A SIMULATION OPTIMIZATION METHOD FOR DESIGN AND CONTROL OF SIGNALIZED INTERSECTIONS IN URBAN AREAS

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ABSTRACT
The signalized intersections play a significant role in road network management. Bad traffic light control system results in more waste time the drivers spend on waiting and other negative influences like gaseous pollutant emission, more fuel usage, further deteriorating the environment and lowering the overall living standard. However, traditional analytical techniques are difficult to be applied to traffic lights due to its randomness, complexity and nonlinearity. Thus, simulation could be instrumental in designing and controlling signalized intersections and analyzing various situations by evaluating postulated "what-if" scenarios. This paper first utilized the AHP (analytic hierarchy process) method to determine the weights of evaluation indicators of traffic lights, and then applied simulation modelling (Simphony) to optimize the signalized intersection for the objectives of efficient design and control. Then, some comparisons of different lane designs were made to give some suggestions to road construction. The results demonstrated the effectiveness of the methodology.

Keywords: AHP, signalized intersections, simulation, optimization

1. INTRODUCTION

With the rapid development of regional economy, the residents tend to pursue material and spiritual life with high quality when basic living standard is guaranteed. One typical phenomenon is a great many of households could afford at least an automobile. Take China as an instance. There were 0.12 billion private vehicles in 2014 and the annual number had increased at the rate of 117.5% (National Bureau of Statistics, 2014). The automobile provides convenience for people's work and life to large extent, but the massive cars flooring into the urban area bring in serious traffic issue, especially traffic congestion. In terms of the drivers, they are reluctant and bored to waste most of time on waiting. Besides, the time spent idling in traffic wastes fuel, increases emissions, deteriorates the environment, and affects the overall standard of living (Sadoun, 2003). Meanwhile, traffic flow may largely exceed the maximum load capacity of the road compared with its initial setting. Thus, traffic congestion has become the main bottleneck of urban sustainable development, extremely concerned by city planners, engineers, local governments, urban policy makers, legislators, economists, and law enforcement agencies, among others.

The intersection is the important node in road network, and the signal control strategy has a significant effect on the traffic conditions. If one or several intersection signal setting is unreasonable, it will lead to slow traffic in the related roads, more seriously can cause a large number of vehicles stranded and the regional road network paralysis (Wunderlich et al., 2008). Moreover, the number of lanes and various types of roads also influence traffic congestion. Thus, how to design the new signalized intersections and adjust the existing signalized intersections are considered as the most complex task in the management of traffic system, due to its randomness, complexity and nonlinearity. Currently, there are two main traffic light signal control systems, that is, tradition control and adapting control (Sadoun, 2003). The former depends on historical data and prestored timing plan offline, so it's more easy and cost-effective to control traffic light signal system. By contrast, the latter adapts to actual traffic condition and is capable to perform continuous optimal system, but it needs to deploy traffic detectors and surveillance equipment in advance. Actually, traffic conditions could be divided into peak time, general time and slack time in a given day except bad weather conditions, accidents and holidays, and so on. As for the three phases, different scenarios should be set to meet various traffic conditions. Considering the features of the two main methods, they ignore the utilization of resources (e.g. green traffic lights and the lanes) and limit to make the adjustment based on the roads with the fixed number of lanes. Simphony is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent and intelligent environment for both the development and the utilization of construction SPS (special purpose simulation) tools (Hajjar and AbouRizk, 1999). Also, Simphony provides various services that enable the users to easily control different behaviors in the developed tool such as simulation behaviors, graphical representation, statistics, and animation (AbouRizk and Mohamed, 2000). Besides, how to evaluate each simulation result is also an essential part, since traffic light signal control belongs to a multi-index evaluation and the important degree of indicators should balance the needs from different stakeholders on a certain traffic issue. Based on this, this paper combines the AHP (analytic hierarchy process) method to determine the weights of indicators and simulation modelling (Simphony) to optimize the signalized intersection for the objective of efficient design and control.

