Performance Measures of Manual Multi-Modal Traffic Signal Control

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Abstract

Traffic control agencies (TCAs), which including police officers, firefighters or other traffic law enforcement officers, who override automatic traffic signal controls, are crucial to mitigate non-recurrent traffic congestion caused by planned and unplanned events. An unanswered question is how well TCAs perform compared with state-of-practice automatic traffic signal controls. This paper assesses the performance of TCA-based manual multi-modal traffic signal control during special events. First, an interview was designed to understand the control rules of TCA's and the current practice of manual traffic signal control. Second, a simulation-based experiment was conducted to record their control actions during multi-modal traffic flows, which contain buses, pedestrians and passenger cars. Third, a TCA performance index was developed by comparing to the optimal solutions from an online optimization model, which assumes that rich vehicle information is available, to determine the best control strategies. The results show that manual traffic control can significantly improve the control performance, even approaching that of the optimized timing plan; however, large variations were observed during the study.

Keywords: manual multi-modal traffic signal control; human performance assessment; traffic control agency.

1. Introduction

Large-scale planned events, such as sporting games, concerts, parades and conferences, and unplanned events, such as traffic incidents, disasters, inclement weather and infrastructure failures, either attract high-volume multi-modal traffic, or reduce the existing network capacity, both of which result in significant non-recurrent traffic congestion [1]. Despite the fact that there exists advanced signal control technology, the additional benefit of this technology is limited during periods of non-recurrent congestion because most of the control is not designed for event-based operation. Properly managing traffic during an event is crucial for traffic safety and mobility.

Human intervention for event traffic conducted by police or other traffic control agencies (TCAs), who can override traffic lights to direct traffic movements, still serves as the most commonly adopted approach to handle severe event traffic congestion. The primary function of manual traffic control is to move vehicles and pedestrians safely and expeditiously through or around an incident or special event site while protecting on-site personnel and equipment. There are two typically used methods to manually control traffic, as shown in Figure 1(a) and 1(b). The first method allows TCAs standing in the middle of the intersection to control traffic by hand signals, as illustrated in Figure 1(a); in the other method, depicted in Figure 1(b), the control traffic signals are manually controlled via a cord switch in a cabinet and can only adjust the green times in each phase, not the phase sequences. Although the second method is less flexible than the first one, TCAs remain in safe positions because drivers do not expect to be directed by hand and their actions can be unpredictable.

Different than most of automatic traffic signal control systems, experienced TCAs can effectively balance queue length, increase network throughput, and prevent pedestrian-vehicle crashes. Recently, multi-modal traffic signal control has garnered much attention [2]-[5]. Typical event traffic generally consists of three modes of traffic: buses, pedestrians and passenger cars. When event traffic over-saturates the network, it is important to understand how TCAs control non-recurrent congestion and prioritize multi-modal traffic.

(a) (b)

Figure 1. Two manual signal control methods: (a) via hand signals; (b) using a manual signal control switch in the cabinet

Manual control is believed to be an extremely effective method to handle non-recurrent, multi-modal traffic conditions. However, the performance of manual signal control, compared to that of the state-of-practice automatic signal control methods, has not been fully investigated in the last few decades. In this paper, to understand the performance of manual signal control, human operator based interviews and experiments were conducted. This study explicitly assesses the performance of TCAs based on the Manual Intersection Control Simulator (MIC-Sim), which was developed on a commercial traffic simulation platform. Therefore, the goal of this paper is to evaluate the performance of TCAs compared with that of automatic control and the optimal control of an isolated intersection. It is expected that the results of manual operation will benefit national wide transportation authorities who are responsible for event traffic planning and management.

2. Literature Review

It has long been recognized that non-recurring events can cause as least half of the total traffic congestion [6]. Over the years, a large amount of effort has been invested in studying how to alleviate non-recurrent congestion with automatic signal control methods [7]-[9]. There have been a few studies that focused on manual control operation. Mahalel, Gur, and Shiftan (1991) [10] collected field data at a single intersection to understand the differences between automatic and manual signal control. The authors concluded that manual signal control improved the operation of congested signalized intersections, measured in terms of the degree of saturation, total throughput and how well the capacity could be controlled above the demand. The handbook of managing special events [1], emphasizes that traffic control officers have a large role in maximizing the intersection operating efficiency. The officer commands a driver's attention and works to control the speed of vehicles entering and departing the intersection that subsequently reduces rubbernecking, particularly at traffic incident sites. Wojtowicz and Wallace (2010) [11] used tabletop exercises for the traffic management of special events using traffic microscopic simulation software. In a scenario of event egress, results from their simulation showed that when police control is used at critical intersections, there is more than a 50% reduction in discharge time. Lassacher et al. (2009) [12] examined traffic management strategy for a large football game and concluded that signal retiming and manual traffic control strategies allowed for dramatic improvements in the traffic level of service. Lee et al. (2012) [13] conducted Hardware-in-the-Loop Simulation (HILS) experiments to evaluate manual traffic control performance under oversaturated conditions. The authors demonstrated the performances of manual traffic signal control and concluded that manual control had the best results among the proposed strategies at an oversaturated intersection. However, the participants in their experiments were college students, who have much less field intersection control than professional TCAs. Therefore, the performance measured does not completely reflect the TCA's traffic control results in real-world events. In addition, only one traffic mode, the passenger car, was taken into account in that study.

