Comparison of Three Unconventional Arterial Intersection Designs: Continuous Flow Intersection, Parallel Flow Intersection, and Upstream Signalized Crossover

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Abstract— This research is aimed to evaluate and compare the operational performance of three unconventional intersections: Continuous Flow Intersection (CFI), Parallel Flow Intersection (PFI) and Upstream Signalized Crossover (USC). For this purpose, various experimental designs, including traffic conditions, geometric features and signal plans, were set and the average delays were compared for movements of through-only traffic and left-turn-only traffic. From the results of analysis, all three unconventional intersections outperformed conventional one and among the unconventional intersections, CFI outperformed the others except for some traffic conditions. In the balanced traffic condition scenario, at the low traffic volume level, the average delays of through traffic for PFI were smaller than that of CFI and very similar at the moderate traffic volume level. And this research showed one possibility that the average delays of left-turn-only traffic at PFI will be closer to that of CFI as the traffic volume increases. In the unbalanced traffic condition scenario, under some traffic conditions, PFI outperformed CFI or showed very similar average delay with CFI. And generally, there were not much difference in the average delays between CFI and PFI as compared with that between CFI and USC under the experimental traffic conditions of this research. Considering the accessibility and land use problems of CFI, PFI is a good alternative to reduce the average delays, which is comparable to CFI, and as well reduce the property impact and cost.

I. INTRODUCTION

TRAFFIC congestion at the intersections of arterial roads is mainly caused by the high left-turn traffic volume to the arterial or cross roads. Transportation engineers around the world have adopted many conventional measures, including signal planning and double left-turn lanes, for alleviating this problem [1]. The using of these conventional measures are limited as the modifications of intersection design, such as widening interchanges and building bypasses, are expensive and disruptive [1]. In contrast, the unconventional arterial intersection design (UAID) is one of the methods that can efficiently reduce the congestion with less cost as compare with the conventional measures. General principles of operation and management strategies of the UAID include: 1) emphasis on through traffic movements along the arterial; 2) reduction in the number of signal phases (e.g. left-turn arrow phase); and 3) reduction in the number of intersection conflict points [2]. These principles allow the UAID to reduce the traffic congestion at the intersection and improve the traffic safety.

Many researches suggested that safety and operational efficiency are the major benefits of UAIDs over conventional intersection design. Superstreet, continuous flow intersection (CFI), center turn overpass, and roundabouts can achieve significant reductions in accident frequency, accident severity, stopped delay, and queue length [2]. The CFI can significantly reduce the overall delay and queue lengths respectively by 64% and 61% during the PM peak hour [3]. The modern roundabouts reduce the injury crashes by reducing the traffic speeds and conflicts [4]. The quadrant roadway intersection (QRI) can reduce the system delay by 46%, travel time by 15%and maximum queue length by 88% [5]. Both the parallel flow intersection (PFI) and CFI showed similar results at, respectively, 80% and 75% less delay than the conventional and modern roundabout intersections [6]. The upstream signalized crossover (USC) showed promise in reducing average vehicle delays for intersections that experience higher traffic volumes [7].

The purpose of this research is to compare the operational performance of three UAIDs: CFI, PFI, and USC. These unconventional intersections are similar in that they displace the left-turn traffic to the opposite side of the road and have been already analyzed by previous researches that they outperform the conventional intersection under certain traffic conditions. On the other hand, the way treating the through and left-turn movements, and the operational performance are different for each of these UAIDs. By comparing the

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unconventional intersections with similar characteristics, it will give a better understanding of these intersections and help transportation engineers to apply the UAIDs to current conventional intersections.

This paper consists of the followings: (1) Methodology used to evaluate and compare the operational performance of the UAIDs. (2) Characteristics, including the signal plans and movements, of three UAIDs (3) Experimental designs used for analysis. (4) Results of analysis. Conclusions and further studies are given at the end of this paper.

II. METHODOLOGY

The main procedure for this research is shown in Fig. 1 below. Before analyzing the operational performance of intersections, measure of effectiveness (MOE) should be determined. The Highway Capacity Manual (HCM) suggests the level of service (LOS) criteria for signalized intersection in terms of total control delay [9]. The total control delay is defined as the time in queue delay plus acceleration -deceleration delay. But this criterion is not available for the unconventional intersections considered in this research. In this research, average delay is used as a MOE for operational performance of the signalized intersections. Average delay is a critical performance measure of operations on interrupted-flow facilities and clearly reflects the greater discomfort caused to drivers than travel time [8]. This research compared the average delay of through-only traffic and left-turn-only traffic for each intersection.

