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# Pedestrian Timing Alternatives and Impacts on Coordinated Signal Systems Under Split-Phasing Operations

Zong Z. Tian, Tom Urbanik, Roelof Engelbrecht, and Kevin Balke

**Split phasing can sometimes be more efficient in serving vehicular traffic under certain geometric and traffic flow conditions, such as the case in which a high volume of left-turning traffic is served from a shared-lane configuration. However, pedestrian crossing-time requirements can have a significant impact on intersection operations, especially in coordinated signal systems. Various alternatives for providing pedestrian timings under split-phasing operations are presented. The advantages and disadvantages, implementation strategies, and potential impact on intersection operations, especially on coordinated signal systems, are addressed with regard to each timing alternative. Further, the concept of the two-stage crossing design and the use of an exclusive pedestrian phase under split-phasing operations are investigated. The proposed model can be used to determine when exclusive pedestrian phasing can actually improve operational efficiency.**

Split phasing is a commonly used signal-phasing scheme that can serve vehicular traffic efficiently under certain geometry and traffic flow conditions, such as on a side street where a high volume of left-turning traffic is served from a shared left and through lane. However, lack of consideration of pedestrian crossing-time requirements may significantly reduce the efficiency of intersection operations. The purpose of this paper is to evaluate various split-phasing alternatives with respect to pedestrian timing considerations. The study focuses on the impact of various split-phasing alternatives on traffic operations, the implementation strategies, and identification of the most efficient split-phasing schemes.

A number of issues exist related to split-phasing and pedestrian timing treatments. So that a driver unfamiliar with an intersection may understand that he or she has a protected movement, a left-turn arrow must be displayed; however, the display with a left-turn arrow would require serving the pedestrians on each crosswalk in two separate sequential phases. A significant impact can be imposed by pedestrian crossings because the time required for a pedestrian to cross a major arterial street is usually significantly longer than the time required serving the traffic demand on a split phase.

In a recent study, Urbanik et al. (*1*) provided comprehensive evaluations of the various split-phasing alternatives with respect to pedestrian crossing treatments. The researchers evaluated the split-phasing alternatives currently being used in practice from the point of view of efficiency and safety. The study proposed a new split-phasing scheme, namely, a protected/permitted left-turn display, which would display a green ball when the opposing (to the left turn) pedestrian phase is active and a left-turn arrow when the opposing pedestrian phase is not active. Such a phasing scheme would improve the operational efficiency while maintaining safety. Some earlier studies (*2, 3*) focused on pedestrian safety associated with right-turning movements and investigated various techniques for minimizing the conflicts, including the use of exclusive pedestrian phases. Tian et al. (*4*) investigated various techniques to minimize the pedestrian impact on coordinated signal systems, such as the use of lead/lag phasing on the side street. None of these studies, however, have dealt in much detail with the impact of split phasing on coordinated signal systems. It is also necessary to further investigate other potential design alternatives with split-phasing operations.

Various pedestrian timing treatments within modern signal controllers are addressed first. Different split-phasing alternatives with respect to pedestrian timing considerations are then identified. The advantages and disadvantages of each phasing alternative are discussed, and the operational efficiency of each timing alternative is examined on the basis of coordinated signal system operations. A model is proposed to quantitatively compare the standard split-phasing scheme with the exclusive pedestrian-phasing scheme. A summary and conclusions are provided at the end of the paper.

## PEDESTRIAN TIMING TREATMENT IN SIGNAL CONTROLLERS

In modern signal controllers, pedestrian timing is normally handled with the following four approaches: (*a*) no pedestrian timing consideration, (*b*) pedestrian timing concurrent with vehicle phases, (*c*) a special pedestrian overlap phase, and (*d*) an exclusive or "scramble" pedestrian phase. Each of these four approaches is discussed below.

### No Pedestrian Timing Consideration

A pedestrian signal head will not be provided at the crosswalk when pedestrian timing is not considered. Pedestrians would have to observe the vehicular signals and cross with the parallel traffic flows. The phase duration is totally controlled by vehicular demand. Although this is the least costly alternative, it is not the preferred alternative in many urban areas.

### Pedestrian Timing Concurrent with Phases

Pedestrian timing concurrent with vehicle phases is a common practice at most signal locations. Pedestrians cross the street concurrently with the adjacent through-vehicle movements and are provided with

Texas Transportation Institute, Texas A&M University System, College Station, TX 77843-3135.

"Walk" and flashing "Don't Walk" (FDW) indications while they are crossing the intersection. The "Walk" and FDW intervals are a portion of the timing of the adjacent vehicle phases. Sufficient time should be provided for the "Walk" and FDW intervals to ensure safe crossing of the street. When there is no pedestrian call, the actual duration of the phase is governed by the vehicle demand. When there is a pedestrian call, the actual duration of the phase is governed by the maximum of the time required to serve the vehicle demand and the required pedestrian crossing time. Although concurrent phasing does not separate the conflicts between right-turning vehicles and pedestrians, it provides positive information to the pedestrians when it is generally safe to cross the intersection. Because the minimum required pedestrian crossing time is included in the vehicle phases, frequent activations of the pedestrian phase can significantly reduce the intersection capacity.

### Special Pedestrian Overlap Phase

Overlap pedestrian phases are mainly used for the purpose of improving operational efficiencies. This technique allows a specifically designated pedestrian phase to overlap with its parallel vehicle phases, thus minimizing the total time consumed by pedestrian crossings. Details of this technique and the implementation strategies are discussed later in this paper.

