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Research Article

An Empirical Framework for Intersection Optimization Based on Uniform Design

Ying Zhang,[1,2] Daniel Jian Sun,[1,2] and Alexandra Kondyli[3]

[1] *State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China*
[2] *Center for UAV Applications and ITS Research, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, China*
[3] *Department of Civil, Environmental, and Architectural Engineering, University of Kansas, Lawrence, KS, USA*

Correspondence should be addressed to Daniel Jian Sun; danielsun@sjtu.edu.cn

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Operational performance optimization of signalized intersections is one of the most important tasks for traffic engineers and researchers. To compensate for the limitations of practical implementation, simulation software packages have been widely used to evaluate different optimization strategies and thus to improve the efficiency of the intersections as well as the entire network. However, for the existing optimization studies on signalized intersections, the relationships among various optimization measures and the combination of strategies have not been fully investigated. In this paper, uniform design experimentation was introduced to combine different optimization measures into strategies and achieve the minimum time cost in model construction. VISSIM software package was then calibrated and used to evaluate various optimization strategies and identify the one with the best measurement of performance, namely, control delay at the signalized intersection. By taking a representative congested intersection in Shanghai as a case study, the optimal strategy was identified to reduce the overall control delay by 27.3%, which further verified the modeling capability of the proposed method.

1. Introduction

Optimizing operation at signalized intersections has long been an issue for congestion mitigation in urban areas. Microsimulation packages, such as VISSIM, TSIS/CORSIM, AIMSUN, and PARAMICS, were developed and have become major tools in testing the operational performance of intersections and evaluating management strategies, in an effort to provide solutions for intersection optimization.

Among the microsimulation packages, VISSIM is one of the most commonly used tools. Varieties of efforts have been made to prove its practicality under different traffic conditions [1–4]. Leng et al. [1] proved that the calibrated model of VISSIM was able to simulate right-turn lane (RTL) plus U-turn (UT) at urban intersections. A typical signalized intersection with left-turn waiting zones (LTWZ) was successfully studied by Chen et al. [2]. Moreover, two different types of intersections, namely, stop-controlled intersection and yield-sign intersection, were modeled and validated in VISSIM and compared afterwards [3]. Autey et al. [4] analyzed four unconventional intersection schemes, that is, crossover displaced left turn, the upstream signalized crossover, the double crossover intersection, and the median U-turn, using VISSIM software. The four schemes were then compared in terms of average control delay and the overall intersection capacity. The existing comparative studies between VISSIM and the other simulation packages including PARAMICS [5], CORSIM [6], TSIS [7], and AIMSUN [8] also demonstrated the accuracy and efficiency of VISSIM.

In terms of intersection performance, considerable research and application efforts using VISSIM have primarily focused on signal control, while channelized layout is determined under the guidance of the design specifications. Li et al. compared six signal control plans, by choosing traffic delay and queue length as the performance measures [9], while Liang et al. compared three green wave timing plans, using traffic delays, parking time, and number of stops as the performance measures [10]. A stepwise genetic fuzzy logic controller was proposed by considering traffic flows and queue lengths of motors and motorcycles as state variables and then compared with two pretimed timing plans and three adaptive signal timing models [11]. An improved adaptive signal control method based on dynamic programming was proposed and implemented in VISSIM by Chen and Sun [12] with three objective functions, that is, delay, queue length, and throughput, taken into consideration. Aiming at minimizing queue length at oversaturated intersections, a cycle length optimization method was developed and validated within VISSIM [13]. A coordination control model was developed by Wu et al. [14] based on the shockwave theory under oversaturated situation, which was proved effective according to the simulation results.

In the developing countries, such as China, the design specifications for signal intersections are not detailed enough. As a result, channelized layout is taken into consideration together with signal control, composing the combinational management strategy. The optimized scenario was compared with the base scenario to prove its effectiveness [15]. In the city of Zibo, Shandong Province, China, three optimization strategies considering pedestrian overpass, medial strip, bus transit lane (BTL), and forms of bus stop were established. VISSIM was then used to evaluate the performance of each scheme and identified the one with the minimum queue length [16]. Similar operations were conducted in Beijing [17] and Harbin, China [18]. Generally, the procedure for these studies can be summarized into four steps: put forward optimization measures, combine different measures into combinational strategies, build simulation models, and choose the best strategy. However, the determination of optimization strategies was based on practical experience. Unfortunately, the interrelations within different measures were generally ignored and the combinations of measures have not been studied systematically. Consequently, the optimal solution may be limited, particularly when it comes to practical applications.