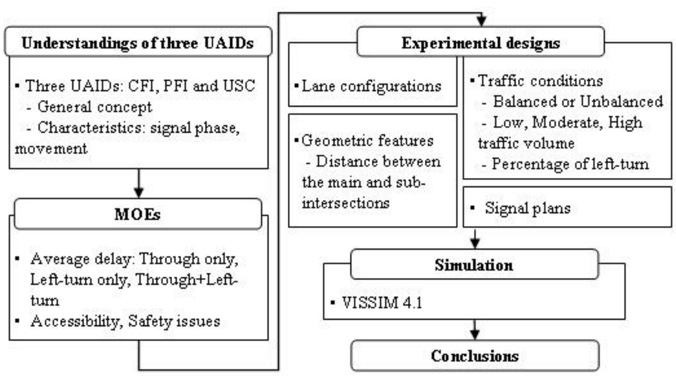

Fig. 1. Research Procedure

In this research, firstly, unconventional intersections are compared with conventional intersection in terms of average delay. After that, average delays of the three unconventional intersections are compared with each other.

III. UNDERSTANDINGS OF THREE UAIDs

The three unconventional intersections, CFI, PFI, and USC, have common general concepts. They (1) eliminate the conflicts between the through and left-turn traffic at the main intersection by displacing the left-turn movements to the opposite side of the road; (2) apply only two signal phases at the main intersection; and (3) create sub-intersections ahead of the main intersection. But each UAID has a different way to treat the through and left-turn movements. In this section, the characteristics of each UAID are described in details.

A. Continuous Flow Intersection

The main element of the CFI is the removal of the left-turn movements out of the main intersection. It is accomplished by adding a signal-controlled, mid-block intersection on the approach approximately 300 feet from the main intersection [3]. At this mid-block intersection, left-turn traffic enters a left-turn lane and then crosses the oncoming traffic during a protected phase that coincides with the green phase of the cross-street traffic at the main intersection.

CFI creates 4 sub-intersections ahead of main intersection and allows 2 signal phases at the main intersection. At the main intersection in phase 1 of Fig. 2, through traffic from EB and WB go through and left-turn traffic from EB and WB, which from the opposite side of the road, make left-turn to the North and South using the same signal phase with through traffic. At the sub-intersection WB, through traffic go through and the vehicles which want to make left-turn stop at this intersection while the through traffic from EB go through. At the sub-intersection NB, through traffic from SB stop at this intersection and the vehicles that want to make left-turn from NB move to the apposite side of the road by crossing this intersection and stop in front of the main intersection.

