다이아몬드 인터체인지의 3현시 신호운영 평가

Assessment of Three-Phase Actuated Signal Operation at Diamond Interchanges

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목 차

ABSTRACT

The performance of two single-barrier three-phase actuated control systems at diamond interchanges was evaluated for various traffic conditions. To emulate the actuated signal control, hardware-in-the-loop system combined with CORSIM simulation program was used. Two performance measures, average delay and total stops, were used for the evaluation process.

Results showed that the two three-phase systems gave similar performance in terms of average delay, but not stops. The delay performance of each phasing system was generally dependent on the traffic pattern and ramp spacing. The total stops decreased as the spacing increased, and it was the most sensitive variable that can differentiate between the two three-phase systems. It was also shown that the hardware-in-the-loop control could provide a good method to overcome the limitations of current simulation technology.

I. INTRODUCTION

The interchange is a critical facility in urban and suburban locations that serves conflicting demands from freeways and arterials. Diamond interchanges are particularly adaptable to major-minor crossings where left turns at grade on the minor road are large and can be handled with minimal interference to traffic approaching the intersection from either direction (*1*). A study reported that diamond interchanges were the most commonly used interchange configuration (*2*). Traffic movements at the diamond interchanges were controlled by traffic signals, and most interchanges had two semi-actuated signal controllers, one controller for each intersection.

Pretimed or traffic actuated signal control may be employed. However, actuated signal control is more common in recent years due to it's functional flexibility and responsiveness to varying traffic demands. Various factors have an effect on the operational performance of actuated traffic operation at diamond interchanges. Factors include traffic patterns, type of phasing, detector design, geometric features, and controller settings.

Three-phase control is one of the effective control strategies for diamond interchange facility (*3*). Especially three-phase with a single-barrier system gives great flexibility in phase operation, and it may respond well to unbalanced traffic demands. Three-phase with a single barrier system can have two different barrier locations without disrupting signal coordination: (1) end of frontage road phase and (2) start of frontage road phase. The two three-phase systems are frequently used in practice, but operational characteristics of the two systems are not reported in previous researches. In addition, the effect of ramp spacing on three-phase operation has not been extensively investigated. This is partly because available simulation tools do not support the necessary functional requirement.

In this paper, the operational performance of the two three-phase systems at diamond interchanges is investigated. A CORSIM simulation with Hardware-in-the-Loop is used to implement the actuated signal operations. A barrier design method is presented to simulate the two single-barrier systems with the Eagle EPAC 300 controller.

The effect of ramp spacing on the performance of each control system is also assessed. Performance is evaluated in terms of average delay and total number of stops.

The two single-barrier three-phase systems are described. Then, several issues on experimental design are discussed including signal timing, detector layout, and controller settings. Next, study results will be discussed, then a summary of the results is presented in the final section.

II. THREE-PHASE CONTROL

1. TRAFFIC MOVEMENTS

Signal operation at diamond interchanges has unique operational characteristics. A diamond interchange has eight conflicting movements. They are the four external inbound movements and four internal outbound movements. The movements and identifying numbers used in this study are shown in Figure 1.

