane-use assignment optimization in the process of TOD division, and the final TOD division result has not been further tested according to lane-use assignment, signal phase, and timing scheme.

In summary, a lot of achievements have been made in the current research on clustering algorithms for seeking TOD breakpoints. Most of the studies use the total traffic-flow data of a single dimension at the intersection to carry out the TOD division, while a few use multidimensional phase traffic-flow data to carry out the TOD division. Recent studies have adopted Synchro software to carry out signal timing optimization and adopted SimTraffic traffic simulation software for benefit evaluation to determine the optimal number of clusters in the process of TOD division. In general, the TOD division needs to serve phase timing design, and phase timing optimization is based on the traffic flow of straight and left turn at the intersection as the design basis and is closely related to the lane-use assignment of entrance lanes. Therefore, the integrated optimization of TOD division, phase timing, and lane-use assignment based on multidimensional traffic-flow data in each controlled direction at the intersection is an urgent topic to be studied, which is rarely involved at present.

Therefore, based on the traffic flow of each controlled direction at the intersection, we propose a space-time resource integrated optimization method for TOD division at the intersection based on multidimensional traffic flow data. This method is based on the traffic-flow sequence of different dimensions corresponding to straight-through and left-turn traffic at the intersection and uses the Fisher clustering algorithm, which has more advantages in ordering sample clustering [25], to complete the time segment division of the traffic-flow sequence of different dimensions. On this basis, the preliminary TOD division is completed, and then the optimized signal phases and timing schemes are completed. Furthermore, the lane-use assignment is further considered to optimize. Finally, the preliminary time periods are merged and tested to complete the final result of the TOD division. In order to verify the feasibility of the proposed method, the TOD division schemes based on traffic-flow data of different dimensions are further completed with the actual intersection data. The vehicle delay of different schemes is evaluated by VISSIM traffic simulation software, and the conclusions of this paper are proposed.

This study makes the following contributions in comparison with past work in the area: first, an integrated optimization method of TOD division, phase timing, and lane-use assignment based on multidimensional traffic-flow data is proposed, and the rationality of the final result of TOD division is further tested according to the lane, phase, and timing schemes. Second, the TOD division results based on traffic-flow data of different dimensions and the corresponding traffic benefit are compared, and the effect of multidimensional traffic-flow data clustering on the TOD division is further analyzed. Third, in the process of signal phase timing design of the preliminary TOD division, the phase combination optimization method based on lane-use assignment optimization is further considered, and the adjacent time periods are merged and tested based on the lane-use assignment optimization results, so as to further improve the traffic benefit of the TOD division results.

The remainder of the paper is organized as follows. Section 2 presents the methodology of TOD division of intersection based on multidimensional traffic flow. Section 3 presents the test and results of a case study at the actual intersection of Wuhu City, China. The effectiveness of the method proposed in this paper is discussed in Section 4. Finally, Section 5 summarizes the main outcomes of this paper.

2. Methodology

2.1. Dimension Analysis of Traffic Flow at Intersection Used for TOD Division. As shown in Figure 1, it is assumed that a_t ($t = 1, 2, \ldots, 8$) is the main controlled traffic flow of straight and left turn at a typical intersection. The vehicles turning right are not controlled by the signal and yields to conflicting traffic flow. q_t is the traffic-flow sequence of a_t in 24 h. Current methods usually take the total traffic flow at an intersection as the basis for TOD division. That is, the TOD division is carried out based on the traffic-flow sequence of one dimension. As mentioned above, some methods take multidimensional phase traffic-flow data to carry out TOD division, and the signal phase design at the intersection is usually a conventional four-phase scheme: the first phase is for north-south straight-through traffic, the second phase is for north-south left-turning traffic, the third phase is for the east-west straight-through traffic, and the last phase is for east-west left-turning traffic. Two-phase schemes are also common: the first phase is for east-west traffic and the second phase is for north-south traffic. Yet it is the combination of the controlled traffic flow of eight dimensions that determines the phase design. That is, except for one dimension, TOD division can be carried out based on the traffic-flow sequences of two, four, and eight dimensions at a typical intersection. Therefore, in order to analyze the impact of traffic-flow clustering of different dimensions on TOD division, we propose using the traffic-flow sequence of $w\,(w = 1, 2, 4, 8)$ dimensions to optimize TOD division and phase timing at the intersection. Since q_t is an important basis for the signal phase timing design, and TOD division and phase timing need to be carried out in an integrated manner, this paper adopts the traffic-flow sequence Q_v of different dimensions formed by q_t as the basis for TOD division. That is, when $w = 1$, $Q_1 = \sum q_t$; when $w = 2$, $Q_1 = q_1 + q_2 + q_5 + q_6$ and $Q_2 = q_3 + q_4 + q_7 + q_8$; when $w = 4$, $Q_1 = q_1 + q_5$, $Q_2 = q_2 + q_6$, $Q_3 = q_3 + q_7$, and $Q_4 = q_4 + q_8$; and when $w = 8$, $Q_1 = q_1$, $Q_2 = q_2$, $Q_3 = q_3$, $Q_4 = q_4$, $Q_5 = q_5$, $Q_6 = q_6$, $Q_7 = q_7$, and $Q_8 = q_8$.

2.2. Preliminary TOD Division Based on Traffic-Flow Sequences of Different Dimensions

2.2.1. Principle of the Dynamic Fisher Clustering Algorithm. Fisher clustering analysis is a statistical method specifically designed for ordered samples. It has the advantages of multi-index clustering without destroying the original order of the samples. The dynamic Fisher clustering algorithm is composed of the ordered sample clustering method and the dynamic clustering method. It can better determine the TOD division results according to the predetermined target [26].

Assuming that $W = \{w_1, w_2, \ldots, w_n\}$ is an ordered sample, the value of the sample point w_i on variable $V(w)$ is v_i, and the elements similar to $V(w_i)$ are all classified into the same category P_i, but the sample size of each category must be continuous. That is, $P_i = \{V(w_i - k_1), \ldots, V(w_i), V(w_i), V(w_i + 1), \ldots, V(w_i + k_2)\}$, where $0 < k_1$, $k_2 < n$. The main steps are as follows:

(1) Set the preliminary segment number of the ordered sample as z and calculate all possible class diameters $D(i)$ under the segment numbers z:

$$D(i) = \sum_{j=1}^{n_i} \left(x_{ij} - \overline{x_i}\right)^2,$$
$$\overline{x_i} = \frac{1}{n} \sum_{j=1}^{n_i} x_{ij}, \tag{1}$$

where x_{ij} is the characteristic value of the sample.

(2) Calculate the objective function $B(n, z)$:

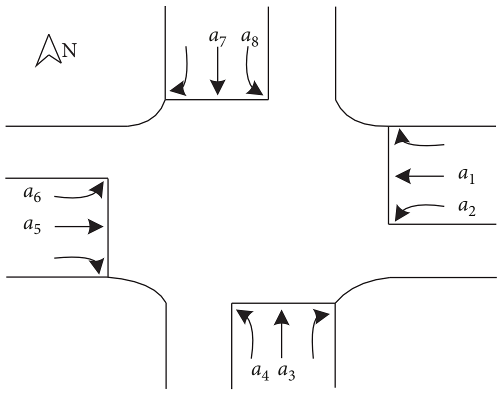

Figure 1: Main controlled traffic flow at a typical intersection.

$$B(n,z) = \min \sum_{i=1}^{z} (D_i). \quad (2)$$

(3) Solve the optimal classification.

The ordered sample classification has the following theorem: the optimal z class segmentation must be formed by adding another class on the basis of the optimal $z-1$ class segmentation, so there is the following recursive formula:

$$B(m,z) = \min_{1\le j\le n}\left[B\left(n_j, z-1\right)\right] + D(z). \quad (3)$$

(4) Change the value of z, reset the segment numbers, and calculate the class diameter until all the preset segment numbers are realized.

(5) Select the appropriate segmentation result from all segment numbers, which is to draw the curve of the value of objective function $B(n,\ z)$ changing with segment number z, and check the segment number z at the bend or smoothing point of the curve as the optimal segmentation result [25].

2.2.2. Time Segment Division of Traffic-Flow Sequence Using the Dynamic Fisher Clustering Algorithm

Step 1: Obtain the average one-day traffic-flow data of the lanes in each controlled direction at an intersection on working days and nonworking days [23]. Select the statistical interval of 15 min with more stable traffic-flow characteristics [24], as described in Section 2.1, form the multiple traffic-flow sequences with 96 ordered sample characteristic values corresponding to w dimensions.

Step 2: Set the segment numbers of z. Since the number of traffic time periods is generally 4 to 8 [26], in order to effectively find the bend point of the curve of the objective function $B(n,\ z)$ and determine the optimal value of z, the value range of z can be appropriately expanded on the premise of considering the computational efficiency of the computer program. Therefore, the preset value range of z in this paper is 2 to 14.

Step 3: Use equation (1) to calculate all possible class diameters in the case of the segment numbers of z and use equation (2) to calculate the objective function.

Step 4: Use equation (3) to find the optimal clustering point.

Step 5: Change the value of z and return to Step 3 until all preset segment numbers are calculated and stop.

Step 6: Draw the curve of objective function $B(n, z)$ and take the value of z at the bend point as the optimal segmentation result of the traffic-flow sequence.

Step 7: According to the optimal segmentation results, the time segment of traffic-flow sequence of w dimensions are divided, different colors are used to distinguish them, and different boundaries are formed between different colors, as shown in Figure 2.

2.2.3. Time Segment Division of Traffic-Flow Sequence of Different Dimensions

Step 1: According to the multiple partition boundaries of the time segment of a traffic-flow sequence of w dimensions, the time segment of the traffic-flow sequence of different dimensions are divided according to the same time order.