### Exclusive or Scramble Phase

Exclusive or scramble pedestrian phases have been used at locations where significant pedestrian activity and high turning traffic volume exist. Using an exclusive pedestrian phase completely separates the conflicts between vehicular movements and pedestrians. Pedestrians cross in all directions during the exclusive pedestrian phase, which provides maximum protection to the pedestrians. However, intersection capacity may be significantly reduced because of the time consumed to exclusively serve the pedestrians.

## SPLIT-PHASING DESIGN ALTERNATIVES

In this section various forms of split-phasing design will be identified with respect to various treatments of pedestrian timing. The techniques to be used for implementation in the signal controllers will be addressed. The potential impact of each timing alternative on traffic operations will also be discussed.

### No Pedestrian Signal Display

When pedestrian timing is not provided, a typical phasing scheme for a traffic signal with split-phasing operation on the side street can be as illustrated in Figure 1. Figure 1*a* shows a traditional phasing scheme, and parts *b* and *c* show two alternatives for the controller phase and ring configurations for implementing the split-phasing scheme in a controller. It can be seen that the two approaches can be controlled either by using the two phases in Ring 1 (Φ3 and Φ4) or by using the two phases in different rings (e.g., Φ4 and Φ8) with a barrier in between.

The phasing scheme without consideration of pedestrian timing does not provide the means to eliminate pedestrian and vehicle conflicts. Although pedestrian crossing does not directly affect the signal operations, it is not a preferred alternative because of the lack of protection for pedestrian crossings and the related safety concerns.

### Protected Left-Turn Arrow Display

Split phasing with a protected left-turn arrow display, the preferred display from a driver's point of view, requires that a green arrow be displayed while the approach has the green phase. To implement this display, a four- or five-section signal head must be used. As shown in Figure 2, the two crosswalks have to be served in two separate sequential phases. For example, the pedestrians using the east crosswalk would be served while the northbound (Controller Φ3) receives the green, and the pedestrians using the west crosswalk would be served when the southbound (Controller Φ4) receives the green. (A dashed left-turn or right-turn arrow in all the illustrations presented in the following text indicates a permitted movement in which the vehicles have to yield to the pedestrians.) The proposed ring and phase configurations for such a phasing scheme are shown in Figure 2*b*. The pedestrian timing ("Walk" and FDW intervals) is accommodated in the concurrent vehicular phases (Φ3 and Φ4).

The main advantage of such a phasing design is that it eliminates the conflicts between the left-turning vehicles and the pedestrians. From a traffic operations standpoint, however, this phasing is less efficient because of the time consumed by pedestrians when pedestrian crossing must be accommodated on both crosswalks during the same cycle. The impact is more dramatic when the required pedestrian crossing time is significantly higher than the time required to serve the vehicle demand, which is typically the case for the side street, where split phasing is often used. Another issue related to split phasing with protected left-turn display is the potential impact on a coordinated signal system, which will be addressed in more detail later in this paper. To minimize the pedestrian impact, an alternative solution is to provide a pedestrian signal at only one crosswalk; however, this may not be the preferred design from the point of view of pedestrian safety and convenience.

### Permitted Left-Turn Ball Display

In order to reduce the impact of pedestrian timing with the protected left-turn arrow display, some jurisdictions use a permitted left-turn ball display for split-phasing operation. With this alternative, a green ball is displayed for the approach receiving the green phase. As with normal permitted left-turn phasing operations, the left-turning vehicles have to yield to pedestrians in the crosswalk. Figure 3 shows the permitted left-turn ball display phasing scheme and the recommended controller phase and ring configurations. A three-section signal head is sufficient for this application.

With a permitted left-turn display, the pedestrian phase (Φ8) overlaps the two vehicle phases (Φ3 and Φ4). This arrangement permits pedestrians to cross in both crosswalks during both side street phases.

The major advantage of this phasing design is that pedestrian crossings are accommodated in a single phase, which minimizes the impact of pedestrian timing and improves operational efficiency. However, use of a green ball display with such a phasing scheme has raised concerns among traffic engineers. The first concern is that a left-turning vehicle might get trapped when it has already entered the intersection and is yielding to a pedestrian on the left but its own vehicle phase terminates. The second concern is that the green ball display under