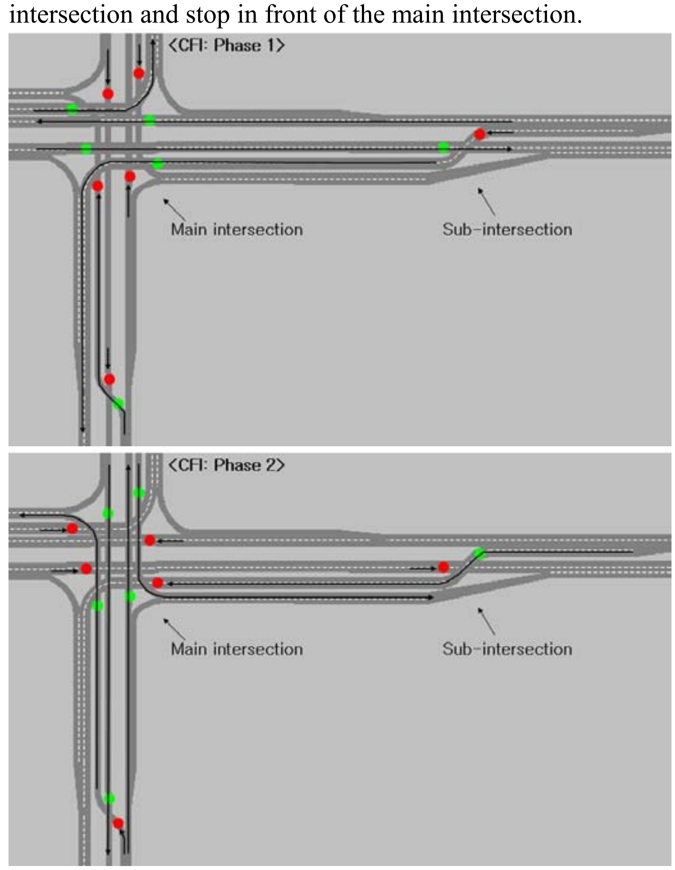

Fig. 2. Signal Phases and Movements of CFI

B. *Parallel Flow Intersection*

The PFI is similar to the CFI in that left-turns cross over opposing travel lanes during the cross-street-through-movement phase [6]. This process of concurrent left-turn and through movements permits a larger volume of through traffic to proceed with no lost time due to the protected left-turn phases. Unlike CFI, however, the PFI accomplishes this operation with bypass-turn lanes parallel to the cross-street center lanes, resulting in a smaller intersection with different characteristics [6].

PFI also creates 4 sub-intersections ahead of the main intersection and allows 2 signal phases at the main intersection. At the main intersection in phase 1 of Fig. 3, through traffic from EB and WB go through. During this signal phase, the left-turn traffic from NB and SB, which go parallel with the through traffic from the EB and WB, make left-turn to the opposite direction of EB and WB and stop in front of the sub-intersections EB and WB. At the sub-intersection WB, through traffic go through and the vehicles that want to make left-turn to South stop at the left-turn bay in front of the main intersection. The vehicles making left-turn from the SB stop at this sub-intersection. At the sub-intersection NB, through and left-turn traffic stop at this intersection and the left-turn vehicles from the WB cross over this intersection and merge to the south direction of the road.

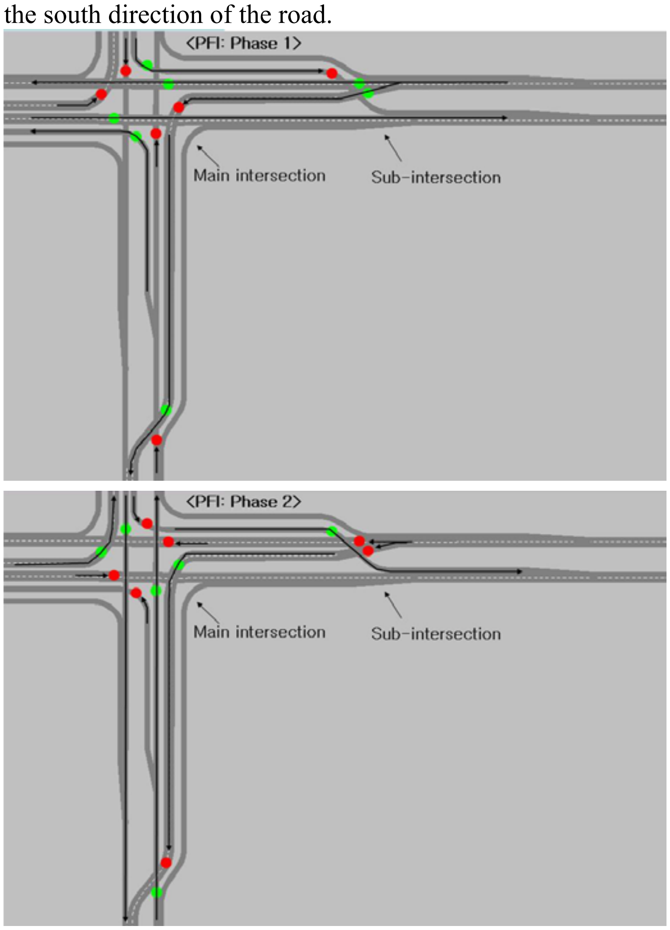

Fig. 3. Signal Phases and Movements of PFI

C. *Upstream Signalized Crossover*

The USC also has similar concept as CFI that left-turn traffic is crossed over to the other side of the road. However, the major difference is that through traffic is also displaced to the other side of the road resulting in a complete switch of traffic at the main intersection [7].

