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A COMBINED ALGORITHM RESEARCH AND APPLICATION IN ROAD INTERSECTION DESIGN

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Abstract: The traditional algorithm on intersection design separates spatial design (geometric design), temporal design (signalization) and evaluation of the design result. This paper presents a new combined algorithm for road intersection design, aiming at solving the problems of traditional one. Software based on this algorithm is developed by the author. The program is based on Visual C++, ObjectARX and database technology. Case study shows that the calculate result using the proposed algorithm meet the demand of optimizing design for a given intersection. This means that the algorithm can be applied into the practical engineering and satisfactory results can be obtained.

Key words: Intersection, Design, Combined Algorithm

1. INTRODUCTION

In recent years, the intense growth of vehicles has caused heavier traffic congestions on the roads and intersections, which are even worse during the traffic peak time. An intersection which is not well designed, will not only increase the travel time of the vehicles but also cause more traffic accidents. Besides, if the channelization of the intersection is not reasonable, road surface deterioration will be more serious within the intersection area due to many factors such as frequent start-stop, slow speed and so on. Therefore, it is necessary to make the design of the intersections more reasonable.

The traditional method for intersection design includes three stages: spatial design (geometric design), temporal design (signalization) and evaluation of the design result. The spatial design mainly indicates the location and configuration of those intersection elements, including stop line, roadways, bicycle lanes, crosswalk, medians, traffic separators, all kinds of signs and markings, etc. Temporal design chiefly indicates the design of signal control plan, including the phase plan and timing plan. The final evaluation is about to appraise the result of the two former procedures. The primary evaluation indices contain capacity, saturation degree, vehicular delay and level of service, etc. Usually, we take level of service as our main index.

It has been a long time for engineers who used a set of traditional design algorithms in the cities' constructing and reconstructing process. Although several steps were improved a bit, the overall flow hasn't changed much.

2. TRADITIONAL INTERSECTION DESIGN ALGORITHM

Figure 1 shows the flow chart of traditional intersection design algorithm, which proceeds in such order as: spatial design, temporal design and evaluation of the result.

2.1 Determining the Design Volumes

Design traffic volume allocated to each direction of each approach is determined by converted peak-hour traffic volume, which is computed by peak-quarter volume. If there is no real data on peak-quarter volume, the design volume can be computed by peak-hour volume and peak-hour coefficient.

2.2 Determining the Integral Intersection Elements

As is mentioned in the introduction, the spatial design mainly indicates the design of the location and configuration of all the intersection elements. As the whole content is so complicated, here we just make a simple introduction to the computation of the number of roadways, which is very basic and has great relations with the overall algorithm.

There are two different situations: new intersection that has not been actually constructed and reconstructed intersection. As for reconstructed intersection, the characteristics of roadways have to be determined by design volumes. Under the restriction of road widths and other conditions, the designers assign as many roadways as possible in order to enhance the intersection capacity. As for new intersection, if there is data obtained from the demand forecast, the design process is similar to that of the reconstructed intersection; otherwise, human experience has to be used to assign the roadways initially.

