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Placement and Management of Bus Bypass Segments in Dense, Congested Cities

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NATIONAL INSTITUTE FOR CONGESTION REDUCTION

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16. Abstract

In this research, simulation is used to explore how a bus bypass segment, also called a queue jump, affects traffic on a signalized arterial. Residual queues form at the site's critical bottleneck and expand to street links upstream. A bypass, when designed to serve a bus stop as per AASHTO guidelines, is shown to reduce bus delays—if the stop resides on a congested link that is upstream of the one feeding traffic to the critical bottleneck. In contrast, using a bypass for a bus stop located immediately upstream of the critical bottleneck starves that bottleneck of flow. The damage thus done to car traffic also penalizes buses operating in the congested lanes that they share with cars. This damaging cross-modal influence can nullify the benefits that buses receive from the bypass segment. The value of a simple alternative, and the generality of the present findings, are verified via parametric tests.

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Executive Summary

In this study, researchers used simulations to test how a bus bypass, or queue jump, affected travel on an idealized urban arterial. The site had a critical signalized intersection from which residual queues expanded to multiple arterial links upstream. A bypass, designed as per AASHTO's guidelines, became a concern when installed at a bus stop immediately upstream of this critical bottleneck, even though queues persisted there for the greatest durations. Problems arose because periodic interruptions to car traffic from the bypass operations created voids in flow that propagated through the critical bottleneck, thus diminishing system exit flow. The heightened delays to cars penalized buses too because they shared lanes with cars. This damaging cross-modal influence diminished, and often negated, any delay savings that the bypass offered buses. A similar disruptive effect occurred when the critical bottleneck's bus stop operated in in-line fashion, such that buses served the stop's boarding and alighting passengers by dwelling in a lane. A more effective bus-favoring intervention often entailed converting the in-line stop to an off-line one, or pullout, even though buses then encountered modest delays when exiting the stop. The bypass served buses more effectively when installed on a congested link further upstream of the critical bottleneck. The voids created in car flows no longer propagated through the critical bottleneck because they were fully compressed upon encountering residual queues on the arterial link downstream. Further parametric tests show the value of placing bypasses on longer street links, and in conjunction with a little-known signal coordination strategy suitable for congested cities.

Chapter 1. Introduction

This study focuses on dense urban settings when queues grow long during a rush and spillover from one street link to the next. The objective is to prioritize the movements of transit buses in these settings. The constraint is not to impede further the already congested car flows. This constraint is not necessarily ideological (e.g., based on fairness), nor politically motivated (e.g., to avoid motorist outcries), but can be justified on practical grounds: further degrading car flows already impeded by queues will undermine, and can even negate, the benefits afforded buses by the intervention used to prioritize their movements.

This cross-modal influence is easier to appreciate when large portions of a street network are comprised of travel lanes shared by both buses and cars. If a bus-favoring intervention is allowed to degrade already impeded car flows, then the damaging effects will be felt upstream by all vehicles in the congested shared-use lanes, including buses. The negative effect can be so substantial that the intervention ultimately worsens, rather than improves, conditions for buses. Unintentionally conjuring this Pareto-worsening outcome can be easier than one might think, as demonstrated in this study.

The influence is also at work, albeit less dramatic, when buses travel entirely in their own reserved lanes. Queues in regular-use freeway lanes exert a “friction effect” to slow traffic in adjacent carpool lanes (Jang et al., 2012; e.g., Schroeder et al., 2012; Thomson et al., 2012). This effect is expected to impede travel in exclusive bus lanes as well (Cassidy et al., 2009).

The constraint precluding further degradation to car flows will be treated as soft, rather than held inviolate. This is because the delay saved by buses from an intervention that diminishes congested car flows can in many cases outweigh the negative cross-modal influence. Yet we will illustrate how, in these cases, a simple alternative that honors the constraint can equivalently benefit buses and produce lower vehicle- and person-hours traveled in a network (i.e., the VHT and PHT, respectively).

Hence, the present constraint does not always preclude, but cautions against the use of, certain bus-favoring interventions in congested cities. Included in the list are signal priority schemes that take green times from cars to accommodate an arriving bus (e.g., Zhou et al., 2017), even if sparingly applied only to late-running buses (Anderson & Daganzo, 2020). Converting shared-use lanes to exclusive bus lanes (e.g., Basso et al., 2011; Tsitsokas et al., 2021) might also be avoided, even if said conversions are activated intermittently, either as in Eichler & Daganzo (2006) or in Saade et al. (2018). And our focus on dense cities is to suggest that space is at a premium, which might render infeasible the addition of new bus-only lanes to the network (e.g., Russo et al., 2022).

