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Traffic Signal Design and Simulation for Vulnerable Road Users Safety and Bus Preemption

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***Abstract*—**Mostly, pedestrian-car accidents occurred at a signalized interaction is because pedestrians cannot across the intersection safely within the green light. From the viewpoint of pedestrian, there might have two reasons. The first one is pedestrians cannot speed up to across the intersection, such as the elders. The other reason is pedestrians do not sense that the signal phase is going to change and their right-of-way is going to lose. Developing signal logic to protect pedestrian, who is crossing an intersection is the first purpose of this study. Another purpose of this study is improving the reliability and reduce delay of public transportation service. Therefore, bus preemption is also considered in the designed signal logic. In this study, the traffic data of the intersection of Chong-Qing North Road and Min-Zu West Road, Taipei, Taiwan, is employed to calibrate and validate the signal logic by simulation. VISSIM 5.20, which is a microscopic traffic simulation software, is employed to simulate the signal logic. From the simulated results, the signal logic presented in this study can protect pedestrians crossing the intersection successfully. The design of bus preemption can reduce the average delay. However, the pedestrian safety and bus preemptive signal will influence the average delay of cars largely. Thus, whether applying the pedestrian safety and bus preemption signal logic to an isolated intersection or not should be evaluated carefully.

***Keywords*—**vulnerable road user, bus preemption, signal design.

I. Introduction

ACCORDING to the aging trend in Taiwan, the mobility and accessibility of elder persons are getting more and more attention. Not only the mobility and accessibility of elders are getting more attention, but the mobility and accessibility of children and disability are also getting more attention [1-2]. Actually, vulnerable individual protection service (VIPS), which improves the mobility, accessibility and safety of vulnerable individuals, is one user service in the national system architecture of intelligent transportation system in Taiwan. VIPS is designed to apply ITS technologies to protect pedestrians, bicycle and motorcycle riders, and disability [3]. Therefore, the scope of vulnerable road users mentioned in this study are not only restricted to elders, children and disability, but also normal pedestrians. We try to develop a priority strategy for traffic signal to protect pedestrians when they pass through intersections.

Designing, implementing, optimizing and adjusting traffic control system involve quite effort and knowledge. The effectiveness of traffic control systems depends on its ability to react upon changes in traffic patterns. According to this concern, if we only consider the priority of the vulnerable road users, the total delay of the intersection and the level of service of the intersection may become unacceptable. Therefore, an intelligent traffic signal logic, which can react to changes in traffic conditions, will be developed for vulnerable individual in this study. The proposed traffic signal logic will consider both the safety of vulnerable individual and the level of service of the intersection. Also, scenarios of simulation are investigated to compare the logic and strategies so as to adjust and fine-tune the logic and signal timing. The remaining content of this study is given as follows. In Sec. 2, the traffic signal of pedestrian protection and bus preemption is discussion briefly. Then, the signal logic will be proposed in Sec. 3. Section 4 shows the collection and calibration of empirical data and Sec. 5 gives the simulation results and discussion. Finally, some conclusions are drawn in Sec. 6.

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II. Pedestrian Protective and Bus Preemptive Signal

The main purpose of a bus-preemption signal control system is to give a preferential treatment to high occupancy vehicles at the signalized intersections [4-6]. Before showing the pedestrian protective and bus preemptive signal, the brief introduction of traffic signal systems will be presented firstly.

Traffic signals are capable of operating in a number of different types of vehicles. The best operation mode for a given intersection is a function of several parameters, including the location, configuration, and traffic conditions at that particular intersection. The different modes of operation for a traffic signal are described as follows [7-10]:

Pretimed operation. The signal cycle length, intervals, and phases are predefined or fixed and are insensitive to current traffic volumes. A pretimed signal could have different "pretimed" plans for different times of the day, such as the morning peak, evening peak and off-peak periods.

Semiactuated operation. If there are a major and a minor street could be clearly identified, semiactuated operation is a good alternative. To apply semiactuated operation, traffic detectors are used only on the approaches of the minor street, and the major street maintains the green until vehicles are detected on the minor street. In addition, minimum green should be given to the minor street. Therefore, the cycle length of semiactuated operation varies largely and depends on the arrival pattern of vehicles on the minor street.