2.3 Determining Signal Control Plan

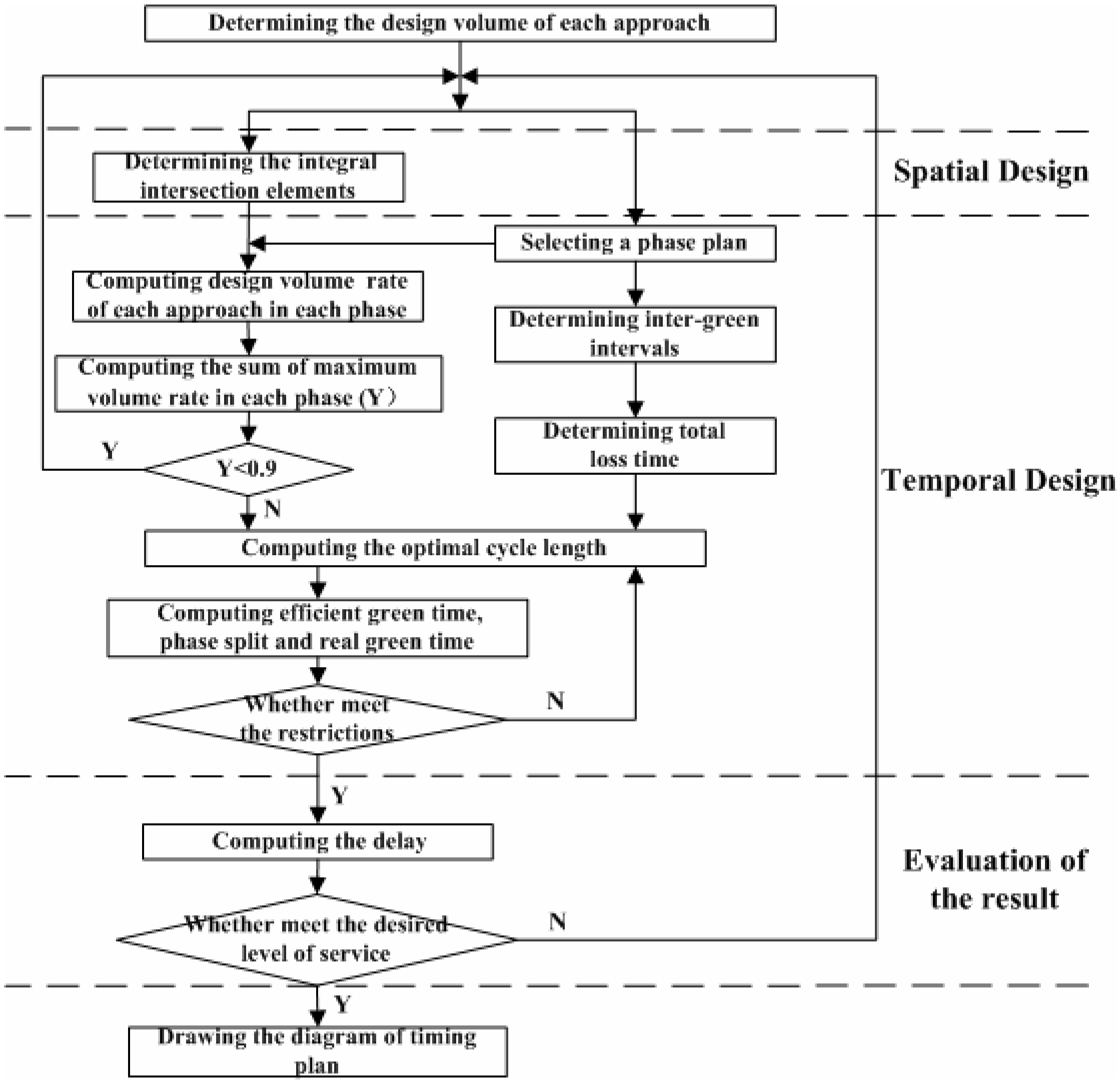

Figure 1. The Flow Chart of Traditional Intersection Design Algorithm

Signal control plan includes phase plan and timing plan. Phase plan should take geometric characteristics and design volumes into account and reduce traffic conflicts. Different from those in actual use, the phase plan in the intersection design stage needs to consider the all-day traffic flow condition in order to achieve optimization.

On the basis of the phase plan, the design volume ratio (traffic volume divided by saturation volume) for each direction of each phase could be derived according to the design volumes and the configuration of roadways which are determined above. Furthermore, the maximum volume ratio of each phase can be obtained. Finally, a summation is made. The equation is shown in equation (1):

$$Y = \sum_{j=1}^{J} \max[y_j, y_j', \cdots\cdots] = \sum_{j=1}^{J} \max[\left(\frac{q_d}{S_d}\right)_j, \left(\frac{q_d}{S_d}\right)_j', \cdots\cdots] \tag{1}$$

here: Y ——sum of all the maximum design volume ratios of each phase;

J ——the number of phase in a cycle;

y_j ——a design volume ratio of phase j;

q_d ——design volume (pcu/h);

S_d ——design saturation volume (pcu/h).

Generally speaking, if Y is bigger than 0.9, either roadway design or phase plan, or both, have to be improved. Concrete improvement often depends on human experience.

The next step is to compute the optimal cycle length, the total efficient green time, the efficient green time allocated to each phase and the phase splits could be calculated. The equations are omitted here.

2.4 Calculating the Level of Service

Commonly the level of service is determined by average intersection delay. Roughly saying, the average intersection delay consists of three parts: uniform delay generated when vehicles arrive uniformly, additive random delay generated due to vehicles' random arriving and over saturation delay generated when the intersection achieves to saturation. The third one can be omitted when we design a new intersection.

The corresponding relation between average intersection delay and the level of service is according to Highway Capacity Manual. As for new intersection, the level of service must achieve B or average intersection delay must be less than 20 seconds.

3. THE SHORTCOMINGS OF THE TRADITIONAL ALGORITHM

Although the traditional algorithm has long application history and may be familiar with engineers, it still has some drawbacks that can bring on inefficient design, long design period and less comprehensive consideration.