These considerations underscore that, in settings of greatest concern (dense, congested cities), options for prioritizing bus movements can be limited. The one well-known intervention left standing is a bus bypass, also called a queue jump or queue bypass (AASHTO, 2014). This will be the intervention tested in the present report.

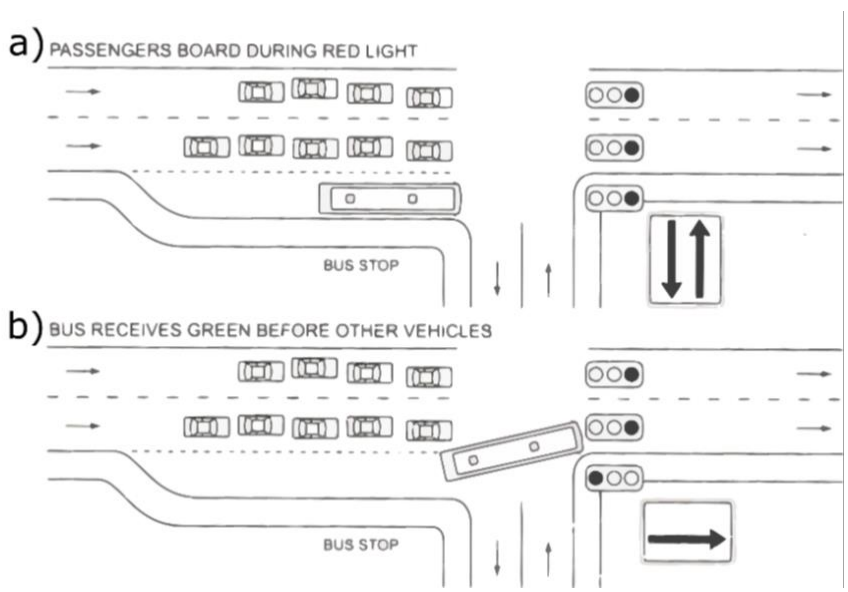
1.1. Background

Consider the bypass design in the AASHTO Guidebook (AASHTO, 2014). It entails adding a lane segment of 75 to 300 meters in length on an approach to a signalized intersection, and a dedicated traffic signal to control bus movements (see Figure 1a). The dedicated signal provides buses with their own green indication of 5 to 10 seconds duration. It initiates, when needed, ahead of the regular green for car movements in the adjacent lane(s) to enable buses to merge back into the shared-use lane in advance of discharging cars (see Figure 1b). We assume that bypasses are to be used only at bus stops, as inferred in Figure 1.

Cities are, of course, composed of more than a single intersection. Yet, absent from the AASHTO Guidebook (AASHTO, 2014) is any discussion on how to deploy a bypass in a congested city when, during a rush, one or more sets of congested street links become connected by queues; that is, residual queues emerge at an intersection that we shall call a critical bottleneck and expand to multiple street links upstream. We might remedy the omission by borrowing from the literature on freeway incident management (Menendez & Daganzo, 2004), as explained below.

We know that freeway traffic accidents can be especially damaging when they occur immediately upstream of a bridge, tunnel, or some other form of critical bottleneck. In these cases, any accident-inducing reduction in flow propagates forward through the bottleneck, thus reducing exit flow from the system. The more flow-constraining the accident, the greater the harm to the system. In contrast, the damage done even by severe accidents that occur further upstream from a critical bottleneck can be eliminated if the reduction in traffic flow can be kept from propagating through the bottleneck.

The story turns out much the same for bus bypasses. We shall see how the story ought to influence where to locate a bypass and how to time its dedicated signal. Some findings may seem counterintuitive, owing to the cross-modal influence of cars. As examples, placing a bypass where queues persist for the greatest durations is often not a good strategy; and a simple alternative treatment that delays buses by modest amounts can often be the preferred option for both buses and cars.