Full-actuated operation. Traffic detectors should be used on all approaches. The cycle length, sequence, and duration of phases are determined by the observed volumes.

Computer-based control. This kind of method uses a computer to link the operation of a group of signalized intersections into a coordinated system. The computer will select the optimal signal plan for the whole system based on the traffic information provided by the traffic detectors according to the algorithm. In this study, the signal logic is assumed to implement by a computer-based control. Basically, there are three kinds of strategies to implement preemptive signal [11-13]: (1) green extension is used to extend the phase for the transit vehicle to clear the signals; (2) phase advance is used which truncates or skips other phases to return earlier to provide approaching buses the green phase; (3) red truncation is used to start the green for the phase serving the buses in advance. The study of Yedlin and Lieberman [14] analyzed the effects of active signal priority showed that there was a reduction of person-delay up to 67% without causing significant impact on other road users. Chang et al. [15, 16] reported the optimizing signal timings based on adaptive control algorithms for bus preemption would significantly reduce passenger and vehicle delays at intersections. Also, the same successful experiences were implemented in Sweden [17]. Bus priority trials were found to cause an increase of 33% and 38% in average bus speed along two different routes studied. Hsu et al. [18] developed optimal bus-preemption control logic with green extension and red truncation strategies according to the net benefit of delay reduction.

Vulnerable road users protection for pedestrians is an integral system, which includes pedestrian detectors, signal-mounted speakers, transmitter/receiver systems, push-button systems and accessible pedestrian signals. The system is design to protect pedestrian when they are crossing signalized intersections [2]. In this study, the protection of pedestrian safety is the first priority and then the bus preemption will be considered.

III. Signal Logic

Signal logic is the most important part of signal design. The purpose of this study is designing intelligent signal logic so as to protect pedestrians and provide bus a higher priority to pass through the intersection. To implement bus preemption signal, bus exclusive lanes should be installed on the approaching link. Another criterion to achieve our purpose is that pedestrians have the highest right-of-way. In simulation, this criterion can ensure that vehicles will yield pedestrians if there exists potential conflicts. Although pedestrians have the highest right-of-way, they still have to obey the traffic signal. In addition, to prevent the delay of vehicles on competitive approaches, maximal green and minimum green constraints are considered. If the green time is less than the minimum green time, then the system will extend the phase. If the green time is more than the maximum green time, the system will terminate the phase immediately and switch the phase. The setting of minimum green duration should consider the start delay, the width of road and walking speed [19-21]. In this study, the minimum green time is given as follows.

$$G\min = Psd + \frac{Iw}{Pv} - Y \geq 15 \text{ ,} \qquad (1)$$

where $G\min$ is minimum green time(second, sec), Psd is start delay of pedestrians (sec), Iw is road width(meter, m), Pv is walking speed of pedestrians (meter per second, m/s) and Y is amber time (sec).

If a pedestrian cannot pass through the road in the remaining green time or a bus is approaching the intersection, the green time will be extended discretely until the green time is larger than the maximum green. The increment of green time should be designed for pedestrian and buses separately. The increment for pedestrian extension green is determined by

$$Pge = Iw/Pv \text{ ,} \qquad (2)$$

where Pge is the extension green for pedestrian (sec). The increment for bus extension green is determined by

$$Bge = \frac{Al}{ABs} + ASt + \frac{Iw}{ABs} \text{ ,} \qquad (3)$$

where Bge is the extension green for bus (sec), Al is the length of approaching link (m), ABs is the average speed of bus (m/s)and ASt is the average service time of bus (sec).

The competitive determination is based on the traffic optimization logic (TOL) assumption. The TOL is often applied in adaptive signal control. The main concept of TOL is evaluating the net benefit of extending current phase to determine whether it should switch the phase. The net benefit is given by

$$NB = Bb\frac{LFb}{LFv} - Bd\frac{LFb}{LFv} + Vb - Vd \text{ ,} \qquad (4)$$

where NB is the net benefit of the intersection, Bb is the benefit of bus, LFb is the loading factor of bus, LFv is the loading factor of car, Bd is the bus delay, Vb is the benefit of car and Vd is the car delay. LFb is set to be 30 passengers and LFv is set to be 1.5 passenger. According to the assumptions and equations, the signal logic of this study is as follows.

