

# Leading Through Intervals versus Leading Pedestrian Intervals: More Protection with Less Capacity Impact

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## Abstract

When pedestrian, bike crossings, or both are concurrent with a vehicular phase, leading through intervals (LTI) and leading pedestrian intervals (LPI) are signalization techniques that provide a partially protected crossing. With LPI, for a short interval at the start of the crossing phase all traffic is held, enabling some pedestrians to arrive at the conflict zone and thus reinforce their priority before turning vehicles are released. LTI functions similarly except that during the leading interval only turning traffic is held; through traffic is allowed to run. This lessens the negative effect on capacity of LPI, and consequently allows LTI to have a longer leading interval, thus affording pedestrians and cyclists greater protection. Experience of LTI in the cities of Montreal, New York, and Charlotte is reviewed. A model is developed to estimate capacity loss from using LPI and LTI for a range of scenarios in which right turns share a lane with through traffic, in which case LTI can indirectly block through vehicles positioned behind a turning vehicle. While LTI's capacity loss increases with the proportion of right turns, for the wide range of right turn proportions tested, it is still far lower than the capacity loss for an LPI of the same length, especially on multilane approaches.

There is growing interest in many cities to find intersection signalization treatments which improve safety for crossing pedestrians and cyclists while still providing needed vehicular traffic capacity. A common safety concern is conflicts with vehicles making outside turns, that is, right turns as well as left turns from a one-way street (hereafter referred to only as right turns or more simply “turns”) from the street parallel to the paths of pedestrians and cyclists. The conflict is most serious when either the turning speed is high, which could be because of a skew intersection angle, a large curb radius, or a wide receiving roadway, or when the turning volume is high. Conflicts with left turns from two-way streets are also a serious safety concern, often addressed by using protected left-turn phasing, but are outside the scope of this research.

Traditional phasing techniques permit conflicts with right-turning vehicles either during the entire crossing phase or not at all. This study compares two signalization techniques, leading pedestrian interval (LPI) and leading through interval (LTI), which offer an intermediate position, providing a short, conflict-free interval for crossing pedestrians and bikes (typically from 3 s to 11 s), after which right-turn conflicts are permitted. In the sections that follow, this paper reviews four phasing techniques which offer full or partial protection for crossings,

describes analytical models developed to determine the capacity impact of LPI and LTI, and compares LPI and LTI in relation to a capacity–protection tradeoff. It also discusses practical aspects of the relatively unknown LTI technique.

## Signalization Techniques with Full or Partial Crossing Protection

### Exclusive Pedestrian Phase

In an exclusive pedestrian phase, all vehicular movements are held while pedestrians are allowed to cross in all directions. In some applications, pedestrians are formally allowed to cross diagonally (1, 2), in which case it can also be called a pedestrian scramble or a Barnes dance; in others, diagonal crossings are not (formally) permitted because they require more clearance time and therefore a longer signal phase.

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Exclusive pedestrian phases protect pedestrians from all vehicular conflicts and can be especially useful where there is a heavy demand for diagonal crossings. Their main drawback is the large amount of lost time they add to a signal cycle, which either makes its application infeasible or, where feasible, forces the cycle length to become much longer, increasing delay to vehicles and pedestrians alike (2–4). The long waiting time that exclusive phases force on pedestrians can actually work counter to pedestrian safety by inducing pedestrians to walk against signal (2, 4).

### *Concurrent Yet Protected Phasing*

Crossings concurrent with a vehicular phase can still be fully protected if right turns, like left turns, have their own lane and their own phase (5) running at a different time from the crossing phase. One phasing solution is to split the through movement's phase into two parts, one running concurrent with the crossing and the other concurrent with right turns. Another is to use an "overlap" in which right turns run concurrent with a parallel left-turn movement. For greater flexibility, using a combination of overlap and splitting the through phase is also possible (5). A drawback of this technique is that it requires sufficient road space for right-turn lanes, which can be a challenge in urban contexts; however, it is sometimes possible to convert a shared through-right lane into a right-turn lane and still have sufficient capacity without adding any new lanes, as found in one case study (5).

New York City has used concurrent yet protected phasing on several of its one-way avenues in connection with one-way, left-side protected bike lanes that have been installed since 2007. During most of the through phase, the bike and pedestrian phases run concurrently while left turns are held by a red arrow. When the crossing phases are finished, the left-turn phase runs during the remainder of the through phase. This separation in time comes at the price of increased delay for pedestrians, bikes, and turning traffic, however, whose phases are all shortened compared with traditional concurrent phasing. Moreover, in practice, cyclists often cross during the left-turn phase once the left-turn queue has cleared, because the through-phase green light is highly visible, signaling that there will be no conflicting traffic from the cross street. This practice has not had any known safety impact (Ryan Russo, personal communication). These factors have motivated New York to consider the less restrictive LTI phasing technique described below.

### *LPI*

LPI is a short interval at the start of a street's split, typically 3 to 7 s in duration, in which the street's vehicular

signals remain red while the crosswalk phase begins, and after which traffic is released while the crossing phase continues. The leading interval gives pedestrians a head start which allows them to establish their priority in the crosswalk before vehicular traffic, in which right-turning vehicles are typically mixed with through vehicles, is released. The working idea is to enable pedestrians to reach the conflict zone (where the pedestrian path intersects the path of right-turning cars) before turning cars, reinforcing their priority over turning cars and thus engendering improved yielding compliance by turning motorists (6). LPI is commonly used in several U.S. cities, has been widely studied (1, 3, 7–9), and is recommended in several manuals dealing with urban intersections and complete streets (10–13).

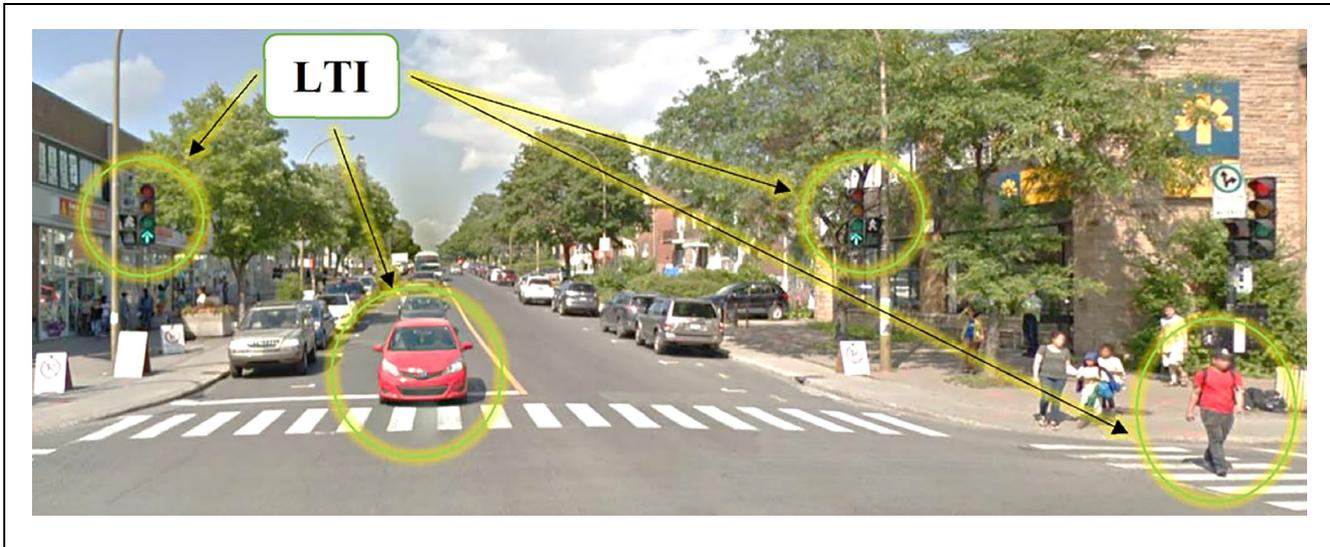
Because all traffic is held during the leading interval, the duration of the leading interval must be limited to avoid a large loss in vehicular capacity. For this reason, LPIs are typically only 3 s to 5 s in duration. That is often enough time for pedestrians starting at the near side to establish their presence in the conflict zone, but rarely enough for pedestrians starting at the far side. Depending on crossing length, pedestrian crossing volume, and turning volume, a right-turn flow can become established before far-side pedestrians reach the conflict point, creating a stressful and potentially dangerous situation.