Although manual signal control is crucial to ensure road safety, avoid queue spillover and enforce traffic law under event occurrences, this research topic has not been extensively studied; there have only been a few studies that have been conducted on the topic. Moreover, most of the previous studies have only summarized empirical observations and experiences. These studies hardly considered either transit vehicles or pedestrians in event traffic. Therefore, there is a pressing need to pursue a systematic study on this topic.

The objective of this paper is to evaluate the performance of TCA-based manual signal control during multi-modal event traffic and to present the results compared with that of automatic control and optimal control. The outline of this paper is as follows: Section 3 describes the designed interview and simulation-based experiment to capture the performance of experienced TCAs in multi-model event traffic. In Section 4, a performance index is developed by comparing manual control with that of actuated signal control and optimal control. Finally, Section 5 provides concluding remarks, the discussion and suggestions for future work.

3. Human Subject Experiments

3.1 Interview

3.1.1 Procedure

At the beginning of the study, the TCA participants were asked to take a 15-minute interview, which was composed of three sessions. The first session obtained the basic background of the participants in manual traffic control, including their title and working experience and where their skills were learned as well as circumstances and frequency of when they perform manual traffic signal control. In the second session, the participants reported the general rules they follow when conducting manual signal control in the field. The third session required them to explain their detailed manners to control traffic under different circumstances, which included oversaturated intersections, traffic accidents, power outages, construction sites and special events.

3.1.2 Participants

The experiments recruited eight participants, in which seven were police officers and one was a firefighter. Table 1 summarizes the information collected during the interviews, including general information about the subjects and their control behavior. To maintain sample diversity, the subjects were of different genders, had different job titles and had different years of experience in traffic control. On average, TCA participants had 14 years of experience, where the number of years ranged from 2.5 years to 27 years. All TCA participants learned their traffic control skills at the police academy, through on-site practice, and via paired training with seniors. All of the police officers reported that they perform manual traffic control for car accidents, power outage and special events; several officers also mentioned other reasons, such as extreme weather conditions. Firefighters are mostly involved in emergency events or regular events with hazardous materials. For example, firefighters typically conduct annual two-day manual traffic control during a household hazard disposal event. The frequency of manual traffic control generally varies from 10 to 30 times per year, although there is a small probability that the frequency is less than 5 times or greater than 40 times per year.

From the interviews, it was learned that most of the participants gave more control attention to the number of vehicles in the queue than the queue length; two other aspects, queue spillover and pedestrians, were considered. The weights assigned to each control attention are shown in Table 1. Participants were also asked to assign weights to prioritize three traffic modes, including bus, pedestrians, and emergency vehicles (EV). Assuming the weight for a passenger vehicle is always 1, three traffic modes were weighted by a score from 1 to 10 from TCAs. The average assigned weights are shown in Table 1. Several of weights are denoted “N/A” because the corresponding TCAs did not report the values. Among all the reported weights, EV always had the highest score of 10, and most of the TCAs did not grade a high weight for buses (4.4). The TCAs allocated high weights for pedestrians in groups (6.4) due to their high vulnerability. The normalized average weights for passenger cars, buses and pedestrians were 0.08, 0.37 and 0.54, respectively.

Table 2 shows TCAs’ control manner under five different scenarios: oversaturated intersection, traffic accident, power outage, construction site and planned events. Police always perform manual traffic under all the proposed scenarios, whereas firefighters are typically involved in emergency or hazardous events. When performing manual control at a congested or even oversaturated intersection, most of the TCAs will attempt to flow as many cars as possible and avoid queue spillover if it is a large intersection. Occasionally, TCAs will first stop traffic in all directions and allow the direction with the longest queue to go and go, then make the decision on if they will shut down the left turning lines to only allow the through traffic to proceed. If it is a small intersection, TCAs will let one direction proceed for 30 seconds (reported by 2 TCAs), followed by the other directions in rotation. In addition, several of the TCAs mentioned that a one-quarter mile of queue length is a priority. If pedestrians are waiting at the intersection, TCAs will allow them to pass through as a group.

Table 1: Summary of interview results

General information							Control behavior						
TCA NO.	**TCA job title**	**Gender**	**Years of experience**	**Sources where traffic control skills were learned**	**Reasons for manual control**	**Manual control frequency (/year)**	**Control attention**			**Priority weights of traffic modes**			
							Num. of vehicles in queue	**Queue length in feet**	**Others**	**E.V.**	**Car**	**Bus**	**Ped.***
A	Police supervisor	M	15	Police Academy; On-site practice; paired training	Events; Car accidents; Power outage; Extreme weather conditions; Firefighters on-duty	20~30	N/A	N/A	N/A	-	-	-	-
B	Police supervisor	M	25			10~12	0.67	0.33	N/A	10	1	5	7
C	Police supervisor	F	18			1~5	0.67	0.33	N/A	10	1	5	8
D	Police supervisor	M	8.5			10~12	N/A	N/A	N/A	-	-	-	-
E	Police officer	M	4.5			>40	N/A	N/A	N/A	-	-	-	-
F	Police officer	M	2.5			20~30	0.2	0.3	Queue spillover: 0.5	10	1	2	6
G	Fire fighter	M	27			10~12	0.67	0.33	N/A	10	1	3	5
H	Police officer	M	10			5~6	0.5	0.25	Pedestrian : 0.25	10	1	7	6