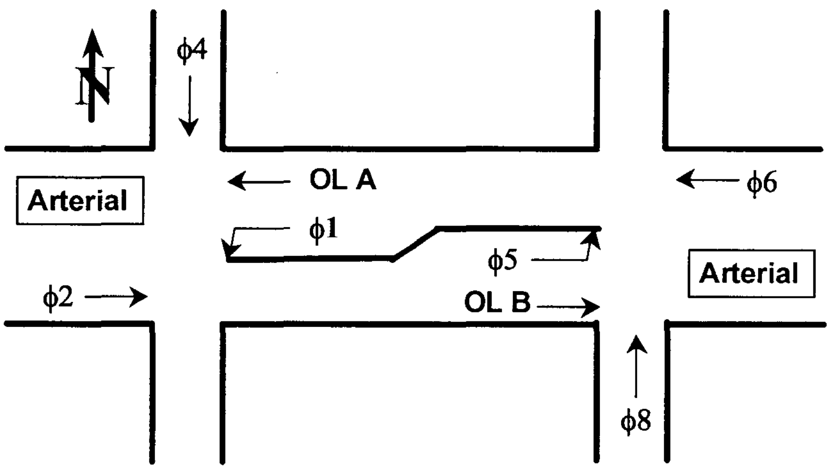

FIGURE 1 Diamond Interchange Signal Phases Modeled

Arterial phases are considered as being the main street, and the two frontage road (or ramp) movements are served by the two other external phases (i.e., φ4 and φ8). The internal through movements do not conflict with either arterial movements or internal outbound left-turn movements. Thus, two overlap phases (OLϕ) are defined at each side of the intersections (i.e., OL A (ϕ1+ ϕ2) and OL B (ϕ5 + ϕ6)).

2. THREE-PHASE SYSTEMS

Two single-barrier three-phase systems are considered in this study. The ring structures of the two phasing systems are shown in Figure 2. As shown in Figure 2, both phasing systems have a lag-lag phasing pattern, and they are designed to provide flexible signal operation because any phase of each intersection can concurrently run with all phases of the other side intersection.

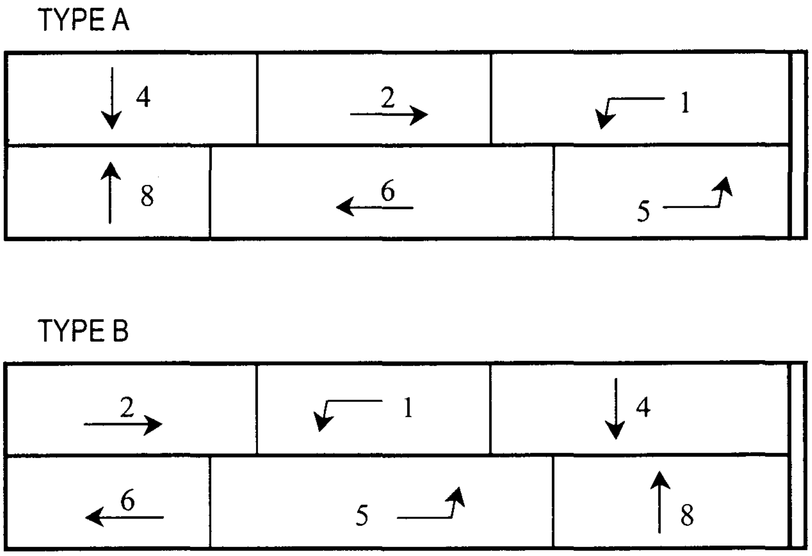

FIGURE 2 Two Single-Barrier Three-Phase Systems

In type A phasing, the phasing starts with the two frontage road phases at the same time. Then, one of the two frontage road phases can be terminated earlier than the other phase, depending on traffic demand. Thus, two overlap phases, (ϕ4 + ϕ6) and (ϕ2 + ϕ8), may follow after the two frontage road phases. Based on the ring structure, the frontage road phases can be run with outbound left-turn phases ($\phi1 + \phi8$) and ($\phi4 + \phi5$) when there is no arterial movement. It is believed that this situation is not frequently observed in real traffic conditions because the arterial movements are typically the higher volume approaches. When the two frontage road phases are terminated, the pair of arterial phases ($\phi2 + \phi6$) follows. During the arterial phase intervals, two additional overlap phases, ($\phi2 + \phi5$) and ($\phi1 + \phi6$), may be presented if there is unbalanced traffic demand from both arterial approaches. Lastly, outbound traffic demands are served by the two left-turn phases ($\phi1 + \phi5$). These two phases terminate at the same time because a barrier is located at the end of these phases. Therefore, a phase will dwell when its approach experiences demand starvation during the left-turn phase.

A similar interpretation can be made for the type B phasing system. One major distinction is the location of the barrier. In type B phasing system, the barrier is located at the end of the frontage road phases; thus, the following two arterial phases always start together. Then the arterial movements will be served by two progression phases, ($\phi1 + \phi5$). The frontage road phases may start separately, but they have to end at the same time.