In principle, cyclists could be allowed to get a head start during the leading interval as well, though to the authors' knowledge that has not yet been put into practice in North America, in part because doing so would require installing dedicated signals for bikes. Where LPI is implemented, bikes are often observed starting during the leading interval.

### *LTI*

LTI is a short interval at the start of a street's phase during which both through traffic and parallel cyclist and pedestrian crossing is allowed, but right-turning traffic is held. After the leading interval, right-turning traffic is released, while the pedestrian/cyclist crossing phases continue. However, because LTI involves less loss in traffic capacity, the leading interval can be longer than might be allowed for LPI. A longer leading interval can mean enough time for far-side pedestrians to reach the conflict zone before turning cars are released, and more conflict-free time for crossing cyclists.

To the authors' knowledge, the only cities where this technique has been used are Montreal, New York, and Charlotte, NC. LTI has been widely used in Montreal at least since 2005, and at the time of writing was implemented at more than 100 intersections (Jean Hamaoui, chief traffic engineer, City of Montreal, personal



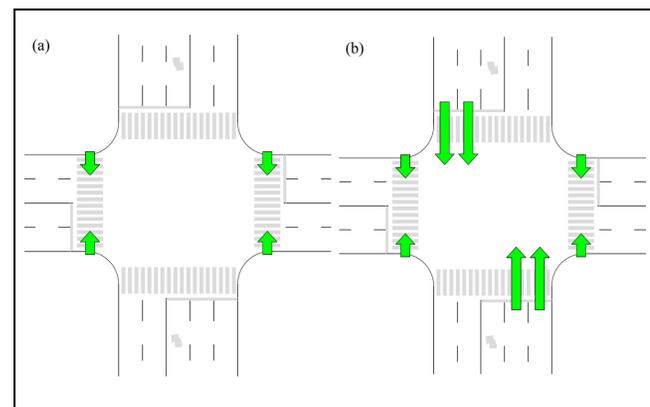
**Figure 1.** An intersection during LTI in Montreal.

communication). Several of the streets with LTI also have protected bike lanes. The signal display during the leading interval is a simple green through arrow, as shown in Figure 1. One can see the green through arrow and white pedestrian signal; one can also see that a turning car (in this case, a left-turning car, though the restriction applies equally to right-turning vehicles) remains waiting at the stop line, waiting for a green ball; at the same time, pedestrians are crossing.

Figure 2 compares LPI with LTI in relation to which movements are allowed during the leading interval. It is helpful to visualize that through traffic is not in conflict with pedestrian or bike crossings; therefore, wherever an LPI is used or being considered, it is reasonable to consider allowing through traffic to run during the leading interval, transforming it to an LTI.

Most of Montreal's LTI applications are on approaches lacking an exclusive turn lane, meaning that when a turning vehicle is held during the leading interval, through-going vehicles behind it will be blocked. (This phenomenon is visible in Figure 1.) The duration of the leading interval is most often 7 s or 9 s; often, it is set equal to the duration of the WALK interval, which is 7 s at minimum. Montreal guidelines set the limit for a leading interval at 14s based on experience with motorist non-compliance with long leading intervals (14).

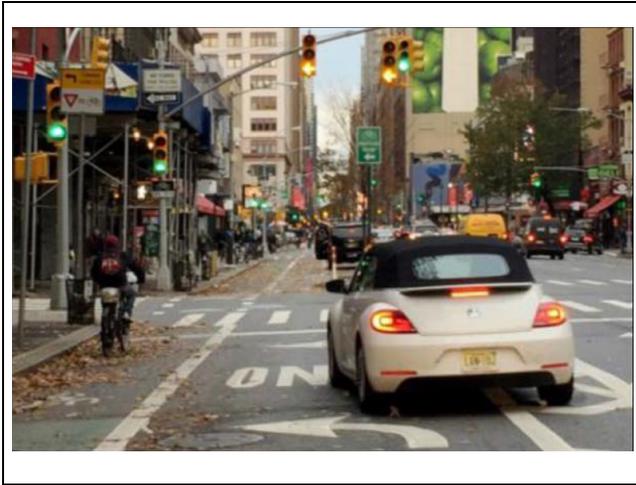
Where the proportion of right-turning traffic is high, Montreal prefers LPI to LTI for partially protected crossings. If LTI is used in such a case, there is a high chance of through motorists being blocked while seeing a green through arrow, which is frustrating; and if the lane is going to be blocked anyway during much of the leading interval, then the signal indication during that interval may as well be a simple red ball, that is, LPI.



**Figure 2.** Movements allowed during the leading interval: (a) LPI and (b) LTI.

In New York, based on their experience with protected-yet-concurrent crossings for protected bike lanes described earlier, city officials decided to begin using the LTI technique, allowing bikes and left-turning vehicles from one-way avenues to run concurrently after a leading protected interval. As of 2016, LTI had been applied at 37 intersections (13). Unlike Montreal, New York has applied LTI only in conjunction with an auxiliary turning lane, created by taking over part of the parking lane. This means that turning vehicles held by LTIs do not block through traffic.

During the leading interval, a green ball is displayed while outside turns across the bike lane (in this case, left turns) are held by a red arrow. After the leading interval, the red arrow facing the left-turn lane is replaced by a flashing yellow arrow, indicating that vehicles may proceed to turn but must yield right of way to bikes and



**Figure 3.** A New York intersection just after LTI has ended. Source: (13).

pedestrians. Figure 3 shows a New York intersection with LTI just after the leading interval has ended, with the flashing yellow arrow showing.