Step 1. Compute the lasting green time of this phase.

Step 2. If the green time is less than the minimum green time, then the system will keep the phase unchanged and go back to Step 1. If the green time is larger than the minimum green time, the system will check if there are buses coming from the competitive approaches.

Step 3. If there are buses competing for preemption, the system will use Eq. (4) to check the benefit of competition. If the system decides to change the phase, then the system will examine if there are pedestrians crossing the intersection or not. If there is no bus competing for preemption, then go to Step 5.

Step 4. If there is no pedestrian, then red truncation strategy will be activated. Otherwise, the green extension for pedestrian is activated.

Step 5. If the green time is equal to the maximum green time, then check if there are buses approaching the intersection in this phase. If yes, then extend green time for one green-extension interval. If no, then change to next phase. Before switching phase, the pedestrian detection will be activated. If there are pedestrians crossing the intersection, green extension for pedestrian will be activated.

The signal logic is given in Fig. 1.

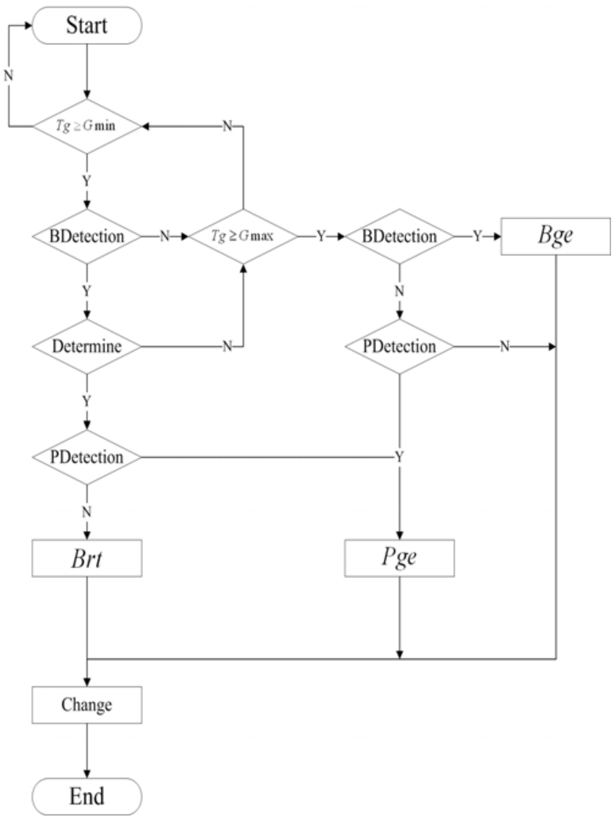
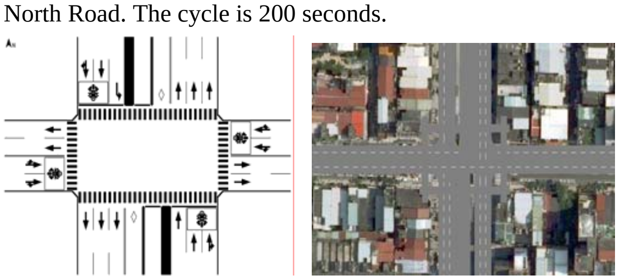


Fig. 1 The signal logic for pedestrian safety and bus preemption. *BDetection* is to activate the detection of bus, *PDetection* is to activate the detection of pedestrians, *Determine* is to decide the efficiency between current phase and competitive phase, *Bge* is to execute the green extension for bus, *Brt* is to execute the red truncation and *Change* means changing phase. *Tg* is the lasting green time (sec), *Gmin* is the minimum green time (sec) and *Gmax* is the maximum green time (sec).