It also creates 4 sub-intersections ahead of main intersection and allows 2 signal phases at the main intersection. At the main intersection in phase 1 of Fig 4, through traffic from EB and WB go through and left-turn traffic from EB and WB make left-turn to the North and South. At the sub-intersection NB, traffic from NB stops at this sub-intersection and the vehicles making left-turn from the WB cross this sub-intersection and go to South. At the sub-intersection EB, while the through and left-turn traffic from the EB cross this sub-intersection and go to the main intersection, through traffic from the WB stop at this sub-intersection.

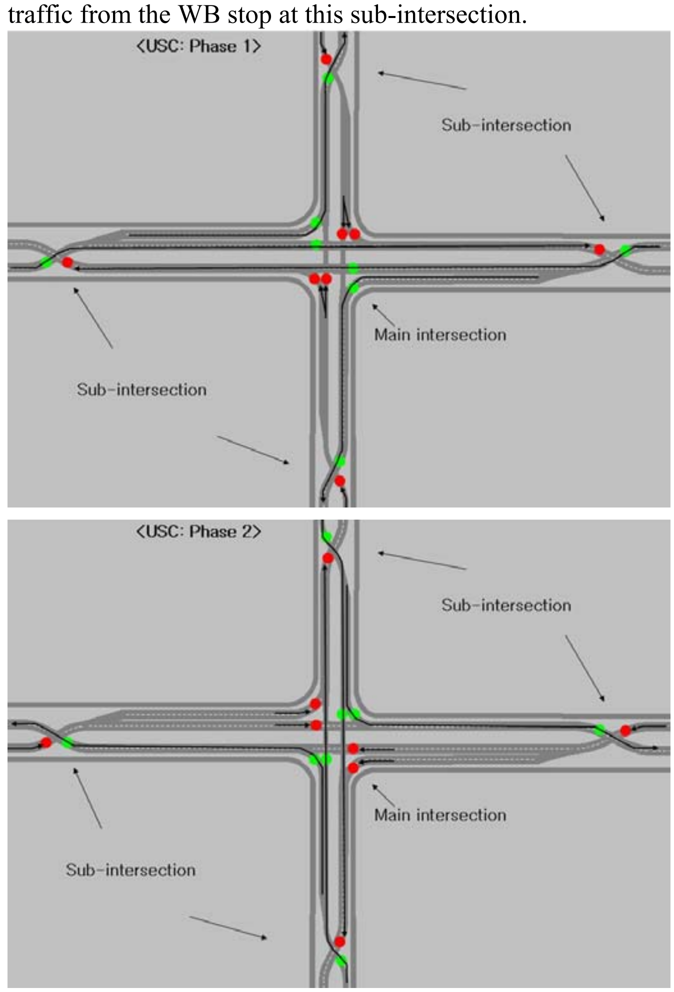

Fig. 4. Signal Phases and Movements of USC

IV. EXPERIMENTAL DESIGNS

Average delay, which is the MOE to compare the operational performance of intersections, is affected by many factors such as through and left-turn traffic volumes, geometric designs, and signal plans. To evaluate and compare the average delay of intersections properly, various traffic conditions with proper geometric design and signal plans should be considered. This paper considered two scenarios which are balanced and unbalanced traffic condition between the main arterial road and minor cross road. In this section, various experimental designs, including lane configurations, geometric features, traffic conditions and signal plans, used for each scenario are described.

A. Lane Configurations

For the four intersections (CFI, PFI, USC and conventional intersection), the following lane configurations were used: (1) all intersections have four approaches (2) for the balanced traffic condition, each intersection has the same number of lanes per approach (two through lanes, one left-turn lane, and one right-turn lane) (3) for the unbalanced traffic condition, the approaches of the main arterial road (East and West bound) have two through lanes, two left-turn lanes, and one right-turn lane per approach and the approaches of minor cross road (North and South bound) have one through lane, one left-turn lane, and one right-turn lane (4) each left-turn movement has an exclusive left-turn lane of 100m in length (5) right-turn movements are channeled through a separate lane of 100m in length.

B. Geometric Features

With the lane configurations, the distance between the main and sub-intersections of the UAID should be determined because this length will affect the capacity of storing the left-turn traffic. Some researches have suggested a distance from 300ft (90m) to 500ft (150m) between the main and sub-intersections for UAIDs [2, 3].

In this research, for the balanced traffic condition scenario, this distance is set to be 100 m for the CFI and PFI, and 120m for USC. And for the unbalanced condition, this distance is calculated by considering the maximum queue length not to block the sub-intersections. It varies from 100m to 250m with respect to the traffic volume level for each UAID.