Step 2: Processing of "outliers." Due to the extra signal transition loss, if the time segment is too short, the minimum span of the time segment is set to 30 min [22, 24]. However, step 1 is likely to produce 15 min time segment, called "outliers." In order to make the TOD division more practical, the outliers need to be merged [22]. The specific processing method is as follows: define the minimum time segment T as 30 min. If the divided time segment in step 1 is less than T, calculate b_1 and b_2, where b_1 is the difference of traffic flow between the time segment and the previous time segment, and b_2 is the difference of traffic flow between the time segment and later time segment. If $b_1 \le b_2$, the time segment is merged with the previous time segment; If $b_1 > b_2$, the time segment is merged with the later time segment. The divided result of the 15 min time segment (11:30) in the traffic-flow sequences of 8 dimensions is shown in Figure 3.

Step 3: Repeat Step 2 until all the time segments are longer than or equal to T. Then, the preliminary TOD division of the traffic-flow sequence of different dimensions has been completed.

2.3. Signal Phase Timing Design Based on the Preliminary TOD Division

2.3.1. Optimization Method of Phase Combination. According to Figure 1, assuming that the flow ratio corresponding to the controlled flow a_t is y_t, which can be calculated by (4). Without Figure 2 considering the phase sequence, a_t can form 36 different phase schemes, and 6 phase schemes (Figure 3) can be formed in east-west and north-south directions, respectively, among which phase

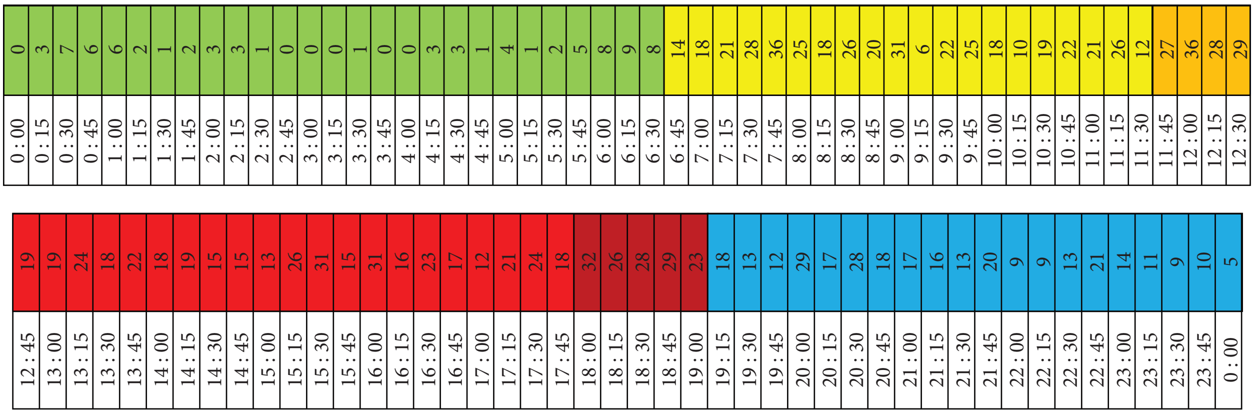

Figure 2: Time segment division results of traffic-flow sequence using the dynamic Fisher clustering algorithm.

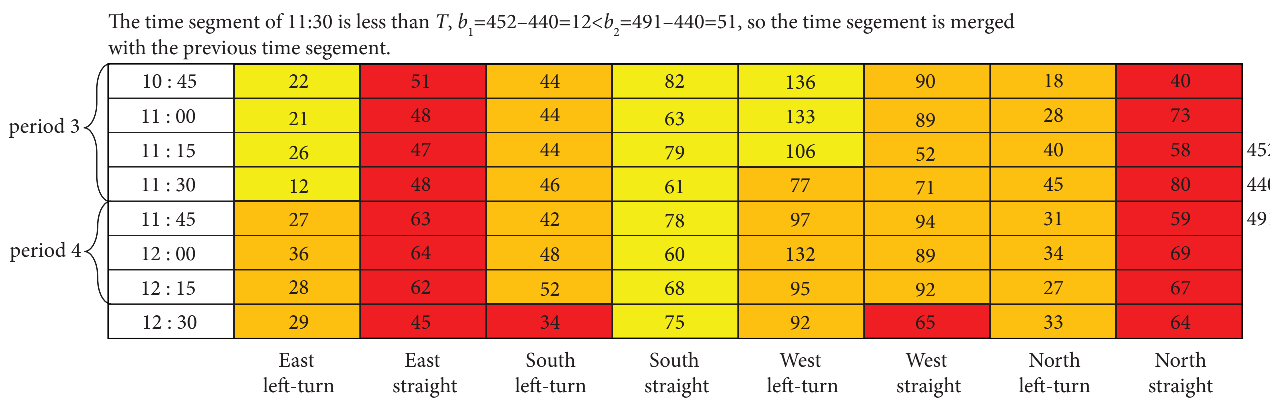

Figure 3: Example of the outlier processing of time segment division of traffic-flow sequence of 8 dimensions.

schemes 1 to 6 belong to the east-west direction, and phase schemes 7 to 12 belong to the north-south direction, as shown in Figure 4. Phase schemes 1 and 7 have no protected left-turn phases, which allow the traffic flow of straight and left turn in the opposite directions to be released at the same time and are suitable for the intersection with less traffic flow of left turn. Phase schemes 2 and 8 are the conventional symmetric phases, which are suitable for the intersections with more balanced traffic flow in opposite directions. Schemes 3 and 9 are phases that allow the traffic flow of straight and left turn in a single direction to be released at the same time, which are suitable for the intersections with the balanced traffic flow of straight and left turn in a single direction. Phase schemes 4, 5, 6, 10, 11, and 12 are the overlapping phases [27], which are suitable for intersections with the uneven flow in opposite directions. The above-given phase combination can not only form a multiphase scheme but also form a two-phase or three-phase scheme according to the traffic flow. For example, phase schemes 1 and 7 can form a two-phase scheme, phase schemes 1 and 8 or phase schemes 1 and 9 can form a three-phase scheme, and phase schemes 7 and 2 or phase schemes 7 and 3 can form a three-phase scheme. The flow ratio calculation formulas and setting conditions of each phase scheme are listed in Table 1, where Y_i ($i = 1, 2, 3, 4, 5, 6$) is the flow ratio of the 6 phase schemes in the east-west direction, and Y_j ($j = 7, 8, 9, 10, 11, 12$) is the flow ratio of the 6 phase schemes in the north-south direction.

$$y_t = \frac{q_{dt}}{PHF \cdot S_t}, \tag{4}$$

where q_{td} and S_t are the lane traffic flow and saturation flow ratio of the controlled traffic flow a_t, respectively, unit: PCU/h. PHF is the peak-hour coefficient, the value of which for the main road is 0.75, the value of which for the subsidiary road and others is 0.85.

The sum of Y_i and Y_j is the cycle flow ratio Y_u and the impact of Y_u on the signal cycle time C can be analyzed with Webster's formula:

$$C = \frac{1.5L + 5}{1 - Y_u}, Y_u < 0.9, \tag{5}$$

$$\begin{aligned} Y_u &= Y_i + Y_j, \\ i &= 1, 2, 3, 4, 5, 6, \\ j &= 7, 8, 9, 10, 11, 12, \end{aligned} \tag{6}$$

where C is the signal cycle time and L is the total signal loss time.

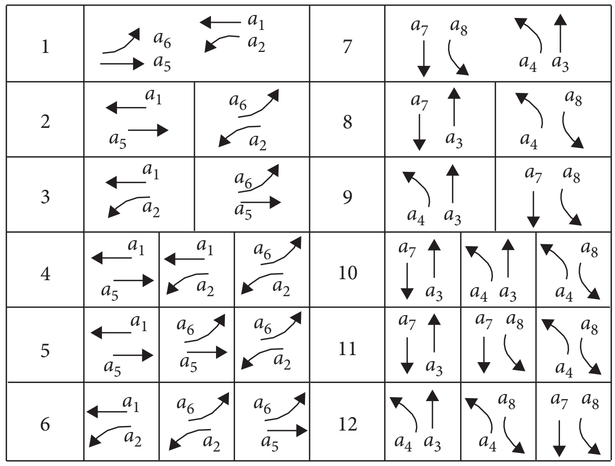

Figure 4: Phase schemes corresponding to the controlled traffic flow at intersection.

Table 1: Phase schemes and flow ratio calculation of the controlled traffic flow at intersection.

No.	Direction	Phase combination			Flow ratio of phase combination	Set conditions
1	East-west (E-W)	a1, a2, a5, a6			Y1 = max (y1, y2, y5, y6)	$(y_2S_2 < 100)$ or $(100 \leq y_2S_2 < 200$ and $y_2S_{2*}y_5S_5 < 50000)$ $(y_6S_6 < 100)$ or $(100 \leq y_6S_6 < 200$ and $y_1S_{1*}y_6S_6 < 50000)$
2		a1, a5		a2, a6	Y2 = max (y1, y5) + max (y2, y6)	$y_2S_2 > 200$ or $y_6S_6 > 200$
3		a1, a2		a5, a6	Y3 = max (y1, y2) + max (y5, y6)	
4		a1, a5	a1, a2	a2, a6	Y4 = max $(y1 + y6,\ y2 + y5)$	$y_1S_1 > y_5S_5$ and $y_2S_2 > y_6S_6$
5		a1, a5	a5, a6	a2, a6	Y5 = max $(y1 + y6,\ y2 + y5)$	$y_1S_1 < y_5S_5$ and $y_2S_2 < y_6S_6$
6		a1, a2	a2, a6	a5, a6	Y6 = max $(y1 + y6,\ y2 + y5)$	$y_2S_2 > y_1S_1$ and $y_6S_6 > y_5S_5$
7	South-north (S–N)	a3, a4, a7, a8			Y7 = max (y3, y4, y7, y8)	$(y_4S_4 < 100)$ or $(100 \leq y_4S_4 < 200$ and $y_4S_{4*}y_7S_7 < 50000)$ $(y_8S_8 < 100)$ or $(100 \leq y_8S_8 < 200$ and $y_3S_{3*}y_8S_8 < 50000)$
8		a3, a7		a4, a8	Y8 = max (y3, y7) + max (y4, y8)	$y_4S_4 > 200$ or $y_8S_8 > 200$
9		a3, a4		a7, a8	Y9 = max (y3, y4) + max (y7, y8)	
10		a3, a7	a3, a4	a4, a8	Y10 = max $(y3 + y8,\ y4 + y7)$	$y_3S_3 > y_7S_7$ and $y_4S_4 > y_8S_8$
11		a3, a7	a7, a8	a4, a8	Y11 = max $(y3 + y8,\ y4 + y7)$	$y_3S_3 < y_7S_7$ and $y_4S_4 < y_8S_8$
12		a3, a4	a4, a8	a7, a8	Y12 = max $(y3 + y8,\ y4 + y7)$	$y_4S_4 > y_3S_3$ and $y_8S_8 > y_7S_7$

As can be seen from formula (5), the larger value of Y_u is, the larger value of C will be, resulting in a larger vehicle delay in the signal cycle. Therefore, the phase scheme with the least value of Y_u can be selected as the preferred scheme to improve the control efficiency of the signal cycle. When formula (5) is used to calculate the signal cycle time, Y_u is required to be less than 0.9. When Y_u is more than 0.9, the lane-use assignment needs to be further optimized.