2. LITERATURE REVIEW

A complete design and control of signalized intersections involves analysis, modelling and simulation to obtain an efficient system. Basically, the process includes three important components: phases and sequence of traffic light, the cycle length and the duration for green light of each phase. According to various setting methods of the three elements, pretime operation, semiactuated operation and fully actuated operation are proposed to control traffic signals (Sadoun, 2003). Pretimed control needs to preset the cycle length, phases and all intervals of each signalized intersection (Clement and Koshi, 1997). In semiactuated operation, detectors are placed on minor approaches to the intersection, while both cycle length and the green-light time for every phase of the intersection can be varied in fully actuated operation based on mounted detectors (Sadoun, 2003).

Pretime operation belongs to the traditional signal control system, which depends on historical data and prestores timing plan offline. Therefore, it's more easy and cost-effective to control traffic light signal system, but not responsive to dynamic traffic demand. Semiactuated operation and fully actuated operation are the adaptive traffic light signal control system. Due to the detectors installed, the system could adapt to actual traffic condition and perform continuous optimization. There is some industry standard of the adaptive control system, such as SCATS, SCOOT, LHOVRA, UTOPIA, PRODYN and OPAC. However, these adaptive signal control systems control traffic on an areawide basis rather than an uncoordinated intersection basis, and are only applied to that specific case (Sadoun, 2003). Besides, large expenditure is spent on detector installation at the early stage and operating in the usage phase.

From the above, it could be seen that the two main signal control systems both have advantages and disadvantages. Simphony proposed by AbouRizk (1999) has been widely used in construction simulation. Simphony provides various services that enable the users to easily control different behaviors in the developed tool such as simulation behaviors, graphical representation, statistics, and animation (AbouRizk and Mohamed, 2000). Also, it could realize the dynamic simulation in a convenient and economical way, and directly reflect the simulation results (e.g. waiting time, queue length and utilization of resources). Thus, it's worthy and meaningful of applying Simphony to facilitating the traffic management, which could overcome the shortages of the signal control systems above and provide the simulation results that the users need.

3. METHODOLOGY

In this part, we firstly introduce some basic knowledge of traffic signal including traffic phases, traffic signal evaluation index and traffic arrival pattern. Based on this, the methodology will be proposed to present how to optimize signalized intersections by the means of the AHP method and Simphony.

3.1. Basic Knowledge of Traffic Signal

3.1.1. Traffic Phases

Traffic phase is the portion of the signal timing cycle that is allocated to one of these sets of movements (Davol, 2001). Typically, each phase consists of three intervals, that is, green, yellow and red. A phase will progress through all its intervals before moving to the next phase in the cycle. In reality, a three-leg signalized intersection and a four-leg signalized intersection are most common in the daily life. The corresponding layout and phase plans of the two forms of traffic intersections could be seen in Figure 1.

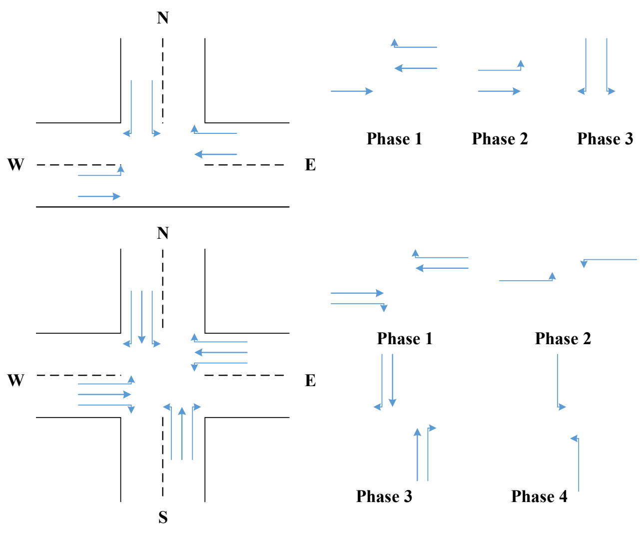

Figure 1: The Layout and Phase Plans of Two Typical Signalized Intersections

3.1.2. Traffic Signal Evaluation Index

Through literature review, traffic signal evaluation index adopted by the scholars is listed in Table 1.