The purpose of this study is to develop an empirical model for signalized intersection optimization, by taking a representative congested intersection in Shanghai as a case study. The remainder of the paper is organized as follows. In Section 2, the simulation model is implemented and calibrated through field survey data in VISSIM microsimulation package. In Section 3, uniform design experimentation is introduced to combine different optimization measures into executable strategies. Simulations of different strategies were then carried out. Section 4 presents the statistical analyses to determine the strategy with the best performance in terms of control delay. Finally, conclusions and future work are summarized in Section 5.

2. Model Implementation and Calibration

Simulation background of this study was selected as the Jianchuan Rd. & Humin Rd. intersection, Minhang District, Shanghai, China. With its unique geographic location near the industrial zones and the major public transit lines, the intersection plays an important role in transporting outbound industrial freight, as well as a large number of local pedestrians [19]. The daily traffic operation and management are remarkably complicated because of the oversaturated volume and the highly mixed traffic flow.

Field surveys were conducted to collect input data on five consecutive weekdays in December 2015 [20]. Traffic information including channelized layout, traffic volume, traffic capacity, vehicle speed distribution, traffic composition, control delay, maximum and average queue length, signal timings and splits, and ambient traffic policies was recorded.

2.1. Simulation Model in VISSIM. The intersection was implemented in VISSIM, according to the layout shown in Figure 1. Notably, a convertible lane was set up in the western approach (with solid arrow as in Figure 1) and the length of each approach was extended to about 250 m distance. Simulation runs were performed with the field survey data, such as traffic volumes, speed distributions, traffic compositions, and signal timings.

The shaded areas within Figure 1 indicate left-turn waiting zones (LTWZ). When there are exclusive left-turn lanes and protected left-turn phases, LTWZ is an option to set up beyond the conventional stop lines, allowing the left-turn vehicles to enter into the intersection and wait right at the zones during the through green phase [21]. Previous research proved that the adoption of LTWZ could increase the capacity of the left-turn lane by 17.8% [22]. However, since LTWZ is not frequently used in the western countries, the German-based software VISSIM does not automatically support this function. A modification in VISSIM was introduced as follows.

As presented in Figure 2, each strip represents one signal light, while the length of the strip represents the time duration for different signals. Compared with the situation without LTWZ, additional signal lights were added in the situation with LTWZ, following the conventional left-turn splits. Meanwhile, to allow the vehicles to enter LTWZ, the left-turn signal light is altered to green when the through phase is green.

2.2. Model Calibration. Multiple runs of simulation were carried out, with a simulation period of 3600 s. The first 30 minutes was used as the warm-up period, and only the data from the latter half hour were recorded for further investigations. Defaulted parameters for driving behaviors were initially adopted. However, the control delays obtained from simulation were severely deviated from the monitored results. As a result, model calibration concerning driving behavior is necessary before analysis.

According to previous research on simulation calibration [23, 24], five parameters were chosen as the calibration factors, that is, average standstill distance, additive part of desired safety distance, multiplicity part of desired safety distance, minimum headway, and maximum waiting time before diffusion. The candidate values and the calibration for each parameter were presented in Table 1. Traversal searching procedure was introduced with the assistance of COM interface, and only one parameter was changed following the corresponding variance step within each experiment.

Table 1: Calibration parameters in VISSIM.

Parameter	Default	Min.	Max.	Step	Calibrate
Average standstill distance (m)	2	1	5	0.1	1.5
Additive part of desired safety dist. (m)	2	1	5	0.1	3.3
Multipart of desired safety dist. (m)	3	1	5	0.1	4.2
Min. headway (s)	0	0	3	0.1	1.9
Max. waiting time before diffusion (s)	60	30	120	15	90