Source: Adapted from TCRP Project D-09 Task 7-4 Bus Pull-Outs, p. 7, and reproduced in AASHTO (2014)

Figure 1. A bus bypass and its dedicated signal:
(a) bus waiting in bypass; (b) bus responding to special green.

1.2. Study Scope

The issues were studied via simulations of a signalized arterial, one with just enough complexity—but no more than needed—to illustrate the impacts of bypass placement and dedicated-signal timing, including the cross-modal influence that these induce. The site and simulation model are described in Chapter 2. Parametric tests, including those for a simple alternative treatment for a bus stop near a critical bottleneck, are presented in Chapter 3. Practical implications and caveats are reviewed in Chapter 4.

Chapter 2. Experimental Setup and Simulations

This chapter discusses the study site, its signal control strategies, and travel-demand patterns, and then presents details on how these inputs were simulated.

2.1. Idealized Case Studies

Explorations featured the signalized arterial in Figure 2, which may be viewed as a portion of a city's larger street network. The site was endowed with features that provided needed realism for the tests to come and forewent extraneous details that would have complicated the presentation and obscured the findings. For example, downstream-most Intersection 1 was designated to be the critical bottleneck by assigning it queue discharge flows lower than at other intersections. This exogenous designation rids our tests of the complexities that dictate where critical bottlenecks emerge in real-world networks but does not render the findings less valid and useful.

To balance realism and simplicity, the site consists of homogeneous street links, each with two lanes to serve traffic in a single (rightward) direction. Links are numbered 1–15 in reverse direction to traffic. To represent networks in dense urban cores, each link was 120 meters in length (Sevtsuk et al., 2016) in all tests save three. Vehicles entered the arterial via upstream-most Link 15 and proceeded (rightward) through the site's 15 signalized intersections. Each intersection was assigned the number of its upstream feeding link. Traffic was presumably prohibited from turning onto and from the cross-streets. This heroic assumption simplified the presentation; for example, it prevented jammed queues from blocking cross-streets, as discussed momentarily. Other caveats with respect to realism are examined in Chapter 4.

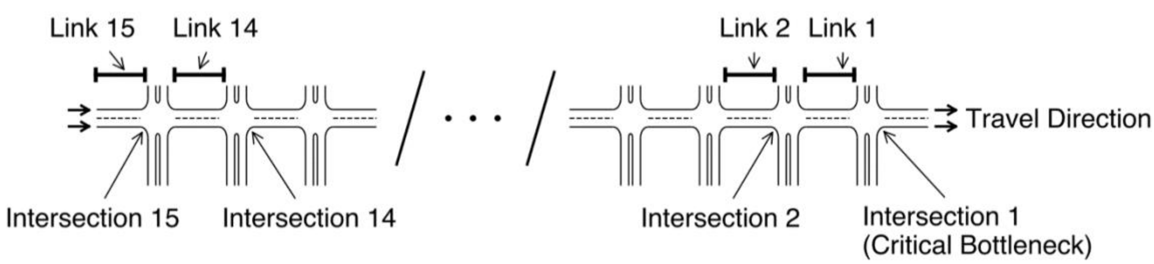


Figure 2. Study site: one-way signalized arterial.

Arterial links at Intersections 2–15 were assigned the default queue discharge flow used by the simulation model, 1,800 vehicles per hour per lane (vphpl). Intersection 1 was made the critical bottleneck to mimic what can occur at real-world intersections characterized by narrowed lanes, or on-street parking conflicts, for example.

As is good practice for congested conditions such as those studied herein, traffic signals operated with a long 90-second cycle length to maximize intersection capacity by reducing lost times over the longer run (Newell, 1989). The cycle length was common to all intersections to facilitate signal coordination along the arterial. All tests, save one, featured the zero-offset coordination strategy, meaning that green indications for arterial traffic were always initiated simultaneously across all intersections (Daganzo & Geroliminis, 2008; e.g., Newell, 1989). This strategy is known to work well in congestion (Daganzo &

Lehe, 2016; Newell, 1989). One test featured a lesser-known coordination strategy that is also suited to congestion.

Green splits, like cycle length, were also the same at all signals. This timing feature, combined with zero offsets and the absence of turning traffic onto the arterial, ensured that a residual queue was always fully contained within its link; that is, an intersection was never blocked by a jammed (stopped) queue from downstream. As explained in Newell (1989), this setup ensured that any jammed queue at a red phase was comprised solely of the vehicles that were already contained on the link at the start of the red. The duration of the arterial green was half the cycle length, 45 seconds (including amber), to mimic what might occur when the arterial's cross-streets had high demands. Amber times were the minimum allowable, as determined by the simulation model.