2.3.2. Phase Combination Optimization Method for Further considering Lane-Use Assignment. Lane-use assignment refers to the traffic direction distribution of the entrance lanes at the intersection, which is generally divided into straight, left, and right turn. At present, lane-use assignment adjustment is mainly realized through the variable lane at an intersection, which refers to the dynamic adjustment of lane-use assignment according to the change trends of traffic flow at different time periods of one day [28], which is an important factor to be considered in the process of TOD division, but it is less involved in the current research literature. The lane-use assignment is closely related to the signal phase. We seek the optimal combination of lane-use assignment and signal phase mainly through the enumeration method [29]. Taking the main controlled flow in Figure 1 as an example, assume that there is at least one straight lane, one left-turn lane, and one right-turn lane at each entrance of the intersection. The specific steps are as follows :

Step 1: Establish objective function $Y\,(N_{ET}, N_{EL}, N_{WT}, N_{WL}, N_{ST}, N_{SL}, N_{NT}, N_{NL}, u)$.

$$Y\left(N_{ET}, N_{EL}, N_{WT}, N_{WL}, N_{ST}, N_{SL}, N_{NT}, N_{NL}, i, j\right) = \min\left(Y_u\right), \tag{7}$$

where N_{ET} and N_{EL} are the numbers of straight lanes and left-turn lanes at the east entrance, respectively. N_{WT} and N_{WL} are the numbers of straight lanes and left-turn lanes at the west entrance, respectively. N_{ST} and N_{SL} are the numbers of straight lanes and left-turn lanes at the south entrance, respectively. N_{NT} and N_{NL} are the numbers of straight lanes and left-turn lanes at the north entrance, respectively. The total number of entrance lanes minus the number of straight lanes and the number of left-turn lanes equals the number of right-turn lanes.

Step 2: Establish constraint conditions according to objective function variables.

$$s\cdot t\cdot\begin{cases} N_{ET}, N_{EL}, N_{WT}, N_{WL}, N_{ST}, N_{SL}, N_{NT}, N_{NL} \geq 1 \\ N_{ET} + N_{EL} < N_E, N_{WT} + N_{WL} < N_W \\ N_{ST} + N_{SL} < N_S, N_{NT} + N_{NL} < N_N \\ y_1 = \dfrac{q_{ET}}{N_{ET}\cdot PHF\cdot S_1}, y_2 = \dfrac{q_{EL}}{N_{EL}\cdot PHF\cdot S_2}, y_3 = \dfrac{q_{ST}}{N_{ST}\cdot PHF\cdot S_3}, y_4 = \dfrac{q_{SL}}{N_{SL}\cdot PHF\cdot S_4} \\ y_5 = \dfrac{q_{WT}}{N_{WT}\cdot PHF\cdot S_5}, y_6 = \dfrac{q_{WL}}{N_{WL}\cdot PHF\cdot S_6}, y_7 = \dfrac{q_{NT}}{N_{NT}\cdot PHF\cdot S_7}, y_8 = \dfrac{q_{NL}}{N_{NL}\cdot PHF\cdot S_8} \\ Y_u = Y_i + Y_j < 0.9, i = 1,2,3,4,5,6, j = 8,9,10,11,12, \end{cases} \tag{8}$$

where N_E, N_W, N_S, and N_N are the number of lanes at the east entrance, west entrance, south entrance, and north entrance of the intersection, respectively. q_{ET} and q_{EL} are the straight traffic flow and the left-turn traffic flow at the east entrance, respectively. q_{WT} and q_{WL} are the straight traffic flow and the left-turn traffic flow at the west entrance, respectively. q_{ST} and q_{SL} are the straight traffic flow and the left-turn traffic flow at the south entrance, respectively. q_{NT} and q_{NL} are the straight traffic flow and the left-turn traffic flow at the north entrance, respectively. S is the saturation flow ratio of the lane. The formulas of Y_i and Y_j are shown in Table 1.

Step 3: Enumerate all possible allocation results of the number of straight and left-turn lanes at each entrance at intersection, list all lane-use assignment combinations that meet the constraint conditions, and calculate the value of Y_u according to equation (8).

Step 4: Select N_{ET}, N_{EL}, N_{WT}, N_{WL}, N_{ST}, N_{SL}, N_{NT}, N_{NL}, i, and j corresponding to the minimum value of Y_u according to the objective function (7) to determine the optimal scheme of the signal phase and lane-use assignment combination.

2.3.3. Signal Timing Calculation and Test

Step 1: According to the optimal phase combination, equations (5) and (9) are used to calculate the signal cycle time C and the total effective green time G_E, respectively.

$$G_E = \sum g_{et} = C - L, \tag{9}$$

where g_{et} is the effective green Table 2 time of controlled flow a_t.

Step 2: Select the optimal phase combination corresponding to east-west and north-south directions in Table 2 to calculate g_{et}.

Step 3: If g_{et} is less than the minimum green time $g_{\min t}$, then multiply G_E by the adjustment coefficient, which is the maximum value of $g_{\min t}/g_{et}$, and return to Step 2.

Step 4: Calculate saturation x_t of a_t according to the following equation:

$$x_t = \frac{y_t}{\lambda_t} = \frac{y_t C}{g_{et}}, \tag{10}$$

where λ_t is the green time ratio of a_t.

Step 5: The queue at the intersection increases rapidly when x_t is more than 0.95. In order to avoid this situation, the maximum limit value of x_t is set as 0.95 [30]. Judge whether x_t is more than 0.95. If not, go to Step 6. If so, $x_t = 0.95$, recalculate C and g_{et} according to equations (10) and (9), so that x_t meets the requirements and then go to step 6.

Step 6: Calculate the display green time g_t of each controlled flow a_t according to the following equation:

$$g_t = l_t + g_{et} - A_t, \tag{11}$$

where l_t is the startup loss time of a_t, which is generally 3 seconds. A_t is the yellow time, which is generally 3 seconds.

Table 2: Signal timing calculation of different phase combinations at intersection.

No.	Phase combination			Effective green time g_{et}
1	a1, a2, a5, a6			$g_{e1} = g_{e2} = g_{e5} = g_{e6} = G_E \max(y_1, y_2, y_5, y_6)/Y_u$
2	a1, a5		a2, a6	$g_{e1} = g_{e5} = G_E \max(y_1, y_5)/Y_u, g_{e2} = g_{e6} = G_E\max(y_2, y_6)/Y_u$
3	a1, a2		a5, a6	$g_{e1} = g_{e2} = G_E \max(y_1, y_2)/Y_u, g_{e5} = g_{e6} = G_E\max(y_5, y_6)/Y_u$
4	a1, a5	a1, a2	a2, a6	$g_{e1} = G_E\max(y_1 + y_6,\ y_2 + y_5)/Y_u \cdot y_1/y_1 + y_6, g_{e6} = G_E\max(y_1 + y_6,\ y_2 + y_5)/Y_u \cdot y_6/y_1 + y_6$ $g_{e2} = G_E\max(y_1 + y_6,\ y_2 + y_5)/Y_u \cdot y_2/y_2 + y_5, g_{e5} = G_E\max(y_1 + y_6,\ y_2 + y_5)/Y_u \cdot y_5/y_2 + y_5$
5	a1, a5	a5, a6	a2, a6	
6	a1, a2	a2, a6	a5, a6	
7	a3, a4, a7, a8			$g_{e3} = g_{e4} = g_{e7} = g_{e8} = G_E \max(y_3, y_4, y_7, y_8)/Y_u$
8	a3, a7		a4, a8	$g_{e3} = g_{e7} = G_E \max(y_3, y_7)/Y_u, g_{e4} = g_{e8} = G_E\max(y_4, y_8)/Y_u$
9	a3, a4		a7, a8	$g_{e3} = g_{e4} = G_E \max(y_3, y_4)/Y_u, g_{e7} = g_{e8} = G_E\max(y_7, y_8)/Y_u$
10	a3, a7,	a3, a4	a4, a8	$g_{e3} = G_E\max(y_3 + y_8,\ y_4 + y_7)/Y_u \cdot y_3/y_3 + y_8, g_{e8} = G_E\max(y_3 + y_8,\ y_4 + y_7)/Y_u \cdot y_8/y_3 + y_8$ $g_{e4} = G_E\max(y_3 + y_8,\ y_4 + y_7)/Y_u \cdot y_4/y_4 + y_7, g_{e7} = G_E\max(y_3 + y_8,\ y_4 + y_7)/Y_u \cdot y_7/y_4 + y_7$
11	a3, a7,	a7, a8	a4, a8	
12	a3, a4	a4, a8	a7, a8	

Step 7: Finally, complete the calculation of all phase timing schemes of preliminary time periods.