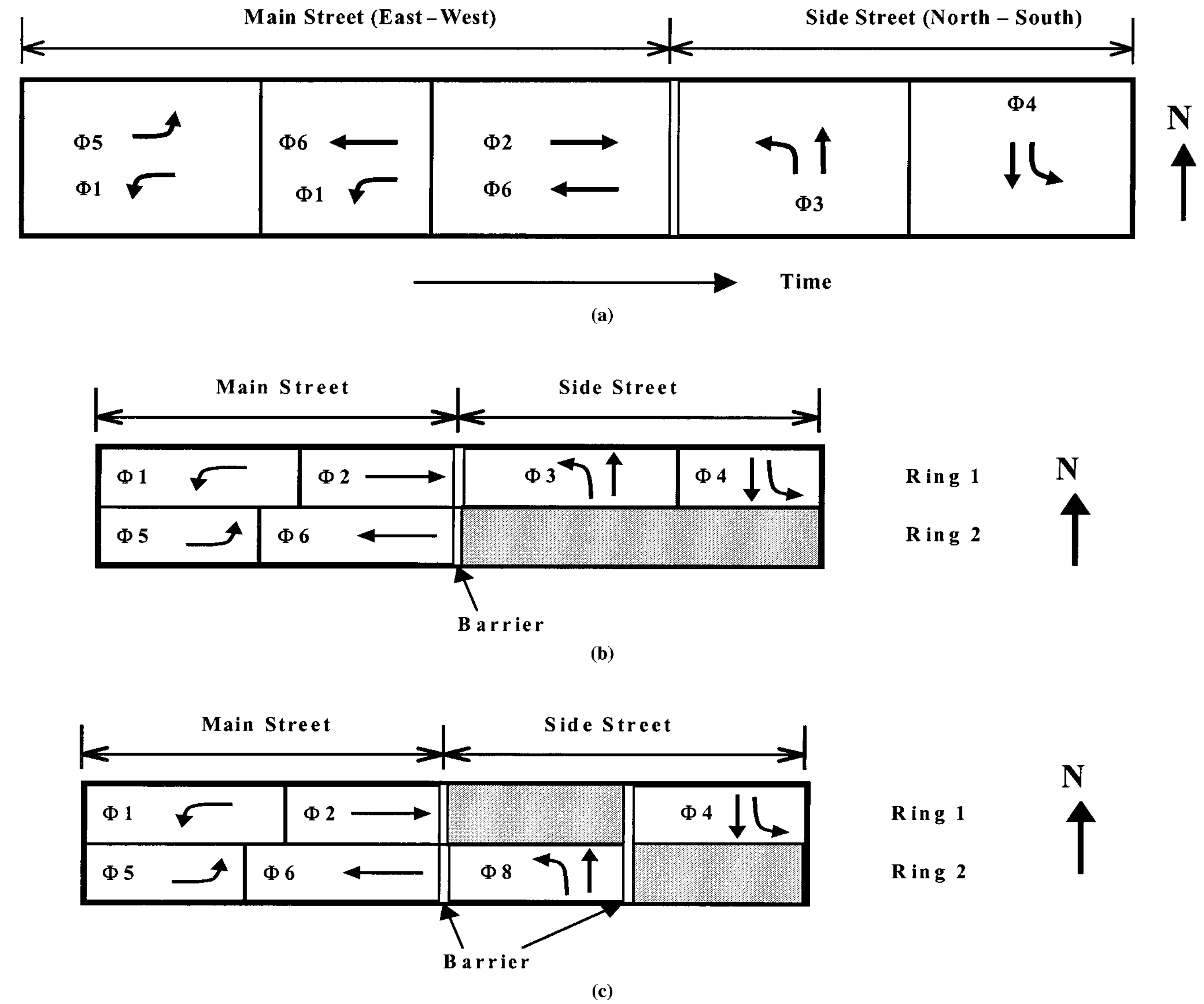



FIGURE 1 Split phasing without pedestrian phase: (*a*) phasing scheme, (*b*) controller phase and ring configurations using phases in Ring 1, (*c*) controller phase and ring configurations using phases in Ring 1 and Ring 2.

split-phasing operation could condition drivers to incorrectly assume that left turns are protected, which could cause a driver to make a left turn without yielding to opposing traffic at a permitted left-turn location (*3*). The third concern is the likely increase of start-up lost time because a green ball does not provide a clear indication to a driver unfamiliar with the operation of the intersection whether he or she is supposed to accelerate and proceed. Despite the various concerns, the permitted left-turn display under split-phasing operation has gained acceptance by some traffic engineers and jurisdictions.

## Protected/Permitted Left-Turn Display

Because of the efficiency and safety concerns related to the protected or permitted left-turn display phasing scheme, an alternative solution, namely, a protected/permitted split-phasing scheme, was proposed by Urbanik et al. (*1*). The basic idea is to provide a protected left-turn arrow when the conflicting pedestrian phase is inactive but to provide a permitted green ball when the conflicting pedestrian phase is active. For example, when a pedestrian is being served or a pedestrian call has been placed before the side street phase begins, the conflicting left-turn arrow would be omitted. On the other hand, if a left-turn arrow were being displayed (i.e., no pedestrian call is placed before the side street phase starts), no pedestrian call would be served until the next cycle.

Because of the complexity of this phasing scheme, a controller must be able to handle multiple phases and a flexible ring structure if it is going to be implemented in the field. For example, implementing this phasing scheme would require the use of 10 phases and 4 rings. Figure 4 illustrates the phasing scheme and the proposed controller phase and ring configurations. Details on the implementation process can be found in the study by Urbanik et al. (*1*).

The proposed protected/permitted phasing scheme provides an alternative solution between the permitted and protected left-turn phasing schemes. Such a phasing scheme would provide efficiency and safety during the protected phase (e.g., reducing start-up lost time) and would minimize the impact of pedestrian crossing by accommodating the pedestrians in two parallel pedestrian phases.