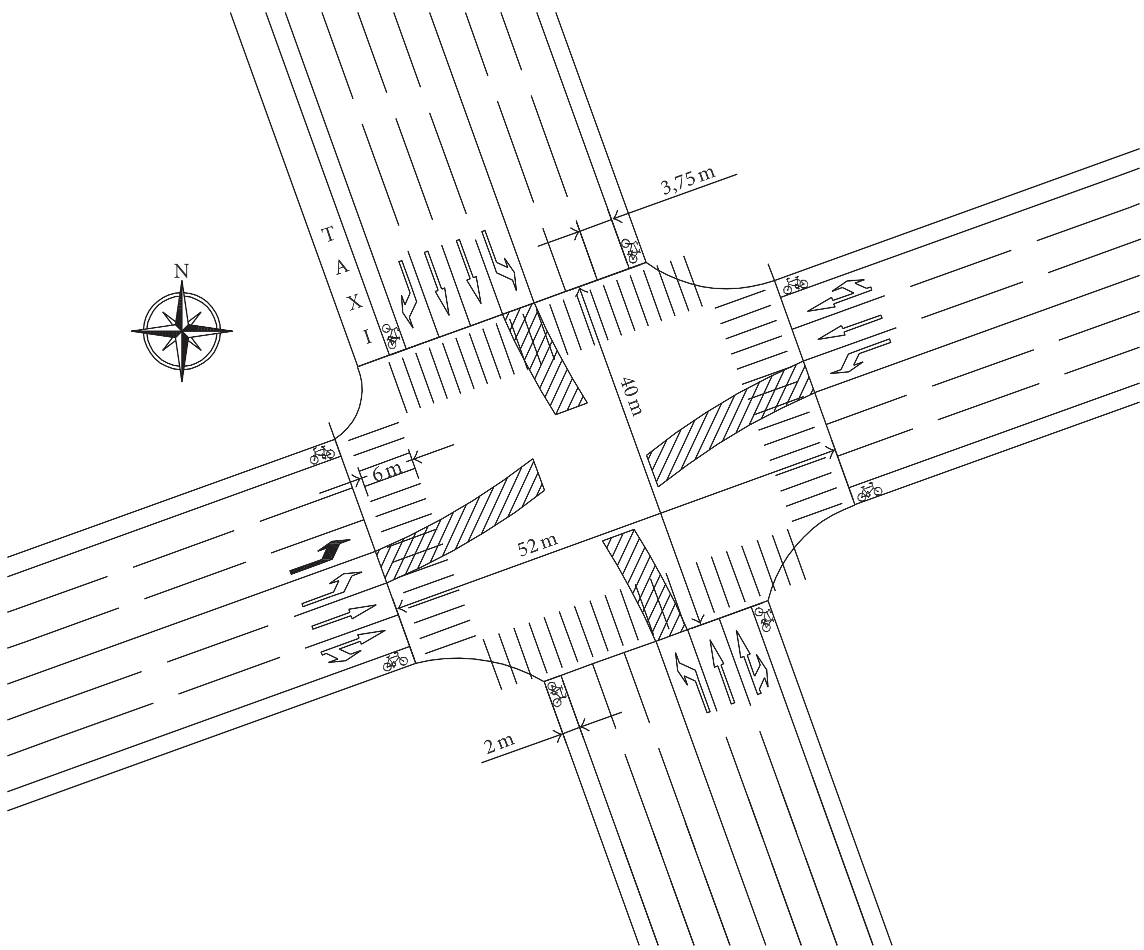

Figure 1: Layout of the study area (PM peak).

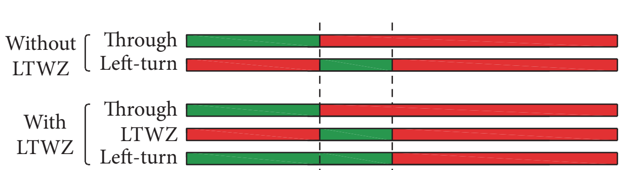

Figure 2: Signal control for left-turn waiting zone.

By choosing control delays in the southbound and eastbound directions, the absolute differences of control delays between simulation results and field measurements for the two directions were calculated. Values leading to the minimal difference in the sum of two directions were used as the calibrated values, as presented in Table 1.

With the calibrated parameters, 100 simulation runs were carried out, which was validated to satisfy minimal requirement $N \gg 1.96^2 S^2/e^2$ (S^2 is the variance of control delay calculated from 100 runs, e is selected as 5% of the average control delay, and 1.96 was selected as the critical value corresponding to the 95% confidence level). The average control delay after calibration was calculated as 104.5 s and 159.1 s in southbound and eastbound direction, respectively. Compared with the field-measured values of 105.7 s and 159.4 s, the errors were within 3%. Consequently, the overall performance of the calibrated model was considered to replicate the real traffic conditions.

Table 2: Direction distribution coefficient (DDC) for four directions (c = 215 s).

Location	v (vph)	t(s)	F_{major} (vph)	F_{minor} (vph)	DDC
Northbound	208	48	932	305	0.75
Westbound	346	43	1730	381	0.82
Southbound	272	48	1218	497	0.71
Eastbound	280	43	1400	253	0.85

Table 3: Traffic flow data at the intersection (unit: vehicles per hour, vph).