2.4. Merging and Testing of Adjacent Periods of the Preliminary TOD Division. Since the divided time periods need to be merged and tested [22], adjacent time periods of the preliminary TOD division need to be further merged and tested. Due to the TOD division is closely related to the lane-use assignment, phase scheme, and signal timing, and current literature about TOD division with less considering the lane-use assignment, in order to further reflect the impact of lane-use assignment on TOD division, the adjacent time periods of the preliminary TOD division are merged and tested under the two conditions of whether the lane-use assignment is considered or not in this paper.

Case 1: Adjacent time periods are merged and tested without considering the lane-use assignment.

Step 1: Suppose that the two adjacent time periods are D_a and D_b, respectively, and the phase timing schemes calculated by the method in Sections 2.3.1 and 2.3.3 are A and B, respectively. If the phase schemes of A and B are the same, and the signal cycle time difference ΔC is not more than 15 s [20], then the adjacent time periods can be merged and go to step 2.
Step 2: Calculate the saturation x_{at} of each controlled flow of Scheme A in time period D_b and the saturation x_{bt} of each controlled flow of Scheme B in time period D_a according to equation (10). The maximum limit value of saturation set by step 5 in Section 2.3.3 is 0.95 [30], and the time periods are merged according to the following rules.
If $x_{at} \leq 0.95$ and $x_{bt} \leq 0.95$, the time periods D_a and D_b are merged, and the phase timing scheme with the shorter signal cycle time C in Scheme A and B is adopted.
If $x_{at} \leq 0.95$ and $x_{bt} > 0.95$, the time period D_b is merged into the time period D_a, and the phase timing Scheme A is adopted.
If $x_{at} > 0.95$ and $x_{bt} \leq 0.95$, the time period D_a is merged into the time period D_b, and the phase timing Scheme B is adopted.
If $x_{at} > 0.95$ and $x_{bt} > 0.95$, the time period D_a and D_b cannot be merged.
Step 3: Repeat the merge and test of adjacent time periods according to step 1 and step 2 until any two adjacent time periods cannot be merged, then complete the final result of TOD division.

Case 2: adjacent time periods are merged and tested considering lane-use assignment.

The steps for case 2 are similar to those for case 1, the difference is that in step 1, the optimal lane-use assignment, signal phase, and timing scheme are obtained by the method described in Sections 2.3.2 and 2.3.3. If the lane-use assignment and signal phase scheme are the same in the adjacent time periods, and the signal cycle time difference ΔC is not more than 15 s [20], then the adjacent time periods can be merged, and go to Step 2. The remaining steps are the same and are not described here.

3. Test and Results

3.1. Data Collection and Analysis. In this paper, the traffic flow of each lane at the Jiuhua Road and Zheshan Road intersection in Wuhu City, China, is collected for one continuous week using a microwave detector. Because the TOD division and phase timing design methods for the working and nonworking days are the same, we used more representative traffic-flow data on working days for verification. Through statistics, the traffic-flow data of 24 h in a working day at the intersection are obtained at 15 min intervals, as shown in Figure 5.

As shown in Figure 5, there is a large number of traffic flow at the intersection in the daytime. According to the change trends of the whole-day traffic flow of an intersection, Xu et al. [22] divided the intersection into hump type, constant-peak type, and multipeak type. And, this intersection tends to be a constant-peak type, characterized by a large number of traffic flow, mainly including shock-peak values and normal-peak values, where the low-peak values appear in a relatively short time [22]. In addition, there are some differences in the traffic flow between different directions of the intersection, especially between the east entrance and the west entrance. The traffic flow of the west straight and west left-turn is much more than that of the east

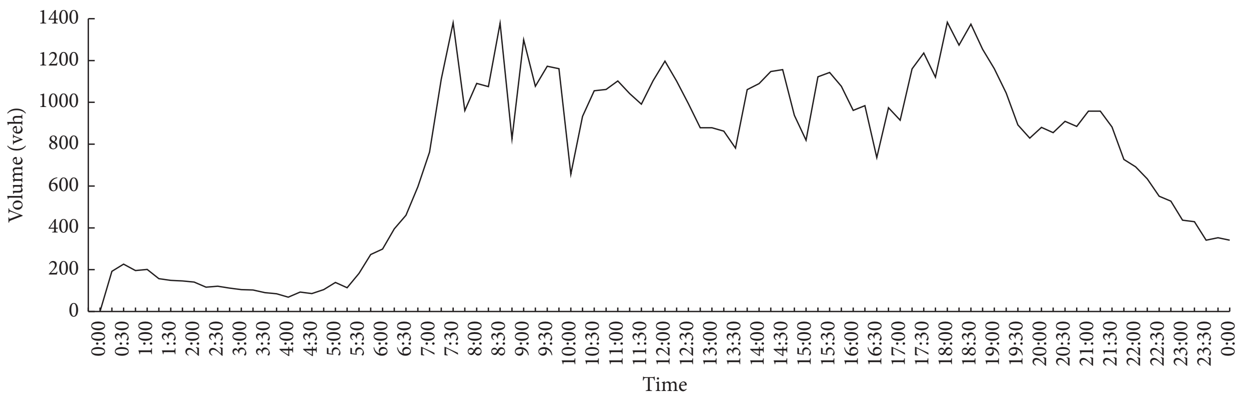

Figure 5: Traffic-flow data of 24 h in a working day at Jiuhua road and Zheshan road intersection.

straight and east left-turn. The channelization diagram of this intersection is shown in Figure 6.

3.2. Design Schemes. In order to analyze the impact of traffic-flow data clustering of different dimensions on the TOD division results, according to the traffic-flow data shown in Figure 5, the traffic-flow sequence of different dimensions are counted, as described in Section 2.1. Schemes $A(w = 1)$, $B(w = 2)$, $C(w = 4)$, and $D(w = 8)$ are adopted to carry out TOD division and phase timing design. Meanwhile, in order to further analyze the effect of lane-use assignment on TOD division results, scheme $E(w = 8)$, considering lane-use assignment) is adopted to further carry out TOD division and phase timing design at the intersection.

3.2.1. Preliminary TOD Division. The method described in Section 2.2.2 is used to complete the preliminary TOD division of schemes A, B, C, D, and E. Since all the corresponding z value at the bend point of the objective function $B(n, z)$ curve of the different traffic-flow sequence is 6 (take the objective function $B(n, z)$ curve of the traffic-flow sequence of north left-turn as an example, as shown in Figure 7). Therefore, the optimal segmentation number of each traffic-flow sequence is 6. The preliminary TOD division results of different schemes are shown in Figure 8. Since the traffic-flow dimensions adopted by schemes D and E are the same, the preliminary TOD division results of schemes D and E are the same.

It can be seen from Figure 8 that the preliminary TOD division results are determined according to the combination of the change intervals of the traffic-flow sequence of different dimensions. The more dimensions, the more combinations of the change intervals, the more time periods in the preliminary TOD division, and the more it can reflect the change trends of traffic flow of different direction. Among them, the number of time periods in the preliminary TOD division by schemes A, B, C, D, and E is 6, 8, 10, 18, and 18, respectively. These preliminary time periods still need to be merged and tested.

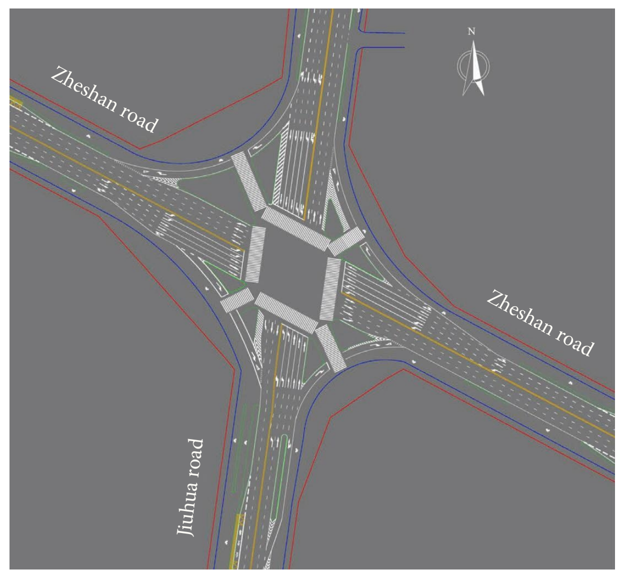

Figure 6: Canalization diagram of Jiuhua road and Zheshan road intersection.

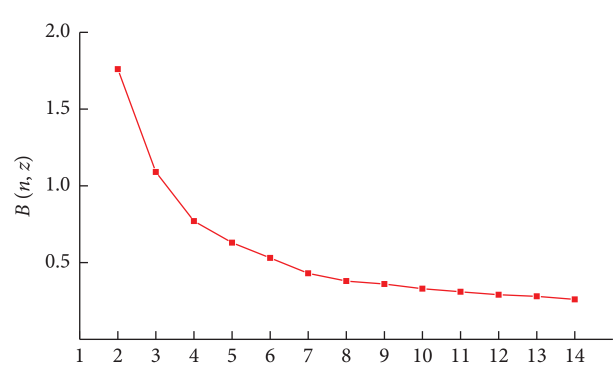

Figure 7: Objective function $B(n, z)$ curve of the traffic-flow sequence of north left-turning.