The performance of type A phasing was investigated in a previous study (*4*). Based on field observations, type A phasing provided less queuing delay and shorter cycle length than four-phase with two-overlap phasing. A simulation study was conducted to investigate the performance of actuated three-phase lag-lag operation (*5*). However, the simulation study used a three-phase strategy having the conditional service feature, thus more flexibility was provided for the study. No reference is available on the performance of type B phasing.

III. EXPERIMENTAL DESIGN

1. DETECTOR DESIGN

A 100-ft long inductive loop detector, operating in the presence mode, was placed in each lane for all approaches. The detector layout used for the two three-phase operation is shown in Figure 3. The detectors on the four external approaches call the phases corresponding to the approach movements. The outbound left-turn phases ($\phi 1 + \phi 5$) were activated by the detectors placed both on the left-turn bay and on the through lanes within the internal links.

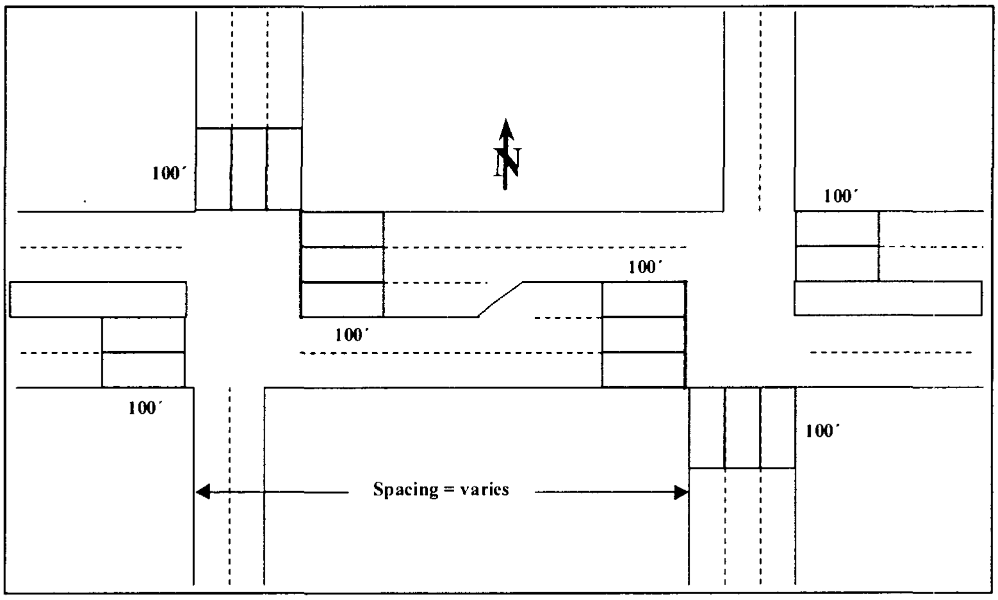

FIGURE 3 Detector Layout for Three-Phase Operation

The free-flow speed was fixed at 30 mph for each approach. The user's guide for PASSER III recommends the setback distance of the loop detector based on approaching speed (*6*). When the speed of approach traffic is 30 mph, a 100-ft setback distance can be selected. The advance detector placement was not selected because the approach speed is not considered to be high. A wide range of ramp spacings was considered in this study: 260 ft, 400 ft, 600 ft, and 800 ft. This range should encompass most signalized ramp spacings found in urban areas.

2. SIGNAL TIMING

The performance of actuated control is known to be sensitive to both controller settings and detector design. The controller settings include passage time, minimum green time, and maximum green time. A study has been conducted to develop a guideline for the optimal controller settings at diamond interchanges (*7*). However, the scope of the study is limited to basic three-phase actuated operations. Currently, no optimum guidelines which produce minimum delay operation are available for the two three-phase phasing systems at diamond interchanges.