3.1 It Separates Spatial Design from Temporal Design

The limitation of intersection resources determines that we should make full use of both spatial and temporal ones. They are both important parts of intersection resources. To meet these demands, we should combine the two aspects when designing the intersection. However, the traditional design algorithm firstly processes the design of spatial elements and phase plan. The timing plan is designed later based on the former two steps. Such method violates the principle discussed above and it will conduce following problems:

First, spatial design is lack of some necessary parameters which come from temporal design, such as phase splits, which have to be obtained after temporal design.

Second, temporal design is restricted by spatial design and could not give necessary feedback to it. The locations and configurations of intersection elements are fixed at the end of spatial design. Also, we could not find a good way to reflect the result of temporal design on spatial design.

Third, the traditional method sometimes may depend much on people's experience. It does not give clear illustration about how to improve the whole design.

3.2 It Separates Design from Evaluation

A reasonable and complete intersection design should combine the design process and the evaluation one. The combination represents two aspects: on one hand, the result of design provides evaluation with comprehensive and quantitative data; on the other hand, the result of evaluation can offer advice or direction for the improvement of former design.

The traditional algorithm has problems with the second aspect. If the level of service could not achieve the demand, no concrete advice is provided for improvement, which has to still depend on people's experience.

3.3 The Elements Taken into Account in the Design Is Not Comprehensive

In traditional algorithm, spatial design mainly considers design volumes and spatial factors, but little about phase plan and timing plan. Besides, temporal design is generally bases on the configuration of roadways and neglects other important factors such as bicycle lanes, sidewalks and so on. Such incomplete consideration may lead unreasonable design.

3.4 It Is Not Convenient for Developing Programs

As is mentioned above, some steps in the design process need designer's subjective judgment, which makes it hard in programming. This shortcoming largely impedes people from using computer to shorten design cycle and improve design efficiency.

Besides, in actual design, strictly sticking to the judging criteria -- the sum of maximum design volume ratio in each phase must be bigger than 0.9 -- often could not meet the demand of high level of service. At the same time, it makes programming difficult, which we will discussed later.

4. A COMBINED ALGORITHM IN INTERSECTION DESIGN

4.1 Principles and Originality

Owing to the drawbacks of traditional method, we design a new one for intersection design. Before the research of the new design algorithm, three principles were proposed:

(1) The new algorithm is based on the traditional one and just makes some improvement. Having already been used for many years, some steps in traditional one are mature and reasonable, so a complete new method is not economical and difficult for the designers to accept.

(2) The new algorithm should make up the shortcomings in traditional one. It should combine the spatial design and temporal design, making the two considering feedbacks of each other. It should combine the design and evaluation: the design provides quantitative data for evaluation, while evaluation provides advice for improving the design. Finally, the design and evaluation should consider more elements in intersection.

(3)The new algorithm should orient to programming. Nowadays, many design work employ the computers and intersection design should also follow this trend. The nature of programming language requires that all the steps of design should be clear and objective. The new method should make all the steps and their joins unambiguous in order to give a certain direction for developing.

4.2 Research Ideas

Based on the principles above, we begin to design the new algorithm flow, which roughly including the following aspects. Those conforming to the traditional method will not be repeated.

The first idea is to combine the spatial design and temporal design. In the whole design process, the step that combines the two most closely is the determination of the type and number of roadways; besides, most transport design consider the traffic of motor vehicles firstly. Accordingly, the configuration of roadways can be taken from spatial design and put into temporal design. In addition, as the computation of volume ratio needs its information, the configuration of roadways should be put between the selection of phase plan and the computation of design volume ratio.

The design of phase plan is subjective to some extent. Considering the demand of programming, we could put this step forward. In the application, the program can offer a default plan or automatically generate a plan according to the input condition such as design volumes.

When Y (the sum of all the maximum design volume of each phase) is bigger than the predefined value, some improvement should be done in spatial design or temporal design. The new algorithm gives two kinds of adjustment -- small one and big one. Small adjustment means to change the configuration of roadways, especially the roadways of the phase which has the maximum volume ratio. Big adjustment means to select a new phase plan.

When Y meets the demand, we can finish the next step -- the computation of optimal cycle length, total efficient green time, phase splits and efficient green time of each phase. After this, other intersection elements can be designed based on the results. Thus, the basic spatial and temporal design is completed. Before the evaluation, some simple judgments should be done in order to reduce the program's running cost. Concretely, the judgments include such factors as whether the roadways are too many, whether approaches are widened too much, whether the configuration of bicycle lanes is reasonable and so on. Unreasonable judgment results indicate that the original input information or design plan may have problems, for example, the design volumes may not accord with real situation or may be beyond the capacity of intersection. If so, the algorithm has to go back to the first step.