Charlotte has applied LTI at about 10 intersections, and roughly another 10 are in the process of changing over to LTI. Their first application won an ITE innovation award in 2016 (15). As in New York, LTI is used only on approaches with an auxiliary turn lane, and a flashing yellow arrow appears during the period of permitted conflict. New York City’s LTIs last from 7 s to 10 s (13, 16); Charlotte’s LTIs last 10 s (15). However, in off-peak periods, at some intersections, Charlotte extends the leading interval to coincide with the entire pedestrian phase (WALK as well as pedestrian clearance), which is tantamount to the concurrent-yet-protected phasing treatment.

In Montreal and New York, LTI is implemented primarily in business districts with heavy pedestrian traffic, and occurs every cycle. In Charlotte, LTI is applied mainly at intersections outside of the central business district, where cycle lengths tend to be long (around 120 s) and pedestrian volumes low. Pedestrian phases are pushbutton activated, and the LTI occurs only in cycles with a pedestrian phase.

In Montreal, this phasing technique is known as “partially protected mode with leading arrow” (14), as distinct from “partially protected mode with leading red,” the term used for LPI. In New York, it is called “split leading bicycle interval” or split-LBI (13, 16). In Charlotte, it is called LPI-Plus (LPI + ). The authors have coined the more parsimonious term “leading through interval.”

To the authors’ knowledge, field study of the safety of LTI has been done only in New York, where Kothuri et al. (16) analyzed conflicts between bikes and turning vehicles at two New York intersections with LTI. One of them—6th Avenue @ 23rd Street, with bikes in a left-side bike lane along a one-way avenue—affords a before-after comparison, with the before situation being a short LPI (which was not intended for bikes, though some cyclists used it), and the after situation a 7 s LTI followed by the period of permitted left turns with a flashing yellow arrow. Another change from before to after was the creation of a left-turn lane by removing some parking, so that the turning vehicles held by LTI had their own lane to queue in.

Table 1 shows a before-after comparison using the report’s data (16), which is here normalized to indicate conflicts per 1,000 bikes. The two most important conflicts—near misses and collisions that would have happened had there been no evasive action—show a strong decline after introduction of the LTI together with an exclusive left-turn lane. There was a small increase in the frequency of cyclists having to ride around a car (something that occurs usually because a car began its turn, but then stopped for crossing pedestrians).

### Critical Lost Time as a Measure of Capacity Impact

Changes in signal phasing can affect traffic operations in numerous different ways. The measure of impact used in this evaluation study is the *critical lost time* added to the cycle, that is, time during which no critical phase can run. Critical phases are those whose needs govern the cycle length. For an intersection with the full array of protected left turns, there are normally four critical phases: one of the east–west street’s through movements, one of

**Table 1.** Traffic Conflict Measures Before and After Implementation of LTI for 6th Avenue @ 23rd Street, New York

	Before: permitted turn conflict throughout the bike phase	After: leading protected interval (7 s) followed by permitted turn conflict
Bikes	1,952	1,300
Per 1,000 bikes:		
Near misses	4	0
Collisions if no evasive action taken	75	35
Bike rode around car	32	41

Source: (16).

the north–south street’s through movements, and the two left turns that oppose the critical through movements. For this study, we assume that the turning movement held by an LPI or an LTI is not critical, while the parallel through movement is.

With an exclusive pedestrian interval, the entire interval contributes to critical lost time. With LPI, leading intervals that delay a critical phase contribute to critical lost time. Thus, if LPIs lasting 4 s are provided for all crosswalks, they contribute 8 s to critical lost time. LTIs contribute to critical lost time if they block through traffic.

Increasing critical lost time reduces intersection capacity for a given cycle length, which increases delay. The degree of saturation, also called volume/capacity ratio, for an intersection as a whole is

$$X = \frac{\sum(v/s)}{1 - \frac{L_{crit}}{C}} \quad (1)$$

where  $\sum(v/s)$  is the sum of the volume/saturation flow rate ratios summed over the critical phases,  $C$  is the cycle length, and  $L_{crit}$  is lost time summed over the critical phases. Equation 1 can be interpreted as saying that intersection-level degree of saturation equals the fraction of a cycle’s green time *needed* by critical phases divided by the fraction of the cycle’s green time *available* to critical phases. Taking a derivative with respect to  $L_{crit}$ , the change in degree of saturation for each second increase in critical lost time is

$$\frac{dX}{dL_{crit}} = \frac{C \sum(v/s)}{(C - L_{crit})^2} = \frac{X}{C - L_{crit}} \quad (2)$$

While specific impacts will vary from case to case, an examination of a sample of common combinations of  $X$ ,  $C$ , and  $L_{crit}$  indicates that  $dX/dL_{crit}$  is roughly equal to 0.01, that each additional second of critical lost time will increase degree of saturation by roughly 0.01, if cycle length is held constant.

Consider, for example, an intersection with  $X = 0.85$ ,  $C = 100$  s, and  $L_{crit} = 16$  s; for this case,  $dX/dL_{crit} = 0.0101$ . If a 4 s LPI is added for all crossings without altering cycle length and splits are adjusted to balance supply with demand, critical lost time will increase by 8 s. Using Equation 1, the degree of saturation of the intersection will rise from 0.85 to 0.94. LPI lasting 10 s would raise the degree of saturation to 1.12.

Traffic managers can also respond to an increase in lost time per cycle by increasing cycle length, which reduces the lost time per hour. One benchmark is the increase in cycle length needed to maintain a constant degree of saturation. Rearranging Equation 1,

$$C_{needed} = \frac{L_{crit}}{1 - \frac{1}{X_{target}} \sum(v/s)} \quad (3)$$

where  $X_{target}$  is the target degree of saturation (for this purpose, the current degree of saturation can be considered that target) and  $C_{needed}$  is the cycle length needed to achieve that target degree of saturation. Taking a derivative with respect to  $L_{crit}$  while holding degree of saturation unchanged,

$$\frac{dC_{needed}}{dL_{crit}} = \frac{C}{L_{crit}} \quad (4)$$

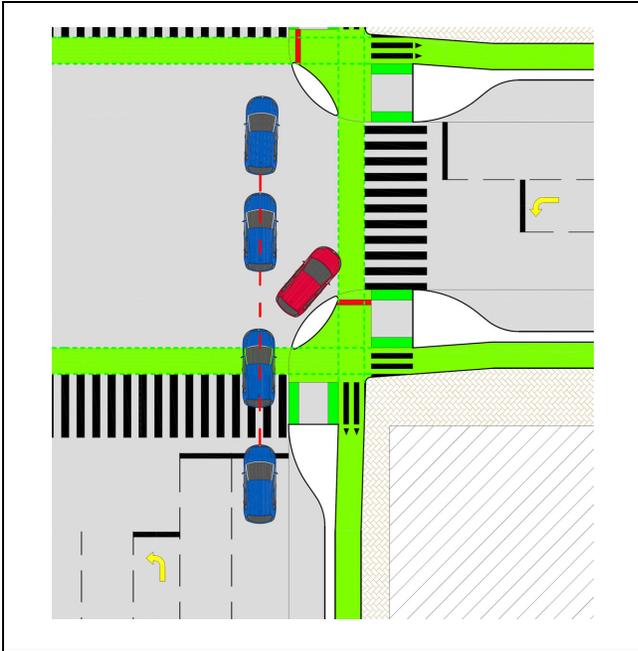
For the previous example,  $C/L_{crit} = 6.25$ , and so for every second of critical lost time added, the cycle length would have to increase by 6.25 s to maintain the same degree of saturation. Thus, adding 8 s to critical lost time would necessitate increasing the cycle length by roughly 50 s to keep the intersection’s degree of saturation unchanged. Of course, traffic managers can respond to an increase in lost time by a combination of increasing the cycle length and accepting an increase in the degree of saturation.