IV. Data Collection

In this study an isolated intersection is simulated and the parameters are calibrated by empirical data from the intersection of Chong-Qing North Road and Min-Zu West Road, Taipei, Taiwan on April 16, 2009. The surveyed time period is from 7:00 to 10:00 am and 4:00 pm to 7:00 pm. The geometry of the intersection and its layout in VISSIM are illustrated in Fig. 2. Table 1 gives the surveyed data. In this intersection, the bus lane is only installed on Chong-Qing North Road. The cycle is 200 seconds.



(a) (b)

Fig. 2 (a) The geometry of studied intersection. (b) The studied intersection in VISSIM.

TABLE I

VOLUME DATA OF CHONG-QING NORTH ROAD AND MIN-ZU WEST ROAD

Chong-Qing North Road southbound

Direction / Period	Bus lane	Left-turn bus	Left-turn car	Left-turn motorcycle	Straight bus	Straight car	Straight motorcycle	Right-turn bus	Right-turn car	Right-turn motorcycle
7:00-8:00	89	18	375	280	22	825	985	9	149	7
8:00-9:00	81	49	354	474	32	909	1404	23	120	16
9:00-10:00	76	53	438	98	37	685	622	29	124	14
16:00-17:00	63	24	281	77	55	801	504	14	139	18
17:00-18:00	81	17	293	59	38	837	1078	2	151	22
18:00-19:00	74	11	317	81	35	1082	974	8	139	24

Chong-Qing North Road northbound

Direction / Period	Bus lane	Left-turn motorcycle	Straight bus	Straight car	Straight motorcycle	Right-turn bus	Right-turn car	Right-turn motorcycle
7:00-8:00	86	6	62	575	334	42	65	20
8:00-9:00	97	24	35	624	371	50	101	25
9:00-10:00	98	39	53	624	252	61	104	36
16:00-17:00	83	54	59	759	299	47	96	42
17:00-18:00	77	59	37	801	370	50	100	32
18:00-19:00	116	102	38	764	517	46	98	42

Min-Zu West Road eastbound

Direction / Period	Left-turn bus	Left-turn car	Left-turn motorcycle	Straight bus	Straight car	Straight motorcycle	Right-turn bus	Right-turn car	Right-turn motorcycle
7:00-8:00	10	116	57	39	763	1394	20	88	5
8:00-9:00	5	84	69	55	764	1535	20	61	13
9:00-10:00	17	111	43	58	477	669	34	73	7
16:00-17:00	11	130	29	16	763	294	16	75	17
17:00-18:00	8	126	21	29	472	372	18	85	12
18:00-19:00	6	108	46	31	602	491	18	103	19

Min-Zu West Road westbound

Direction / Period	Left-turn bus	Left-turn car	Left-turn motorcycle	Straight bus	Straight car	Straight motorcycle	Right-turn bus	Right-turn car	Right-turn motorcycle
7:00-8:00	4	29	118	9	260	271	22	84	15
8:00-9:00	5	40	108	5	344	262	18	74	13
9:00-10:00	1	45	39	12	351	259	23	91	26
16:00-17:00	5	59	84	14	396	370	17	85	18
17:00-18:00	10	75	184	8	440	777	17	97	11
18:00-19:00	6	75	174	7	440	899	19	115	34

Pedestrian

	East	South	West	North
7:00-8:00	160	227	118	298
8:00-9:00	168	232	100	281
9:00-10:00	139	153	99	217
16:00-17:00	145	167	130	162
17:00-18:00	204	248	165	217
18:00-19:00	201	255	226	273

V. Simulation and Analysis

In this section, four scenarios are presented to show the pedestrian protection and bus preemptive logic. The signal logic is implemented by VISSIM 5.2 [22]. VISSIM is a microscopic traffic simulation software for multiple modals.