The user's guide for PASSER III recommends that phase split times obtained by Webster's method can be used as a maximum green time provided the volume-to-capacity ratios are not greater than 0.85 (*6*). It also suggests the selection of passage time is based on the desired maximum allowable headway. The maximum allowable headway of 2.5 seconds is a corresponding value based on the user's guide for PASSER III when the approach speed is 30 mph (*6, 7*).

The passage time per phase was set at zero seconds. Then detector design of this study produces a 2.7 second maximum allowable headway. Five-second minimum green time was applied to each phase. Maximum green time was decided based on optimum phase splits from PASSER III program outputs with an inflation factor chosen to be 1.8. Therefore, generous maximum green time was provided for the study. Yellow and red clearance intervals were selected as 3.5 and 1.5 seconds, respectively.

3. TRAFFIC VOLUME SCENARIOS

Four traffic volume scenarios, encompassing a wide range of traffic patterns, were developed and used during the evaluation process. The traffic volume scenarios are listed in Table 1. Traffic demand from the left-side intersection is quite heavy for scenario A. All approaches have heavy movements in scenario D. Maximum ramp left-turn volume was set as 400 vph, but the range was 300 - 350 vph for most cases except for the right-side intersection of scenario A. It was assumed that U-turn traffic from the frontage road approaches was 20 percent of the left-turn volume.

TABLE 1 Traffic Volume Scenarios Studied

Traffic Pattern (Scenario)	Approach Volume (vph)						X_c
	1	2	4	5	6	8	
Heavy EB & SB (A)	220	1150	1300	430	450	300	0.82
Heavy EB & WB (B)	360	950	750	320	1000	700	0.77
Heavy NB & SB (C)	380	550	1100	310	800	1000	0.77
Heavy All Throughs (D)	310	1000	1200	360	950	1050	0.84

Note: X_c: Critical volume-to-capacity ratio of the interchange.

4. IMPLEMETATION OF SIGNAL PHASINGS

The two three-phase systems are not built-in phasings available directly from the signal controller, but they can be implemented using a standard eight-phase NEMA ring structure. In the Eagle EPAC 300 controller, the barrier is added by defining concurrent phases (*8*). To implement the two three-phase systems, all phases of one intersection should be concurrently defined to all phases of the other intersection. However, this definition cannot guarantee synchronous beginning of the two arterial road phases or two frontage road phases. To deal with this problem, a "phase overlap" treatment was used.

Figure 4 shows ring structures implemented in the controller for the two signal phasing systems. For type A phasing, each frontage road phase is divided into two phases: one has a fixed duration (i.e., $\phi 4$), and the other has a variable duration (i.e., $\phi 3$). The minimum green time for the frontage road phase was assigned as a maximum green time for the fixed duration phase. Remaining maximum green time went to the maximum green time of the variable phase. This "phase overlap" treatment is necessary to ensure that both frontage road phases will start together and end separately. Because the minimum green time was assigned to the fixed phase, this treatment might provide almost similar flexibility with type A phasing system. A similar procedure was applied to type B phasing, but the internal overlap phase was replaced with two arterial phases instead of two frontage road phases.