Location	Volume		Capacity	V/C ratio
	Motor (L, Th, R)	RHV (L, Th, R)		
Northbound	1430 (208,760,462)	(0.12,0.09,0.03)	1418	1.01
Westbound	806 (346,226,234)	(0.08,0.22,0.08)	990	0.81
Southbound	1164 (272,612,280)	(0,0.11,0.04)	701	1.66
Eastbound	884 (280,300,304)	(0.04,0.23,0.16)	701	1.26

3. Experimental Design and Determination

Traffic simulation generally includes building a layout of traffic network, including a lot of human labor instead of programmed operation. However, optimization in channelized layout will cause the alteration in simulation layout, which can significantly reduce time and manpower expenditure. Consequently, uniform design (UD) experimentation was introduced to combine different optimization measures and create optimization strategies systematically and efficiently.

3.1. Selection of Optimization Measures. Considering the current traffic performance and the management strategy at the selected intersection, four optimization measures were proposed, that is, convertible lane, right-turn lane (RTL), pedestrian overpass, and signal control.

3.1.1. Convertible Lane. A convertible lane has been set from about 200 m west of the subject intersection since Feb. 2011, allowing small passenger vehicles to take over the inner lane of the opposite direction during the peak hours. It was found to improve the passing rate from the west side to the north side by 62% [25]. Since the convertible lane has achieved rather good performance for the eastbound traffic, this configuration may be replicated in the other directions.

According to Transportation Research Board (TRB) [26], two major technical standards have to be satisfied to set up a convertible lane. First, there must be more than three lanes in each direction and no obstacles such as medial strip, which were satisfied in all four directions according to the layout in Figure 1. Secondly, the direction distribution coefficient (DDC), reflecting the volume of the major direction over the summation of both directions, should be larger than 2/3. Taking the characteristics of intersection into consideration, directions approaching the intersection were considered as the major directions. The lane-based saturation flow rate for the left-turn lane in the major direction was calculated as $F_{major} = c \times v/t$. Here, c is the signal cycle, t is the particular phase splits, and v is the traffic volume in the major direction obtained during field measurement. The lane-based saturation flow rate in the minor direction F_{minor} was estimated as the average measured traffic volume in the minor direction for each lane. The calculations for each direction were presented in Table 2, which showed that the convertible lane option was suitable for all four outbound branches.

As shown in Figure 3, four new designs were proposed together with the current design, as presented in Figure 3(a). A convertible lane (lane with red arrow) was added to the southbound, northbound, and eastbound directions, respectively, in Figures 3(b)–3(d). Taking the extremely high volume for the southbound through traffic into consideration, the conventional left-turn lane in the southbound direction was replaced by a shared left-turn lane, as shown in Figure 3(e).

3.1.2. Right-Turn Lane. Table 3 presents the field-measured flow data, in which RHV represents the ratio of heavy vehicles for each movement. The three numbers within the two parentheses represent values for left-turn, through, and right-turn movements, respectively. The V/C ratios (volume/capacity) were found to be higher than 1.2 in the southbound and eastbound directions. As a result, an additional lane should be considered to satisfy the extra demand. As there is no enough space for an additional lane in the eastbound direction, only the southbound direction was included in the plan. In this study, an additional RTL was introduced between nonmotorized vehicle path and sidewalk.

3.1.3. Pedestrian Overpass. Mixed traffic and improper traffic behavior of nonmotor vehicles are largely existing, which imposes enormous negative impact on the performance of intersections [27]. As the intersection selected served large volumes of cyclists and pedestrians, separation of motor vehicles from nonmotor vehicles and pedestrians was attempted. Pedestrian overpass was considered to connect with the light rail station located in the northwest corner of the intersection. It is also worth noticing that the overpass is generally considered as a reserved plan because of the large amount of budget and resources required for construction.

