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A low-cost alternative for higher capacities at four-way signalized intersections

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ABSTRACT

Protecting left-turn movements on all four approaches to a signalized intersection conventionally requires a minimum of two extra phases per cycle. Losses in capacity often result. Various intersection designs have been proposed to combat those losses. Perhaps the best known of these designs is the continuous flow intersection. It features specially-configured approach lanes and mid-block pre-signals. These enable opposing left-turn and through-moving vehicles to proceed through the intersection free of conflicts, and without need for additional protected-turn phases.

The present paper offers an alternative design for four-way intersections, which to our knowledge has not previously been proposed. The design furnishes lower capacities than do continuous flow intersections, but spares the expense of having to reconfigure approach lanes. Pre-signals store queues and route traffic through the intersection much as in a continuous flow design. The distinguishing feature of the alternative is that it enables all four turn movements to be served during a single protected phase. Only one additional phase is therefore required per cycle. Numerical analysis shows that the plan regularly achieves higher intersection capacities than do conventional designs. Capacity gains as high as 80% are predicted. The proposed design is rather mentally taxing to drivers. Hence, opportunities for deploying the design in real settings are discussed with an eye toward the more connected and automated driving expected in the future.

1. Introduction

Signalized intersections with sufficiently high demands often come with protected turn phases (e.g. Newell, 1989). Where driving occurs on the right as in the US, it is the left-turns that usually require protection. This is conventionally achieved by displaying a left-turn phase concurrently with either: the through phase for the same approach; or a protected left-turn phase for the opposing approach (e.g. Webster, 1958; Rodegerdts et al., 2004). Either way, the signal must as a result display more than two phases each cycle. Additional phases mean more change intervals and greater lost times (e.g. Greenshields et al., 1947; Koonce et al., 2008). And in commonly-occurring cases in which an intersection has fewer turn lanes than through ones, protected left-turn phases likely serve lower discharge flows; see Xuan et al., 2011. The resulting losses in intersection capacity can create or exacerbate residual queues on high-demand approaches, with delays that may steadily increase over time.

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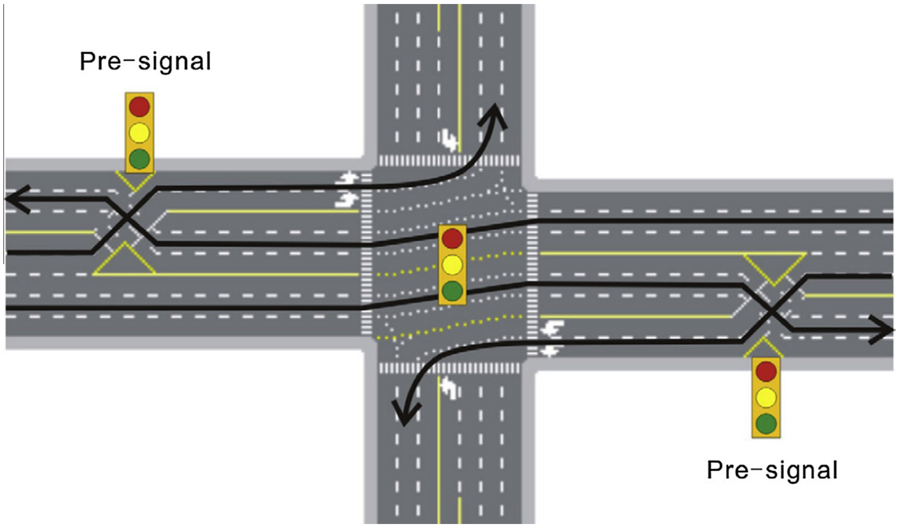

Fig. 1. Continuous flow intersection on two approaches. Arrows depict the movements allowed during the (single) green phase for those approaches. Figure taken from Xuan et al. (2011).

One creative solution entails a continuous flow design (Al-Salman and Salter, 1974), as depicted for two opposing intersection approaches in Fig. 1. While the intersection's signal is red for those approaches, pre-signals (upstream of the intersection) display greens. These pre-signals allow left-turners to enter special pockets situated on the approaches' extreme left-hand sides. Note from Fig. 1 how the opposing left-turns are protected from conflicts when eventually given greens at the intersection. And since these left-turners enter the intersection together with the parallel through-moving traffic in both directions, protection is achieved without additional phases and the attendant losses in capacity.

The design can be deployed: on only two opposing intersection approaches as in Fig. 1, when higher capacities are needed in those directions alone; or on all four approaches, when demands are high in all directions. On the downside, the design cannot be turned on and off to accommodate time-varying demands over a day. Once the required alternations are deployed on opposing approaches, they must operate in the continuous flow mode all day long, day after day. And since said alterations include substantial reconfigurations to the approach lanes, deployment can be expensive; see Goldblatt et al., 1994.

Moreover, the design introduces certain complications to the driving task. In addition to the unorthodox maneuvering required of left-turners as they approach the intersection, note from Fig. 1 the zig-zag-like movements to be performed by through-moving vehicles as they discharge. Right-turners on perpendicular approaches, moreover, must avoid the special left-turn pocket(s) at the intersection and thereafter pursue zig-zag paths as well. Yet, these complications have not prevented continuous flow intersections from being deployed in real settings (Hughes et al., 2009). This suggests that traffic engineers (and society) are willing to tolerate unconventional designs in exchange for greater capacities at high-demand intersections.

With the above considerations in mind, the present paper offers another alternative to protect turn movements at four-way intersections, one not previously conceived of. Much like the continuous flow design (e.g. Al-Salman and Salter, 1974) and other designs (e.g. Xuan et al., 2011, 2012; Guler and Cassidy, 2012), the proposed plan features mid-block pre-signals to store queues and re-route certain movements through the intersection. The design does so in ways that enable left-turn movements in all four directions to discharge together during a single protected phase. Because that one extra left-turn phase is required, the plan tends to furnish lower capacities than do continuous flow intersections, particularly when all four approaches operate in continuous flow fashion. But the proposed design does not require costly realignments of the approach lanes, and can be turned on and off over the course of a day to suit an intersection's time-varying needs for added capacity.

The design is described in the following section. Capacity models are formulated thereafter and numerical analysis shows that the proposed plan regularly outperforms conventional signal designs, often by large amounts. The paper concludes with discussion on how the plan might be deployed to fill certain niches, particularly as advances in connected and automated vehicle technologies may render the vehicle maneuverings required of the plan less taxing on drivers and enhance safety to boot.

2. The plan and its workings

Where driving occurs on the right, the problem is that left-turns on one approach to a four-way intersection conflict with their counterparts on perpendicular approaches. To wit, the dashed arrows in Fig. 2a delineate the paths of left-turners as they negotiate an intersection. Resulting conflict areas are highlighted with cross-hatching.