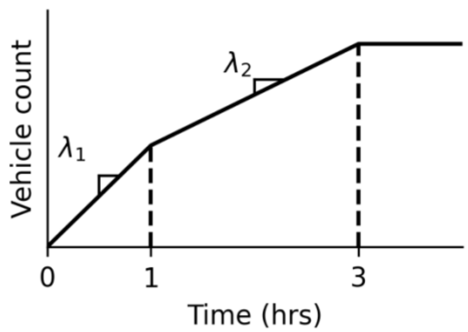


Figure 3. Cumulative count curve of car demand.

As regards demand, cars sought entry to the system (via Link 15) as shown by the cumulative curve in Figure 3. An initial demand varied parametrically: λ_1 = (1,400, 1,500, 1,600) cars per hour. The rate persisted for 1 hour, creating residual queues that emanated from the critical bottleneck, and thereafter affected links, one-by-one, along an upstream path of expansion. During each green phase, forward-moving vehicles might fill a link to restrict vehicle entries from the link upstream. At the end of a first hour, car entry demand dropped to λ_2 = (1,200, 1,420) per hour, either to slow or halt the queues' upstream expansion, and thereafter persisted for 2 hours. Demand dropped to zero at the 3-hour mark and remained so thereafter, so that all vehicles could be served by the end of each simulation.

Buses began arriving via Link 15 at the 1-hour mark, and in most tests at an average rate of 12 per hour. The resulting average headway, 5 minutes, is commensurate with what is reported in many cities during a rush (Senevirante, 1990), and one that is comfortably below the Guidebook's maximum of 15 minutes, said to no longer justify the installation of a bypass. Bus headways were normally distributed with a standard deviation equal to the mean and truncated at zero. The truncation mimicked the occasional occurrence of bus bunching (with zero headways), as is common with high-frequency bus service. By allowing bunched buses to proceed through a single display of special green, we reduced the total number of cycles interrupted by AASHTO's scheme, thus presenting a more optimistic case for the AASHTO bypass design.

A single bus stop was placed on the arterial, either on Link 1 or 2, and always 36 meters in advance of its downstream intersection, as per Gu et al. (2014). Impacts of in-line stops, where each dwelling bus can block car flows behind it, were compared against those in which the stop was served via a bypass. Its length was typically 75 meters, the Guidebook's minimum, though a longer length of 200 meters was tested in three instances. These lengths were always sufficient to enable buses to circumvent car queues without added delay. An off-line stop, also termed a bus pullout or turnout, was tested on Link 1 as well. Buses were assumed always to visit the designated stop, as might occur on a high-demand route, and bus dwell times at the stop were normally distributed with a mean of 20 seconds and a standard deviation of 5 seconds.

2.2. Notes on Simulations

Micro-level simulations were performed using the AIMSUN platform (TSS, 2015). Its default parameters were adopted for emulating bus and car movements, including bus visits at the designated stop. A speed limit of 50 km/h was imposed on all arterial links.

Script written in Python was implemented in the platform to emulate the operation of a bypass' dedicated signal. It was coded to activate intelligently so that special greens were displayed only in cycles when one or more buses were waiting to merge from the bypass back into traffic. On rare occasions, a bus that finished serving its patrons and that was confronted by a regular green indication forced its way back into traffic, without waiting for its special green in the following cycle.

Downstream-most Intersection 1 was made the critical bottleneck by coding a meter there to restrict the intersection's discharge flows during regular greens. The metering rate was set to 2,860 vph across both arterial lanes (1,430 vphpl) in all but one set of tests, when the rate was set to only 2,400 vph (1,200 vphpl).

The first hour of each simulation, marked by queue expansion under car demand, λ_1, was treated as warm-up time. Measurements were extracted starting at hour 1 and ending when the last vehicle exited the system. The tails of any residual queues that spilled beyond upstream-most Link 15 were stored as first-in-first-out vertical queues, such that vehicles entered Link 15 after waiting their turns.