3.1.4. Signal Control. According to Table 3, traffic volumes of opposing travel directions are unbalanced. However, in the

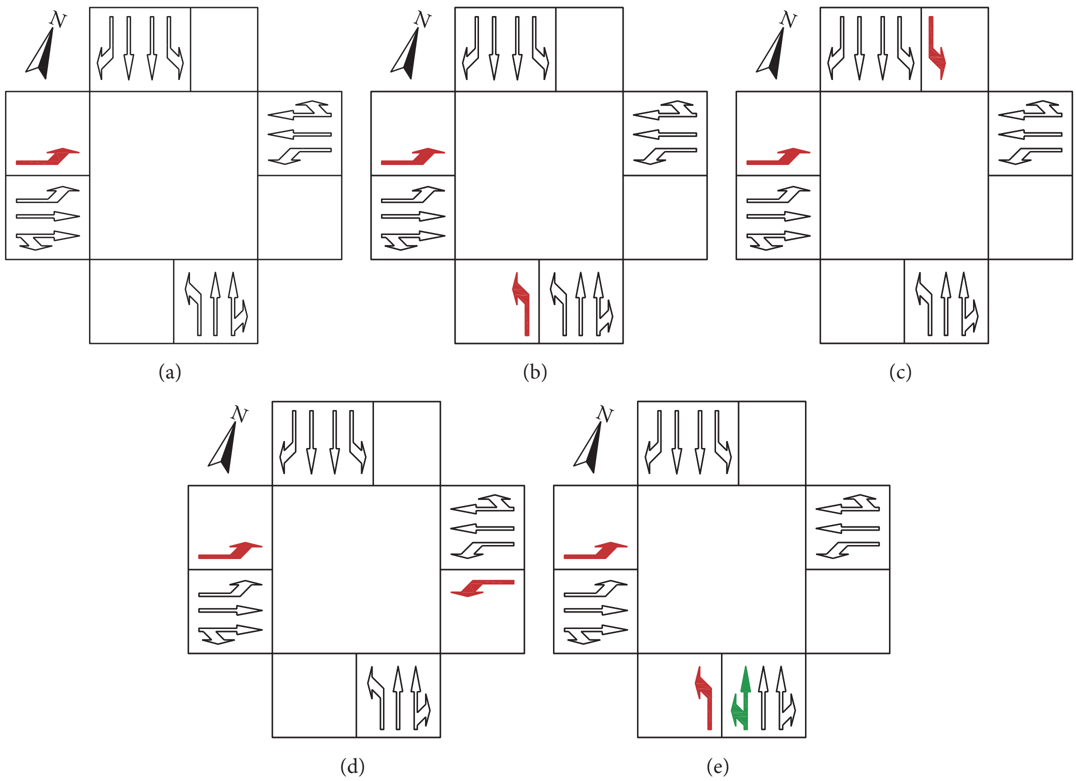

Figure 3: Designs of convertible lane.

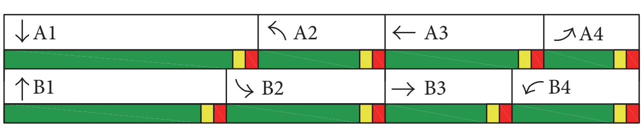

Figure 4: Sketch view of signal control plan.

current four-phase signal control plan, same-phase movements with different volumes share the same passing time, and consequently the green time may not be sufficiently utilized. To achieve a higher level of utilization, unbalanced signal timings were adopted.

As signal control optimization is closely related to channelized layout and traffic condition, it is easier to be adjusted as required. Therefore, for each altered channelized layout, the optimal signal cycles and splits of standard dual ring with eight phases were obtained by Synchro, widely used software for signal phases and splits optimization [28]. As presented in Figure 4, the signal cycle started from the northbound and southbound through phase and ended at the eastbound and westbound left-turn phase, with no restrictions planned for the right-turn traffic. The yellow time and red time for each signal plan were set as 3 s, respectively, and the corresponding signal cycle and green ratio for each phase was provided in Table 4. Further connections between the signal control and certain road conditions were discussed in Section 4.

3.2. Uniform Design. Initially proposed by Fang et al. [29], uniform design experimentation (UD) is one of the most commonly used experimental design methods within chemical engineering and other experimental subjects. The method provides preset tables called uniform tables to help arrange tests. These tables were carefully designed to satisfy the uniform distribution of test points and the minimum test numbers simultaneously. Compared with orthogonal design, neat comparability of test points is provided in UD, leading to smaller test numbers but more complicated mathematical analyses after experiments.

During this study, optimization measure was considered as the experimental factor, while detailed designs of the measure were considered as levels of the factor. For the selected intersection, four factors, with no more than 10 levels each, were proposed and traffic delay was chosen as the performance measurement. According to the number of factors and levels, a uniform table U_{10} (10^8) was chosen as shown in Table 5, in which eight columns and ten rows were included. X_j represents level j of experimental Factor X. Each column is able to place the levels of one experimental factor in the predetermined sequence. Then, four factors were placed in columns 1, 3, 4, and 5 to achieve minimum discrepancy and better homogeneity. Each row represents one optimization strategy composed of four factors, which was considered as one test in UD. Finally, altogether, ten tests were proposed.