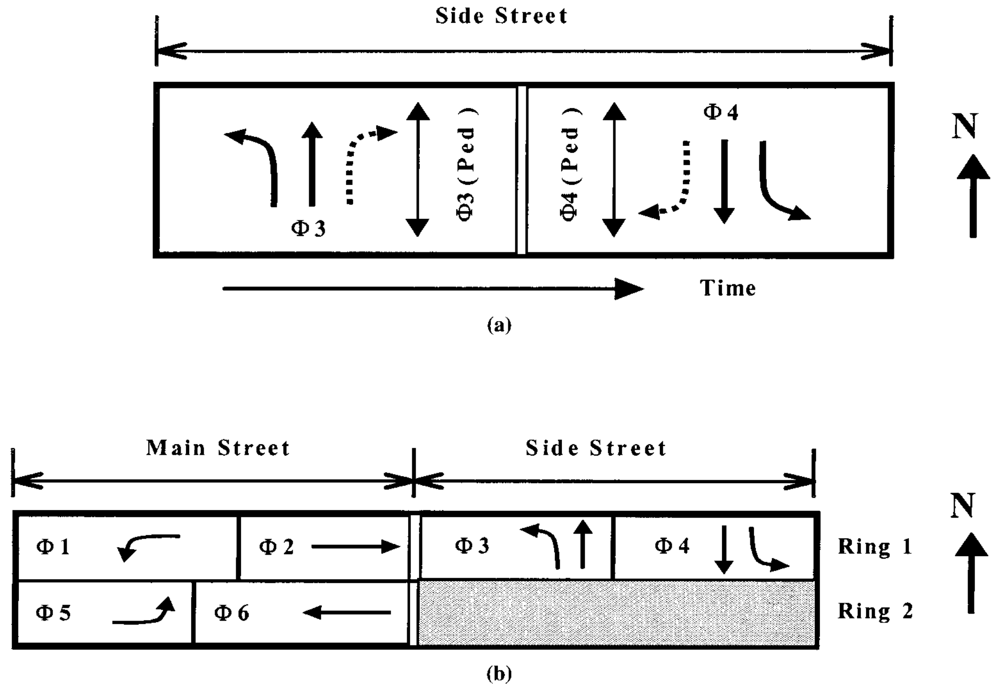



FIGURE 2 Split phasing with protected left-turn arrow display: (*a*) phasing scheme, (*b*) controller phase and ring configurations.

### Protected Left-Turn Display with Two-Stage Crossing

Two-stage crossing refers to the case in which a pedestrian crossing has to be completed in two stages. Pedestrians would have to observe pedestrian signal indications during both crossing stages. The use of a two-stage crossing design is appropriate when the street to be crossed is wide and a median refuge island exists. An appropriate phasing design with two-stage crossing could minimize the impact of the protected left-turn display. Figure 5 shows the phasing scheme and the proposed controller phase and ring configurations. The left-turning movements are controlled by standard protected left-turn displays.

As shown in Figure 5, the pedestrian phases for the first stage on each crosswalk are handled concurrently with the parallel vehicle phases. A designated pedestrian phase (Φ8) is proposed for the second stage on each crosswalk and overlaps with the two vehicular phases. In this case, the pedestrians would still be allowed to cross to the median while a left-turn arrow was being displayed, which would

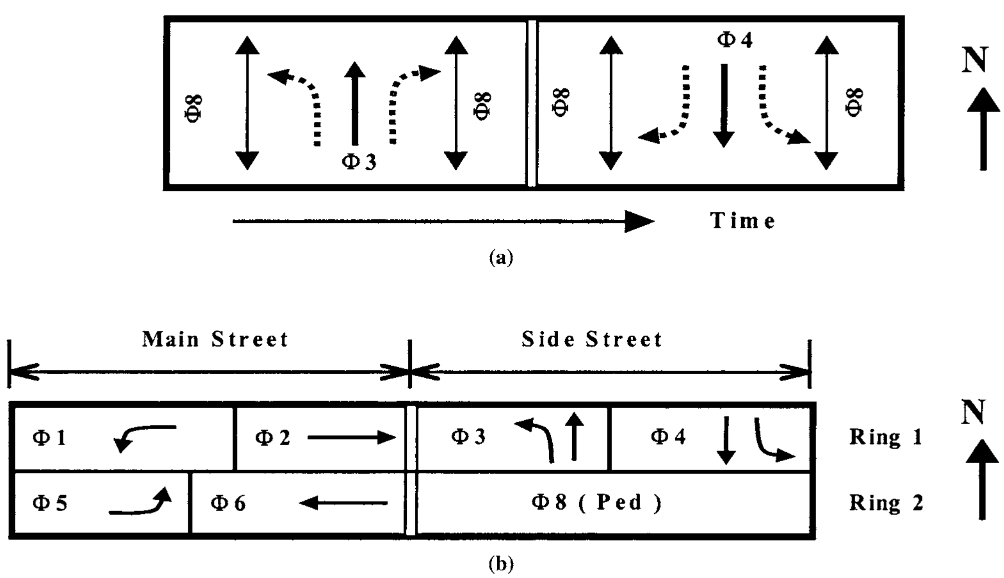
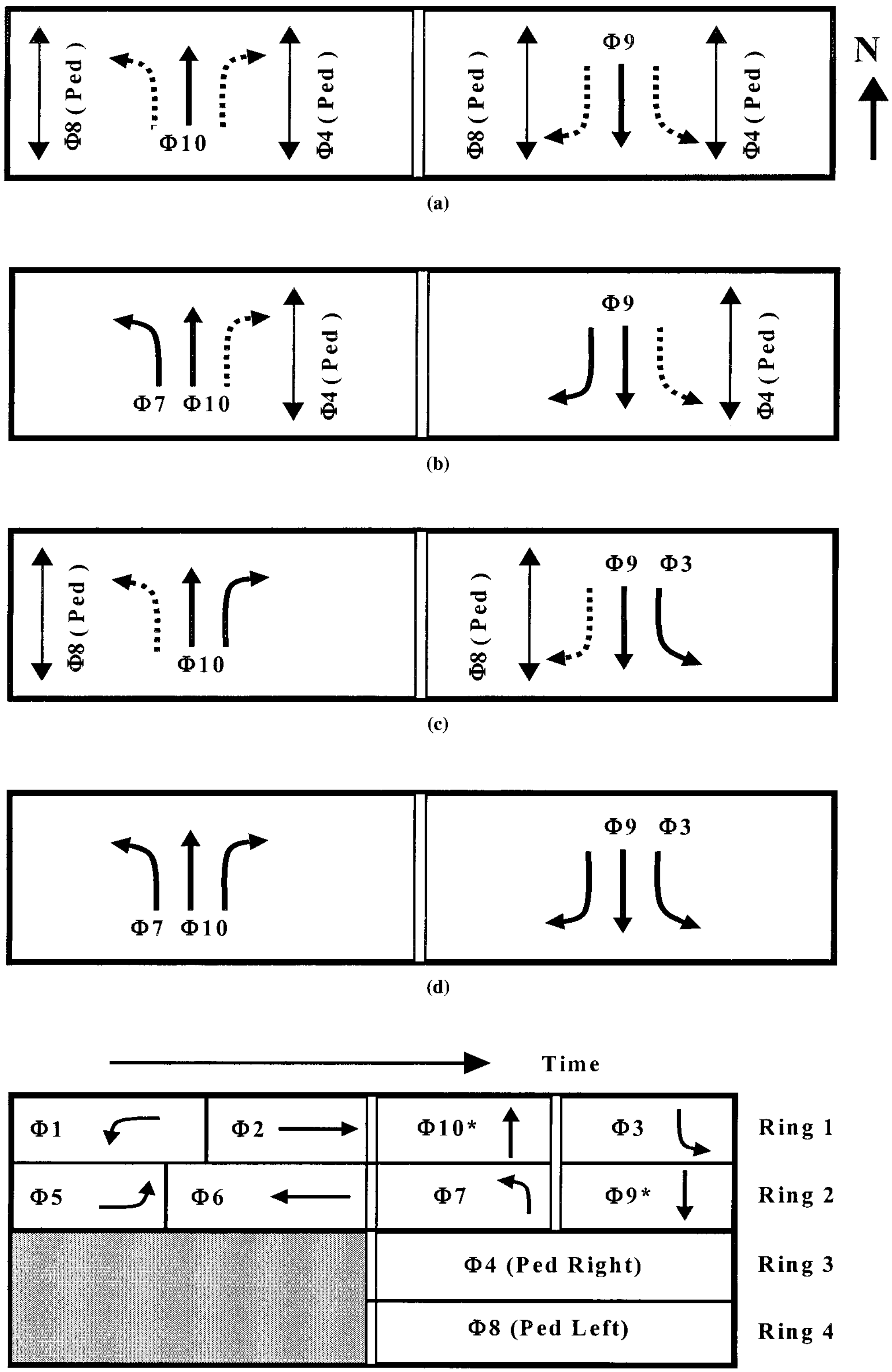