*: Particularly for a group of pedestrians

Table 2: Summary of Control Manners

<table>
<tr><th>TCA NO.</th><th>Oversaturated Intersection</th><th>Traffic Accident</th><th>Power Outage</th><th>Construction Site</th><th>Events</th></tr>
<tr><td>A</td><td>Manually control and cooperate with other officer</td><td>Protect the scene, may block roads</td><td>Close the road or reduce the travel; block lanes or convert to 4-way stop</td><td rowspan="6">Different from traffic accident, construction site is always pre-planned; use signs to direct the traffic around. Police are only involved if a large congestion occurs.</td><td rowspan="8">Have the traffic plan before event, including the route and officers' assignments;
Group the pedestrians.</td></tr>
<tr><td>B</td><td>Rotate the direction and have as many cars proceed through the intersection as possible; group the pedestrians</td><td>Safety comes first; reroute the traffic</td><td>Manually control the intersection</td></tr>
<tr><td>C</td><td>4-way stop, let each direction proceed for 30s</td><td>Direct the traffic around or shut down the road if necessary</td><td>Convert to a 4-way stop</td></tr>
<tr><td>D</td><td>Keep the queue even and rotate the direction one by one</td><td>Safety comes first and move the car involved in the accident to allow traffic through</td><td>Manually control the intersection</td></tr>
<tr><td>E</td><td>Keep the flow as long as possible</td><td>If people are badly injured, block the intersection to the accident site and protect the scene; if there are no injuries, move the car and allow the traffic through</td><td>Manually control the intersection</td></tr>
<tr><td>F</td><td>Allocate time to the approaches according to the congestion based on queue length</td><td>Protect the scene, avoid a secondary accident</td><td>Consistently flow traffic on an approach until the other side backs up</td></tr>
<tr><td>G</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>H</td><td>Let the direction with the longest queue go first</td><td>Direct the traffic around the scene; or shut down and reroute the traffic</td><td>Manually control the intersection</td><td>Treat similar to a traffic accident</td></tr>
</table>

When a traffic incident occurs, safety is the priority. TCAs will first ensure that people are safe, then protect the incident scene, block the roads and detour the traffic if necessary. Additionally, TCAs will direct traffic to avoid a secondary accident and begin to recover the traffic from the incident once investigators take pictures of the scene. In the case of a power outage, which could be caused by a natural disaster, the signalized intersection will either be changed to a 4-way stop intersection or manually controlled by TCAs. TCAs may also close the road or block lanes to reduce traffic if it is a minor intersection. Normally, 2 or 3 TCAs will be assigned to the intersection for manual control. In the case of construction sites, which are planned ahead of time, the control strategy is different than in a traffic accident. Most of the construction sites are pre-deployed with barricades and signs to direct traffic, thus TCAs will not be assigned unless the safety of the construction site is a concern. Similarly, special events are always fully pre-planned with traffic routes and officer assignments. When special events occur, the assigned TCAs will manually control the traffic according to the planned event traffic route. Because a large number of pedestrians will show up for the event, they receive the highest priority and are arranged as a group to pass through.

3.2 Simulation-based Experiments

3.2.1 Experimental Platform and Tasks

The experiment was conducted using the Manual Intersection Control Simulator (MIC-Sim), which is shown in Figure 2. MIC-Sim consists of three components in a loop: a human, a human-traffic control interface and a commercial traffic simulator, as shown as Figure 2(a). MIC-Sim builds the human-traffic control interface on a microscopic simulator, VISSIM, with Java and COM (Component Object Model) technology. The participant is provided a 3D view of the traffic condition at a simulated intersection. The traffic condition, such as the number of vehicles in the queue, is displayed on the screen and will dynamically change via an animation. Once the participant understands the traffic condition at the intersections, he/she can manually control the traffic signals in real-time by clicking the corresponding traffic movement phases in the control panel, as illustrated in Figure 2(b). Typically, a TCA will begin to manually control traffic within the first minute. Once the TCA begins to take over, intersection traffic will continue to be manually controlled through the simulation horizon. The control actions and traffic data are recorded in files for further analysis.

In the experiment, subjects were asked to apply their own control experiences to manually control traffic at the intersection of Millersport Highway and Amherst Manor Drive at the North Campus of SUNY Buffalo, as shown as Figure 2(c).

The traffic data in the experiment was collected from a campus football game that was scheduled at 7 pm on September 19, 2012. The attendance of this game was 9,764 people, which was counted from the ticket scanner in the stadium. The game traffic was monitored two hours before its starting time. Many people parked south of Amherst Manor Dr. and thus a large number of northbound pedestrians were observed before the game began. The before–game inbound traffic, including both passenger cars and pedestrians, are shown in Figure 2(e).