C. Traffic Volume Conditions

For the balanced traffic condition scenario, the approach traffic volume for each UAID is set to be 1000vph as the low volume level, 1500vph as the moderate volume level and 1800vph as the high volume level. For the conventional intersection, it is set to be 1000vph and 1200vph. The percentage of right-turn volume is fixed at 10% and various percentage of left-turn volume (5%, 10%, 20%, and 25%) is set to consider the effect of the volume for left-turn traffic. For the unbalanced condition, the approach traffic volume of main arterial road is set to be 2000vph as the moderate volume level and 2500vph as the high volume level and the approach traffic volume of minor cross road is set to be 600vph as the low volume level, 900vph as the moderate volume level and 1300vph as the high volume level.

D. Signal Plans

For the main and sub-intersections, the minimum cycle length is calculated by using the equation (1). To do this, V/C and PHF are assumed to be 0.9 and 0.95, respectively. The green time for each phase is calculated by assuming the 3 seconds amber and 1 second red interval for all intersections and considering the critical lane volume for that phase. For the sub-intersections, the off set is set to be 5 seconds by considering the average speed and the distance between the main and sub-intersections.

TABLE 1 shows the signal plans for this research including signal phases and green time length.

$$Cycle = \frac{L}{1 - [\frac{V_c}{1615 \times PHF \times (v/c)}]}$$

$$g_{TOT} = Cycle - L$$

$$g_i = g_{TOT} \times (\frac{V_{ci}}{V_c}) \qquad (1)$$

L : Loss time (redtime+ambertime)

V_c : Critical lane volume

g_{TOT} : Total green time

g_i : Green time of approach i

V_{ci} : Critical lane volume of approach i

TABLE 1. Singal Plans

Traffic volume level (vph)		Cycle length for each intersection (sec)						
		Conventional	CFI/PFI			USC		
Main road	Minor road		1*	2**	3***	1*	2**	3***
Balanced condition								
1000	1000	70	30	30	30	30	30	30
1500	1500	90	50	50	50	50	50	50
1800	1800	-	70	70	70	70	70	70
Unbalanced condition								
2000	600	65	30	30	25	35	45	30
	900	85	35	35	30	40	45	35
	1300	100	45	35	35	50	50	45
2500	600	-	35	35	30	40	50	30
	900	-	40	35	35	40	50	40
	1300	-	50	40	40	50	55	50

*: Main intersection
**: Sub-intersections of the main road (East and West bound)
***: Sub-intersections of the minor road (North and South bound)

E. Simulation Module

In this research, VISSIM 4.1 is used to analyze all experimental designs. Generally, default parameters of VISSIM 4.1 were used, with no change to drive characteristics, lane width (3.5m), grades, or vehicle distributions. Truck percentages were assumed to be 2% and average speed of 50km/h was assumed for all approaches. Travel time detectors were placed relatively far upstream and downstream of the main intersection for better capture of the delays caused by the intersection. TABLE 2 shows the experimental designs used in this research.

TABLE 2. Experimental Designs

Approach volume (vph)		Intersections	Turning fraction	Vehicle composition
Major road	Minor road			
Balanced condition				
1000	1000	CFI,USC,PFI, and conventional	85 / 5 / 10 80 / 10 / 10 70 / 20 / 10 65 / 25 / 10	car: 98% truck: 2%
1500	1500	CFI,USC,PFI, and conventional(1200)		
1800	1800	CFI,USC,PFI		
Unbalanced condition				
2000	600	CFI,PFI, USC, and conventional	main :75/20/5, minor:83/9/8	car: 98% truck: 2%
	900		main :75/20/5, minor:78/17/5	
	1300		main :75/20/5, minor:77/19/4	
2500	600	CFI,PFI, USC	main :72/24/4, minor:83/9/8	
	900		main :72/24/4, minor:78/17/5	
	1300		main :72/24/4, minor:77/19/4	

V. RESULTS OF ANALYSIS

In this research, average delay is compared for two movements: through-only traffic and left-turn-only traffic of the balanced and unbalanced traffic condition scenarios. As the right-turn traffic is assumed to be free right turn, it is not considered for the comparison.

A. Balanced traffic condition scenario

1) Average Delay of Through-only Traffic

In TABLE 3, all three unconventional intersections reduced significantly the average delay as compared with the conventional one.