According to the setting of parameter, traffic control and management strategies and traffic flow of links and networks can be simulated. Before showing simulation results, setting of parameters will be presented. The first one is the desired walking speed of pedestrians. There are two kinds of pedestrians, elders and normal walkers. The walking speed of elders is between 0.6 m/s to 1.0 m/s and the walking speed of normal walkers is between 1.0 m/s to 1.4 m/s. The desired speed of bus is between 30 kilometer per hour (km/hr) to 40 km/hr and the speed of car is between 45 km/hr to 55 km/hr. The loading factor of bus is 25.07 persons and the loading factor of car is 1.5 persons. From our empirical data, the bus flow is 85 vehicles per hour, that is, one bus will arrive at the bus stop every 42.35 seconds in average. Poisson distribution is employed to generate cars and pedestrians. The arriving rate is based on the empirical data. The passenger car equivalents (PCE) of turning cars, motorcycles and trucks are calibrated by the empirical data to make the error of simulated flow and empirical flow be within 10%. The PCEs used in our simulation are given in Table 2.

TABLE II
THE PCES OF TURNING CARS, MOTORCYCLES AND TRUCKS IN THE EVENING.

direction	car			truck			motorcycle		
	Left-turn	straight	Right-turn	Left-turn	straight	Right-turn	Left-turn	straight	Right-turn
Chong-Qing North Road southbound	1.5	1.0	1.3	2.3	1.5	2.0	0.0	0.0	0.2
Min-Zu West Road westbound	1.2	1.0	1.3	1.8	1.5	2.0	0.0	0.0	0.2
Chong-Qing North Road northbound	1.2	1.0	1.3	1.8	1.5	2.0	0.2	0.2	0.4
Min-Zu West Road eastbound	1.2	1.0	1.3	1.8	1.5	2.0	0.0	0.0	0.0

Firstly, we discuss the case of pedestrian protection signal logic only. We simulate four time periods, 7:00~9:00, 17:00~19:00, 9:00~10:00 and 16:00~17:00. The first two periods are considered as peak hours and the others are considered as off-peak hours. The minimum green time is set to be 30 seconds and the cycle is 200 seconds. The empirical volume of pedestrian, car and motorcycle are used in the simulation. Figure 3 illustrates the increment of average delay. Table 3 is the comparative table of road users and their assigned numbers. From the figure, when pedestrian protection signal logic is activated, only average delays of westbound and eastbound cars decrease. The average delays of the others increases. Because the westbound and eastbound direction (Min-Zu West Road) is the minor arterial, the green time is shorter than the major arterial (Chong-Qing North Road). The width of Chong-Qing North Road is wider than the width of Min-Zu West Road. If pedestrian protection is activated, the westbound and eastbound direction may earn more green time. Therefore, the average delays of westbound and eastbound cars decrease. Secondly, we discuss the case of changing bus volume. We simulate two time periods, 16:00~17:00 and 17:00~19:00, which are off-peak hours and peak hours, respectively. The minimum green time and the cycle length are kept the same. The empirical volume of pedestrian, car and motorcycle are used in the simulation. The incremental rate of bus volume on Chong-Qing North Road varies from -100% to 90%. Figures 4 and 5 illustrate the variation of average delay according to various bus volumes during off-peak and peak hours, respectively. From the results, the delay of both bus passengers and car passengers increases sharply when the incremental rate of bus volume varies from 40% to 50%. Therefore, we can observe that the bus volume is under critical volume in the present situation and the critical volume could be considered as 1.4 times the present bus volume and the critical volume is given in Table 4. For each bus passenger, the preemptive signal can only reduce his/her delay slightly. Nevertheless, the total amount of bus passengers is much more than the amount of car passengers. Thus, the total delay of the whole intersection could be reduced. The trend of pedestrian delay is similar to the trend of car passenger delay. We only discuss the variation of car passenger delay here. For car passengers, there exists an invariant interval during both off-peak and peak hours. That is, when the bus volume is within this interval, the bus preemptive signal would not increase delay of car passengers. Maybe the invariant interval of bus volume could be the feasible range of applying bus preemptive signal in this intersection. However, if the bus volume is out of the range, the delay of car passengers increases largely. Hence, the signal logic and the phase plan should be designed carefully.