Table 1: Traffic Signal Evaluation Index

Year	Authors	Index
2003	Sadoun	average waiting time, average queue length, average utilization of green-light time
2008	Yang et al.	traffic flow, average delays

2009	Ou et al.	average trip duration, volume of link, total volume, total stop
2013	Černický and Kalašová	delay time, mean speed, number of stop, stop time
2014	Liu et al.	average queque length, maximum queue length, delay time
2014	Wang et al.	average waiting time, average queque length, average number of vegicles, service intensity
2016	Osorio and Chong	average travel time

Due to various research objects, there exists some difference in the selection of traffic signal evaluation index. Ou et al. (2009), and Osorio and Chong (2016) mainly focused on large-scale urban transportation problems with the indicators like average trip duration, while other scholars tended to study signal time change influencing the vehicle behavior in a signalized intersection or multi-signalized intersections. The selection of evaluation index not only facilitates the traffic light optimization in the next stage, but also guarantees simulation results meet the needs from different stakeholders.

3.1.3. Vehicle Arrival Pattern

In the signalized intersection simulation, the first step is to collect data of the inter-arrival time for the vehicles, analyze and conform to the specific distribution. Currently, scholars have proposed three common vehicle arrival distribution models in different situation, that is, Poisson distribution, binomial distribution, and negative binomial distribution (Tohti et al., 2015). Where, Poisson distribution is used to describe the traffic flow which has short counting interval and low traffic density, without much interaction between the vehicles and other external interference (Wu, 2003). The basic form of Poisson distribution is described as below:

$$P(X = x) = e^{-\lambda}\lambda^{x}/x! \quad (x = 0,1,\ldots,n) \tag{1}$$

By contrast, binomial distribution and negative binomial distribution are more suitable for heavy traffic (Yang et al., 2008). The basic forms of two distributions are shown as below, respectively.

$$P(X = x) = \frac{n!}{x!(n-x)!} p^{x}(1-p)^{n-x} \quad (x = 0,1,2,\ldots,n) \tag{2}$$

$$P(X = x) = \frac{\Gamma(k+x)}{x!\Gamma(k)}\left(1+\frac{\mu}{k}\right)^{x}\left(\frac{\mu}{\mu+k}\right)^{n} \quad (x = 0,1,2,\ldots,n) \tag{3}$$

3.2. A Simulation Optimization Methodology for Signalized Intersections

3.2.1. Evaluation of Simulation Results Based on the AHP Method

From Table 1, scholars selected different indicators to evaluate the simulation results from various perspectives. Of them, some index refers to the features of vehicle and drivers' behavior, such as delay time and number of stop. Delay time refers to the difference between the necessary time a vehicle needs to pass by the leading way of crossing entry in a forbidden position and the time a vehicle needs to use while be in no hindering position (Wang, 2006). Average trip duration is selected as the index for the large-scale urban transportation issue. Based on this, two assumptions are given first: (1) all the automobiles as independent individuals; (2) the duration for a vehicle to go through a signalized intersection involves the influences from drivers' behavior and the features of vehicle. This paper will choose average waiting time, average queue length and traffic flow (out) as the traffic signal evaluation indicators. The index is mainly utilized to evaluate a signalized intersection or multi-signalized intersections and could meet the needs from various stakeholders.

As for the multi-index evaluation problems, the importance degree of each indicator should be determined and then weightings and values are integrated to obtain the final evaluation results. Based on this, this paper will introduce the AHP method proposed by Saaty (1977), which has been extensively applied and studied for weighting determination and decision making. The evaluators are from different stakeholder, so it guarantees the values of weightings are suitable for the certain simulation environment.

3.2.2. A Simulation Optimization Methodology

Based on the literature review and research objectives, this paper combines the AHP method and Simphony to propose a simulation optimization methodology, which could be applied to optimize one or more signalized intersections in the phases of design and control. The methodology framework could be seen in Figure 2.