TABLE 3. Comparison of Conventional and Unconventional intersections for Through-only Traffic

Movement	% of Left-turn volume	Average delay (sec/veh) (1000vph)			
		CFI	PFI	USC	Convent.
Through-only	5%	20.8	11.4	31.9	47.5
	10%	19.6	11.1	31.8	43.4
	20%	17.3	10.9	31.6	39.9
	25%	16.4	10.9	31.7	39.3

In Fig. 5, at the low traffic volume level (1000vph), PFI showed smaller average delays than CFI for the through traffic. By increasing traffic volume, the average delays of PFI increased more rapidly than CFI and they showed very similar performance at the moderate traffic volume level (1500vph). For the further increase in traffic volume, the average delays of PFI still increased more rapidly than CFI and finally, PFI showed larger average delays than CFI at the high traffic volume level (1800vph). Even though PFI showed smaller average delays than CFI at the low traffic volume level and larger delays than CFI at the high volume level, these average delays were much smaller than that of the USC.

2) Average Delay of Left-turn Traffic

In TABLE 4, under all percentage of left-turn volume conditions, the average delay of left-turn-only traffic for all three unconventional intersections were reduced significantly as compare with the conventional intersection.

Movement	% of Left-turn volume	Approaching traffic volume (vph)	Average delay (sec/veh)		
			CFI	PFI	USC
Through-only	5%	1000	20.8	11.4	31.9
		1500	24.4	23.0	60.7
		1800	31.0	40.0	75.5
	10%	1000	19.6	11.1	31.8
		1500	22.4	22.7	58.9
		1800	27.1	38.2	72.5
	20%	1000	17.3	10.9	31.6
		1500	19.8	22.5	57.7
		1800	23.6	37.8	73.1
	25%	1000	16.4	10.9	31.7
		1500	18.5	22.2	57.4
		1800	22.1	37.1	76.5

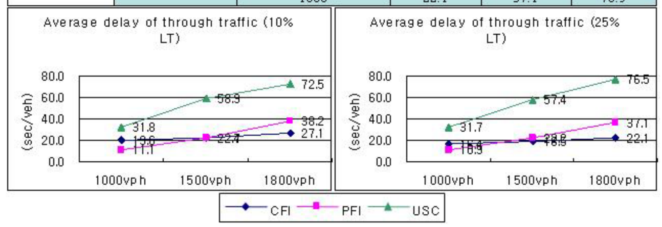

Fig. 5. Average Delay of Through-only Traffic of UAIDs

TABLE 4. Comparison of Conventional and Unconventional intersections for Left-turn-only Traffic

Movement	% of Left-turn volume	Average delay (sec/veh) (1000vph)			
		CFI	PFI	USC	Convent.
Left-turn-only	5%	10.2	19.7	34.8	37.3
	10%	10.8	19.4	35.7	39.3
	20%	13.6	21.7	36.5	39.4
	25%	16.4	22.2	38.0	41.4

In Fig. 6, the CFI showed the smallest average delays followed by the PFI and USC. Similar to the results of through-and-left-turn traffic, CFI outperformed the other unconventional intersections but the difference of average delays between CFI and PFI were smaller than that between CFI and USC.

However, the increasing rates of average delay with respect to the increase of volume were different for these three UAIDs. Increasing rate of delay for PFI was decreased, in contrast to an increase in CFI and USC, as the traffic volume increases. It seems that more analyses are needed to test whether the average delay of left-turn-only traffic at PFI will become closer to that of CFI as the traffic volume increases.

Movement	% of Left-turn volume	Approaching traffic volume (vph)	Average delay (sec/veh)		
			CFI	PFI	USC
Left-only	5%	1000	10.2	19.7	34.8
		1500	18.8	31.2	50.0
		1800	31.1	37.5	73.0
	10%	1000	10.8	19.4	35.7
		1500	20.7	31.7	51.7
		1800	32.9	39.5	69.7
	20%	1000	13.6	21.7	36.5
		1500	22.8	35.7	51.6
		1800	35.9	43.2	75.1
	25%	1000	16.4	22.2	38.0
		1500	24.5	37.4	53.2
		1800	39.2	44.7	77.1