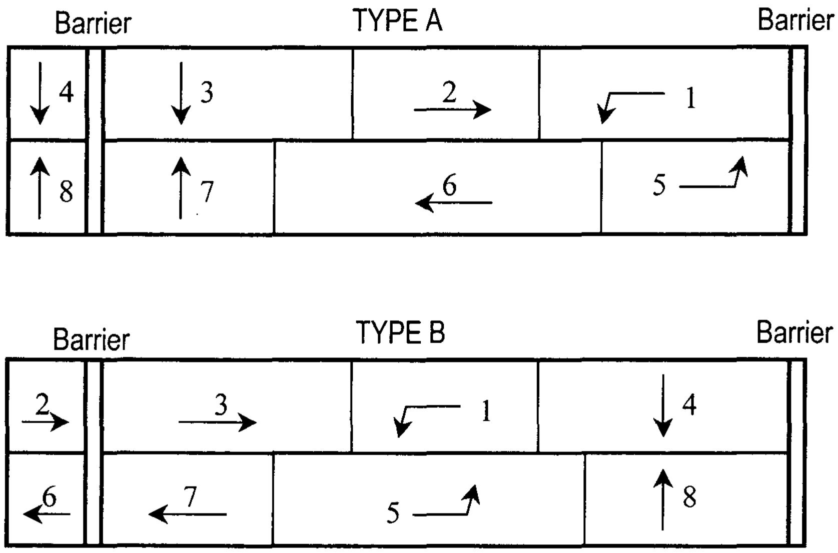

FIGURE 4 Two Three-Phase Systems Implemented

IV. STUDY RESULTS

Each traffic volume scenario was simulated with four different ramp spacings. Two measures of effectiveness were identified from the simulation outputs for use in performance comparisons: average delay and total number of stops.

1. AVERAGE DELAY

Average delay for each volume scenario at various spacings is shown in Figure 5. Results are volume-weighted averaged values computed from the individual movements.

Several observations can be made from the delay results. Firstly, the performance of each phasing system was different as to traffic pattern, but practically no large difference of the delays was observed from the figures except for scenario D. The two systems produced similar performance with ramp spacing up to 600 ft when traffic demand of the two intersections was unbalanced significantly. For this unbalanced traffic pattern, type A is considered a better phasing strategy than type B because it tends to provide longer internal left-turn phases than type B. Therefore, the heavy demand from either approach will be served without incurring additional delay to non-critical movements. When the traffic patterns of each intersection are balanced (i.e., scenario B), the performance of the two strategies is almost identical as can be shown in Figure 5.

Secondly, the delay pattern was relatively stable up to a certain ramp spacing (i.e., 600 ft) for most scenarios. If the spacing is wider than this distance, the delay tends to increase sharply. This trend may be related to the cycle length results. When the actuated signal control is operated under the capacity of the system, only the uniform delay component is a major contributor to control delay. The uniform delay estimated from HCM delay equation is a function of the cycle length. The analysis results of the cycle lengths indicate that the cycle lengths are relatively stable up to 600 ft. Then, the trends of cycle lengths increased after that. These cycle length trends were similar to those of delay trends.

Thirdly, the delay function has a convex form in relation to different ramp spacings; therefore, there is an optimal spacing that gives minimum delay operation. For the type B phasing results, the delays from 260 ft spacing were higher than those from 400 ft spacing for all traffic patterns. In addition, the delays were higher at 800 ft spacing than at 600 ft spacing for all traffic patterns. Therefore, the minimum delay ramp spacing can be found between 400 ft and 600 ft.