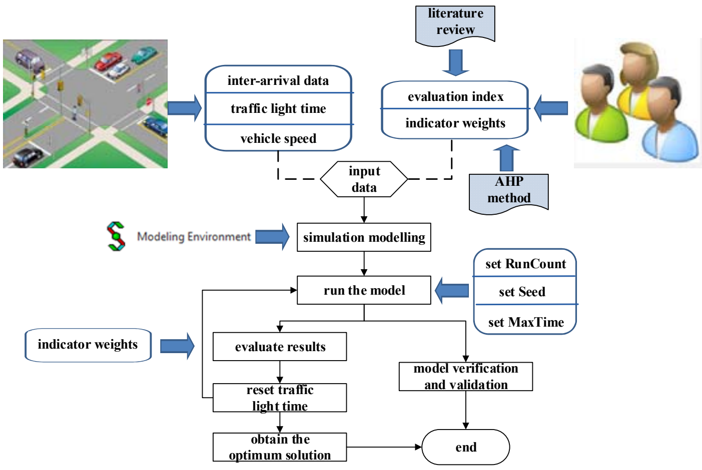

Figure 2: A Simulation Optimization Methodology for the Signalized Intersections

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4. SIMULATION OPTIMIZATION FOR A SIGNALIZED INTERSECTION

4.1. Abstract of the Signalized Intersection

This paper utilized a real signalized intersection given by Liu et al. (2014) to present how the methodology proposed to realize the optimization for traffic lights. The signalized intersection of Jianshe Ave and Xin Hua Lu is a typical four-leg intersection located in Wuhan city of China (see Figure 3). The west entrance road and the east entrance road are comprised of three lanes while only two lanes are on the other side of the road. In contrast, the north entrance road and the south entrance road consist of four lanes while only three lanes are on the other side of the road. To be mentioned, the right lanes of all the roads are shared by straight drive and right turn. And two directions of each road have different numbers of lanes and the total lanes of two roads are also various, that is, asymmetry.

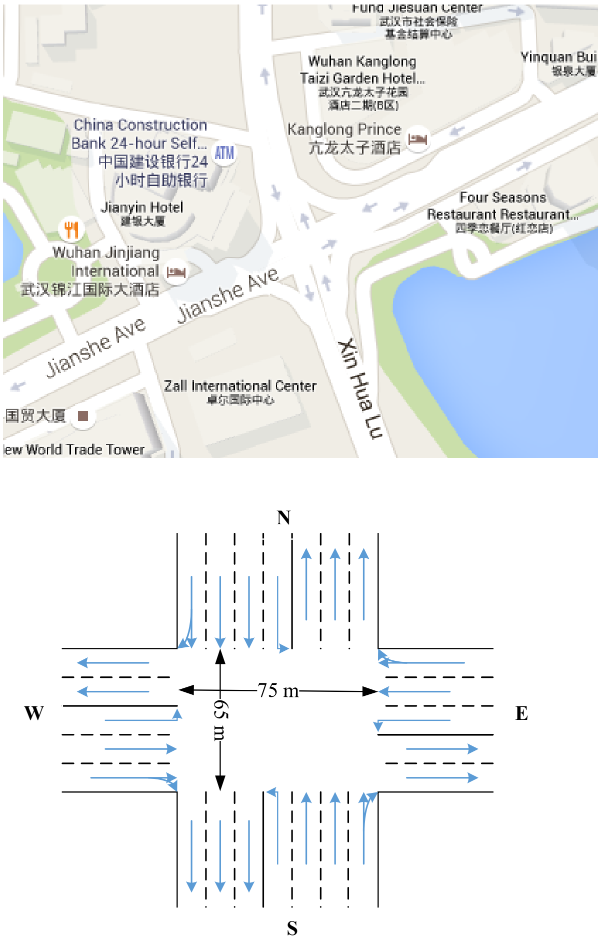


Figure 3: A Signalized Intersection in Wuhan City

4.2. Data for the Signalized Intersection

The traffic flow at the entrance of each road was monitored in Table 2 (Liu et al., 2014). Based on vehicle arrival pattern used by scholars in Section 3.1.3, Poisson distribution was selected to describe the inter-arrival time in the signalized intersection and the means of inter-arrival time could be calculated on the basis of traffic flow in Table 2. The initial duration of the signalized intersection could be summarized in Table 3, which will be applied to the input data for the simulation.

Table 2: Traffic Flow Data of the Signalized Intersection

		Lane	Traffic Flow (pcu/h)
East	Left	1	238
	Straight	2	727
	Right	1	198
South	Left	1	257
	Straight	3	1000
	Right	1	222
West	Left	1	275
	Straight	2	741
	Right	1	177
North	Left	1	240
	Straight	3	1227
	Right	1	200

* pcu indicates passenger car unit.