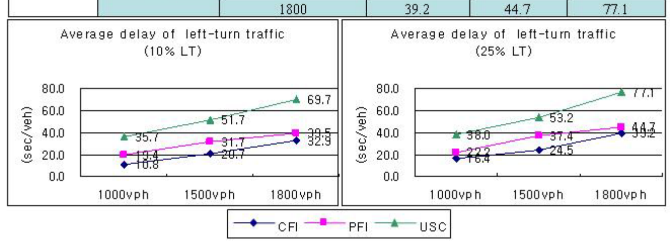

Fig. 6. Average Delay of Left-turn-only Traffic of UAIDs

B. Unbalanced traffic condition scenario

1) Average Delay of the Whole Intersection

In Fig. 7, all three unconventional intersections reduced significantly the average delay as compared with the conventional one under the moderate traffic volume level at the arterial road. In general, CFI outperformed other two unconventional intersections under all traffic conditions but at the low and moderate traffic volume level of the minor road, CFI and PFI showed very similar average delay. And the difference of average delays between CFI and PFI were smaller than that between CFI and USC.

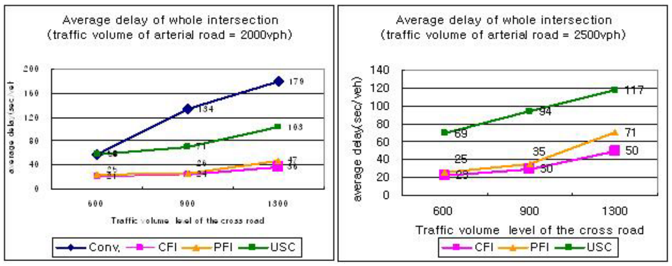

Fig. 7. Average Delay of the Whole Intersection

2) Average Delay of the Arterial Road

As shown in Fig. 8, for the through traffic and left-turn traffic of the arterial road, PFI shows very similar average delay under the low and moderate traffic volume level of the cross road. Generally, CFI outperformed other unconventional intersections but the difference of average delays between CFI and PFI were smaller than that between CFI and USC.

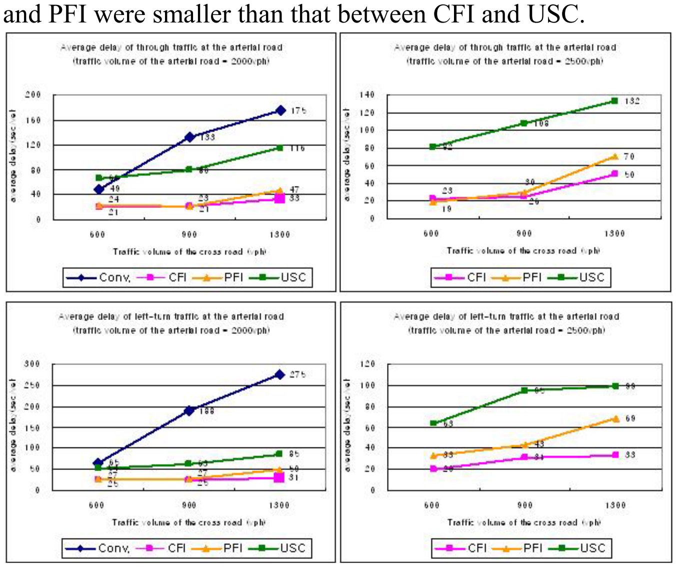

Fig. 8. Average Delay of the Arterial Road

3) Average Delay of the Cross Road

As shown in Fig. 9, for the through traffic of the cross road, PFI shows very similar average delay under moderate and high traffic volume level of the minor road. For the left-turn traffic of the cross road, CFI outperformed other two unconventional intersections under all traffic volume conditions but the difference of average delays between CFI and PFI were smaller than that between CFI and USC.