3.2.2. Final Results of TOD Division and Phase Timing Schemes. The methods described in Sections 2.3 and 2.4 are used to complete the phase timing design and the time periods merge and test of schemes A, B, C, D, and

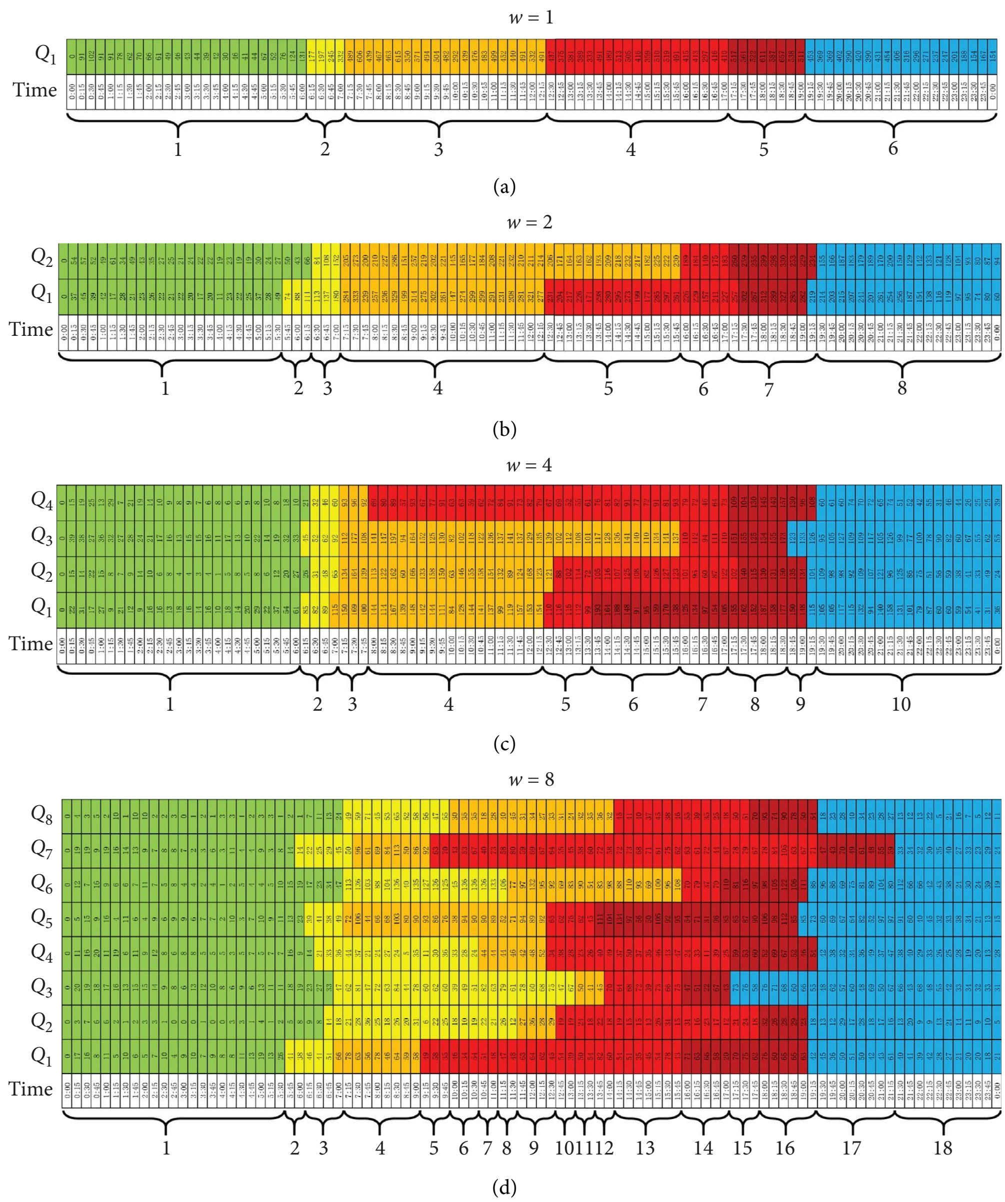

Figure 8: Preliminary TOD division results of Jiuhua Road and Zheshan Road intersection. (a) Scheme A. (b) Scheme B. (c) Scheme C. (d) Scheme D (E).

E. Considering pedestrian crossings and vehicle traffic demand, the minimum green time of the straight phase and left-turn phase is 14 s and 5 s, respectively. The final results of the TOD division are shown in Figure 9. The corresponding phase timing schemes are shown in Tables 3–7.

Among them, scheme E further optimized the lane-use assignment at the intersection; according to the method mentioned in Section 2.3.2, the optional lane-use assignment schemes in the east, west, south, and north entrances are shown in Figure 10. Selecting time period 13 as an example, the calculation results for the optimal lane and phase schemes are shown in Figure 11; the minimum value of Y_i in the east-west direction is 0.41; that is, the lane-use assignment scheme E1 of east entrance and scheme W2 of west entrance are selected, and the selected phase scheme is scheme 4. The minimum value of Y_j in the north-south direction is 0.43; that is, the lane-use assignment scheme S2 of south entrance and scheme N2 of north entrance are selected, and the selected phase scheme is scheme 10. In Table 7, lane-use assignment schemes adopted in different time periods can be realized by variable lane facilities. For example, in the east entrance, the lane-use assignment scheme E1 is adopted in time periods of 1, 2, 12, and 13, and scheme E2 is adopted in other time periods. The lanes marked in the red box in Figure 10 can be set as variable lanes to achieve a different lane-use assignment in the corresponding time periods.

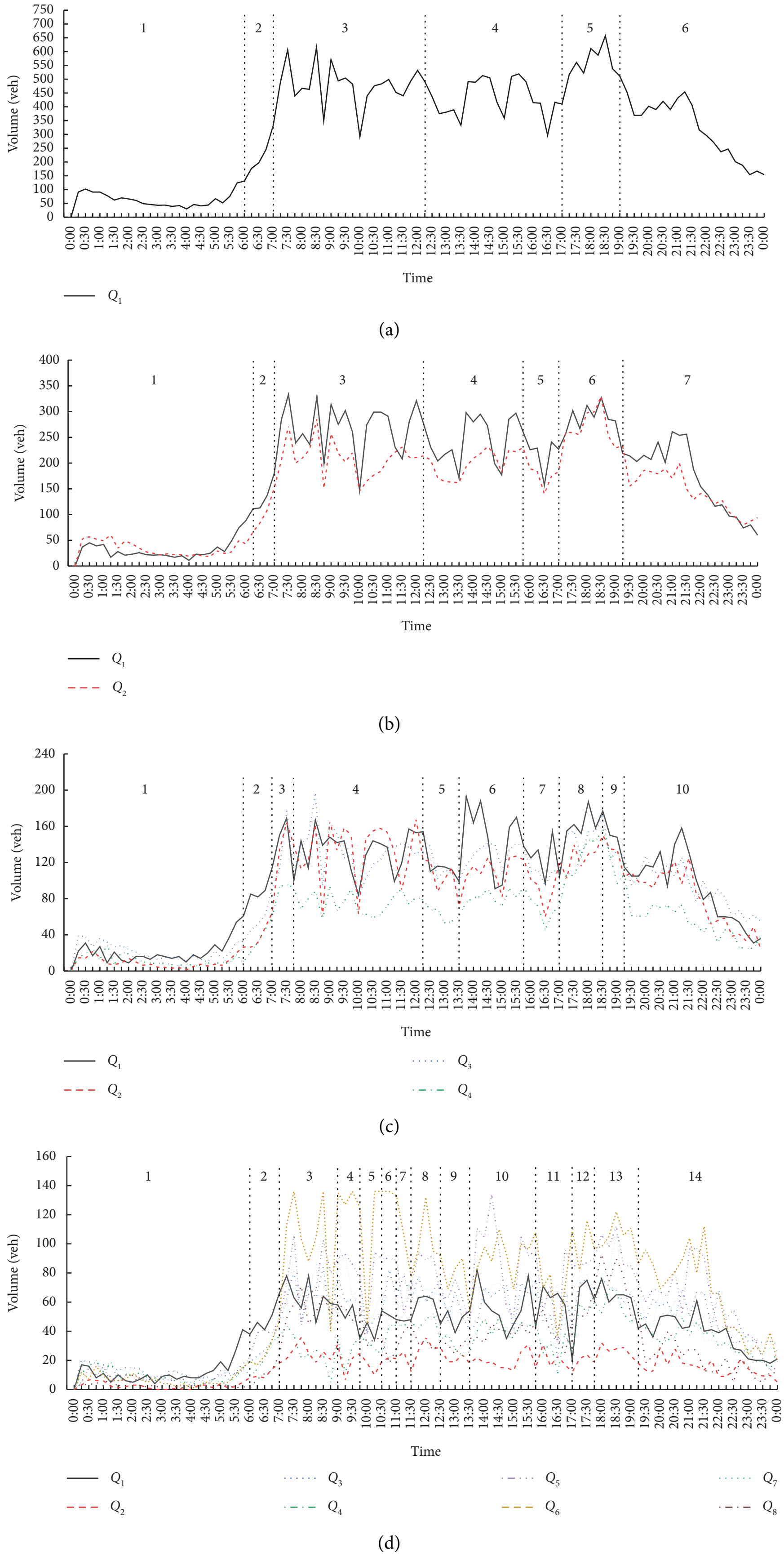

FIGURE 9: Final results of TOD division of Jiuhua road and Zheshan road intersection. (a) Scheme A. (b) Scheme B. (c) Scheme C. (d) Scheme D (E).

Table 3: Phase timing results of time periods of scheme A.

Time periods	Phase schemes		Signal timing (s)								
	E-W	S-N	C	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	1	7	38	18	18	14	14	18	18	14	14
2	2	8	68	18	14	14	10	18	14	14	10
3	3	8	122	23	23	29	16	42	42	29	16
4	3	8	80	16	16	19	11	22	22	19	11
5	3	8	186	37	37	46	37	54	54	46	37
6	3	10	76	14	14	19	14	22	22	14	9

Table 4: Phase timing results of time periods of scheme B.