By altering the traffic network and the signal timings, the simulation model was then transformed into 10 different implementation scenarios corresponding to the tests. The calibration factors remain unchanged because of the same traffic environment and behavioral characteristics. Different

Table 4: Signal cycle and green ratio of signal control plans.

Number	Cycle	A1	A2	A3	A4	B1	B2	B3	B4
1	200	0.26	0.20	0.19	0.24	0.26	0.20	0.19	0.24
2	200	0.26	0.20	0.22	0.21	0.26	0.20	0.19	0.24
3	200	0.26	0.20	0.26	0.17	0.26	0.20	0.19	0.24
4	220	0.21	0.20	0.29	0.19	0.23	0.19	0.20	0.27
5	220	0.23	0.22	0.26	0.18	0.29	0.17	0.20	0.23
6	220	0.23	0.23	0.26	0.17	0.29	0.17	0.19	0.24
7	220	0.26	0.19	0.27	0.17	0.26	0.20	0.19	0.25
8	240	0.27	0.20	0.18	0.25	0.30	0.17	0.19	0.24
9	240	0.27	0.20	0.22	0.21	0.30	0.17	0.19	0.24
10	240	0.27	0.20	0.26	0.17	0.30	0.17	0.19	0.24

Table 5: Tests proposed in uniform table U_{10} (10^8).

Test	Factors							
	1(D)	2	3(A)	4(B)	5(C)	6	7	8
I	1(D_1)	2	3(A_3)	4(B_1)	5(C_1)	7	9	10
II	2(D_2)	4	6(A_1)	8(B_2)	10(C_2)	3	7	9
III	3(D_3)	6	9(A_4)	1(B_1)	4(C_1)	10	5	8
IV	4(D_4)	8	1(A_1)	5(B_1)	9(C_2)	6	3	7
V	5(D_5)	10	4(A_4)	9(B_2)	3(C_1)	2	1	6
VI	6(D_6)	1	7(A_2)	2(B_1)	8(C_2)	9	10	5
VII	7(D_7)	3	10(A_5)	6(B_2)	2(C_1)	5	8	4
VIII	8(D_8)	5	2(A_2)	10(B_2)	7(C_2)	1	6	3
IX	9(D_9)	7	5(A_5)	3(B_1)	1(C_1)	8	4	2
X	10(D_{10})	9	8(A_3)	7(B_2)	6(C_2)	4	2	1

sensors and detectors were set to collect information about traffic delay, queue length, travel time, and so forth for the overall intersection and four intersection approaches. Within each implementation, simulation was repeated 50 times with different random seeds. Similarly, only the results from the latter half hour were recorded within each simulation cycle.

4. Analyses of Simulation Results

In this section, statistical analyses were conducted with SPSS, where the control delays for the overall intersection and at each approach separately were investigated. Sensitivity analysis was carried out to investigate the simulation results with different input traffic flows.

4.1. Preparation. Several tests were undertaken to provide a basic understanding of independent variables, dependent variables, and their relationships. The results from correlation analysis indicate that traffic delay is highly correlated with Factors B, C, and D. Strong correlation also exists between traffic delay and Factor A when the influences of other experimental factors were excluded. Using Kolmogorov–Smirnov test, traffic delays were found to be normally distributed with significance value of 0.174.

Notably, since the independent variables belong to nominal variables, dummy variables were created to assist mathematical analysis. For Factor X with k levels, a set of dummy variables X^i was created according to (1) to satisfy (2). The variables except for the last one were chosen to replace Factor X. The corresponding dummy variables were shown in Table 6. Hence,

$$X^i = \begin{cases} 1, & \text{level of } X = X_{i+1}, \\ 0, & \text{else}, \end{cases} \quad (i = 1, 2, \ldots, k), \tag{1}$$

$$\begin{gathered} \sum_{i=1}^{k} X^i = 1, \\ X^i X^j = 0 \quad (i \neq j), \\ X^{i2} = X^i \quad (i = 1, 2, \ldots, k). \end{gathered} \tag{2}$$

Meanwhile, multicollinearity and interactions may exist between experimental factors because of the complexity of signalized intersections. The multicollinearity relation was considered and controlled through the stepwise regression and VIF (variance inflation factor) test. Interaction variables were tested through the regression procedure but were found to be not statistically significant and, therefore, were removed from the regression model. To ensure the effectiveness of the regression, a test for homogeneity of variance was also conducted.