Table 3: Initial Duration of the Signalized Intersection

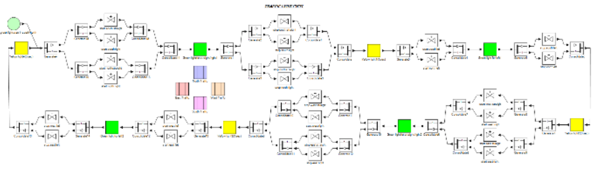
		Inter-arrival time (s)	Phase		Duration (s)
East	Left	P(15)	1	south/north straight	U(5,6)
	Straight	P(5)		to end straight	
	Right	P(18)		green light	50
South	Left	P(14)	2	south/north left	U(4,5)
	Straight	P(3.6)		to end left	
	Right	P(16)		green light	30
West	Left	P(13)	3	west/east straight	U(6,7)
	Straight	P(5)		to end straight	
	Right	P(20)		green light	50
North	Left	P(15)	4	west / east left	U(4,5)
	Straight	P(3)		to end left	
	Right	P(18)		green light	30
Yellow light					3

* P indicates Poisson; U refers to Uniform.

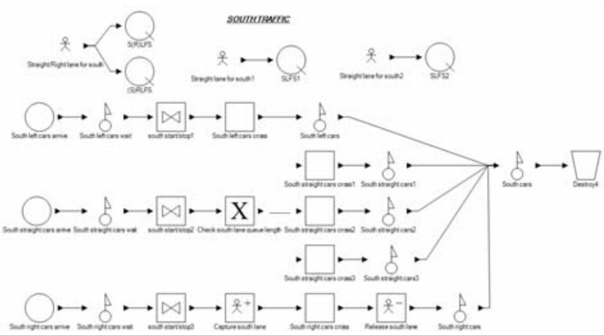
4.3. Simulation Modelling and Evaluation

4.3.1. Simulation Model Layout

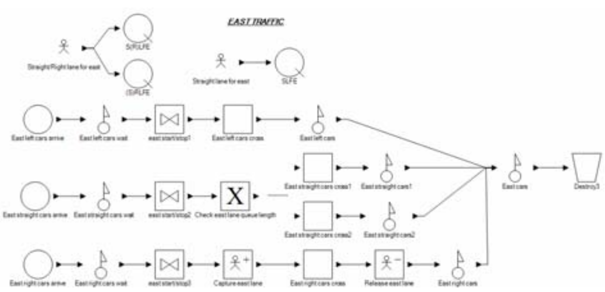
According to the plan view of the signalized intersection in Figure 3 and its input data of duration in Table 3, Simphony.NET was utilized to build the simulation model for the traffic lights in Figure 4. The four composition elements inside the traffic light cycle indicate south traffic, north traffic, west traffic and east traffic. As south traffic and north traffic have the similar model structure, only south traffic model was presented. This is identical to west traffic and east traffic. Assume that (1) the peak time for the traffic is one hour, so the simulation model is to be terminated after 3600 seconds; (2) a car arriving at each entrance will select the lane for straight drive based on the shortest queue length principle; (3) the south (the west) and the north (the east) have the same green times for straight drive/ right turn and left turn, respectively.



(a) Traffic Light Cycle



(b) South Traffic



(c) East Traffic

Figure 4: Simulation Model Layout for the Signalized Intersection

4.3.2. Result Analysis

Based on literature review, average waiting time, average queue length and traffic flow were selected as traffic signal evaluation index. After different stakeholders evaluated the importance degrees of the three indicators, the AHP method was utilized to determine their weights. The weights of average waiting time, average queue length and traffic flow were 0.4, 0.4 and 0.2, respectively. Then, through adjusting the green times for straight drive and right turn as well as left turn of each direction, the simulation results with 100 runs and 1000 seeds could be obtained. The optimum solution to control the signalized intersection could be seen in Table 4.