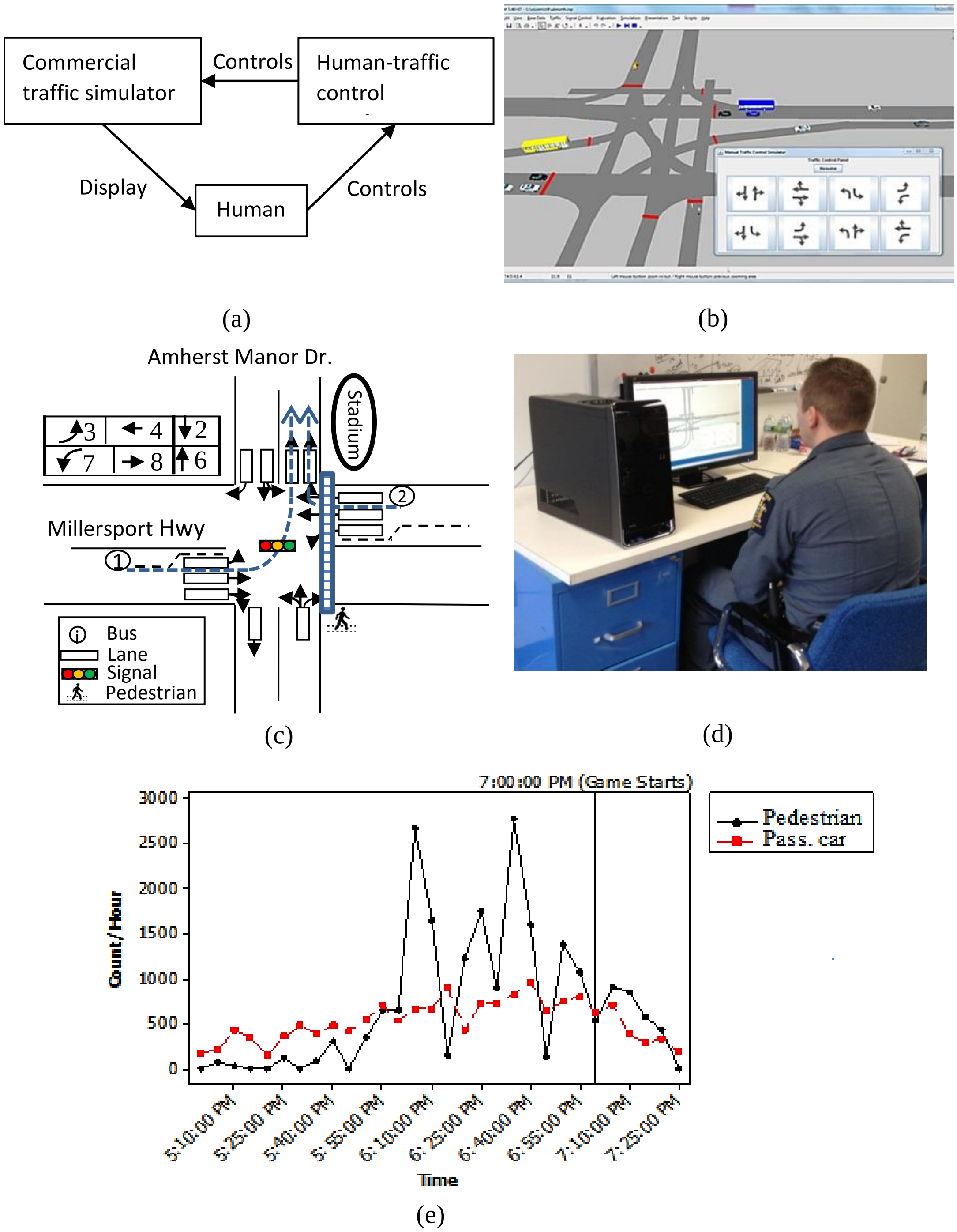

Figure 2: (a) Components of the MIC-Sim; (b) Simulation interface of the MIC-Sim; (c) Layout of the test intersection; (d) TCA in the experiment; (e) Before-game inbound traffic counts at the intersection of Millersport & Amherst Manor on 9/19/2012.

3.2.2 Subjects and Experimental Procedure

Eight TCAs participated in the experiment, as shown in Figure 2(d). One experiment was a 5-minute training session, which consisted of demonstrations and suggestions by the experimenter, combined with practice trials. In this warm-up session, participants were asked to properly adjust the simulation view to minimize the discrepancies between the real-world view and the simulation view. After a warm-up training session, each subject conducted manual traffic signal control under four different scenarios, each of which lasted 30 minutes. The first two scenarios simulated the real multi-modal peak traffic demand from a busy weekday night football game, including three traffic modes, that is, passenger cars, buses and pedestrians and the last two scenarios only had two traffic modes, that is, passenger cars and buses. The detailed multi-modal traffic demand data for 12 turning movements and one pedestrian movement are also provided in Table 3. All scenarios contained two bus lines, which had the same bus demand, 8 buses per hour per line. Scenarios 1 and 3 have the same traffic demand in terms of buses and passenger cars, and scenario 3 does not include pedestrian traffic. Scenario 4 contains an artificial, saturated traffic condition. The traffic conditions are determined by the critical intersection volume-to-capacity ratio in Chapter 18 of the Highway Capacity Manual [14].