When it comes to the combination of design and evaluation, the new algorithm will put emphasis on the method of design improvement which offered by evaluation. The evaluation indices employ some quantitative values, such as capacity, delay and level of service. The adjustment of the design, according to the evaluation result, basically divides into two kinds: one is radical change and the other is partial change. The partial adjustment just modifies the configuration of roadways or the predefined value for the sum of volume ratio. These modifications keep the phase plan and promote the following spatial and temporal design to improve. As for the radical adjustment, design volumes have to be changed. It requires the algorithm go back to the first step.

4.3 New Algorithm

According to the ideas above and considering the implementation of program and feedbacks of test, the final algorithm is generated and shown in Figure 2.

The new algorithm primarily follows the research ideas presented in 4.2. But some amendments are made for the convenience of programming, including:

(1) When Y (the sum of all the maximum design volume ratio of each phase) is bigger than the predefined value, designer could choose to add new lane of current type or change the type of the roadway (for example, changing a permissive left turn lane into a protected left turn lane).

(2) The design result is evaluated by the level of service, and this index is determined by average intersection delay in order to make the evaluation quantitative.

(3) If the level of service cannot meet the demand, the modification on the configuration of roadways is indirectly realized by modifying the predefined value of Y. Because direct modification of the former is easy to make the programs stick in iteration and has lower efficiency.