To obtain better estimates of expected values, each data point presented in the following section is the mean of 20 simulations, each with a distinct random seed. The mechanisms described were unveiled from the averaged outcomes (to be shown in tables) and were confirmed via disaggregate measurements (not shown) together with visual inspections of AIMSUN animations.

Chapter 3. Tests and Findings

We begin section 3.1 by placing the site's lone bus stop on Link 1, just upstream of the critical bottleneck (see Figure 2). Impacts of installing that stop in in-line fashion, off-lane fashion, and as part of a bypass are presented, along with those of moving the stop from Link 1 to Link 2. Parametric tests in section 3.2 unveil that the unfavorable impacts of placing the bypass on Link 1 are not abated by higher bus flows. Tests in section 3.3 illustrate that our findings qualitatively hold for the site when subjected to a lower congestion level. We demonstrate in section 3.4 why a bypass makes sense for Link 1 only when the critical bottleneck's capacity is quite small. Tests in section 3.5 reveal why it is preferable to install bypasses on congested links that are long in length. Impacts of an alternative signal coordination strategy are presented in that section as well.

3.1. It's all About Exit Flow

A first round of tests featured λ_1 = 1,600 cars/h, λ_2 = 1,420 cars/h (see Figure 3), and a critical bottleneck capacity, μ = 1,430 vph. (The μ is the product of Intersection 1's metered rate across both approach lanes, 2,860 vph, and the ratio of green time to cycle length, ½.) A length of 120 meters was used for all links. This setup caused residual car queues to occupy Links 1–10 by the end of warm-up hour 1.

Predictions from placing the bus stop in in-line fashion on Link 1, 36 meters upstream of the critical bottleneck are presented in the first row of Table 1. Note that exit flow from that bottleneck was only 1,409 vph, less than its capacity of 1,430 vph. The diminution was caused by buses dwelling at the in-line stop. Cars blocked by those buses maneuvered around them, but the interruptions created voids in car flow that propagated through the critical bottleneck, degrading its average exit flow as a result.

The diminished exit flow meant that cars spent more time in the system (see Daganzo, 1997) and this penalty was shared with buses, thanks to the shared-use lanes. To quantify these unfavorable effects, the second row in Table 1 presents predictions from converting the in-line bus stop to an off-line one, so that dwelling buses no longer interrupted car flows. Note first that the conversion restored capacity to the critical bottleneck. (That the rate is 1 vph higher than 1,430 is an artifact of AIMSUN's inherent stochasticity.) Now note from the table's first two rows how the stop's conversion diminished average travel time in the system for cars by a full minute, to 12.5 minutes, down from 13.5 minutes. Finally, note how the buses' average travel time fell by nearly the same amount to 14.1 minutes, down from 15. These data unveil how the in-line stop's penalty to cars was shared with buses, and how this was resolved by moving the bus stop off-line to restore car flows.

Interestingly, the off-line stop delayed buses once their drivers had finished serving passengers there and sought to reenter traffic. We estimate the average delay to be 0.3 minutes per bus, as we shall demonstrate shortly. Nevertheless, the stop conversion benefitted buses by virtue of having remedied an unfavorable cross-modal influence.

Installing a bypass on Link 1 might be tempting since this is where residual queues formed first and dissipated last. The third row of Table 1 presents predictions for this placement, for a 75-meter-long bypass, and when the special green times were set to 5 seconds. Note the diminution of exit flow to 1,417 vph relative to the bottleneck's capacity, and the resulting impact on cars; that is, their average travel time rose to 13.1 minutes, up from the 12.5 minutes that occurred by moving the stop off-line.

The average travel time predicted for buses, 14.1 minutes, is equal to that predicted for the off-line bus stop. This equivalence is the result of two opposing forces: the favorable elimination of the delays that buses had incurred when exiting the off-line stop, and the unfavorable manner by which the bypass' penalty to cars was shared with buses. Bus patrons might therefore be indifferent to the off-line and bypass treatments—provided that the bypass' special green time is 5 seconds. We hasten to add, however, that the bypass option generates larger VHT and PHT in the system. (A larger PHT would almost surely persist under the bypass option, even if buses arrived empty to the stop, if patron waiting times at the stop were duly considered.) The advantage of the off-line bus stop is that it honors the constraint of doing no further harm to car flows.