The critical volume-to-capacity ratio for this intersection is

$$X_c = \left(\frac{C}{C-L}\right) \sum_{i \in ci} y_{c,i}$$

$$\text{with } L = \sum_{i \in ci} l_{t,i}\ ,\ y_{c,i} = \frac{v_i}{Ns_i}$$

where C is the cycle length, L is the cycle lost time, c_i is the set of critical phases on the critical path, $l_{t,i}$ is phase *i* lost time, v_i is the demand flow rate, and Ns_i is the saturation flow for phase *i*. Therefore, the critical volume-to-capacity ratios for four scenarios, as shown in Table 3, are 0.775, 0.801, 0.775 and 1.208, respectively.

3.2.3 Evaluation Criteria

The purpose of this research is to evaluate the manual multi-modal signal control performance of TCAs. There are several challenges in multi-modal signal control. First, it is crucial to set weights for different traffic modes. Due to a lack of previous work, we set multi-modal weights according to the TCA interview results. The second challenge is how to select the different evaluation criteria. According to the previous interview, safety is the first priority considered by TCAs. We leave this criterion for future study. Network throughput and average delay are also top criteria; however, occasionally, they conflict with each other. For example, a lower cycle length usually results in lower pedestrian delay, although it increases the total lost time and leads to a lower total throughput.

In this paper, we use two criteria to evaluate signal control: delay and throughput. In addition, each criterion is evaluated based on three aspects of multi-modal traffic: passenger cars, buses, and pedestrians. To compare with the currently practiced automatic control method, fully actuated signal control (ASC) is used as the baseline for traffic control performance. Moreover, we assume optimal control results can be obtained from a control algorithm called PAMSCOD

(Platoon-based Arterial Multimodal Signal Control with Online Data) [4], the objective of which is to reduce multi-modal traffic delay with pre-defined weights. In this study, PAMSCOD assumes Vehicle-to-Infrastructure (V2I) communication is available with a 100% penetration rate, and every vehicle or pedestrian will send the controller a request with its phase and arrival time when approaching the intersection. To conform to this study, we trimmed the constraints of PAMSCOD for an isolated intersection and added delay evaluation constraints for pedestrians. Table 4 shows the simulation results of all subjects for fully ASC and optimal signal control for four scenarios with respect to the three considered traffic modes. Table 5 shows detailed ASC settings used in the experiments. All scenarios have the same settings for minimum green time, vehicle extension, yellow time and all-red time for all six phases. Scenarios that have pedestrians, i.e., S1 and S2, also have the same settings for pedestrian walk and clearance time. To compare the performance of different operations in a uniform approach, the next section describes the method to calculate the performance index.

Table 3: Average multi-modal traffic turning movement counts (per hour) for each scenario

	NBL*	**NBT**	**NBR**	**NB-Ped**	**SBL**	**SBT**	**SBR**	**WBL**	**WBT**	**WBR**	**WBR -Bus**	**EBL**	**EBL -Bus**	**EBT**	**EBR**	**Volume-Capacity Ratio**
S1	25.0	120.0	41.1	1458	72.1	39.8	136.0	167.2	651.0	227.8	8	365.5	8	888.9	151.6	0.78
S2	22.5	108.4	37.1	1338	76.2	42.1	143.7	176.4	687.1	240.5	8	374.9	8	911.7	155.5	0.80
S3	25.0	120.0	41.1	0	72.1	39.8	136.0	167.2	651.0	227.8	8	365.5	8	888.9	151.6	0.78
S4	96.5	464.0	158.8	0	346.7	191.4	653.6	193.7	754.2	263.9	8	392.7	8	955.1	162.9	1.21

*: NB, SB, WB and EB represent northbound, southbound, westbound and eastbound traffic, respectively. L, T and R represent left-turn, through and right-turn traffic, respectively.

Table 4: Multi-modal average delay for each subject in each scenario

	S1			S2			S3			S4		
Subject	Car Delay (s)	Bus Delay (s)	Ped Delay (s)	Car Delay (s)	Bus Delay (s)	Ped Delay (s)	Car Delay (s)	Bus Delay (s)	Ped Delay (s)	Car Delay (s)	Bus Delay (s)	Ped Delay (s)
A	26.53	41.90	33.34	28.15	14.45	54.04	15.65	12.05	-	29.43	36.25	-
B	34.79	36.89	35.04	53.66	57.40	54.04	25.02	43.65	-	39.07	43.15	-
C	33.21	33.90	45.14	33.31	22.95	44.24	26.62	23.76	-	32.98	30.65	-
D	37.25	26.40	51.74	38.53	32.81	53.54	16.85	20.40	-	39.93	36.11	-
E	31.39	28.71	23.64	37.93	37.47	27.34	14.22	15.80	-	28.53	29.43	-
F	32.57	45.85	18.04	26.99	28.80	23.84	18.55	20.80	-	36.41	40.83	-
G	33.26	17.85	37.94	29.77	22.80	33.04	11.95	12.20	-	27.92	12.69	-
H	45.92	46.09	27.74	60.11	58.69	38.34	19.43	15.66	-	37.32	40.89	-
ASC	34.10	38.94	47.00	35.79	60.84	59.20	17.80	29.42	-	38.76	57.28	-
Optimal	22.43	4.70	12.80	21.25	11.35	14.90	14.66	3.25	-	31.49	7.25	-

Table 5: Baseline ASC settings

Phase No.	2,4,8	6	3,7
Min. Green (s)	7	7	7
Veh. Extension (s)	4	4	4
Ped. Walk (s)	N/A	10	N/A
Ped. Clearance (s)	N/A	45*	N/A
Yellow (s)	3	3	3
All Red (s)	2	2	2
Max. Green (s)	80	80	35

*: The pedestrian clearance time is calculated by assuming a pedestrian speed of 3.5 ft/s.