## Modeling the Capacity Impact of LPI and LTI

When the effect of pedestrians blocking crosswalks is considered, the capacity impact of LPI becomes more nuanced than the previous analysis would suggest. By giving queued pedestrians a head start, LPI enables pedestrians to clear the conflict zone sooner, so that during the green time that follows, they will have less blockage effect on right-turning vehicles than they would have otherwise.

For LTI on an approach in which right-turning cars share the lane with through traffic, the capacity impact depends on the proportion of vehicles turning right. The capacity impact of LTI also depends on pedestrian activity. If, during part of an LTI, pedestrians occupy the crosswalk, vehicles held by the LTI would have been blocked by the pedestrians, and so the LTI has (almost) no incremental impact. Intersection geometry also plays a role. If the intersection has space for a right-turning vehicle to wait at the crosswalk without blocking through traffic—a condition termed “informal flare” in this paper—a vehicle trying to turn right while pedestrians occupy the crosswalk will not block through traffic if there is no LTI, but it will block through traffic if there is an LTI. Figure 4 illustrates an informal flare.

We focus on the case in which right-turning vehicles share a lane with through traffic. When the turning vehicles have an exclusive lane, the impact of LTI on through traffic will be negligible, and the impact of LPI is simply



**Figure 4.** An informal flare—space for a right-turning vehicle to wait at the crosswalk without blocking through traffic.

that the leading interval adds to lost time. A simulation case study conducted by Kothuri et al. (14) confirms how small an impact LTI has on intersection capacity when turning vehicles have their own lane. They modeled an intersection in Portland, Oregon, with and without LTI of 5 s duration. There was no discernable impact on parallel through traffic or on cross traffic. The only impact was on the right-turning traffic which was held during the leading interval, and even there the impact was only an increase in average delay of 1 s. This small impact is explained by the fact that, because of right turn on red, assumed to be active in all red periods except the leading interval, the right-turn lane queue was kept small, and so few vehicles were actually held during the leading interval.

This study models a single lane shared by through and right-turning vehicles. The fraction of right-turning vehicles is a parameter that is varied. Because the objective is to measure capacity, we assume an infinite queue and measure how much time it takes to serve a given number of vehicles. Because the treatments studied affect signals for at most 11 s, and because vehicles under ideal conditions depart roughly every 2 s, the eighth vehicle is used as an indicator, measuring the time until the eighth vehicle clears the intersection.

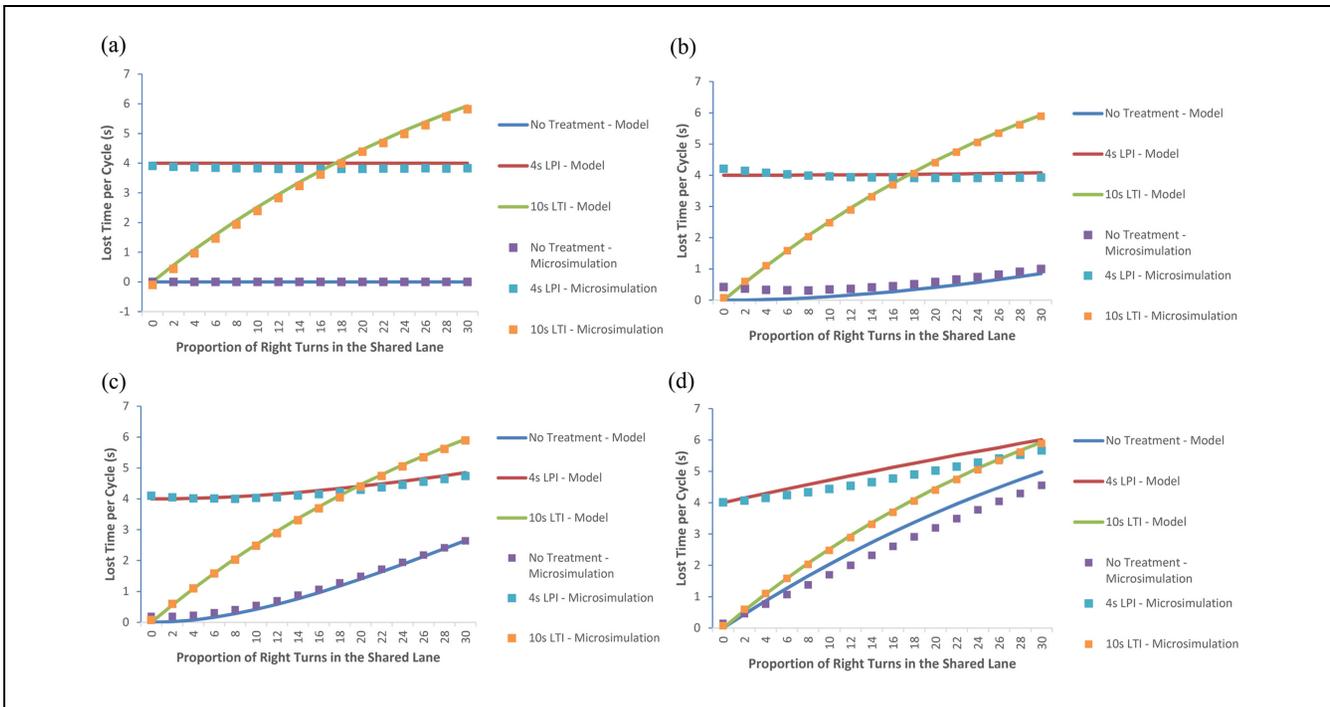
The capacity impact measured is lost time, defined as the difference in time needed to serve the first eight vehicles compared with a base case with the same vehicle composition, but with no treatment and no pedestrian blockage.

Model inputs are as follows:

- Proportion of the right-turn lane volume that is turning right. Examined values are from 0 to 0.28 with increments of 0.04.
- Pedestrian blockage time, which is the time during which pedestrians block turning vehicles from passing through the crosswalk. Three values are examined: 0 s, 5 s, and 10 s. No pedestrian blockage, which is when pedestrian blockage time is zero, is an important case; how much capacity is lost when there are no pedestrians? The two non-zero blockage cases were chosen to typify two common situations: near-side pedestrians only, and pedestrians from near and far sides. Of course, the amount of time needed for pedestrians to clear the conflict zone depends on crossing length; the values chosen are for illustration's sake. While pedestrian blockage can continue long after 10 s, the effects of longer periods of blockage can be expected to affect the treatment cases and the no-treatment case the same, and thus have no effect on incremental lost time.
- Treatment type—LPI, LTI, or none—and duration. LPI durations examined were 3 s, 5 s, and 7 s; LTI durations were 5 s, 7 s, 9 s, and 11 s.
- Presence or absence of an informal flare. It is assumed that the informal flare has space for one, but not more than one, vehicle to wait at the crosswalk while it is occupied without impeding through traffic. Therefore, in cases with an informal flare, it takes two right-turning cars queued at the crosswalk to block through traffic.