Table 4: The Optimum Traffic Light Time for the Signalized Intersection

	Green time for south/ north straight and right turn (s)	Green time for south/ north left turn (s)	Green time for east/ west straight and right turn (s)	Green time for east/ west left turn (s)
Duration	12	10	10	10
	Waiting time (s)	Queue length	Traffic flow (pcu/s)	Evaluat -ion value
South straight	20.86	4.456	0.274	8.81
South right turn	20.99	1.019	0.062	10.19
South left turn	21.86	1.28	0.072	9.27
North straight	20.92	5.412	0.330	10.60
North right turn	20.94	0.904	0.055	8.75
North left turn	21.69	1.175	0.067	9.16
West straight	21.94	3.573	0.196	10.25
West right turn	21.92	0.91	0.050	9.14
West left turn	22.05	1.389	0.077	9.39
East straight	21.91	3.573	0.197	10.23
East right turn	21.91	1.002	0.055	9.18
East left turn	28.78	0.026	0.068	11.54
Evaluation value	South/North: 9.463		West/East: 9.955	

4.3.3. Validation and Verification

Model validation is usually defined as substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model (Schlesinger, 1979). Model verification is often defined as ensuring that the computer program of the computerized model and its implementation are correct (Sargent, 2004). Sargent (2004) summarized various validation techniques and tests to be used in model verification and validation. Where, the “traces” approach is one of the common methods that the behavior of specific entities in the model are traced (followed) through the model to determine if the model’s logic is correct and if the necessary accuracy is obtained.

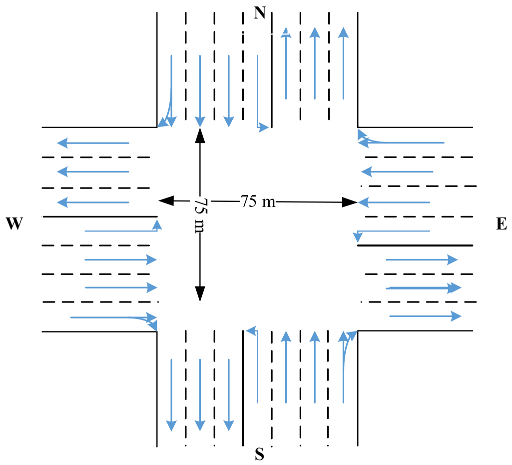
Based on this, to verify the simulation models, the trace functionality provided by Simphony was utilized to prove that the model replicated the logical traffic flow sequence as intended. User-written code was embedded within the model in order that the chronological list of events and "TimeNow" when each car goes across the signalized intersection in the optimum traffic light situation. Part of trace results for this signalized intersection is shown within the trace in Figure 5, where the recorded times for crossing the intersection are found to follow the expected trend; hence the model can be considered reliable.

No.	TimeNow	No.	TimeNow	No.	TimeNow	No.	TimeNow	No.	TimeNow	No.	TimeNow
1	4.435	21	40.878	41	59.056	61	73.702	81	88.998	101	104.940
2	4.558	22	41.042	42	59.711	62	73.996	82	90.732	102	105.968
3	6.904	23	41.046	43	60.175	63	74.371	83	90.766	103	106.101
4	9.702	24	41.498	44	61.204	64	74.866	84	90.818	104	106.741
5	9.872	25	44.933	45	63.323	65	74.999	85	92.468	105	107.497
6	10.116	26	45.666	46	63.622	66	77.445	86	92.676	106	108.777
7	15.462	27	45.995	47	63.903	67	77.747	87	95.099	107	110.047
8	15.849	28	46.373	48	64.204	68	78.469	88	95.420	108	111.229
9	19.003	29	47.537	49	64.215	69	79.553	89	96.036	109	111.922
10	19.613	30	47.602	50	64.226	70	80.123	90	96.586	110	112.974
11	23.537	31	49.226	51	66.955	71	80.311	91	98.676	......	......
12	27.710	32	49.951	52	67.526	72	81.586	92	98.796	5417	3592.679
13	31.722	33	50.573	53	68.434	73	82.225	93	99.106	5418	3595.673
14	32.112	34	52.380	54	68.858	74	82.738	94	99.244	5419	3596.181
15	32.171	35	53.769	55	69.214	75	85.377	95	99.270	5420	3596.380
16	34.182	36	54.383	56	69.332	76	85.406	96	101.616	5421	3597.001
17	34.996	37	54.900	57	69.505	77	85.675	97	102.053	5422	3597.122
18	35.746	38	54.923	58	70.087	78	86.131	98	102.335	5423	3597.424
19	36.415	39	58.404	59	73.263	79	86.295	99	103.259	5424	3598.031
20	36.699	40	58.664	60	73.390	80	86.375	100	103.435	5425	3598.889

Figure 5: Chronological List of Traffic Flow through the Signalized Intersection

4.4. Comparisons with Alternatives

In the signalized intersection, the lanes of the two direction roads are asymmetry. As for city planners, engineers or local governments, they could consider the lane design for the road, which has direct effects on the operation of the signalized intersection. Thus, different alternatives could be compared based on the actual or forecasted traffic information. Then, other two-lane design plans of the signalized intersection in Wuhan city were given in Figure 6.