FIGURE 3 Split phasing with permitted left-turn ball display: (*a*) phasing scheme, (*b*) controller phase and ring configurations. (Φ7 is not used.)




**It may be necessary to output ϕ9 and ϕ10 load switches to ϕ8 and ϕ4, respectively.*

(e)

FIGURE 4 Split phasing with protected/permitted left-turn display: (*a*) conflicting pedestrian crossings on both sides, (*b*) conflicting pedestrian crossings on east side, (*c*) conflicting pedestrian crossings on west side, (*d*) without conflicting pedestrian crossings, (*e*) controller phase and ring structures.

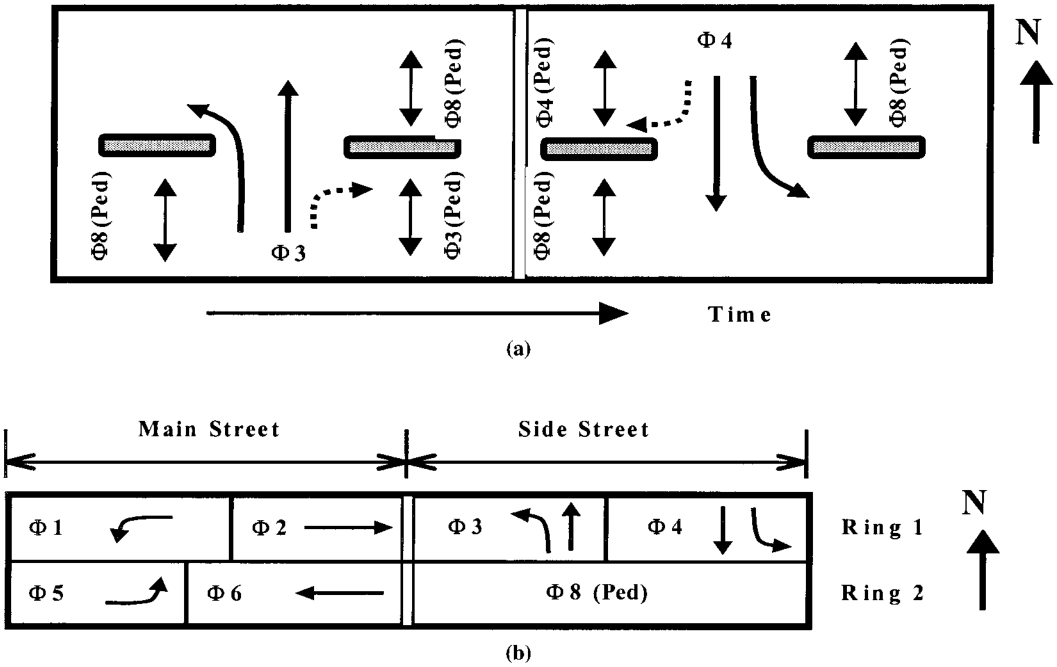



FIGURE 5 Split phasing with two-stage crossing: (*a*) phasing scheme, (*b*) controller phase and ring configurations. (Φ7 is not used.)

have not been possible in the single-stage crossing. As a result, the extra time necessary to serve the pedestrians is reduced.

## Exclusive Pedestrian Phase

With an exclusive pedestrian phase (also called a pedestrian scramble phase), pedestrian crossings occur in all directions while all the conflicting vehicle movements are stopped. An exclusive pedestrian phase is typically used under situations in which significant conflicts exist between pedestrians and turning vehicles or concurrent pedestrian phasing would otherwise cause capacity and queuing problems for the turning vehicles. Figure 6 illustrates the phasing scheme and the proposed controller configurations.