The model is a deterministic simulation, programmed using R. To account for the random vehicle mix in the shared lane, it considers every permutation of through and right-turning cars for a queue with eight cars. (For example, one permutation is that the third car is turning right while the remainder are going through.) The probability of each permutation is determined by the proportion of right-turners in the traffic stream (a parameter of the model). Results for a given proportion of right-turners are a weighted average over all permutations, weighted by their probabilities.

Given a vehicle mix, vehicles advance following rules about headway and start-up lost time. Base headway is 2.0 s for through vehicles and 2.35 s for those turning right (the ratio of these headways, 0.85, corresponds to the *Highway Capacity Manual's* saturation flow rate factor for right turns). Start-up lost time for the first four vehicles is 1.0 s, 0.7 s, 0.2 s, and 0.1 s, respectively; actual headway equals base headway plus start-up lost time. During an LTI, right-turning cars stop at the stopline. A



**Figure 5.** Lost time comparison, deterministic simulation model (“model”) versus microsimulation: (a) No pedestrians, (b) 6 s of pedestrian blockage with informal flare, (c) 10 s of pedestrian blockage with informal flare, and (d) 10 s of pedestrian blockage and no flare.

right-turning vehicle takes 1 s travel time to reach the crosswalk, and may not enter the crosswalk until 1 s after pedestrian blockage is over. Right-turning vehicles are considered to have cleared the intersection once they enter the crosswalk; through vehicles, once they get beyond the point at which they could be blocked by a right-turning vehicle.

The same intersection approach was also modeled with VISSIM for a few representative cases to ensure that the model output is similar to that of a microsimulation in which car following, yielding, and turning are modeled in fine detail. VISSIM car-following parameters were adjusted so that saturation headway equaled 2.0 s. Differences between VISSIM results and those of the deterministic simulation model were then used to adjust the deterministic model’s parameters. After adjustment, the deterministic simulation model replicated VISSIM results with little discrepancy, as shown in Figure 5.

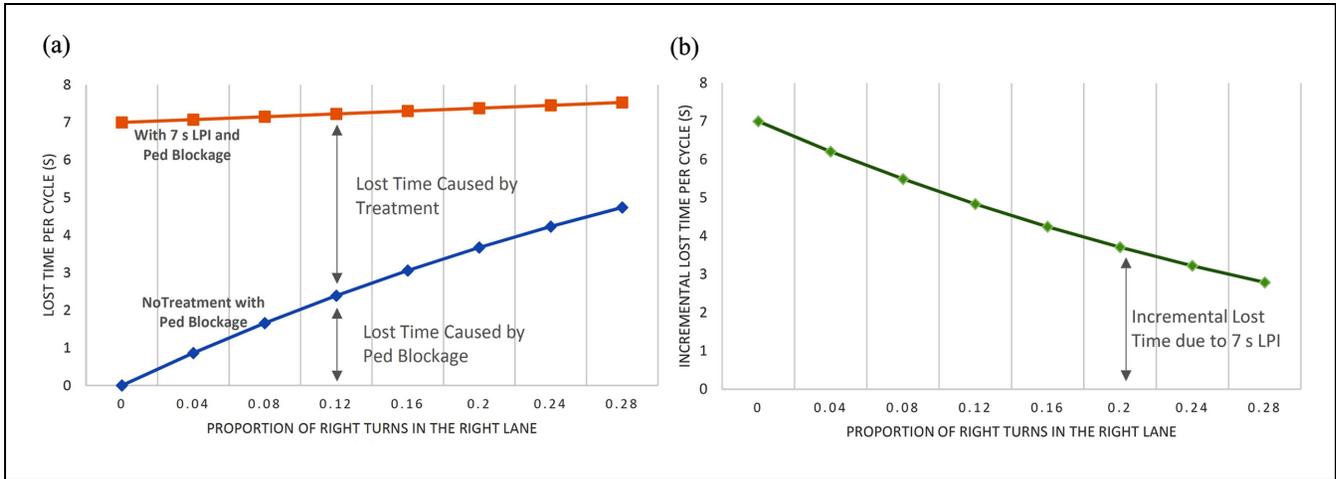
The advantage of using a deterministic simulation model over running a full microsimulation is time and effort. With the deterministic model, every scenario can be modeled in a short time with every permutation considered and given its appropriate weight. With microsimulation, the fact that many vehicle mix permutations are low probability events means that a large number of replications is needed to ensure that results are not unduly influenced by outliers, making the time needed to test every scenario prohibitive.

### Determining Incremental Lost Time

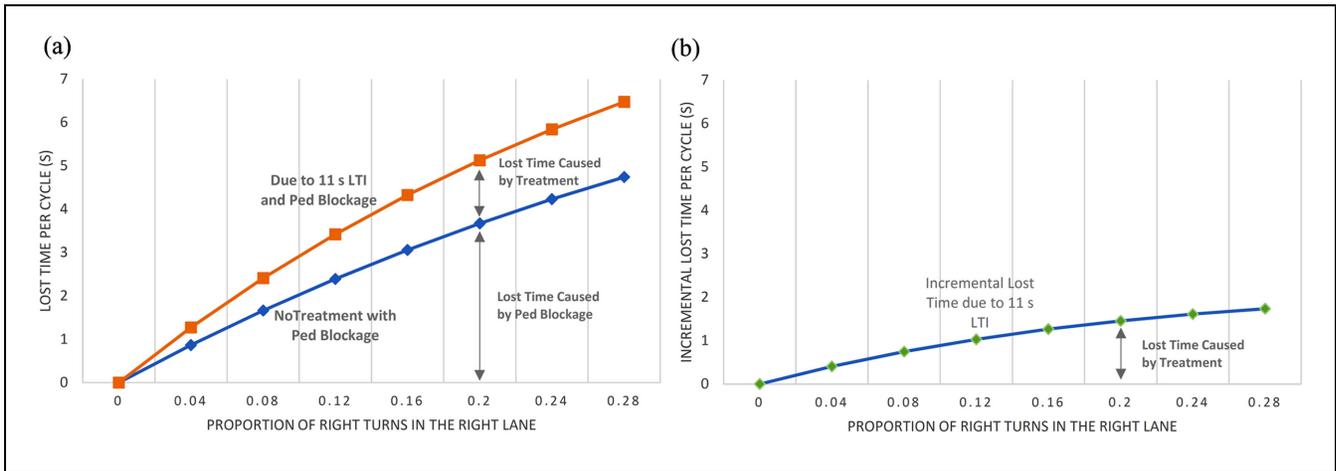
Incremental lost time is the additional lost time in serving the first eight vehicles because of a treatment, measured relative to the no-treatment case. For a given scenario, treatment and no-treatment cases were compared for every possible vehicle mix, with the same informal flare presence and the same duration of pedestrian blockage.