5. SOFTWARE IMPLEMENTATION AND CASE ANALYSIS

5.1 Software Implementation

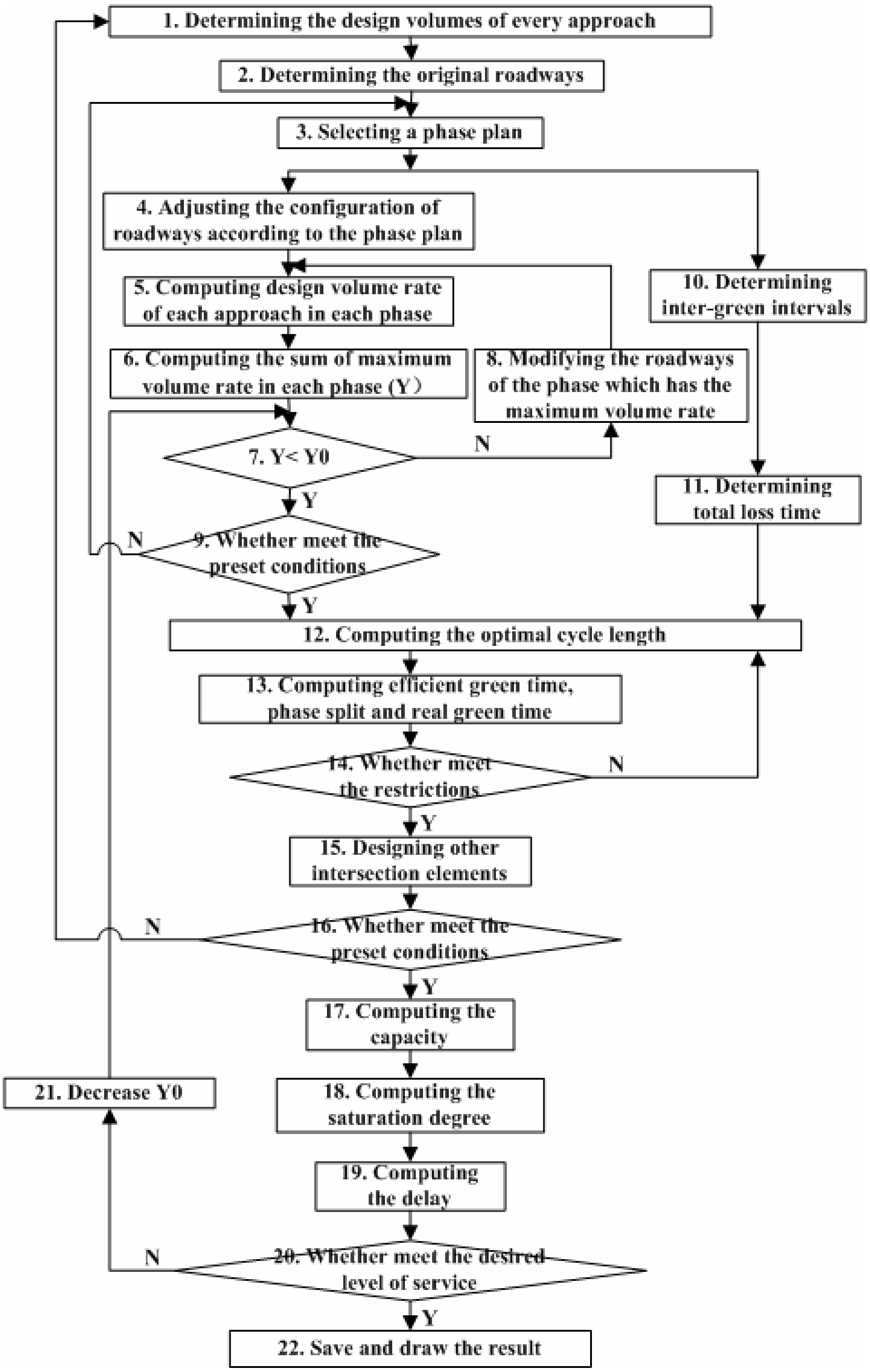

Figure 2. A Combined Algorithm for Intersection Design

In order to demonstrate the rationality of this algorithm, Software based on this algorithm is developed by the author. The program is based on Visual C++ (developed by Microsoft Corp.), ObjectARX (developed by Autodesk Corp.) and database technology.

The main objective of this software is to apply it in intersection planning; it can also be used to the design of intersection reconstruction. With the aid of this software, we can conveniently make the spatial and temporal design of a four-leg intersection. At present, the design of phase plan only offer four of the most common basic plans: a two-phase plan, a three-phase plan and two kinds of four-phase plan.

This research belongs to a project called “development of software for transportation planning and analysis supporting ITS”, which is sponsored by the 10th five-year planning ITS research project by MOST (No.2002BA404A20B) of China. As a function component, this intersection design software not only considers its own independency, but also pays attention to the combination with the main software of the project. The information needed by intersection design can be transferred by main software from the database or input by users independently.

The input of the software primarily includes the information about intersection volumes and intersection legs. Concretely speaking, the volumes mainly indicate peak-hour volumes allocated to different direction of all approaches. Information about the intersection legs includes intersection angles, rank of road, number of current roadways, width of all the roadways, width of bicycle lanes and sideways, the type and width of medians and traffic separators, etc.

Based on the information above, the software could design intersection elements in real time, such as the design of roadways (involved with the adding and widening of lanes, determining of directions of lanes, the configuration of turning roadways, etc.), the configuration of bicycle lanes, crosswalks, and crossovers, etc. The details of these designs, such as location and width, can be correctly derived. As for the signalization, the software can give a detailed timing plan and its diagram. The evaluation of the level of service can also be easily computed. At the same time, the algorithm could set the desired level of service by modifying some initial parameters.

Further more, graphical interfaces and result are developed. The result of design on an intersection can be created in AutoCAD (developed by Autodesk Corp.) in real time.

5.2 Case Analysis

In order to demonstrate the correctness and practicability of the developed software, two cases are offered: one is an ideal intersection and the other is an actual intersection.

Besides, due to the limitation to the length of this paper, we just list several important results of every loop, including the configuration of roadways, signal timing plan and the level of service.

(1) Case 1: Ideal Intersection

The ideal intersection has four legs and the information is shown in Table 1. The angles of four legs are 0, 90, 180 and 270 degree respectively. The angle here indicates polar angle encircling the intersection center. The widths of all the roadways, bicycle lanes, sideways and traffic separators are respectively set to be 3.5 meters, 5 meters, 5 meters and 2 meters. The mainline consists of leg 1 and leg 3.

Table 1. Information of the Legs of the Ideal Intersection

No.	Road class	The maximum width (m)	Through volume (pcu/h)	Left turn volume (pcu/h)
1,2,3,4	Arterial road	60	500	300
No.	Right turn volume (pcu/h)	Grade	Number of lanes of the entrance	Number of lanes of the exit
1,2,3,4	300	0	3	3
No.	Whether a bicycle lane in the entrance exists	Whether a bicycle lane in the exit exists	Whether a side walk in the entrance exists	Whether a side walk in the exit exists
1,2,3,4	Yes	Yes	Yes	Yes
No.	Whether a median exists	Median type	Whether a traffic separator in the entrance exists	Type of the traffic separator
1,2,3,4	Yes	Green belt	Yes	Green belt
No.	Whether a traffic separator in the exit exists	Type of the traffic separator	The mode of people crossing the streets	
1,2,3,4	Yes	Green belt	Crosswalk	

The initial phase plan is a two-phase plan, while each of the phases has green time 20s and yellow time 5s. The initial configuration of roadways is computed base on this plan. As a result, each approach has a through lane, protected left turn lane, protected right turn lane respectively.