4. Performance Index

We use utility functions to measure the TCA's performance. Two attributes, weighted average delay (*d*) and total throughput (*h*), are considered in the utility function:

$$U_{ij}(d,h) = \ln(\frac{h_{ij}}{d_{ij}}),$$

$$d_{ij} = w_c * d_{ij}^c + w_b * d_{ij}^b + w_p * d_{ij}^p,$$

$$\text{and } h_{ij} = O_c * h_{ij}^c + O_b * h_{ij}^b + O_p * h_{ij}^p$$

where $U_{ij}(d,h)$ is a nonlinear utility function. *i* represents the *i*th TCA from A to H and *j* represents the *j*th scenario from 1 to 4. The weights for the three modes, w_c for a passenger car, w_b for a bus, and w_p for pedestrians, were obtained and normalized from interview results (w_c=0.085, w_b=0.373, w_p=0.542, respectively). O_c, O_b and O_p represent the average occupancy of a car, a bus and a pedestrian, respectively. Based on our empirical studies, the value for O_c was set at 1.75, and values for O_b and O_p were set at 40 and 1, respectively. Correspondingly, the delays for a car, bus and pedestrians are d^c, d^b and d^p, where the throughputs for these three modes are h^c, h^b and h^p, respectively.

In this paper, $U_{b,j}$ is the performance utility of the ASC in scenario *j*; $U_{o,j}$ is the performance utility of optimal control and $U_{i,j}$ is the *j*th trial of *i*th subject. Each subject only performs single simulation for each scenario.

The final performance index for the *j*th trial of the *i*th subject is

$$PI_{ij} = \frac{U_{i,j} - U_{b,j}}{U_{o,j} - U_{b,j}},$$

A zero index demonstrates that the TCA achieves the same performance as the ASC, whereas a negative index indicates a worse performance than that using the ASC method. The closer the index is to 1, the closer the performance is to the optimal solution.

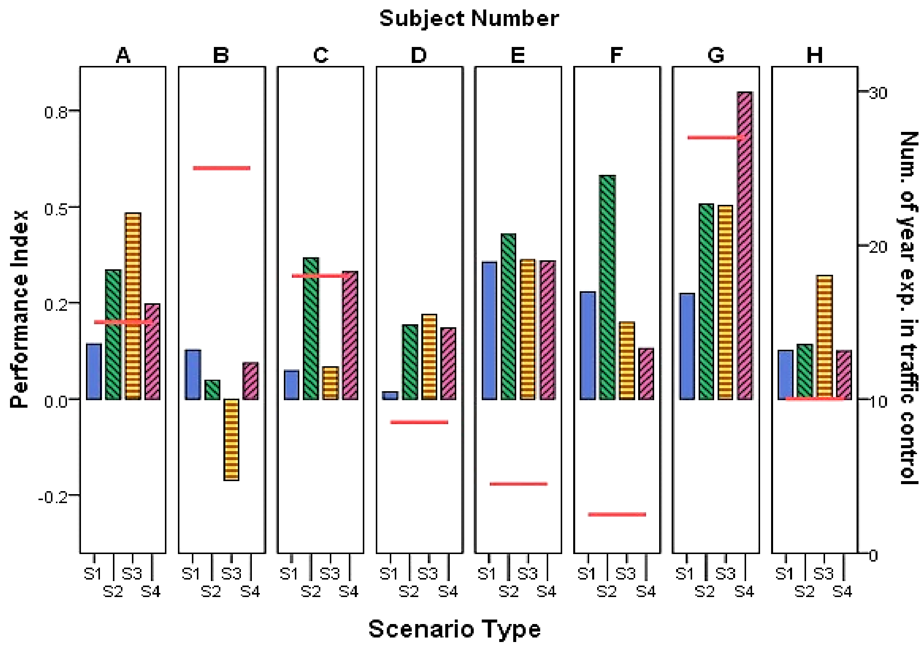

Figure 3: Experience and performance index of all subjects.