Accounting for pedestrian blockage effect in both the treatment and non-treatment cases can lead to some unexpected results. Figure 6 shows lost time for a 7 s LPI and for no treatment when pedestrian blockage lasts 10 s and there is no informal flare. As the proportion of right-turners increases, lost time increases for both cases (Figure 6a). However, incremental lost time for the LPI, which is the difference between its lost time and the lost time of the no-treatment case, decreases with the proportion of right-turners (Figure 6b). This is because when there are many right turning vehicles, many of the cars held by an LPI would have been delayed anyway by pedestrians blocking the crosswalk, reducing the incremental impact of the LPI.

Similarly, Figure 7 shows lost time for an LTI lasting 11 s and for no treatment, in both cases with no informal flare and with pedestrian blockage lasting 10 s. Again, lost time for both cases increases with the proportion of right turners, but in this case incremental lost time increases with the proportion of right turners.



**Figure 6.** Lost time and incremental lost time for LPI of 7 s with no informal flare: (a) Lost time for the treatment and no-treatment cases and (b) incremental lost time for the treatment case.



**Figure 7.** Lost time and incremental lost time for LTI of 11 s with no informal flare: (a) Lost time for the treatment and no-treatment cases and (b) incremental lost time for the treatment case.

### Results for a Single Lane

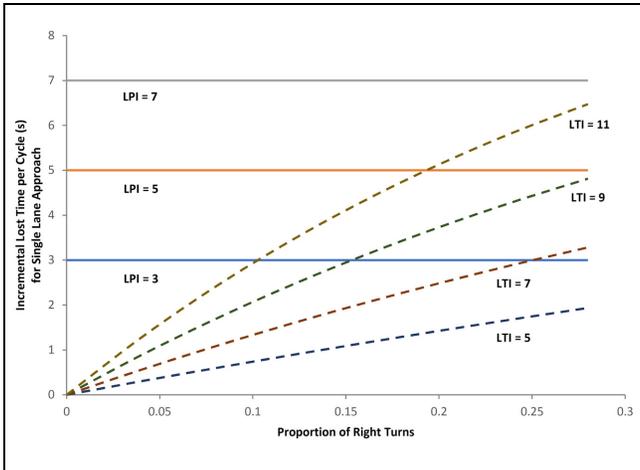
Figures 8 to 10 show how incremental lost time for a single lane shared by through and turning vehicles varies with the proportion of right turners, pedestrian blockage duration, and presence of an informal flare. (In Figure 8, presence of an informal flare is not indicated because it makes no difference when there is no pedestrian blockage.)

When there is no pedestrian blockage, incremental lost time for LPI is simply the duration of the leading interval itself (Figure 8). As explained earlier, when there is pedestrian blockage (Figures 9 and 10), incremental lost time because of LPI decreases with the proportion of right turns because of how pedestrian blockage affects the no-treatment case. In the most extreme case tested—10 s pedestrian blockage, 28% right turns, and no

informal flare—the incremental lost time of a 7 s LPI is not 7 s, but only 2.8 s.

For LTI, incremental lost time is zero when there are no right turners and increases with the proportion of right turners. In the most extreme case considered—28% right turns, an 11 s leading through interval, and informal flares—incremental lost time for LTI reaches about 6 s for the cases of 0 s and 5 s pedestrian blockage, and about 4 s in the case of 10 s pedestrian blockage.

The impact of an informal flare can be significant. Where there is no informal flare, LTIs shorter than or equal in length to the blockage have almost no impact on incremental lost time; this is because if the crosswalk is blocked anyway, holding right turners at the stopline hardly makes a difference. With an informal flare,



**Figure 8.** Incremental lost time for a shared lane versus proportion of right turners for different treatments and durations when there is no pedestrian blockage.

however, an LTI can cause up to 2s of incremental lost time, because it forces right-turning cars to wait at the stopline, where they block through traffic, instead of advancing to the crosswalk.

A comparison of the effects of LPI and LTI indicates that LTI is superior in relation to the capacity-protection tradeoff across the full range of parameters tested. That is, for a given duration of the leading interval, LTI always has less incremental lost time. Looked at another way, LTI can offer more protection for a given amount of capacity loss. For example, for a single lane approach with 20% right turns and 10s pedestrian blockage, an

11s LTI has the same impact on capacity as a 5s LPI where there is an informal flare, and the same impact on capacity as a 3s LPI where there is no flare.

### Applying Results to Multilane Approaches

For approaches with more than one lane for through traffic, the impact on capacity depends on lost time for the lane group as a whole. Where right-turning traffic shares a lane with through traffic, the lane group's lost time can be found by averaging lost time in the shared lane with lost time in the other through lanes, as shown in Equation 5:

$$L^m = \frac{1}{N} (L_{Np}^S + (N - 1)L^T) \tag{5}$$

where

$L^m$  = lost time for a multilane lane group

$N$  = number of lanes used by through traffic

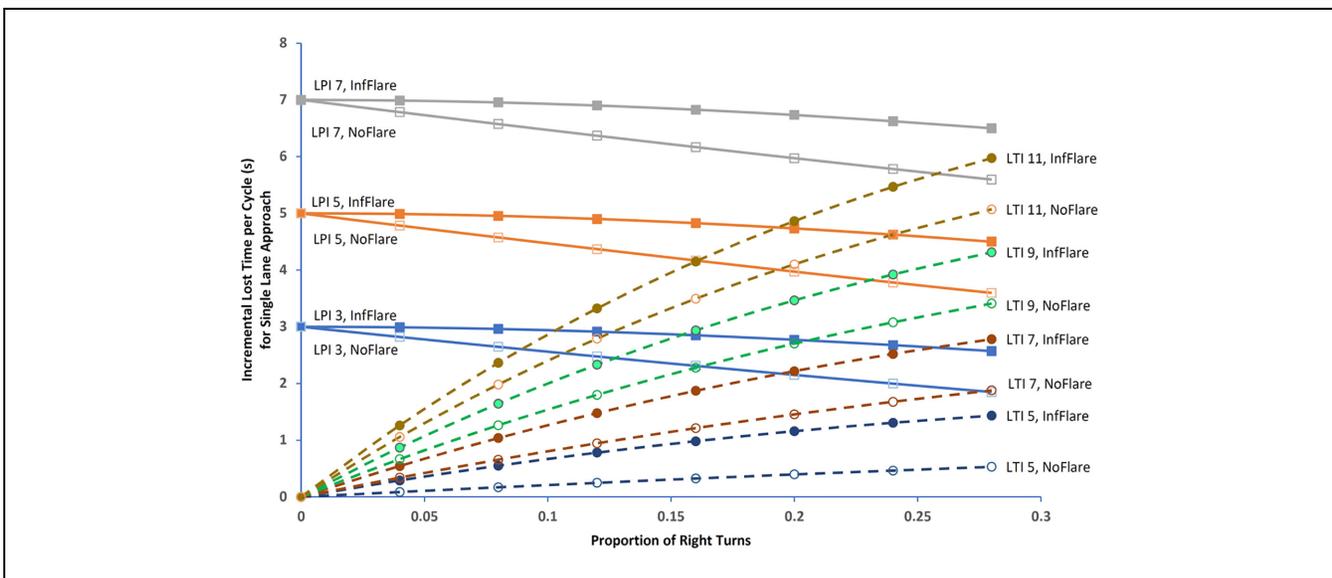
$p$  = proportion of lane group traffic turning right