For the design volumes of each approach is similar to each other, we select a kind of four-phase plan, which includes two protected left turn phases. This plan can fit the configuration of roadways, so modifications are not needed.

We set the initial predefined value of Y (the sum of all the maximum volume ratios in each phase) to be 0.9. From now on, the program runs into the iteration from step 5 to step 8. The process of iteration is listed in Table 2.

Table 2. the Process of Iteration from Step 5 to 8 in Case 1 (the First Time)

Number of iteration		1	2	3	4	5	6	7	8	9
Number of lanes of Approach 1	Protected left turn lane	1	1	1	1	1	2	2	2	2
	Through lane	1	2	2	2	2	2	2	2	2
	Protected right turn lane	1	1	1	1	1	1	1	1	1
Number of	Protected left turn lane	1	1	1	1	1	1	1	2	2

lanes of Approach 2	Through lane	1	1	1	2	2	2	2	2	2
	Protected right turn lane	1	1	1	1	1	1	1	1	1
Number of lanes of Approach 3	Protected left turn lane	1	1	1	1	1	1	2	2	2
	Through lane	1	1	2	2	2	2	2	2	2
	Protected right Turn lane	1	1	1	1	1	1	1	1	1
Number of lanes of Approach 4	Protected left turn lane	1	1	1	1	1	1	1	1	2
	Through lane	1	1	1	1	2	2	2	2	2
	Protected right turn lane	1	1	1	1	1	1	1	1	1
Y		1.60	1.60	1.35	1.35	1.11	1.11	0.95	0.95	0.802

When the program jumps out of the iteration, the value of Y is 0.802. Each approach has two through lanes, two protected left turn lanes and one protected right turn lane. Next, the parameters of timing plan can be computed. Table 3 gives the result.

Table 3. Timing Plan of the Intersection in Case 1 (the First Time)

Cycle length (s)	85
Efficient green time (s)	77

Subsequently, other configurations of intersection elements and the evaluation indices can be computed, which are omitted here. Table 4 just shows the computation result of intersection delay and level of service.

Table 4. the Result of Intersection Delay and Level of Service in Case 1 (the first time)

Intersection control delay (s)	25.8
The level of service	C

The level of service does not achieve the demand B, so the set value of Y should be reset so that the program can run into iteration from step 5 to 8 again. For the set value of Y can be reduced 0.0333 once, it has to decreased to 0.8 so that the iteration could be implemented (because the last Y is 0.802). The process of iteration is demonstrated in the following table.

Table 5. the Process of Iteration from Step 5 to 8 in Case 1 (the Second Time)

Number of iteration		1	2
Number of lanes of Approach 1	Protected left turn lane	2	2
	Through lane	3	3
	Protected right turn lane	1	1
Number of lanes of Approach 2	Protected left turn lane	2	2
	Through lane	2	2
	Protected right turn lane	1	1
Number of lanes of Approach 3	Protected left turn lane	2	2
	Through lane	2	3
	Protected right turn lane	1	1

Number of lanes of Approach 4	Protected left turn lane	2	2
	Through lane	2	2
	Protected right turn lane	1	1
Y		0.802	0.72

The results of timing plan and level of service are demonstrated in Table 6 and 7.

Table 6. Timing Plan of the Intersection in Case 1(the Second Time)

Cycle length (s)	65
Efficient green time (s)	57

Table 7. the Result of Intersection Delay and Level of Service in Case 1 (the Second Time)

Intersection control delay (s)	20.2
The level of service	C

Unfortunately, the level of service still does not achieve B, so the set value of Y is adjusted to 0.70. This time the process of iteration and results are listed in the following tables:

Table 8. the Process of Iteration from Step 5 to 8 in Case 1 (the Third Time)

Number of iteration		1	2
Number of lanes of Approach 1	Protected left turn lane	2	2
	Through lane	3	3
	Protected right turn lane	1	1
Number of lanes of Approach 2	Protected left turn lane	2	2
	Through lane	3	3
	Protected right turn lane	1	1
Number of lanes of Approach 3	Protected left turn lane	2	2
	Through lane	3	3
	Protected right turn lane	1	1
Number of lanes of Approach 4	Protected left turn lane	2	2
	Through lane	2	3
	Protected right turn lane	1	1
Y		0.72	0.64

Table 9. Timing Plan of the Intersection in Case 1(the Third Time)

Cycle length (s)	64
Efficient green time (s)	56

Table 10. the Result of Intersection Delay and Level of Service in Case 1 (the Third Time)

Intersection control delay (s)	18.6
The level of service	B

The goal of the level of service is achieved and the result can be saved. The next stage is to generate the diagram of this design result. Figure 3 demonstrates part of the final diagram (all kinds of signs and markings are omitted here).