As shown in Figure 6, Φ8 is designated specifically for the pedestrian phase with barriers on both sides. The use of an exclusive pedestrian phase allows pedestrians to cross in all directions simultaneously (including diagonal crossing). Thus, the delay to the pedestrians on

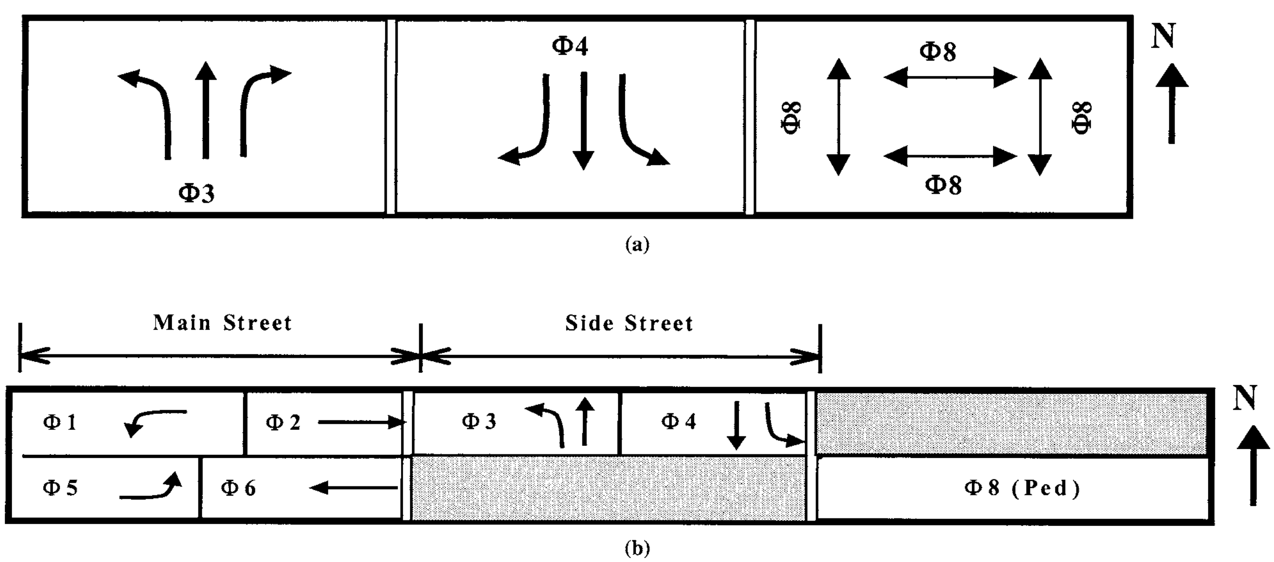



FIGURE 6 Split phasing with exclusive pedestrian phase: (*a*) phasing scheme, (*b*) controller phase and ring configurations. (Φ7 is not used.)

the major street (crossing side street) is usually reduced because the phasing not only allows the pedestrians to cross during the main street concurrent through-vehicle phase, but also allows pedestrians to cross during the exclusive pedestrian phase. Delays to the minor-street pedestrians and vehicles may be increased because the opportunity to serve both the pedestrians and the vehicles concurrently would be excluded.

Practitioners generally believe that the use of an exclusive pedestrian phase under split-phasing operations results in excessive capacity loss for the intersection. Later in this paper, a model is presented to illustrate conditions in which the use of an exclusive pedestrian phase may actually increase intersection capacity under split-phasing operations.

## IMPACT ON COORDINATED SIGNAL SYSTEMS

For coordinated signal systems, traffic engineers have used two general strategies for timing signals to deal with pedestrian crossings: timing based on pedestrian minimums and timing based on vehicle minimums (*4*). Timing based on pedestrian minimums requires accommodation of pedestrian crossing time in the controller phase splits. The major advantage of this strategy is that the signal will remain in coordination regardless of whether there is a pedestrian phase activation; thus, it is a preferred alternative from the point of view of system operations. Timing based on pedestrian minimums has minimal impact on intersection capacity because the extra time not being used by the side street would be reallocated to the main street. One constraint of timing based on pedestrian minimums is the minimum cycle length required to accommodate the pedestrian crossing times on the side street phases. In the following discussion the operational efficiency of the split-phasing alternatives is compared from the point of view of minimum cycle length constraints and the time consumed by the side street phases.

### Minimum Cycle Length Constraints

If the phasing schemes of the major streets are identical but different split-phasing schemes are used on the side street, the minimum cycle length is primarily controlled by the minimum time to be allocated to the side street.

Table 1 provides a summary of such minimum times under each split-phasing alternative. The second column (minimum setting) contains the variables and the equations for calculating the minimum time to be allocated to the side street phases. The third column illustrates the actual values based on the assumed values of each variable. In the examples, it was assumed that the required pedestrian clearance time (FDW) under two-stage crossing is approximately half of that required under single-stage crossing. A 5-s "Walk" time and a 5-s vehicle clearance time (yellow + all red) were also assumed.

From the data in Table 1, the exclusive pedestrian-phasing scheme requires the longest time to be allocated to the side street phases, but the condition will change with different vehicle demand and pedestrian demand. The actual impact of using an exclusive pedestrian phase is discussed in detail in the next section. Among other split-phasing alternatives, the protected left-turn phasing scheme requires the largest time to be allocated to the side street, which would result in the highest cycle length. The condition will not change unless the vehicle demand exceeds the pedestrian crossing time. The permitted left-turn display and the protected/permitted left-turn display have the lowest time to be allocated to the side street phases. The two-stage crossing design also reduces the minimum time compared with the protected left-turn design.