Time periods	Phase schemes		Signal timing (s)								
	E-W	S-N	C	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	1	7	36	16	16	14	14	16	16	14	14
2	2	8	69	17	15	14	11	17	15	14	11
3	3	8	122	23	23	29	16	42	42	29	16
4	3	8	84	16	16	19	13	24	24	19	13
5	2	10	69	15	17	14	8	15	17	17	11
6	3	8	167	32	32	42	33	48	48	42	33
7	3	10	78	15	15	19	14	23	23	14	9

Table 5: Phase timing results of time periods of scheme C.

Time periods	Phase schemes		Signal timing (s)								
	E-W	S-N	C	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	1	7	38	18	18	14	14	18	18	14	14
2	2	8	68	18	14	14	10	18	14	14	10
3	2	10	201	43	72	42	25	43	72	49	32
4	3	8	114	21	21	27	15	39	39	27	15
5	3	8	72	14	14	16	10	20	20	16	10
6	3	8	103	19	19	25	16	31	31	25	16
7	2	10	69	15	17	14	8	15	17	17	11
8	3	8	195	39	39	49	40	55	55	49	40
9	3	10	131	23	23	30	24	40	40	32	26
10	3	10	78	15	15	19	14	23	23	14	9

It can be seen from the above-given final results of TOD division and phase timing that, the number of final time periods after the merge and test of schemes A, B, C, D, and E is 6, 7, 10, 14, and 14, respectively. Among them, scheme A and scheme B both have obvious peak periods in the afternoon, which are 17:00–19:00 and 17:00–19:15, respectively. However, the period span in the morning is obviously longer, both from 07:00 to 12:15, its corresponding signal cycle time is longer, which are 186 s and 167 s, respectively, and there are fewer flat-peak periods, so the signal control efficiency is not high. Scheme C has obvious peak periods in the morning and afternoon, which are 07:00–07:45 and 17:00–18:30, respectively, and the subpeak periods in the afternoon which is 18:30–19:15. Compared with scheme A and B, the flat-peak periods are more, which are 12:15–13:30, 13:30–15:45, and 15:45–17:00, respectively, so the signal control efficiency will be improved. Scheme D has obvious peak periods and subpeak periods in the morning and afternoon. The morning peak period is 09:00–09:45 and the subpeak period is 07:00–09:00. The afternoon peak period is 17:45–19:15 and the subpeak period is 17:00–17:45. And, the flat-peak periods of scheme D in the daytime are significantly more than those of scheme A, B, and C, which are 09:45–10:30, 10:30–11:00, 11:30–11:30, 11:30–12:30, 12:30–13:30, 13:30–15:45, and 15:45–17:00, respectively. Therefore, the signal control efficiency will be greatly improved. The TOD division results of scheme E and scheme D are similar. Since scheme E further optimizes the lane-use assignment, and the signal cycle time of each time periods is shorter than that of scheme D, so its signal control efficiency will be further improved. In addition, the overall trend of TOD division results of various schemes is consistent, and the time nodes of TOD division of most schemes are consistent, such as 06:00, 07:00, 12:15, 15:45, 17:00, and 19:15. Except for the different fineness of TOD division in the daytime, the TOD division results in the evening and at night are the same. In the following, the traffic benefits of the various schemes are further evaluated and validated through traffic simulation.

Table 6: Phase timing results of time periods of scheme D.

Time periods	Phase schemes		Signal timing (s)								
	E-W	S-N	C	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	1	7	36	16	16	14	14	16	16	14	14
2	2	8	68	18	14	14	10	18	14	14	10
3	3	10	121	23	23	25	13	42	42	31	19
4	3	10	151	25	25	32	15	59	59	40	23
5	3	8	85	14	14	18	10	31	31	18	10
6	3	10	129	22	22	32	22	51	51	22	12
7	3	8	97	15	15	24	18	28	28	24	18
8	3	10	121	25	25	33	21	38	38	25	13
9	2	10	73	14	21	17	12	14	21	14	9
10	3	8	106	23	23	24	17	30	30	24	17
11	3	8	74	16	16	18	10	18	18	18	10
12	3	8	144	30	30	34	28	40	40	34	28
13	3	10	182	34	34	43	36	53	53	47	40
14	3	10	73	14	14	17	12	21	21	14	9

3.3. Analysis of Simulation Results. VISSIM traffic simulation software is used to simulate each time periods, phase timing, and lane-use assignment of Schemes A, B, C, D, and E, according to the actual traffic-flow data of the intersection. The average vehicle delay of each time periods of eight controlled flows from a_1 to a_8 in Figure 2 is extracted, and the average vehicle delay data A_{dv}, B_{dv}, C_{dv}, D_{dv}, and E_{dv} of each time periods of each scheme are calculated. The passing vehicle data are extracted by simulation. The total vehicle delay data A_{ds}, B_{ds}, C_{ds}, D_{ds}, and E_{ds} for 24 hours in one day are calculated. The results are shown in Tables 8–12.

It can be seen from Tables 8–12 that the total vehicle delay at the intersection throughout the day of schemes A, B, C, D, and E is 570.9 h, 557.8 h, 494.5 h, 465.0 h, and 364.1 h, respectively, of which scheme D is 6.0% less than scheme C,

Table 7: Lane-use assignment and phase timing results of time periods of scheme E.

Time periods	Lane-use assignment schemes				Phase schemes		Signal timing (s)									
	E	W	S	N	E-W	S-N	C	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	E1	W2	S2	N2	1	7	34	14	14	14	14	14	14	14	14
2	E1	W2	S2	N2	2	7	61	22	16	14	14	22	16	14	14
3	E2	W3	S2	N1	2	8	64	18	10	14	10	18	10	14	10
4	E2	W3	S2	N2	4	10	90	20	9	21	11	32	21	26	16
5	E2	W3	S2	N2	4	10	76	14	7	21	14	29	22	14	7
6	E2	W3	S2	N2	4	8	83	14	7	22	17	25	18	22	17
7	E2	W3	S2	N2	4	10	81	18	8	24	15	28	18	18	9
8	E2	W3	S2	N2	4	10	64	14	8	14	8	19	13	17	11
9	E2	W3	S2	N2	4	10	83	20	6	21	14	31	17	20	13
10	E2	W3	S2	N2	4	8	75	14	5	20	12	26	17	20	12
11	E2	W3	S2	N2	4	10	63	15	6	14	8	20	11	17	11
12	E1	W2	S2	N2	4	8	111	18	20	27	22	30	32	27	22
13	E1	W2	S2	N2	4	10	141	20	28	34	29	35	43	37	32
14	E2	W3	S2	N2	4	10	66	14	5	17	12	23	14	14	9

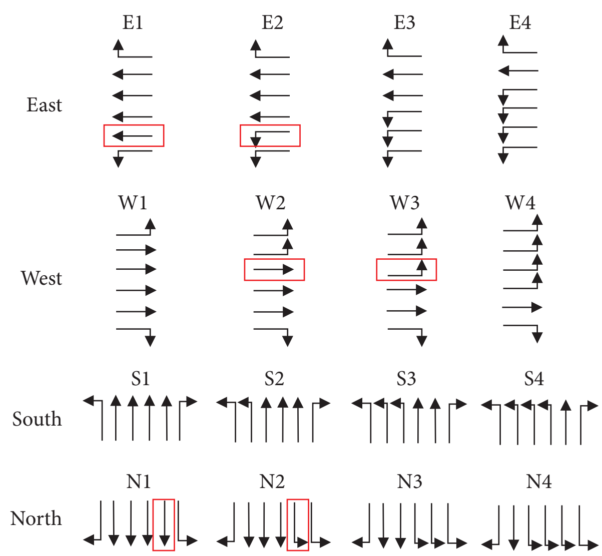

Figure 10: Optional lane-use assignment schemes in the east, west, south, and north entrances.

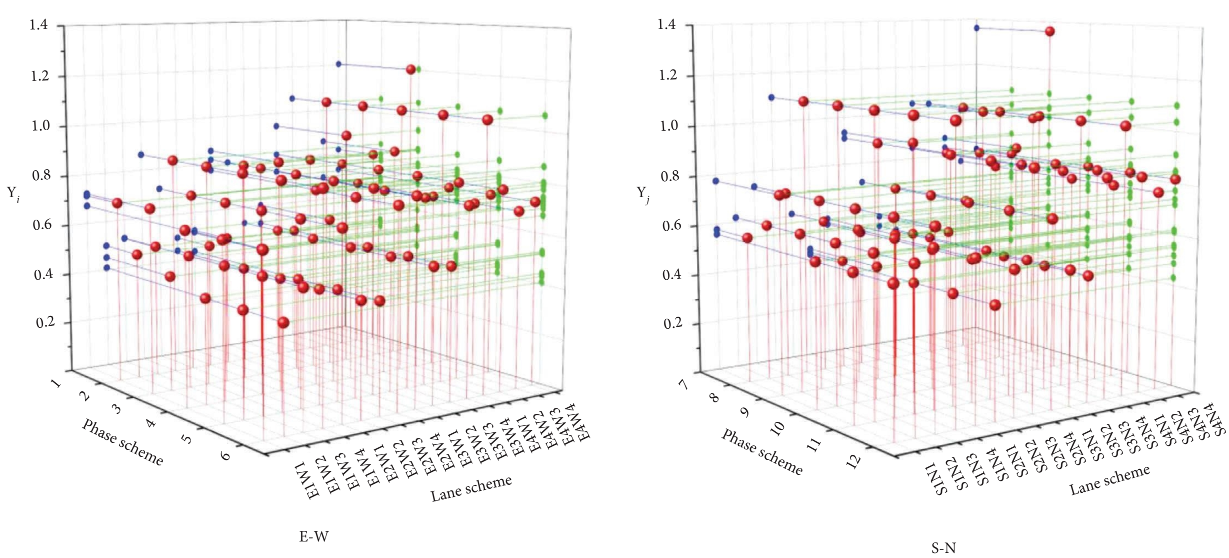

Figure 11: Calculation results of optimal lane and phase schemes in time period 13. (a) E-W. (b) S-N.