$L_{Np}^S$  = lost time for a single shared lane in which the proportion of right turners is  $N \times p$

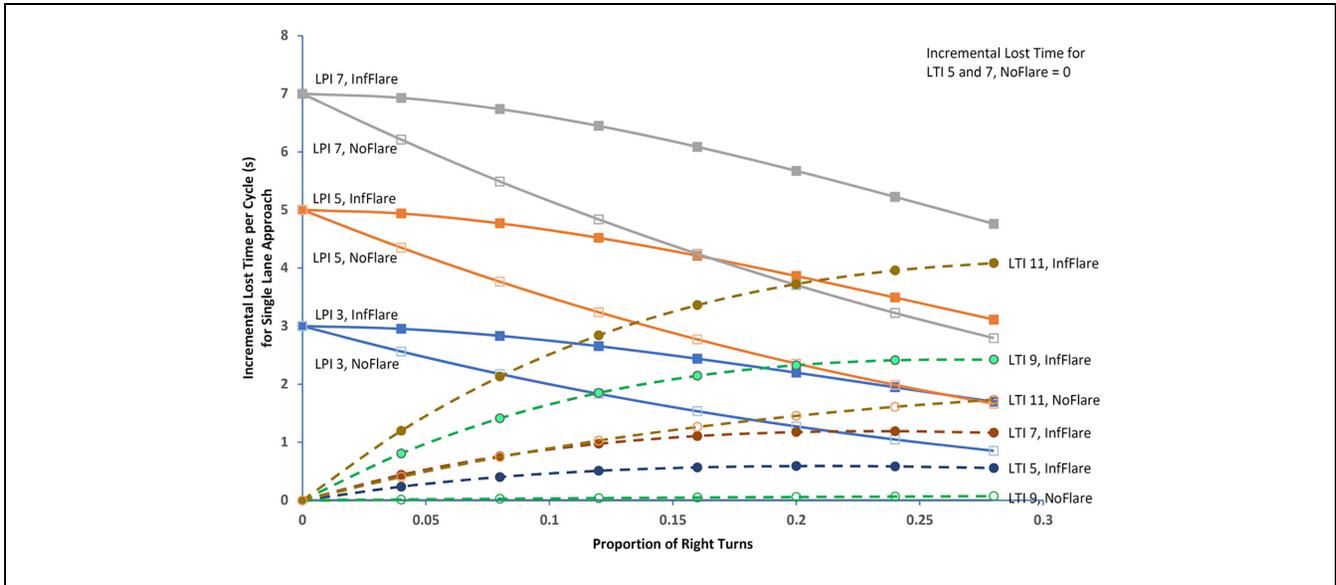
$L^T$  = lost time in through lanes not shared with right turns. For LPI,  $L^T$  = length of the leading interval; for LTI,  $L^T = 0$

Where an exclusive right turn lane is provided,  $L^m = 0$  for LTI, while for LPI,  $L^m$  equals the duration of the leading interval.

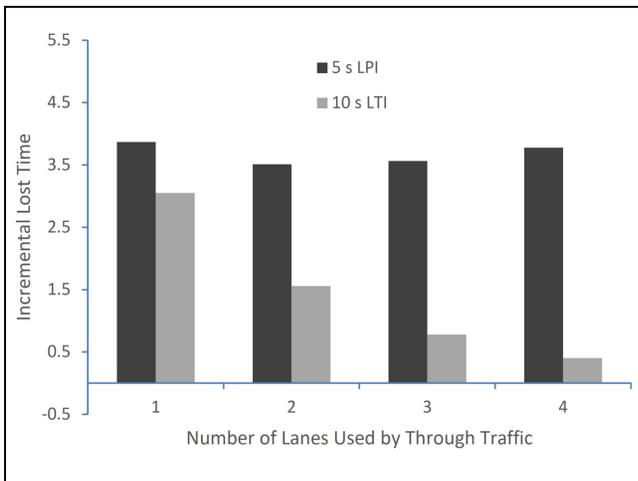
Figure 11 shows how incremental lost time for LPI and LTI varies with the number of lanes used by through traffic for a case in which the percentage of right-turners is 20, pedestrian blockage lasts 10s, and informal flare



**Figure 9.** Incremental lost time for a shared lane versus proportion of right turners for different treatments and durations when pedestrian blockage lasts 5 s.



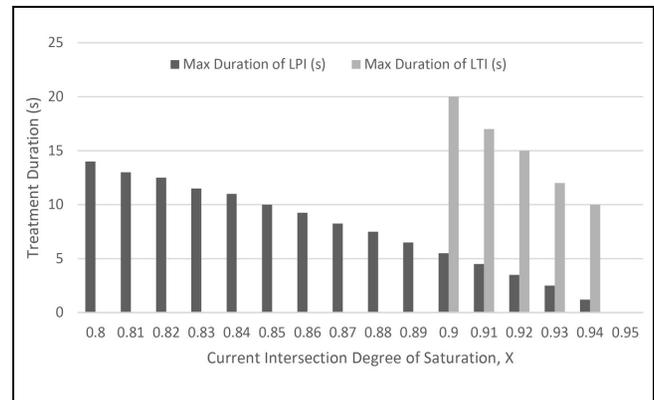
**Figure 10.** Incremental lost time for a shared lane versus proportion of right turners for different treatments and durations when pedestrian blockage lasts 10 s.



**Figure 11.** Incremental lost time for LPI and LTI versus number of lanes used by through traffic, assuming 20% right turners, 10 s pedestrian blockage, no exclusive right turn lane, and an informal flare.

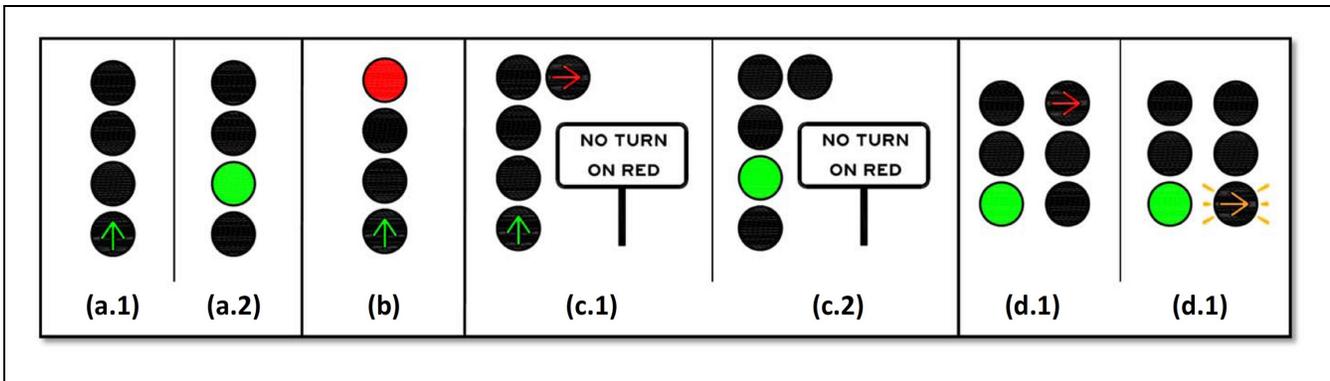
exists. One can see that with LPI, incremental lost time varies little as the number of lanes increases, because the leading interval holds traffic in all lanes; in contrast, with LTI, incremental lost time declines roughly inversely with the number of lanes because only one lane is disturbed by the LTI.