Figure 3 shows the PI of all subjects with the corresponding work experience index (years of experience/30). More experience does not guarantee a higher PI from the study. As shown in Figure 3, when comparing the performance of subject B and F, it is clear that B had a worse performance than that of F, even though B had more experience than F. It is also interesting to observe that subject G, the TCA with the most experience, always achieved high PIs in all scenarios. One noticeable result is that the PI from subject G in S4 is close to 1, which indicates the necessity of manual operation for oversaturated traffic conditions. Moreover, the performances of the same subject from scenario to scenario varied. Most of the subjects were more capable of handling S3 than S1, which has the same traffic condition in passenger cars and buses but with additional pedestrian traffic when compared with that of S3. This result can be explained by the fact that it is easier to handle the condition when pedestrians are not involved. Most likely, subjects will have a better performance in S2 compared with S1 because S2 contains more congested multi-modal traffic than S1. Additionally, it was observed that the PI of subject 2 in S3 is negative because he did not interrupt the predefined fixed time signal plan in this simulation. In such a case, the performance will be worse than that of ASC.

Overall, in Figure 3, there are large performance variations throughout all scenarios. The standard deviations of the PIs were 0.27 across all experiments. Such large discrepancies among the TCAs' performance could be caused by various human factors, such as age, education background, professional training, work experiences, and so on. However, it is clear that a TCA's manual signal control outperforms ASC in most of the scenarios. This result can be explained by the fact that ASC does not work well in a congested multi-modal traffic condition, which is always the case for event traffic. Therefore, manual intersection control is indispensable for such cases, particularly when the advanced adaptive signal control system is not properly equipped.

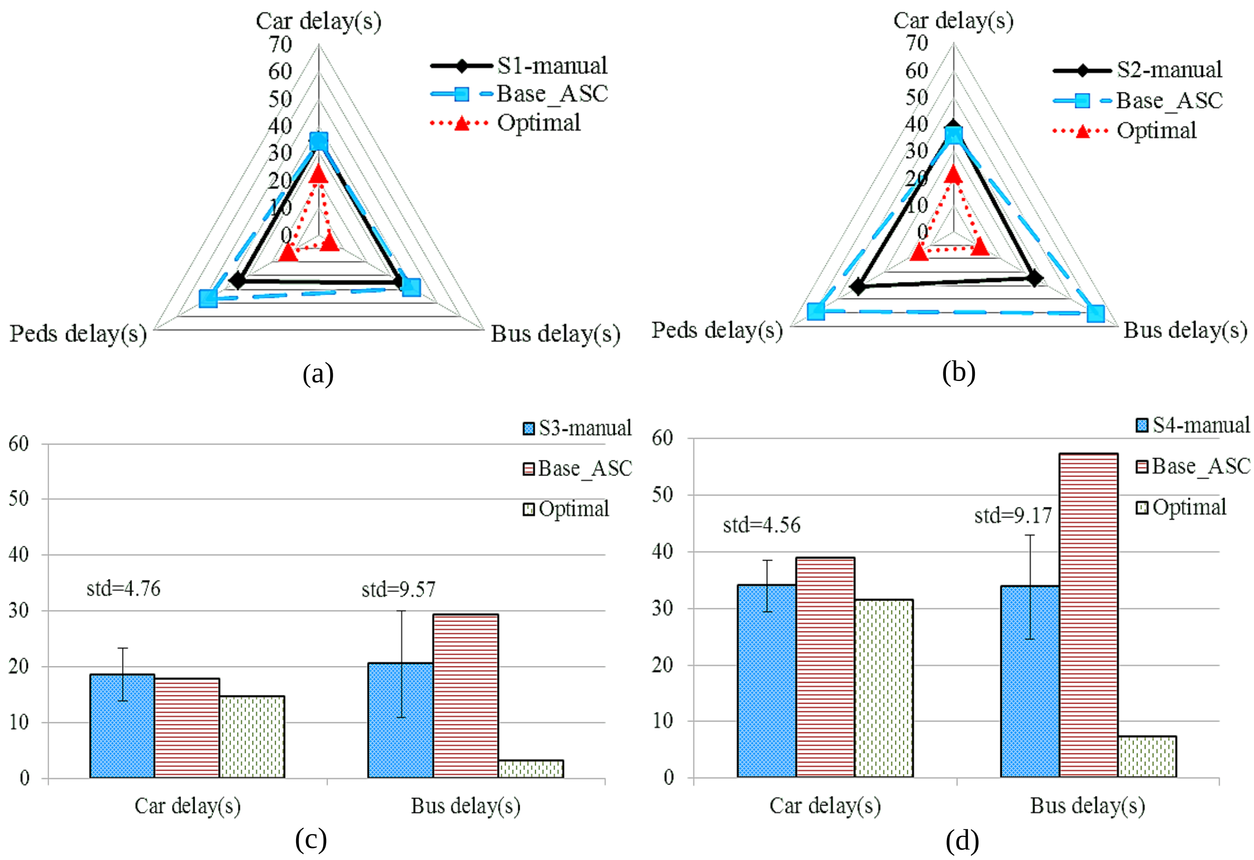

Figure 4: Multi-modal delay. (a) S1-with pedestrians; (b) S2-with pedestrians; (c) S3-without pedestrians; (d) S4-without pedestrian.