Table 8: Analysis results of the average vehicle delay in scheme A.

Direction	Periods					
	1	2	3	4	5	6
d_{a1}	5.7	22.8	53.7	35.6	89.6	30.6
d_{a2}	4.8	22.4	51.2	37.2	66.1	26.4
d_{a3}	7.8	23.3	64.7	26.3	64.9	23.8
d_{a4}	7.5	24.5	50.8	32.4	65.7	27.2
d_{a5}	5.2	20.7	53.4	37.1	79.5	22.6
d_{a6}	5.9	22.2	54.8	39.5	68.4	22.2
d_{a7}	7.3	25.6	51.4	37.4	90.2	30.9
d_{a8}	7.2	27.8	49.6	38.7	65.0	31.7
A_{dv}(s)	6.4	23.7	53.7	35.5	73.7	26.9
A_{ds}(h)	570.9					

Table 9: Analysis results of the average vehicle delay in scheme B.

Direction	Periods						
	1	2	3	4	5	6	7
d_{a1}	5.9	24.5	53.7	38.3	30.3	77.2	32.2
d_{a2}	5.6	21.5	51.2	37.7	21.3	62.1	27.2
d_{a3}	6.7	21.6	64.7	35.6	24.0	57.1	23.8
d_{a4}	7.3	25.8	50.8	32.4	31.0	59.9	28.6
d_{a5}	6.2	21.4	53.4	37.6	26.4	61.7	22.2
d_{a6}	5.8	23.9	54.8	36.6	22.6	59.8	22.1
d_{a7}	7.8	26.8	51.4	35.5	26.7	73.1	33.0
d_{a8}	6.7	27.2	49.6	36.2	25.7	61.6	30.4
$B_{dv}(s)$	6.5	24.1	53.7	36.2	26.0	64.1	27.4
$B_{ds}(h)$	557.8						

scheme C is 11.3% less than scheme B, scheme B is 2.3% less than scheme A. After the lane-use assignment is optimized in scheme E, the total vehicle delay is obviously the least, which is reduced by 21.7% compared with Scheme D. This indicates that the scheme with more dimensions of traffic flow will lead to less total vehicle delay at the intersection, and the reduction of total vehicle delay at the intersection is the most obvious after the lane-use assignment is further optimized.

In order to further analyze the changes of vehicle delays of each scheme, the average vehicle delay data A_{dv}, B_{dv}, C_{dv}, D_{dv}, and E_{dv} at the intersection in each time periods with each scheme from Tables 8–12 are extracted. The change curve of the average vehicle delay at the intersection throughout the day is drawn. In order to reflect the change trends, the total traffic-flow data V of different controlled traffic flow at the intersection for 24 h in one day are extracted as a reference, as shown in Figure 12.

As can be seen from Figure 12, compared with schemes A, B, and C, the average vehicle delay data at the intersection of scheme D better reflects the change trends of the traffic flow throughout the day. It increases with an increase in traffic flow and decreases with a decrease in traffic flow. Especially in the daytime, it reflects multiple change trends with the change of traffic flow. The change trends of the average vehicle delay data at the intersections of schemes C, B, and A decreases one by one. In particular, schemes A and B maintain a large average vehicle delay from 7:15 am to 12: 15 pm, which is obviously directly related to the TOD division and the phase timing results. Scheme E further optimizes the lane-use assignment on the basis of Scheme D, and the average vehicle delay throughout the day is obviously the least. As can be seen from Figure 13, the average vehicle delay at the intersection throughout the day of schemes A, B, C, D, and E is reduced gradually, which are 33 s, 32 s, 30 s, 28 s, and 25 s, respectively.

As explained above, if a scheme with more traffic-flow dimensions is adopted, the average vehicle delay in each time periods at the intersection will be more in line with the change trends of the traffic flow, and the average vehicle delay at the intersection throughout the day will be less. Among them, scheme D is 6.7% less than scheme C, scheme C is 6.3% less than scheme B, and scheme B is 3.0% less than scheme A. After the lane-use assignment is optimized in Scheme E, the average vehicles delay throughout the day is further effectively reduced by 10.7% compared with scheme D.

4. Discussion

The applicability of the method proposed in this paper is discussed from two aspects: the fineness and the traffic benefit of the TOD division.

In terms of the fineness of the TOD division, an important finding of this paper is that the more dimensions of traffic flow data adopted, the finer the TOD division result will be. According to the TOD division method proposed in this paper, the final time period number of TOD division obtained by schemes $A(W=1)$, $B(W=2)$, $C(W=4)$, $D(W=8)$, and $E(W=8)$ is 6, 7, 10, 14, and 14, respectively. Among them, scheme $A(W=1)$ takes the total traffic-flow data at an intersection as the basis for TOD division, and the time period number obtained is the least. The period span in the morning is longer, and there is no obvious morning peak hours. Similar to the above situation, literature [17, 18, 20] used the total traffic-flow data at an intersection to carry out the optimization method research of TOD division, and the optimized time period numbers are 6, 8, and 7, respectively. The period span in the afternoon is longer, without obvious afternoon peak periods. Literature [25] takes the two directions with a large number of traffic flow of west straight and west left-turn as representatives and adopts traffic flow data of 2 dimensions to carry out TOD division optimization. The optimized time period number is 7, and the period span in the afternoon is also longer, without obvious afternoon peak periods. This is similar to the TOD division carried out in scheme $B(W=2)$ based on traffic-flow data of 2 dimensions of east-west and north-south directions at the intersection. The time period number of scheme B is also 7, but the difference is that the period span in the morning is long and there is no obvious morning peak periods. This above situation may be related to the change of traffic flow at the intersection, but it can not be ignored that different optimization methods in different literature all have similar phenomena, which can reflect that the use of traffic-flow data clustering with different dimensions may directly affect the fineness of TOD division results. For example, schemes D

Table 10: Analysis results of the average vehicle delay in scheme C.

Direction	Periods									
	1	2	3	4	5	6	7	8	9	10
d_{a1}	5.7	22.8	62.6	49.4	30.2	35.7	30.3	81.8	54.9	32.2
d_{a2}	4.8	22.4	33.6	40.2	24.7	33.6	21.3	55.4	51.7	27.2
d_{a3}	7.8	23.3	54.1	41.0	25.8	34.1	24.0	53.1	52.4	23.8
d_{a4}	7.5	24.5	54.2	46.5	29.3	30.2	31.0	54.3	52.4	28.6
d_{a5}	10.3	20.7	54.4	45.4	21.5	33.7	26.4	61.3	59.0	22.2
d_{a6}	5.9	22.2	45.2	41.9	23.0	30.8	22.6	53.3	55.9	22.1
d_{a7}	7.3	25.6	60.3	46.4	28.9	42.2	26.7	62.0	63.6	33.0
d_{a8}	7.2	27.8	60.8	48.1	30.1	39.5	25.7	55.8	64.5	30.4
$C_{dv}(s)$	7.1	23.7	53.1	44.9	26.7	35.0	26.0	59.6	56.8	27.4
$C_{ds}(h)$	494.5									

Table 11: Analysis results of the average vehicle delay in scheme D.

Direction	Periods													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
d_{a1}	6.1	22.8	55.9	50.4	38.1	59.5	45.1	50.9	33.1	36.3	33.9	60.7	72.7	29.3
d_{a2}	6.5	22.4	41.6	41.3	28.1	48.0	31.2	39.0	17.9	25.0	26.1	44.1	59.2	24.3
d_{a3}	7.4	23.3	43.3	42.9	28.8	43.7	30.8	36.8	23.9	30.0	22.4	50.7	48.4	23.8
d_{a4}	7.6	24.5	51.5	53.0	36.2	48.5	37.4	47.7	27.4	36.0	31.8	51.4	55.5	27.2
d_{a5}	5.6	20.7	32.5	30.2	21.6	27.8	29.1	36.7	31.0	43.0	25.2	52.0	76.6	22.4
d_{a6}	5.7	22.2	31.9	32.8	19.2	29.5	28.8	36.5	20.3	31.9	25.1	43.6	59.0	21.3
d_{a7}	7.8	25.6	55.9	45.4	37.0	53.9	37.0	51.9	31.1	36.2	30.7	60.7	55.3	29.8
d_{a8}	6.9	27.8	48.2	42.8	34.1	56.5	30.9	50.1	31.2	35.2	32.2	50.1	53.5	30.4
$D_{dv}(s)$	6.7	23.7	45.1	42.4	30.4	45.9	33.8	43.7	27.0	34.2	28.4	51.7	60.0	26.1
$D_{ds}(h)$	465.0													

Table 12: Analysis results of the average vehicle delay in scheme E.