Another interesting way of looking at the capacity–protection tradeoff is to consider, for the two treatment types, how long a leading protected interval could be provided without exceeding a specified degree of saturation



**Figure 12.** Affordable duration of the leading interval versus current degree of saturation for an approach with three through lanes with the rightmost through lane shared with right turns, no exclusive right turn lane, 20% of entire approach’s traffic turns right, 10 s pedestrian blockage, informal flares, and maximum allowed degree of saturation = 0.95.

of the intersection (and keeping cycle length unchanged). Figure 12 shows an analysis for an approach with three lanes used by through traffic, no exclusive right-turn lane, 20% right-turning vehicles, 10 s of pedestrian blockage, and an informal flare, with the specification that the degree of saturation of the intersection should not exceed 0.95. The treatment (LPI or LTI) is assumed to apply only to the main street approaches. LTI can afford a much longer protected interval. For example, if the current degree of saturation is 0.92, the example could only “afford” a leading protected interval of 3.5 s as an LPI,



**Figure 13.** Various signal displays to be shown to motor traffic during and right after a leading through interval: (a) Signal display used in Montreal, (b) wrong display that is forbidden by MUTCD, (c) an easy to understand combination, and (d) signal display for approaches with an exclusive right turn lane.

while with LTI, it could afford a 15 s leading protected interval.

## Discussion

In relation to getting the most protection for a given amount of capacity loss, or the least capacity loss for a given amount of protection, LTI is clearly superior to LPI for every case modeled. The difference is especially striking on multilane roads, where LPI holds traffic in all lanes while LTI holds traffic in a single lane only.

The previous analysis examines only LTIs in which turning traffic shares a lane with through traffic. Where turning traffic has its own auxiliary lane, the superiority of LTI over LPI in relation to capacity impact is obvious, because the LTI has no capacity impact at all on through traffic.

Where right turning vehicles do not have an exclusive turn lane, LTI's performance worsens with increased turn percentage. In addition, Montreal's experience indicates that motorist frustration can reach an unacceptable level if through vehicles are blocked for too long a time by turning vehicles. Together, these trends confirm that (a) separate turn lanes should be considered where possible; (b) where an exclusive turn lane cannot be provided, LTIs should be limited in duration (recall that Montreal's limit is 14 s); and (c) on single lane approaches without an exclusive turn lane, LPI may be preferable to LTI when the turn percentage is high, consistent with Montreal's experience, described above.

## Signal Display Options

The desired function of an LTI is to allow through vehicles to go but not right-turning vehicles. Figure 13 shows several display options. Figure 13a1 and a2 are the display options used in Montreal: a green through arrow

during the leading interval, followed by a green ball, without any red arrow or ball. Figure 13d1 and d2 are the corresponding display options used in New York and Charlotte, intended for an approach with an exclusive turn lane.

Would Montreal's display option work in a U.S. city? A strict reading of the MUTCD indicates that yes, a solitary through green arrow (i.e., not accompanied by a red arrow) prohibits turns; from Section 4D.04, subsection A2, "Vehicular traffic facing a GREEN ARROW signal indication, displayed alone or in combination with another signal indication, is permitted to cautiously enter the intersection only to make the movement indicated by such arrow, or such other movement as is permitted by other signal indications displayed at the same time" (17). However, it is probable that the MUTCD never anticipated a solitary green through arrow for a lane shared by through and turning traffic. In addition, cities considering the Montreal display may need to obtain an interpretation of whether their state vehicle code prohibits turns with the display shown in Figure 13a1. And regardless of the law, will drivers in the U.S.A., who are accustomed to seeing a red signal when a movement is prohibited (unless that movement is prohibited at all times, e.g., with a No Left Turn sign), understand the Montreal display as intended?

Adding a red ball, as in Figure 13b, might seem a good way to satisfy concerns about clarity and driver expectation. However, the combination of a red ball and through green arrow is expressly forbidden by the MUTCD.

Adding a red arrow, as in Figure 13c and Figure 13d1, is a combination that appears to be consistent with the MUTCD, vehicle codes, and driver expectations.

For LTI to work as intended, vehicles must not turn right during the leading interval. This can be accomplished by a No Turn on Red restriction; however, motorist non-compliance with No Turn on Red

restrictions is a concern that may warrant education and enforcement. Two of the jurisdictions that have applied LTI, Montreal and New York City, also happen to be the only places in the U.S.A. and Canada which statutorily prohibit right turn on red. For those cities, then, there is no relevant experience to test whether drivers accustomed to turning right on red will comply with turn prohibitions during an LTI. In Charlotte, however, while state law prohibits right turn on red when a red arrow is displayed (Figure 13d1), drivers are so accustomed to turning right on red that Charlotte's LTI applications include LED blank-out signs with the words "No Turn on Red" during the leading interval (which, as stated earlier, is pedestrian-activated).

### Conclusion and Further Research

LTI, a signalization technique well established in Montreal and recently embraced by New York City and Charlotte, is a valuable tool for creating a degree of protection for pedestrians and cyclists from right-turning traffic. Like LPI, it is a means of "partial protection," meaning that only the early part of the crossing phase is protected, allowing pedestrians and cyclists to establish their priority in the crosswalk, or perhaps completely clear the crossing, before turning traffic is released.

Compared with LPI, LTI makes it possible to offer a considerably longer protected leading interval with less impact on capacity. This effect is especially strong on multilane roads. A longer leading interval can make bike crossings safer, and can improve the safety of pedestrians crossing from the far side.

Research may be needed on signal displays in U.S. cities to communicate an LTI where there is no exclusive turn lane.

The present research indicates a weakness in using standard HCM formulas for capacity analysis at intersections with LPI. Those formulas determine the pedestrian blockage effect by assuming that pedestrians begin crossing at the same time that the vehicular signal turns green. With LPI, however, pedestrians get a head start, and will therefore be out of the way of turning vehicles sooner relative to the start of vehicular green. There is a need for adjustments to the pedestrian blockage factor to account for the presence of an LPI. A workaround for the time being may be to reckon only part of an LPI as lost time, using results as given in Figures 9 and 10.

Capacity analysis methods will also be needed for analyzing the blockage effect of LTIs where turning vehicles share a lane with through traffic, since most practitioners will not want to use simulation models as this research did.

### Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: PGF; data collection: RSR; analysis and interpretation of results: RSR and PGF; draft manuscript preparation: PGF and RSR. Both authors reviewed the results and approved the final version of the manuscript.

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