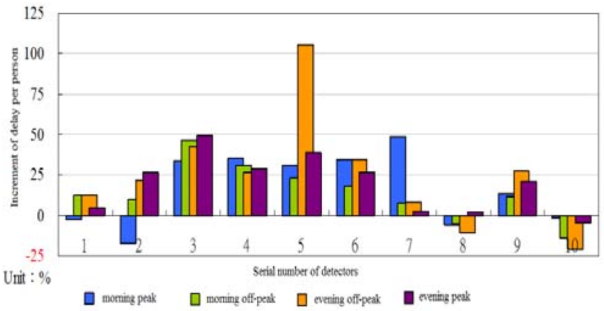


Fig. 3. The increment of average delay of each approach.

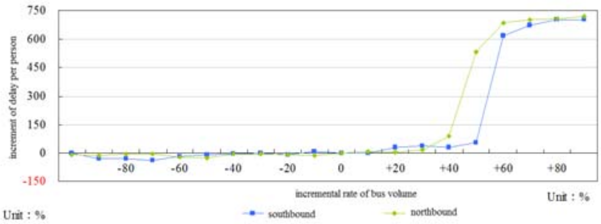
TABLE III
THE COMPARATIVE TABLE OF SERIAL NUMBER OF DETECTORS AND DETECTED OBJECT

detector	1	2	3	4	5
detected object	southbound bus	northbound bus	south/north pedestrian	east pedestrian	west pedestrian
detector	6	7	8	9	10
detected object	southbound car	southbound left-turn car	westbound car	northbound car	eastbound car

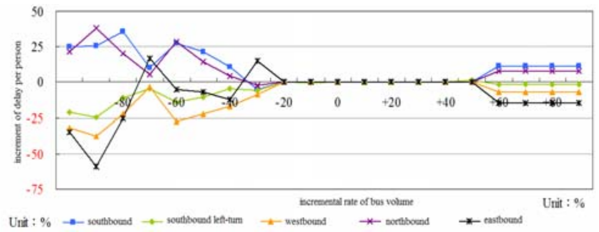
TABLE IV
THE CRITICAL VOLUME OF BUS ON CHONG-QING NORTH ROAD

	evening off-peak	evening peak
Chong-Qing North Road southbound	88 veh/hr	108 veh/hr
Chong-Qing North Road northbound	116 veh/hr	135 veh/hr

Next, we discuss the case of varying car volume. The input data is based on the empirical data and the simulated time periods are also the evening off-peak and peak hours. The incremental rate of car volume varies from -90% to 100% on both Chong-Qing North Road (the same approach of bus preemption) and Min-Zu West Road (the competing approach of bus preemption). Figures 6 and 7 illustrate the variation of average delay of the same approach and the competing approach, respectively. Since cars do not have any preemption in the intersection, varying car volume does not influence the average delay of bus passengers and pedestrians. From the results, varying car volume of the same phase will not increase the average car delay of competing phase, and vice versa. Varying car volume only influences average car delay. For cars coming from the same approach of bus preemption, they have more green time to pass through the intersection because of bus preemptive logic. Their average delay reduces with car volume decreases. The average delay of southbound cars is proportional to car volume and the average delay of northbound cars presents a logistics curve. For cars coming from the competing approach of bus preemption, the average delay varies with car volume. According to Figs. 5 and 6, the critical volume of each approach is given in Table IV.

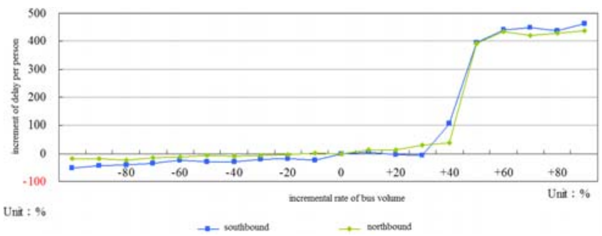


(a)



(b)

Fig. 4. The increment of average delay of (a) bus passenger and (b) car passenger for various bus volume during off-peak hours.