Direction	Periods													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
d_{a1}	6.7	16.0	21.4	37.6	19.3	35.3	19.2	26.1	20.6	33.1	16.3	48.2	64.2	25.4
d_{a2}	7.2	17.1	21.2	41.6	24.3	29.9	27.8	29.1	27.6	41.4	20.5	39.2	51.0	32.9
d_{a3}	6.4	18.9	22.8	30.7	37.2	26.5	32.3	23.0	35.7	23.0	28.2	38.6	48.1	21.1
d_{a4}	6.4	20.8	22.0	37.9	46.4	25.2	40.2	30.6	37.6	29.9	30.7	39.1	53.8	25.4
d_{a5}	6.4	12.2	21.1	33.3	35.3	28.3	32.5	23.5	32.1	28.1	24.1	41.3	74.1	21.6
d_{a6}	6.6	15.7	24.3	31.7	32.5	40.6	29.0	23.3	30.1	26.9	23.6	35.5	44.0	23.0
d_{a7}	6.7	37.6	20.9	34.8	26.2	31.5	26.2	23.2	28.6	28.6	23.7	41.2	55.9	24.9
d_{a8}	5.8	15.7	25.2	34.3	30.7	31.2	29.9	25.0	30.5	30.2	23.4	38.6	50.0	26.8
$E_{dv}(s)$	6.5	19.2	22.4	35.2	31.5	31.1	29.6	25.5	30.4	30.1	23.8	40.2	55.1	25.1
$E_{ds}(h)$	364.1													

and E in this paper adopt traffic-flow data clustering of 8 dimensions to carry out TOD division, the TOD division results are the most refined, with obvious peak periods and subpeak periods in the morning and afternoon, and the time period number is 14. According to the different results of the TOD division obtained by using traffic-flow data clustering of different dimensions in this paper, the overall trend is consistent. The time nodes of the TOD division of different schemes, such as 06:00, 07:00, 12:15, 15:45, 17:00, and 19:15, are the same. Except for the different fineness of the TOD division in the daytime, The TOD division results in the evening and at night are basically the same. Above-given theory shows that with the increase in the number of traffic-flow dimensions, TOD division results and the corresponding phase timing schemes are finer. The TOD division which is carried out based on traffic flow of 8 dimensions of 8 controlled directions, the TOD division results are the most refined and can best meet the change requirements of traffic flow of different controlled directions at the intersection. This finding is similar to the conclusion of literature [24]; that is, the more the number of clusters, the finer the TOD division in the daytime, while is basically the same in the evening. This finding further supports the view of references [22, 23, 25]. That is, using the total traffic flow as clustering

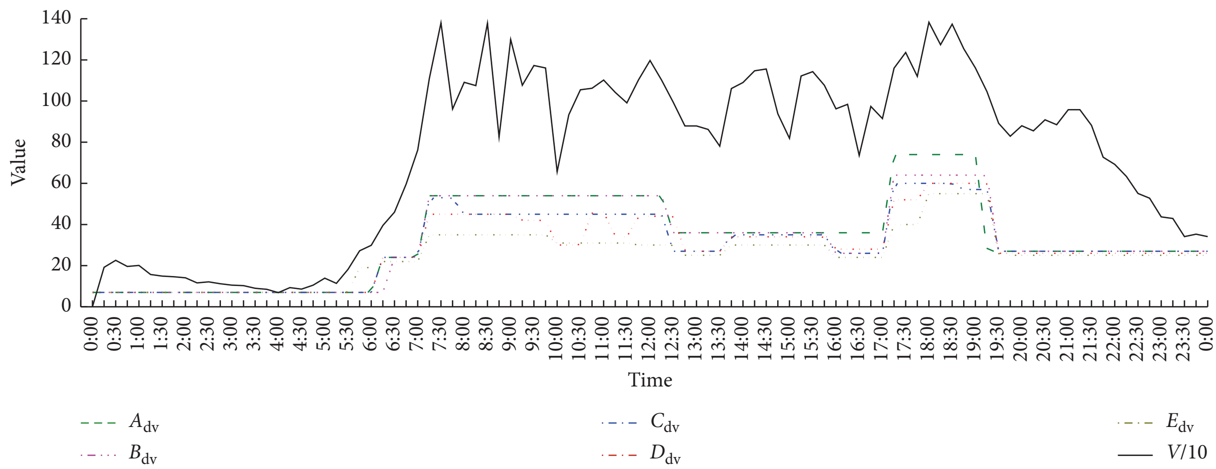

Figure 12: Change curve of the average vehicle delay at the Jiuhua road and Zheshan road intersection in each time periods of one day.

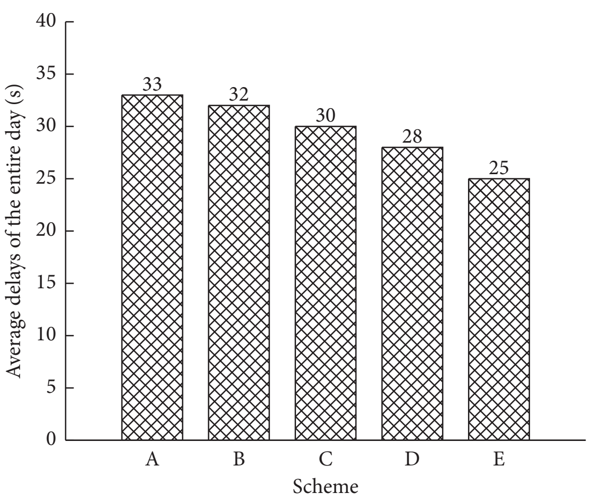

Figure 13: Comparison of the average vehicle delay at the Jiuhua road and Zheshan road intersection throughout the day.

data reflects the overall traffic state at the intersection, but it is too extensive for signal timing, which fails to consider the characteristics of directional traffic flow and may result in the risk of developing TOD timing plans that are not well suited for expected traffic.

In terms of the traffic benefits of TOD division, another important finding of this paper is that the more refined the TOD division results, the less the total vehicle delay at the intersection throughout the day, the average vehicle delay in each time periods at intersection will be more in line with the change trends of the traffic flow, and the less the average vehicle delay throughout the day. After further considering the lane-use assignment optimization, the total and average vehicle delay at an intersection will be further effectively reduced. This paper and existing studies have reached a consensus that TOD divisions serve traffic signal control, and the two have consistent objectives. It is necessary to establish the relationship between TOD divisions and control benefits [20]. Most existing studies use Synchro software to optimize signal timing and use SimTraffic software to complete the benefit evaluation while carrying out TOD divisions [2, 12, 14, 17, 20]. Unlike existing studies, the proposed method integrates the TOD division, phase optimization, and timing design in the whole process, and the lane-use assignment optimization is further considered. Furthermore, the rationality of the final result of the TOD division is further tested according to the lane, phase, and timing schemes. Finally, the final result of the TOD division is evaluated by VISSIM traffic simulation. At present most studies use the index of total vehicle delay to evaluate the superiority of the optimization method [17, 18, 20, 22, 24]. Firstly, the traffic benefit is evaluated by using the total vehicle delay data of 24 h in this paper. It is found that if a scheme with more traffic-flow dimensions is adopted, the total vehicle delay at the intersection throughout the day will be less. Compared with schemes A, B, and C, the total vehicle delay of scheme D is obviously the least. On the basis of scheme D, the lane-use assignment is further considered to optimize in scheme E, the signal cycle time of each period is significantly reduced, and the total vehicle delay of scheme D is further effectively reduced. In order to further analyze the effectiveness of this method, this paper for the first time adopt a change curve of the average vehicle delay of the intersection throughout the day to analyze the matching degree between different TOD division schemes and the traffic flow of the intersection. The scheme (e.g., scheme D) with more traffic-flow dimensions is adopted, and the average vehicle delay in each time periods of the intersection is more in line with the trends in traffic flow. That is the average vehicle delay increases with the increase of traffic flow and decreases with the decrease of traffic flow, reflecting multiple trends, especially in the daytime. Moreover, the average vehicle delay throughout the day at the intersection is also less, and the average delay of vehicles in scheme E is also the least. References [24, 25] select the optimal TOD division scheme on the premise of determining the optimal number of clusters. The authors proposed that there should not be too many time periods for the TOD divisions. Otherwise, this will affect the traffic benefit. On the premise of determining the optimal number of clusters, the proposed method carries out the time segments division in a single-dimension traffic-flow sequence, and further uses multidimensional traffic-flow sequences to complete the final results of TOD division. According to the VISSIM simulation evaluation, the scheme with more time periods is formed, and the vehicle delay is the lowest (e.g., scheme E). This shows that the number of time periods is not the main factor affecting the traffic benefits. The key is to see whether the corresponding lane, phase, and timing schemes of each time periods adapt to the changes in traffic flow. The method proposed in this paper uses multidimensional traffic-flow sequences to carry out the integrated design and inspection of TOD division, phase timing, and lane-use assignment. This may be more suitable for the trends in traffic flow. Therefore, the benefits to traffic are ensured. In addition, the method proposed in reference [22] is not applicable to intersections of the constant-peak type, and its vehicle delay is larger than the traditional total traffic-flow segmentation model. The tested intersection in this paper tends to be the constant-peak type, and scheme A is similar to the scheme for traditional total traffic-flow segmentation models, the vehicle delay of which is the largest, this indirectly shows that the proposed method in this paper has better applicability.

5. Conclusion

Based on the change trends of traffic flow in each controlled direction at the intersection, we carry out a study on space-time resource integrated optimization method for TOD division at the intersection based on multidimensional traffic flow. First of all, the traffic flow of different dimensions for TOD division are analyzed, and the dynamic Fisher algorithm is used to complete the time segment division of the traffic-flow sequence of different dimensions. On this basis, the preliminary TOD division is completed. Then, the signal phases and timing schemes are completed. Furthermore, the lane-use assignment is further considered to optimize. Finally, the adjacent time periods are merged and tested to form the final result of the TOD division. In order to verify the effectiveness of the proposed method, the TOD division schemes based on traffic-flow data of different dimensions is further completed with the actual intersection data. The vehicle delay of different schemes are evaluated by VISSIM traffic simulation software. The results show that adopting traffic-flow data clustering of 8 dimensions (8 controlled traffic flow) to carry out TOD division at the intersection, the TOD division results are the most refined, and the total and average vehicle delay throughout the day are superior to other TOD division schemes of using traffic-flow data clustering of fewer dimensions. On this basis, after further considering the lane-use assignment optimization, the total and average vehicle delay throughout the day at the intersection are further effectively reduced, which indicates that the integration optimization method of TOD division, phase timing, and lane-use assignment based on multidimension traffic-flow data clustering is feasible and has good reference significance in the study of TOD division at an intersection.

Due to limitations with data collection, we only used traffic-flow data from a single intersection during a sample of one week. The results are thus deficient in some ways. Traffic-flow data need to be collected from multiple types of intersections over a longer time to verify the applicability of the proposed method. In addition, in future research, we will use big data and vehicle-road cooperation technology to study TOD divisions for continuous multicoordinated controlled intersections.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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