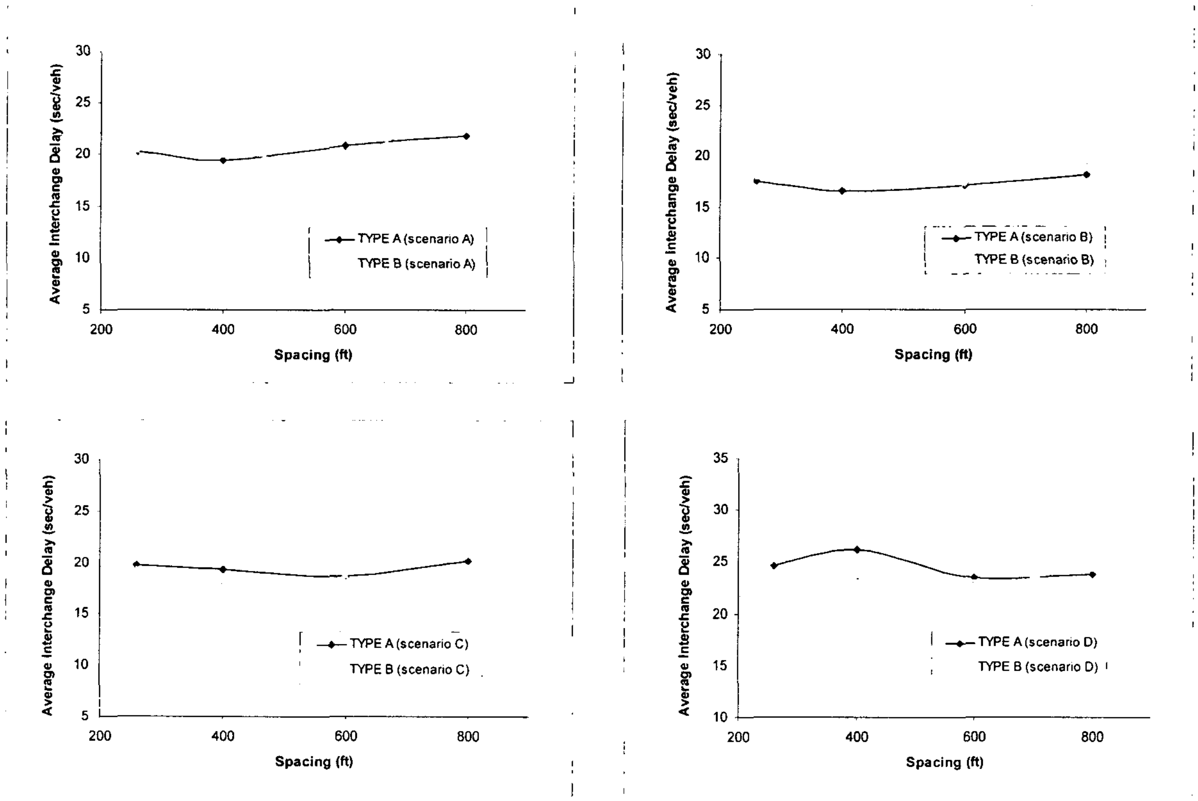

FIGURE 5 Average Delay Simulated

Lastly, type B phasing is a good strategy for short ramp spacings when traffic demand from the two frontage roads is heavy. However, type A phasing tends to outperform type B phasing for all cases when the ramp spacing is wider than 600 ft. Mixed results were observed for the ramp spacings between 260 ft and 600 ft. Type B phasing produced less delay operation in 24 out of 36 total simulation outputs for these ramp spacings (i.e., 3 replications *4 traffic patterns * 3 ramp spacings).

Statistical tests were completed to investigate whether the average delay mean differences were statistically significant. The three-factor ANOVA procedure was used with the simulation outputs (*9, 10*). The factors were: signal phasing (P), traffic pattern

(T), and ramp spacing (S). The factor, signal phasing, has two levels: three-phase type A phasing (i.e., 1) and three-phase type B phasing (i.e., 2). Traffic pattern has four levels: scenario A (i.e., 1), scenario B (i.e., 2), scenario C (i.e., 3), and scenario D (i.e., 4). Four levels were assigned to the other factor of ramp spacing: 260 ft (i.e., 1), 400 ft (i.e., 2), 600 ft (i.e., 3), and 800 ft (i.e., 4).

The null hypothesis (H_o) for the test is that the effects of the three factors are not statistically significant across all levels. Hypothesis test results for average delay are listed in Table 2. The significance of the test (i.e., α) was set to one percent throughout the study.

TABLE 2 Hypothesis Test Results for Average Delay

Source	DF	Sum of Squares	Mean Square	F Value	*p*-value	Reject H_o
P	1	0.0051	0.0051	0.00	.9511	No
T	3	532.0886	177.3628	131.62	.0001	Yes
P*T	3	8.5294	2.8431	2.11	.1077	No
S	3	44.8961	14.9653	11.11	.0001	Yes
P*S	3	13.6536	4.5512	3.38	.0236	No
T*S	9	30.6292	3.4032	2.53	.0152	No
P*T*S	9	8.5667	0.9518	0.71	.7008	No
Error	64	86.2400	1.3475			
Total	95	724.6090				

Note: P: Signal phasing, T: Traffic pattern, S: Ramp spacing

Both traffic pattern and ramp spacing were found to be statistically significant. Traffic pattern was the most dominant factor (i.e., F Value = 131.62). The overall contribution made by two phasing systems was almost zero (i.e., sum of squares: 0.0051). Therefore, the average delay can be affected by both traffic pattern and ramp spacing. This supports the previous average delay analysis results.