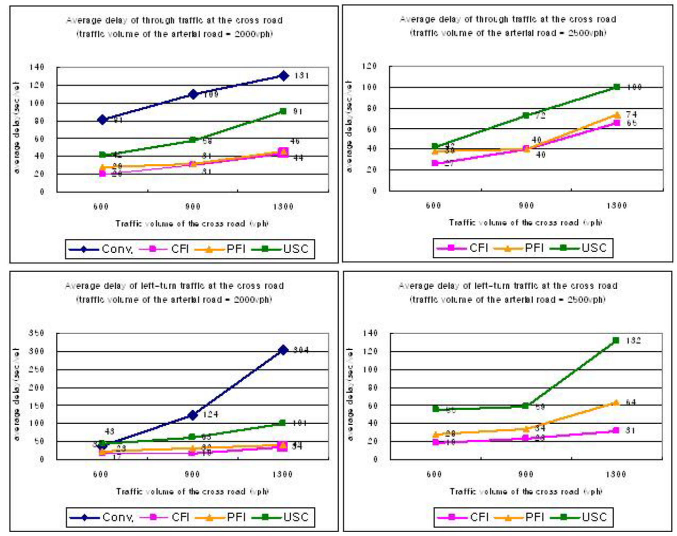

Fig. 9. Average Delay of the Cross Road

VI. CONCLUSIONS AND FUTURE STUDIES

This research is aimed to evaluate and compare the operational performance of three unconventional intersections: CFI, PFI and USC. For this purpose, the average delay was compared for two movements: through-only traffic and left-turn-only traffic. From the results, all three unconventional intersections outperformed the conventional one and among the unconventional intersections, CFI outperformed the others except for some traffic conditions. In the balanced traffic condition scenario, at the low traffic volume level, the average delays of through traffic for PFI were smaller than that of CFI and very similar at the moderate traffic volume level. And this research showed one possibility that the average delays of left-turn-only traffic at PFI will be closer to that of CFI as the traffic volume increases. In the unbalanced traffic condition scenario, under some traffic conditions, PFI outperformed CFI or showed very similar average delay with CFI. And generally, there were not much difference in the average delays between CFI and PFI as compared with that between CFI and USC under the experimental traffic conditions of this research. TABLE 5 shows the summary of results of this research.

Some researches have mentioned the disadvantages of CFI [2, 6]. The CFI is a very efficient alternative to reduce the congestion at the intersection with less cost compared with the widening of intersections or building bypasses, but it restricts the accessibility to the business area near the intersection and requires land for the left-turn bay lanes.

PFI has been mentioned as an alternative to reduce the congestion with less impact and at lower cost than conventional and other unconventional intersection designs. It can reduce property impacts and is flexible in application as compared to other unconventional intersection alternatives [6].

TABLE 5. Summary of Results

Traffic volume level (vph)		Average delay (sec/veh)				
		Main arterial road		Minor cross road		Whole intersection
Main road	Minor road	Through	Left-turn	Through	Left-turn	
Balanced condition a)						
1000	1000	**PFI<CFI<USC**	CFI<PFI<USC	-	-	-
1500	1500	**CFI<PFI<USC**	CFI<PFI<USC	-	-	-
1800	1800	CFI<PFI<USC	CFI<PFI<USC	-	-	-
Unbalanced condition						
2000	600	**CFI<PFI<USC**	**CFI<PFI<USC**	CFI<PFI<USC	CFI<PFI<USC	**CFI<PFI<USC**
	900	**CFI<PFI<USC**	**CFI<PFI<USC**	**CFI<PFI<USC**	CFI<PFI<USC	**CFI<PFI<USC**
	1300	CFI<PFI<USC	CFI<PFI<USC	**CFI<PFI<USC**	CFI<PFI<USC	CFI<PFI<USC
2500	600	**PFI<CFI<USC**	CFI<PFI<USC	CFI<PFI<USC	CFI<PFI<USC	**CFI<PFI<USC**
	900	**CFI<PFI<USC**	CFI<PFI<USC	**CFI<PFI<USC**	CFI<PFI<USC	**CFI<PFI<USC**
	1300	CFI<PFI<USC	CFI<PFI<USC	**CFI<PFI<USC**	CFI<PFI<USC	CFI<PFI<USC

■ : PFI outperformed CFI or PFI and CFI show very similar average delay
a) RT:10%, LT: 5%, 10%, 20%, 25%, Through: 85%, 80%, 70%, 65%

In this research, PFI and CFI showed very similar average delays under certain traffic conditions and even though CFI outperformed PFI, the outperformance is very limited. Considering the accessibility and land use problems of CFI, PFI is a good alternative to reduce the average delays, which is comparable to CFI, and as well reduce the property impact and cost.

Several works can be performed in future studies: (1) The Average delays should be compared by using the optimized signal plans; (2) Analyses with higher traffic volumes are needed to examine the substitutability of PFI for CFI at these traffic volume levels.

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