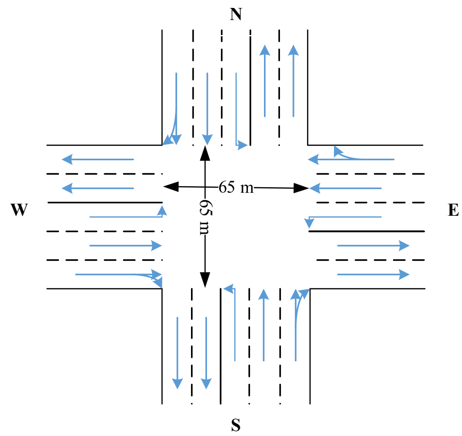


Figure 6: Two Lane Design Plans for the Signalized Intersection

Based on the simulation model of the signalized intersection with the optimum traffic light time, adjust the number of lanes as the above figure and then utilize Simphony to obtain the utilization rate of the lanes in Table 5. Plan 1 is the original lane design; plan 2 and plan 3 are the new design plans.

Table 5: The Comparison of Utilization Rate of the Lanes in Different Design Plans

		Left	Straight	Right
East	Plan 1	30.3 %	78.3 %	74.8 %
	Plan 2	29.9 %	77.5 %	74.8 %
	Plan 3	30.2%	47.0%	59.4%
South	Plan 1	32.2 %	46.0%	85.8 %
	Plan 2	32.1 %	82.2 %	95.6 %
	Plan 3	31.9%	46.6%	86.0%
West	Plan 1	34.4 %	75.7 %	74.6 %
	Plan 2	34.3 %	75.0 %	75.3 %
	Plan 3	34.2%	48.1%	54.5%
North	Plan 1	29.9 %	58.4 %	88.8 %
	Plan 2	29.9 %	96.6 %	98.7 %
	Plan 3	30.3%	58.2%	88.6%

From the table, it could be seen that the utilization rates of the right lanes in all the entrances are large, since the right lanes are shared by the vehicles going straight and turning right. The west and the east in plan 1 and plan 2 have higher usage rates of straight drive than those of plan 3. It shows that increasing the number of lanes could mitigate the road pressure to large degree. The straight lanes of the north and the south in plan 2 bear the tremendous traffic flow, so plan 1 used in the reality should be designed based on the predicted traffic volume. However, the road design (plan 1) was built before a long period, thus resulting currently the straight lanes of the east and the west support relative higher traffic volume. Thus, through the comparison of different lane plans for the roads, city planners could make a scientific decision for the road design based on the predicted lane utilizations in multi-alternatives.

5. CONCLUSIONS

Traffic congestion is the hot topic concerned by the scholar circles and the experts from the industries, since it has become the main bottleneck of urban sustainable development and brings other bad influences on environment and people's life. This paper firstly chose average waiting time, average queue length and traffic flow (out) as traffic signal evaluation indicators, and determined the weights of the index by the AHP method to meet the needs from different stockholders. Then, Simphony was utilized to simulate the traffic lights in various scenarios and further obtain the optimization solution to control the signalized intersections. Also, the simulation models developed were verified and validated by tracing the chronological list of events and observing relevant statistics (e.g. cycle time for a vehicle across the intersection). Besides, the methodology could also facilitate city planners or the government to select the most suitable lane design by comparing the utilization rates of several alternatives.

Besides the major needs from the drivers, other evaluation indicators such as CO2 emission could be considered during the traffic process. Also, CO2 emission should depend on the whole time spent in the intersection and the features of the vehicles. Moreover, the optimum parameters of traffic lights mainly depend on the adjustment of traffic cycle time manually. In future, the simulation process with Simphony could consider environmental influences and integrate optimization algorithm to obtain the optimum parameters of traffic lights automatically and more efficiently.

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