Figure 4 demonstrates the multi-modal delay of four scenarios compared with that of the corresponding ASC and optimal signal timing, where (a), (b) (c), and (d) in Figure 4 represents 1, 2, 3, and 4, respectively. Both scenario 1 and 2 have three traffic modes, including passenger cars, buses and pedestrians, whereas scenarios 3 and 4 only have two traffic modes, passenger cars and buses. As shown in the figure, the delay of either a bus or pedestrian can be always improved by manual signal control. Compared with ASC, manual control can significantly decrease the bus delay and pedestrian delay in scenarios 1 and 2. It can also be seen that a greater delay deduction of both buses and pedestrians is achieved in scenario 2, which has a larger traffic demand compared with that of scenario 1. This result is similar when comparing scenario 3 with scenario 4, whereas scenario 4 has a larger traffic demand and has more car and bus delay deductions. Moreover, the car delay in S1, S2 and S4 is shown to be improved by manual control, whereas it is worse in S3. This result confirms that manual control is a more effective way to handle congested multi-modal traffic conditions. Figure 4(c) and 4(d) also show the standard deviation of car delay and bus delay. As seen, neither of these standard deviations is small, whereas the standard deviation for the bus delay is larger than that for the car delay.

Comparing manual control with optimal control, one can certainly see that there is a large gap between these two control operations. However, optimal control requires expensive detection technology to receive the rich real-time information at the intersection, and currently, it is infeasible in most real-world intersections, particularly in rural areas. In this case, manual signal control can significantly improve traffic conditions at a low cost.

As previously mentioned, scenarios 1 and 3 have the same traffic demand with respect to passenger cars and buses; pedestrians are not considered in scenario 3. The average delay in scenario 3 is reduced by 41% compared with that in scenario 1. This result can also be validated from Figure 3, which shows the performance in S3 has a higher index value than that in S1 for most of the simulations. This result can be explained by the fact that once a pedestrian is involved, the delay at the intersection increases, and it becomes more difficult to control the traffic.

Table 6 shows the different cycle lengths and delay reductions for each scenario between the two control methods, manual and ASC operation. It can be easily seen from the data that the cycle length during manual operation is longer than during ASC operation for S1, S2 and S3 but not S4. Additionally, in S1 and S2, manual control has a longer cycle length than ASC because manual control has longer pedestrian clearance time and walk time, whereas ASC has fixed settings. Due to high traffic volume under oversaturated conditions, ASC simply extends the green time until the phase terminates due to reaching the designated maximum green time for the phase (maximum out). In contrast, during manual operation smart decisions are made regarding green time allocation by considering more important factors than traffic demand, including queue spillover, left turn waiting time, coordination between signals, and so on. Thus, it is more flexible to adjust cycle length according to the congested traffic condition by manual operation. Additionally, one can observe that delay is always less in manual operation compared with that of ASC, and the average delay is reduced by 29.2%. Regarding manual control between S1 and S3, the cycle length in S1 with pedestrians is 34.6 seconds longer than that in S3 without pedestrians. In other words, the cycle length in S3 is only 74% of that in S1. This result can be explained by the fact that cycle length should be long enough to accommodate the pedestrian clearance time needed to cross the street.

Table 6: Average cycle length and multi-modal weighted delay

	S1		S2		S3		S4	
	Cycle length (s)	Delay (s)	Cycle length (s)	Delay (s)	Cycle length (s)	Delay (s)	Cycle length (s)	Delay (s)
ASC	96.92	42.90	106.62	57.83	61.11	27.27	134.03	53.85
Manual-Avg.	132.84	34.33	144.20	38.37	98.24	20.17	109.20	33.79
Manual-Std.	29.92	4.89	42.52	9.39	32.38	8.47	19.04	8.12
Changes from ASC to Manual (%)	37.07	-19.97	35.25	-33.65	60.75	-26.03	-2.95	-37.26

6. Conclusions and Discussion

This paper designed an interview and a simulation-based experiment to mimic the manual multi-modal traffic signal control behavior of TCAs, which included on-duty police officers and firefighters. The study then presents the evaluation results of the performances of manual control compared with the currently used ASC plans and optimal signal timing plans. The performance is measured by a utility function based on two attributes, weighted average delay and total throughput. Three traffic modes, passenger cars, buses and pedestrians, were considered. Manual traffic control not only significantly improved the utility compared with that ASC at an oversaturated intersection in an event traffic condition but was also very close to the performance of the optimized timing plan. In all four scenarios, the delay was reduced by 29.2% on average. The more traffic modes that are considered, the longer the observed cycle length. However, large performance discrepancies exist. The standard deviation of cycle length ranged from 19.04 to 42.52 in the four scenarios, and the standard deviations of the PIs were 0.27 across all experiments.

Although manual control outperformed the currently used ASC operations, the gap between manual control and optimal control still remains significant. Additionally, the performances of the same TCA varies from scenario to scenario. It was shown that it is easier to handle traffic without pedestrians. Thus, there is much room for further improvements in manual performance through professional education and training. Such training can be performed with specially designed traffic scenarios with traffic manual control simulators, such as the MIC-Sim proposed in this paper. We believe that the performance of TCA's will show significant progress after more training sessions are taken.

In the future, human behavior models can be established to mimic a TCA's traffic control behavior in multi-modal traffic. Such models will be able to predict the TCA's response given various different traffic conditions and geometry of intersections. Through human behavior modeling, we can simulate event-based network traffic control with a variety of TCA deployment plans, which may be used as a potential useful tool for proactive event traffic control and management.

7. References

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