### Exclusive Pedestrian Phase Model

To the best of the authors' knowledge, an exclusive pedestrian phase under split-phasing operations has probably never been implemented in practice. The general belief is that the use of an exclusive pedestrian phase under split phasing would significantly affect intersection operations. A model is presented here that compares the standard protected left-turn arrow display phasing scheme (pedestrian timing concurrent with vehicle phases) with the exclusive pedestrian-phasing scheme.

In the two phasing options shown in Figures 7 and 8 for a side street, $T_a$ and $T_b$ represent the average vehicle demand times for the northbound and southbound approaches, respectively, and $t_p$ represents the required pedestrian crossing time.

**TABLE 1 Comparison of Minimum Cycle Length Constraints**

| Split Phase | Minimum Side Street Time with Pedestrian Crossing, (sec) | |
|---|---|---|
| | *Equation* | *Example:* $T_a=25,\ T_b=8,\ t_p=30$ |
| Protected LT | $max(T_a, t_p) + max(T_b, t_p)$ | $max(25,30) + max(8,30) = 60$ |
| Permitted LT | $max(T_a + T_b, t_p)$ | $max(25+8,30) = 33$ |
| Protected/Permitted LT | $max(T_a + T_b, t_p)$ | $max(25+8,30) = 33$ |
| Protected LT with Two-Stage | $max(T_a, t_{p,2}) + max(T_b, t_{p,2})$ | $max(25,20) + max(8,20) = 45$ |
| Exclusive Pedestrian Phase | $T_a + T_b + t_p$ | $25 + 8 + 30 = 63$ |

*Notes:* 1. $T_a$, $T_b$ = *average vehicle demand time for northbound and southbound, respectively*

2. $t_p$ = *required pedestrian crossing time for single-stage crossing,*

$t_p = WALK + FDW + Y(ellow)$, *with* $WALK = 5$ *sec, and* $Y = 5$ *sec*

3. $t_{p,2}$ = *required pedestrian crossing time for two- stage crossing,*

$t_{p,2} = WALK + FDW/2 + Y = t_p/2 + (WALK + Y)/2 = t_p/2 + (5+5)/2 = t_p/2 + 5$

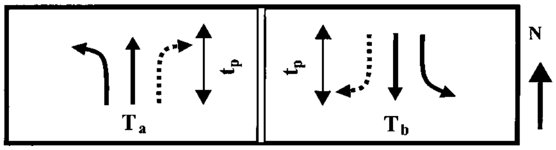



FIGURE 7 Standard protected left-turn display phasing.

To derive the model, the following assumptions were made:

- $t_p$ is greater than both $T_a$ and $T_b$ (usually the case);
- $V_p$, the pedestrian volume in pedestrians per hour, is evenly distributed between the two crosswalks; and
- Pedestrian arrivals are random, and a pedestrian call occurs when the number of pedestrians arriving during a cycle is greater than or equal to 1 at a given crosswalk.

When pedestrian calls exist on both crosswalks during the same cycle, the total amount of time consumed by the side street would be $2t_p$ for the protected left-turn or pedestrian concurrent phasing scheme. On the other hand, the total amount of time consumed by the side street would be $T_a + T_b + t_p$ if an exclusive pedestrian-phasing scheme is used. Since pedestrian crossing may not occur every cycle, the average time consumed by the side street over an hour is related to the pedestrian volume level and the vehicle phase demand. The phasing scheme with a lower total consumed time on the side street would be the most efficient option.

The probability of having at least one pedestrian arriving (assuming a random arrival of pedestrians) during a cycle can be calculated by

$$P(x \geq 1) = 1 - P(0) = 1 - e^{-(V_p/3600)C} \tag{1}$$

where $C$ is cycle length in seconds.

With the exclusive pedestrian-phasing scheme, the total time consumed by the side street over an hour can be calculated by

$$T_1 = \frac{3600}{C}\left\{T_a + T_b + t_p\left[1 - e^{-(V_p/3600)C}\right]\right\} \tag{2}$$

With the standard protected left-turn phasing scheme, the probability of a pedestrian call on a crosswalk is expressed by Equation 3. When a pedestrian call occurs, the actual time consumed by the same approach during a cycle would be $t_p$.

$$p_1 = 1 - e^{-[V_p/(2\times3600)]C} \tag{3}$$

The probability of not having a pedestrian call on a crosswalk is expressed by Equation 4, and the time consumed by the same approach would be $T_a$ or $T_b$.

$$p_{1,0} = e^{-[V_p/(2\times3600)]C} \tag{4}$$

The total time consumed by the side street over an hour can then be calculated:

$$T_2 = \frac{3600}{C}\left(2\left\{1 - e^{-[V_p/(2\times3600)]C}\right\}t_p + e^{-[V_p/(2\times3600)]C}(T_a + T_b)\right) \tag{5}$$

The time difference per hour between the two phasing alternatives would be

$$\Delta = T_2 - T_1 = \frac{3600}{C}\left\{(T_a + T_b - 2t_p)e^{-[V_p/(2\times3600)]C} - (T_a + T_b) + t_p + t_p e^{-(V_p/3600)C}\right\} \tag{6}$$

A positive Δ-value would suggest a time saving by using an exclusive pedestrian-phasing scheme.

If $T = T_a + T_b$, and $\gamma = T/t_p$,

$$\Delta = T_2 - T_1 = \frac{3600}{C}\left\{(1 - \gamma) + e^{-(V_p/3600)C} - (2 - \gamma)e^{-[V_p/(2\times3600)]C}\right\}t_p \tag{7}$$

Figures 9 and 10 are plots of this function with selected cycle length $C$ and pedestrian crossing time $t_p$.