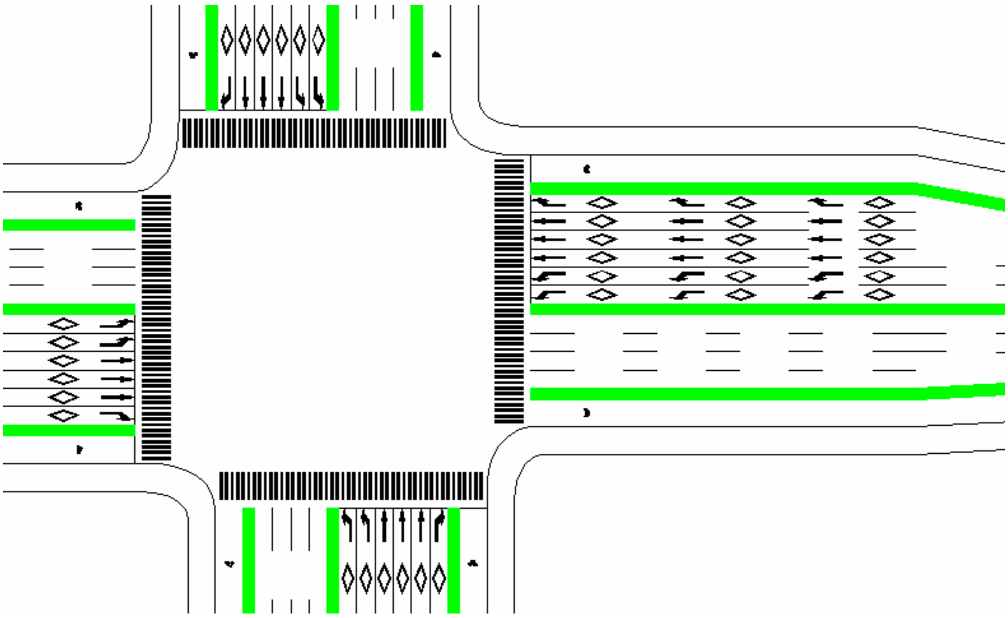

Figure 3. Part of the Intersection Design Diagram in Case 1

(2) Case 2: Actual Intersection

This case is one of the intersections which are waiting to be reconstructed in Liao Ning province, China. The information of this intersection is shown in Table 11 (widths of lanes are omitted here). The design volumes are the results of the traffic demand forecast in the planning project.

Table 11. Information of the Legs of the Actual Intersection

No.	Polar angle	Road class	The maximum width (m)	Through volume (pcu/h)
1	1	Minor road	50	470
2	95	Arterial road	52	519
3	182	Minor road	50	489
4	273	Arterial road	52	614
No.	Left turn volume (pcu/h)	Right turn volume (pcu/h)	Grade	Number of lanes of the entrance
1	95	186	0	2
2	135	297	0	3
3	187	325	0	2
4	212	112	0	3
No.	Number of lanes of the exit	Whether a bicycle lane in the entrance exists	Width of the bicycle lane (m)	Whether a bicycle lane in the exit exists
1	2	Yes	3	Yes

2	3	Yes	4	Yes
3	2	Yes	3	Yes
4	3	Yes	4	Yes

No.	Width of the bicycle lane (m)	Whether a side walk in the entrance exists	Width of the side walk (m)	Whether a side walk in the exit exists
1	3	Yes	5	Yes
2	4	Yes	5	Yes
3	3	Yes	5	Yes
4	4	Yes	5	Yes

No.	Width of the side walk (m)	Whether a median exists	Median type	Median width (m)
1	5	No	--	--
2	5	Yes	Green belt	2
3	5	No	--	--
4	5	Yes	Green belt	2

No.	Whether a traffic separator in the entrance exists	Type of the traffic separator	Width of the traffic separator (m)	Whether a traffic separator in the exit exists
1	No	--	--	No
2	Yes	Barrier	1	Yes
3	No	--	--	No
4	Yes	Green belt	1	Yes

No.	Type of the traffic separator	Width of the traffic separator (m)	The mode of people crossing the streets	
1	--	--	Crosswalk	
2	Green belt	1	Crosswalk	
3	--	--	Crosswalk	
4	Green belt	1	Crosswalk	

Selecting a kind of four-phase plan, which includes two protected left turn phases, a reasonable result can be derived by implementing the algorithm. The process of the whole implementation is shown in Table 12, while the smaller iteration from step 5 to 8 is omitted.