The Tukey's multiple comparison procedure was also conducted, and the results are provided in Table 3. A set of level groups having statistically different means to others is separated using the symbol "/ ". Each traffic pattern showed different level of groups. Two levels of groups were identified from the ramp spacing factor: from 260 ft to 600 ft and 800 ft.

TABLE 3 Tukey's Procedure Results for Average Delay

Signal Phasing			Traffic Pattern			Ramp Spacing		
Level	Mean	Group	Level	Mean	Group	Level	Mean	Group
2	20.50	12	4	24.06	1/ 2/ 3/ 4	4	21.63	123/ 4
1	20.48		1	20.84		1	20.42	
			3	19.45		2	20.02	
			2	17.62		3	19.90	

2. TOTAL INTERCHANGE STOPS

The total interchange stops was obtained by adding the number of stops on all approaches, as shown in Figure 6. Several observations can be summarized from the results. Total interchange stops tends to decrease as the ramp spacing increases for both types of phasings in general. The performance based on the number of stops is also dependent on traffic patterns. As expected, Type B phasing showed better performance than type A phasing when frontage demand was heavy. Type A phasing provided less number of stops than type B phasing when there was an unbalanced demand between the two intersections (i.e., scenario A). As described in the previous section, type A phasing provides longer internal left-turn phases than type B phasing, so it is a better strategy in terms of progression of arterial traffic flow. In this case, the trend was obvious and consistent for all range of spacings. Type A phasing also gave better results than type B phasing for long ramp spacings (i.e., 800 ft) for all scenarios. Similar interpretation can be applied for the balanced traffic pattern of scenario B.

Mixed results were observed for the ramp spacings between 260 ft and 600 ft. Type A phasing produced less stop operation in 20 out of 36 total simulation outputs for these ramp spacings (i.e., 3 replications *4 traffic patterns * 3 ramp spacings). Among the variables investigated, the number of stops was the most sensitive variable between the two systems.