Table 6: Experimental factor and dummy variables.

Optimization measure	Factor	# of levels	Dummy variable
Convertible lane	A	5	A^1, A^2, A^3, A^4
Right-turn lane	B	2	B^1
Pedestrian overpass	C	2	C^1
Signal control	D	10	D^1, D^2, D^3, D^4, D^5, D^6, D^7, D^8, D^9

Table 7: Results of stepwise regression analysis for overall delay.

Variable	Coef.	Beta	Sig.	Adj. R^2
Con.	108.1	—	0.0	
B^1	−32.02	−0.82	0.0	0.97
D^8	−22.15	−0.34	0.0	

4.2. Analyses of Overall Control Delay. To analyze the relationship between the overall control delay and the experimental factors, stepwise regression analysis was conducted. The entry probability of F was set as 0.05, while the removal probability was set as 0.1. The regression results are presented in Table 7, in which Beta represents the standardized coefficient. Generally, the independent variable with the larger absolute value of standardized coefficient has a greater effect on the dependent variable.

As presented in Table 7, control delay of the intersection is significantly influenced by variable B^1 followed by variable D^8. The adjusted R-square value was 0.97. Therefore, the best optimization strategy includes an additional RTL in the southbound direction and changing signal group into Plan 9. Simulation for this strategy was repeated 50 times. The average traffic delay of the intersection was 68.7 s, which is about 27.3% smaller than the current condition (94.5 s).

Despite the significantly decreased traffic delay, the regression result needs further investigation. Based on practical experience, it was assumed that the pedestrian overpass would certainly improve the traffic performance because of the complete separation between motor vehicles and pedestrians. However, the influence of pedestrian overpass is not statistically significant at the selected intersection, which may be explained as follows. Since the signal control and channelized layout proposed during optimization were all carefully designed, separation of motor and nonmotor vehicles was already achieved without pedestrian overpass. Moreover, this phenomenon indicates that the aggregate influence of combined measures is still unpredictable based solely on practical experience, which is also the exact reason why simulation and uniform design are introduced. Notably, convertible lane was also not significantly effective, which is further investigated in the following section.

4.3. Analyses of Partitioned Control Delay. Stepwise regression was carried out for the four intersection approaches, as presented in Table 8. The results were used to conduct the detailed analysis towards the connections between traffic conditions and certain optimization measures. Meanwhile, the reasonableness of the regression results further proves the validity of the simulation model.

(1) Factor A: Convertible Lane. According to the regression results, a convertible lane is recommended in the southbound direction, which confirms that the major problem of this approach is the capacity deficit. However, the design is not suitable for the northbound direction, which may hinder the exit of through traffic. Eventually, the opposite effect of convertible lane for the southern approach may not compensate for the negative effect for the opposite direction, which removes convertible lane from the overall regression equation.

(2) Factor B: Right-Turn Lane (RTL). An additional RTL in the southbound direction is identified to significantly improve southbound, westbound, and eastbound traffic efficiency. No remarkable influence is detected in the northbound direction. Consequently, the additional RTL does not bring about disturbances to other traffic flows, thus making it useful for the entire intersection.

(3) Factor C: Pedestrian Overpass. It is recommended to have a pedestrian overpass in the northbound and westbound directions. As the metro station is located in the northwest corner of the intersection, it inevitably attracts a large volume of pedestrians and nonmotor vehicles. The conflict among mixed traffic becomes severe in these two directions. Although the regression results indicate no significant influence on the overall performance, pedestrian overpasses in these two directions are an option given available resource.

(4) Factor D: Signal Control. The regression result shows that unbalanced signal control has a positive influence on traffic performance of both westbound and eastbound approaches. This may be interpreted as follows: during road planning stage, the north-south Humin Rd. was considered as the major road, which had higher priority over the west-east Jianchuan Rd. However, the traffic demand on Jianchuan Rd. was underestimated. Consequently, the adjustment on signal

Table 8: Results of stepwise regression analysis for partitioned delay.