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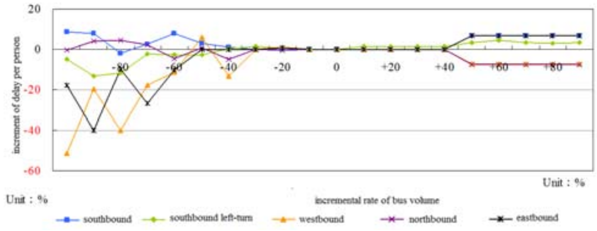
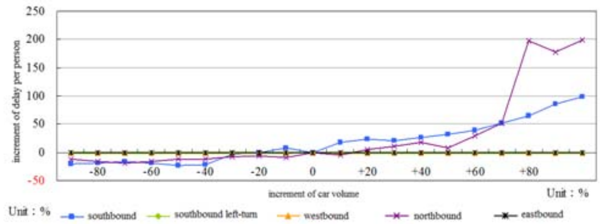
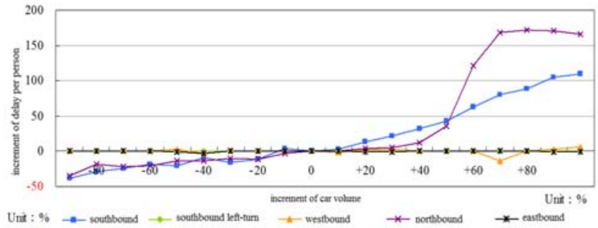


(b)

Fig. 5. The increment of average delay of (a) bus passenger and (b) car passenger for various bus volume during peak hours.

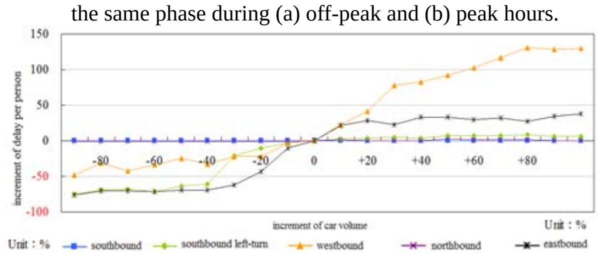


(a)



(b)

Fig. 6. The increment of average car delay of varying car volume in the same phase during (a) off-peak and (b) peak hours.



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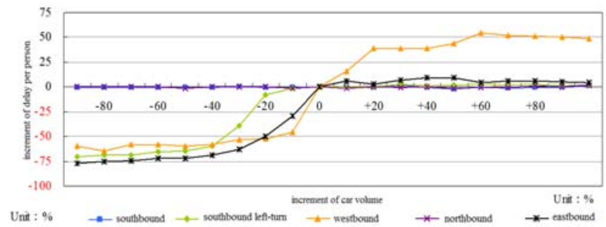

(b)

Fig. 7. The increment of average car delay of varying car volume in competing phase during (a) off-peak and (b) peak hours.

Finally, we discuss the case of changing pedestrian volume. The input data and the simulated time periods are kept the same. The incremental rate of pedestrian volume varies from -90% to 100% on both Chong-Qing North Road and Min-Zu West Road. The average delay of bus and car fluctuates largely because the pedestrian volume is small and pedestrians arrive at the intersection randomly. Fortunately, the average delay only varies from -20% to 20%, which is much smaller than the influence of bus and car.

VI. Conclusion

In this paper, a signal control logic that can deal with vulnerable road users protection and bus preemption is developed. The logic includes: green extension, red truncation and competition evaluation. The simulation is implemented in VISSIM 5.20. Empirical data is employed to calibrate passenger car equivalent and is used as the input data. If pedestrian protection logic is considered, the total delay of the intersection increases significantly. The average delay of minor arterial cars decreases because they may earn more green time. Various bus, car and pedestrian volume are simulated. The influence on average delay of pedestrian volume is oscillated because the arrival rate of pedestrian is random in simulation. Since cars have the lowest priority to pass through the intersection, car volume only influence the average delay of themselves and does not influence the average delay of pedestrian and bus. Bus preemptive signal reduces the average delay of bus passengers; however, if the cycle is fixed, the improvement is restricted. If bus volume is over the critical volume, the average delay will increase dramatically. In this study, there is bus exclusive lane on one approach only and the cycle of signal is fixed. There are still lots of scenarios and conditions left for further researches.

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