Table 12. the Implementation Process of the Software for Case 2

Iteration	1	2	3	4	5
Cycle length (s)	144	127	100	76	65
Intersection control delay (s)	46.8	40.9	31.8	22.8	18.6
Level of service	D	D	C	C	B

The configuration of roadways is shown in Table 13:

Table13. the Configuration of Roadways in Case 2

Number of lanes of Approach 1	Protected left turn lane	1
	Through lane	3
	Protected right turn lane	1
Number of lanes of Approach 2	Protected left turn lane	1
	Through lane	3
	Protected right turn lane	1
Number of lanes of Approach 3	Protected left turn lane	1
	Through lane	3
	Protected right turn lane	1
Number of lanes of Approach 4	Protected left turn lane	2
	Through lane	3
	Protected right turn lane	1

Part of the diagram of the design result is demonstrated in Figure 4.

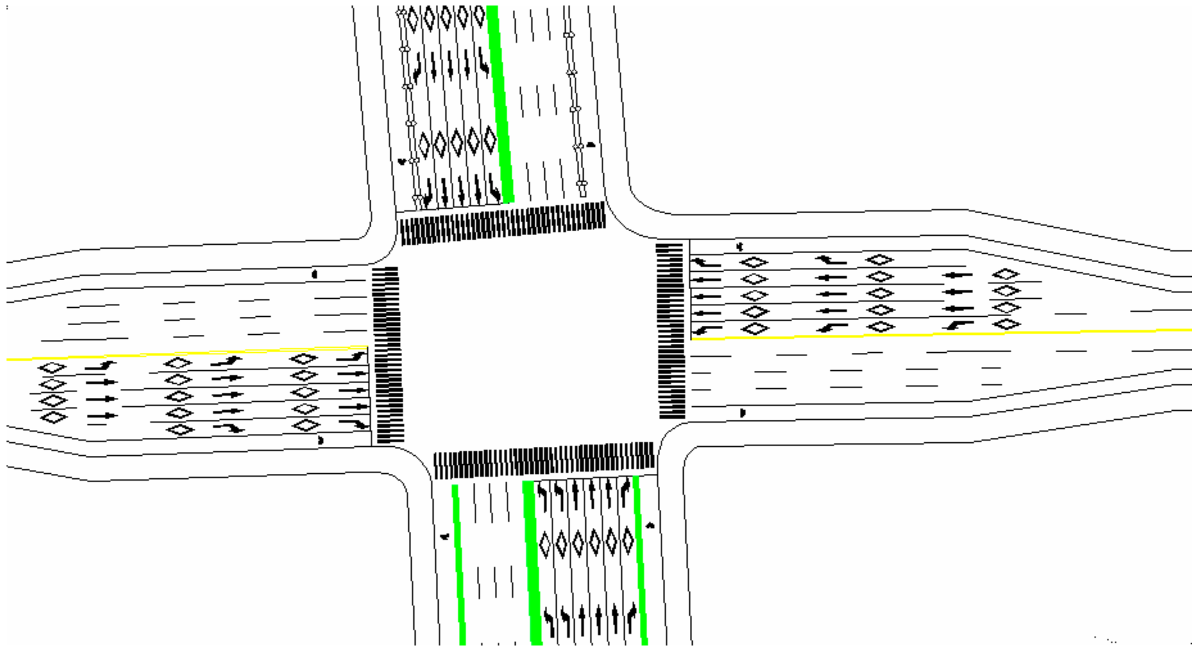

Figure 4. Part of the Design Result in Case 2

As the traditional algorithm can not be implemented by programming, the comparison between the result of the new and traditional one couldn't be done. However, the advantages of rationality and convenience of the new algorithm is obvious.

6. CONCLUSIONS

Aiming at solving the problems of traditional design method, this paper presents a new combined algorithm for intersection design. Based on the analysis above, the new algorithm has such advantages as:

(1) The new algorithm is based on the traditional one and just makes some improvements, so the designer can quickly adapt the new working flow, which is benefit for popularity.
(2) The new algorithm combines the spatial design and temporal design, making the two considering feedbacks of each other.

(3) It combines the design and evaluation: the design provides quantitative data for evaluation, while evaluation provides advice for improving the design.

However, there is still some work that should be done for the improvement and application of this algorithm and its software, such as:

(1) The new algorithm is oriented to programming, so in some judging steps quantitative indices are employed. Accordingly, how to determine the critical values of these indices or how to add people's subjective judgments into the program become important, which will be one of the future tasks.

(2) The software implementation just considers the design volumes of motor vehicles, but not those of bicyclists and pedestrians.

(3) The design of phase plan just offers four of the most common basic plan, which is different from the real situation. Some future researches about the automatically generation of phase plan will be very meaningful.

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