Approach	Variable	Coef.	Beta	Sig.	Adj. R^2
Westbound	Constant	114.8	—	0.000	0.99
	D^9	−39.1	−0.423	0.002	
	B^1	−10.7	−0.194	0.005	
	C^1	−5.7	−0.103	0.030	
Southbound	Constant	106.4	—	0.000	0.81
	B^1	−53.3	−0.493	0.001	
	A^4	−15.2	−0.155	0.008	
Eastbound	Constant	185.3	—	0.000	0.94
	B^1	−71.3	−1.022	0.000	
	D^8	−39.1	−0.337	0.016	
Northbound	Constant	57.2	—	0.000	0.76
	A^4	5.4	0.303	0.000	
	C^1	−2.9	−0.183	0.010	

Table 9: Comparison between single measurement and combinational strategy.

Optimization method	Control delay (s)	# of layouts
Single measurement		
Convertible lane	85.9	6
Right-turn lane	*85.1*	
Pedestrian overpass	88	
Signal control	88.8	
Combinational strategy with UD	68.7	10

shows significant influence on Jianchuan Rd., but no such effect is found on Humin Rd.

4.4. Comparison and Sensitivity Analysis. After analysis, simulation models adopting single optimization measurement were conducted. To obtain the simulation results for all detailed designs, six network layouts were created. As presented in Table 9, the minimum control delay obtained from the single measurement was 85.1 s, which is about 10% lower than the current condition. However, the result is 23.9% higher than the control delay obtained by UD, with only four models reduced. When the number of optimization measurements increases, the advantage of UD becomes more evident.

Based on the field collected traffic volume, sensitivity analyses were carried out for 15 levels of input volumes, changing from 10% to 150% of the field collected demands. Trends of traffic delay for each direction were presented in Figure 5. The relationship between control delay and volume is plotted by the proportion of input volume to field volume on the horizontal axis. Not surprisingly, the delay has a tendency to increase with the improvement of traffic volume. In the eastbound direction, the smooth growing delay obviously accelerates after the volume attains 110%. In the northbound and southbound directions, the peaks start at 100% and stabilize at 130%, while the westbound delay keeps increasing smoothly in the direction.

One possible reason for the different trends is that both volumes and capacities are different in all approaches. In the westbound approach, traffic volume is distributed approximately evenly in each lane and the capacity is sufficient during the analysis, which leads to the steady growth of the delay. In the other approaches, traffic volume reaches capacity at some point. For example, the extremely high volume for right-turn traffic in the eastbound approach reaches capacity at 110%, causing increased delays afterwards.

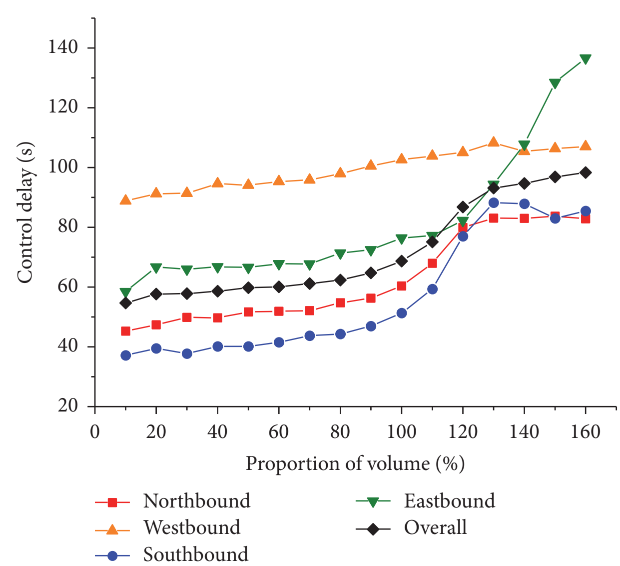

Figure 5: Trend of traffic delay with traffic volume.

5. Conclusions

This study proposes an optimization model for signalized intersections, which improves the traffic delay performance by 27.3% in the case study. VISSIM software package was introduced and calibrated to create simulation models for different traffic conditions and acquire control delays for the purpose of evaluation. Uniform design was introduced to combine different optimization measures into strategies, which provided a systematic view for the measures and their relationships with the minimum time resources. Conclusions were drawn based on the output of empirical simulations as follows:

(1) An additional RTL between cycle path and sidewalk was identified to significantly improve traffic efficiency for the approach and the entire intersection.

(2) In spite of the positive effect in one approach, convertible lane may not demonstrate significant influence and may even have negative impact on the intersection.

(3) With proper channelized layout and signal control, pedestrian overpass may not be a valid choice under heavy mixed traffic.

In future research, additional efforts are needed on the traffic regulations, which can further guide the optimization of other intersections. The evaluation can also be expanded to include efficiency, economics, the environment, and safety issues.

Disclosure

Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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