As can be seen from Figures 9 and 10, the cycle length and the pedestrian crossing time $t_p$ would change the magnitude of time saving only. The decision as to whether an exclusive pedestrian phase should be used depends on the pedestrian volumes and the ratio of vehicle phase demand to pedestrian time, γ. From the data presented in Figures 9 and 10, it can be concluded that when γ is less than 0.5 (i.e., the total vehicle demand times are less than half of the pedestrian crossing time), use of an exclusive pedestrian phase would typically result in more efficient traffic operations. When γ is greater than 1.5 (i.e., the total vehicle demand times are greater than 1 and half of the pedestrian crossing time), use of the concurrent phasing with protected left-turn arrow display would be more efficient. Conditions between these two boundaries would require a study based on actual traffic and pedestrian flow conditions before decisions could be made.

## SUMMARY AND CONCLUSIONS

Various forms of split-phasing schemes resulting from various pedestrian timing treatments have been discussed. The advantages and disadvantages of each split-phasing scheme were examined from the point of view of safety and operational efficiency. The efficiency of each phasing scheme was examined on the basis of coordinated signal system operations. The following conclusions were reached:

- Split phasing with protected left turns eliminates the conflicts between pedestrians and left-turning vehicles; however, the provision of two pedestrian splits could significantly reduce the intersection

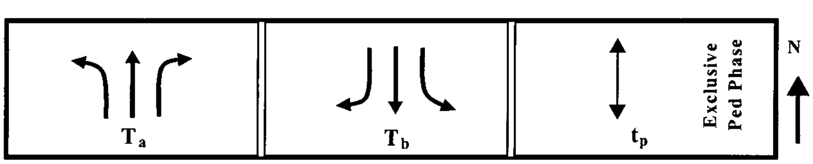



FIGURE 8 Exclusive pedestrian phasing.

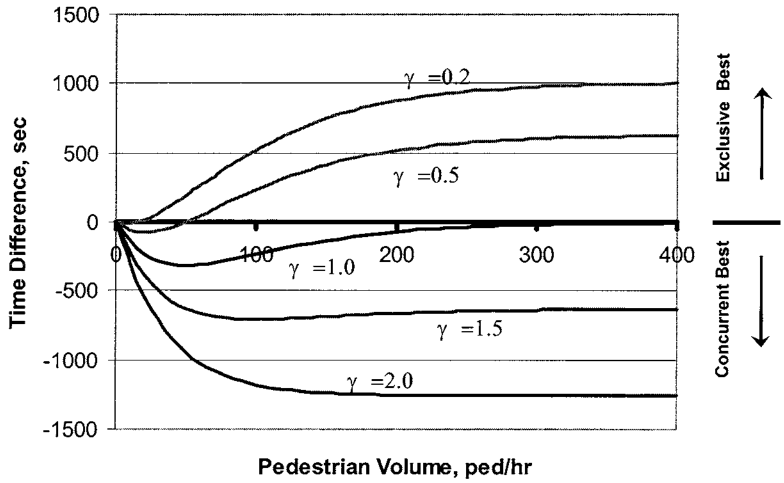



FIGURE 9 Time saving by using exclusive pedestrian phase: $C = 100$ s; $t_p = 35$ s.

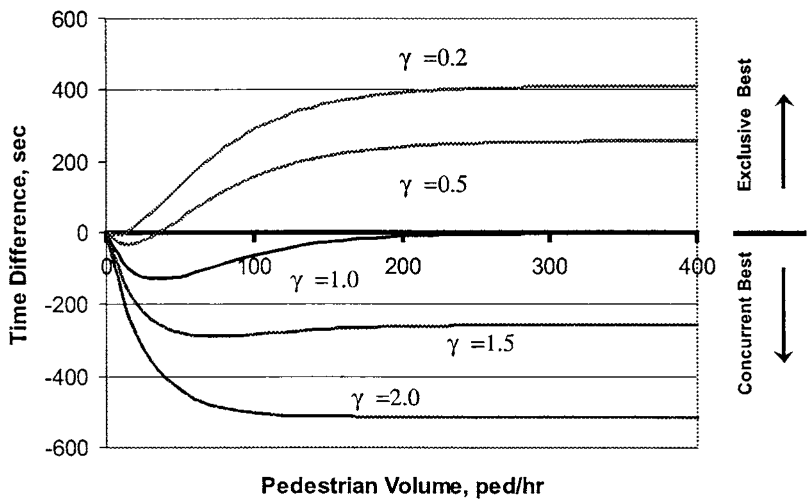



FIGURE 10 Time saving by using exclusive pedestrian phase: $C = 140$ s; $t_p = 20$ s.

capacity and normally requires use of a longer system cycle length in coordinated signal systems to avoid out-of-coordination signals.

- Split phasing with permitted left turns provides more efficient traffic operations because of the accommodation of pedestrian crossing within a single pedestrian phase. However, the display of a green ball may not convey clear information to drivers and could condition them to make a left turn without yielding to opposing traffic at a permissive left-turn location.
- The protected/permitted left-turn phasing scheme provides an alternative solution between the protected and the permitted left-turn phasing schemes. Implementation of such a phasing scheme on existing controllers requires the use of 10 phases and 4 rings. Therefore, the controller must be able to handle multiple phases and flexible ring structures.
- Two-stage pedestrian crossing can also minimize the pedestrian crossing impact compared with a single-stage crossing.
- A model is proposed in this study that can be used to determine when the use of an exclusive pedestrian phase under split-phasing operations can be more efficient compared with the standard protected left-turn display phasing scheme. The use of an exclusive pedestrian-phasing scheme is favored with high pedestrian volumes, wide crossings, and relatively low traffic demand.

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