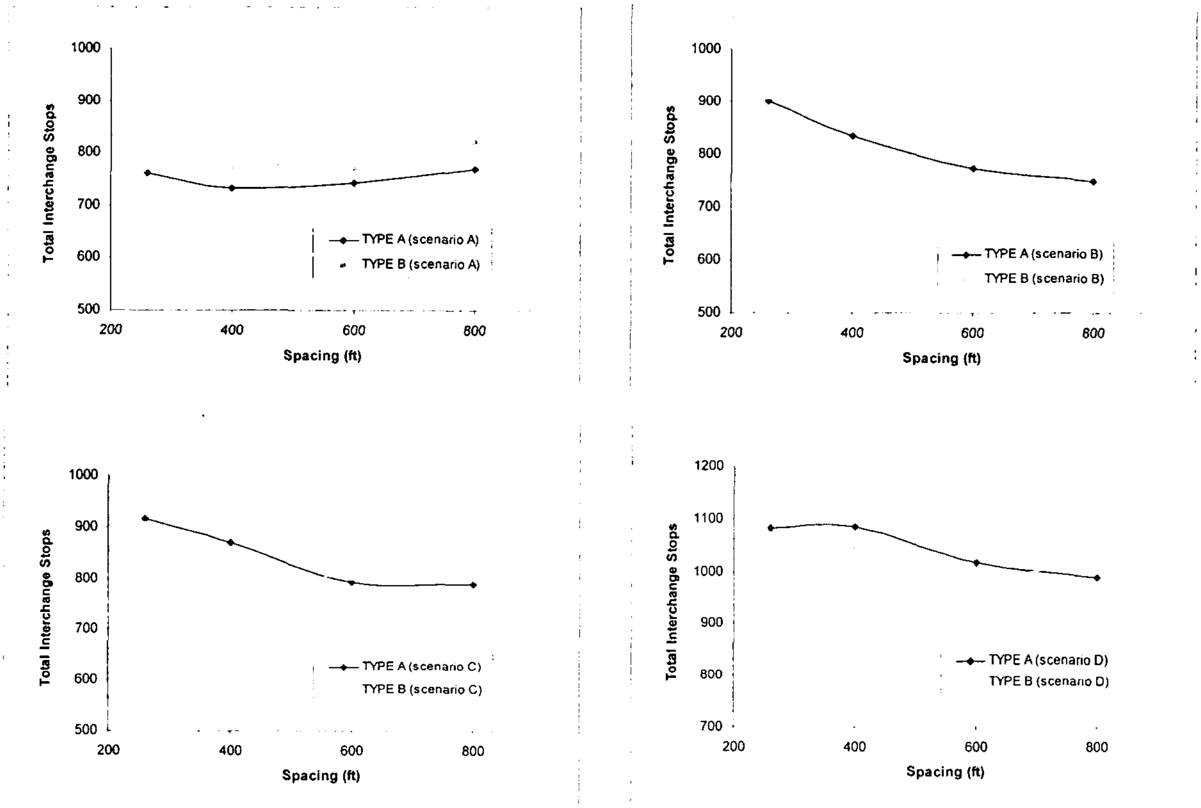

FIGURE 6 Total Interchange Stops Simulated

The ANOVA results for the three-factor analysis for stops are listed in Table 4. Results showed that all three factors were statistically significant to stops. Therefore, the performance of the two three-phase systems could be differentiated using the stop performance index. However, traffic pattern and ramp spacing were the major factors to explain the stop differences.

TABLE 4 Hypothesis Test Results for Stops

Source	DF	Sum of Squares	Mean Square	F Value	p-value	Reject H_o
P	1	3372.5104	3372.5104	7.48	.0081	Yes
T	3	956133.2812	318711.0937	706.61	.0001	Yes
P*T	3	10916.2812	3638.7604	8.07	.0001	Yes
S	3	101303.8645	33767.9548	74.87	.0001	Yes
P*S	3	5152.8645	1717.6215	3.81	.0141	No
T*S	9	51887.0104	5765.2233	12.78	.0001	Yes
P*T*S	9	2440.5104	271.1678	0.60	.7913	No
Error	64	28866.6666				
Total	95	1160072.9895				

Note: P: Signal phasing, T: Traffic pattern, S: Ramp spacing

Two significant interactions between factors were also identified from Table 4: signal phasing and traffic pattern, and between traffic pattern and ramp spacing. The plots of the interactions between signal phasing and traffic pattern may provide good information, but not discussed in this paper. The results of the Tukey's multiple comparison procedure for stops are also investigated. Three levels of groups were identified from each of traffic pattern and ramp spacing. Therefore, it might be concluded that the stop variable was more sensitive than the average delay variable.

CONCLUSIONS

In this paper, the operational performance of two single-barrier three-phase systems was investigated using hardware-in-the-loop system. Type A system had a barrier at the start of both frontage road phases, whereas Type B system had a barrier at the end of both frontage road phases. The modified phasing design was developed and implemented in the controller to emulate the two phasing systems. From the analysis results, following conclusions can be drawn.

The operational performance of the two three-phase controls was similar in terms of average delay. However, the two phasing systems showed performance differences in terms of stops.

The delay performance of each phasing strategy was generally dependent on the traffic pattern and spacing. Type B was a better strategy when frontage roads had heavy traffic demand. Type A phasing outperformed Type B phasing for all cases when the spacing was wider than 600 ft. However, the two phasing strategies gave almost identical delay when the traffic patterns of each intersection were balanced. The trend of delay function showed that the minimum delay ramp spacing could be found between 400 ft and 600 ft.

In general, the stops decreased as the ramp spacing increased. Type B phasing showed less stops when frontage road demand was heavy. Type A phasing showed better performance when there was an unbalanced demand between the two intersections and the spacing was longer than 600 ft. The total stops was the most sensitive test variable.

Signal control of diamond interchanges could be made using a standard eight-phase NEMA control mode for at-grade intersections. The two three-phase systems were emulated under NEMA control mode with a modification of controller phasing design. More flexible phasing strategies could be implemented with the use of the hardware-in-the-loop control.

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