Row 4 of the table shows that using a 10-second special green for the Link 1 bypass would be Pareto worsening. The larger voids periodically created by the longer (10-second) special greens were very damaging to car flows and the damage was passed on to buses. Placing and managing a bypass in this fashion would be worse for the system—and for buses—than doing nothing.

We next move the bus stop from Link 1 to Link 2 upstream and repeat the above tests to the extent warranted. Predictions are presented in rows 5 and 6 of the table. Note from row 5 that an in-line bus stop on Link 2 did no harm to the exit flow from the critical bottleneck further downstream—that flow was kept approximately at the bottleneck's capacity, 1,400 vph. This favorable outcome occurred despite the disruptions to car flows from dwelling buses, now on Link 2. Those disruptions did not in this case propagate through the critical bottleneck as voids. The voids were instead compressed upon encountering the tails of residual queues on Link 1 and disappeared.

As a result, average car travel time was not affected by the in-line bus stop on Link 2. That time of 12.6 minutes is roughly equal to what it was when an off-line stop was installed on Link 1. Bus average travel time (with the in-line stop on Link 2) was 13.8 minutes. Notice that this value is 0.3 minutes less than what buses incurred when an off-line stop was placed on Link 1. (Refer again to row 2 of the table and note the latter value of 14.1 minutes.) This difference is the average delay that each bus encountered when exiting the off-line stop.

Hence, in this case, there would be no value in converting the in-line bus stop to an off-line one. Since car flows were unharmed by the in-line placement on Link 2, said conversion would do nothing more than delay buses.

In contrast, placing a 75-meter bypass on Link 2 saved bus delay as intended, and the savings were invariant to the duration set for the special greens. Whether 5- or 10-second durations were used, the resulting voids in car flow were fully compressed when they propagated to the tails of the residual queues on Link 1. Predictions for this bypass deployment are in row 6 of Table 1. Note from rows 5 and 6 how the well-placed bypass saved nearly a minute (i.e., 0.8 minutes) of travel time for each bus, and this was independent of the special green times.

We thus see that a bypass can be beneficial when not allowed to degrade outflow from the site's critical bottleneck. We further see that a simple alternative treatment that honors our constraint might be advisable when a bus stop is located close to that bottleneck and cannot be moved. These insights did not change much when inputs were varied parametrically, as shown below.

Table 1. Simulation Predictions

Row	Test	Exit Flow (vph)	Car Travel Time (mins)	Bus Travel Time (mins)	
1	In-line stop, Link 1	1409	13.5	15.0	Sec. 3.1
2	Off-line stop, Link 1	1431	12.5	14.1	
3	Bypass, Link 1 (5-s green)	1417	13.1	14.1	
4	Bypass, Link 1 (10-s green)	1380	14.8	15.6	
5	In-line stop, Link 2	1431	12.6	13.8	
6	Bypass, Link 2 (5- & 10-s green)	1434	12.5	13.0	
7	In-line stop, Link 1 (high bus flow)	1392	14.7	16.1	Sec. 3.2
8	Bypass, Link 1 (high bus flow, 10-s green)	1355	16.4	16.9	
9	In-line stop, Link 1 (light queueing)	1407	9.4	10.8	Sec. 3.3
10	Off-line stop, Link 1 (light queueing)	1422	8.6	10.2	
11	Bypass, Link 1 (light queueing, 5-s green)	1414	9.2	10.1	
12	Bypass, Link 1 (light queueing, 10-s green)	1383	10.5	11.3	
13	In-line Stop, Link 1 (low bottleneck capacity)	1192	16.7	18.4	Sec. 3.4
14	Off-line stop, Link 1 (low bottleneck capacity)	1198	16.3	18.2	
15	Bypass, Link 1 (low capacity, 5-s green)	1193	16.7	17.7	
16	Bypass, Link 1 (low capacity, 10-s green)	1161	18.5	19.3	
17	In-line stop, Long Link 2	1432	12.7	13.9	Sec. 3.5
18	Bypass, Long Link 2 (5- & 10-s green)	1435	12.7	12.3	

3.2. Bus Frequency

Having seen the damage done by a poorly placed bypass with a long special green, we next illustrate that higher bus flows do not lessen the damage but worsen it instead. To this end, the site's bus stop is returned to downstream-most Link 1; and bus demand starting at the 1-hour mark is raised from 12 to

20 per hour, with headways generated as per a truncated normal distribution with mean and standard deviation of 3 minutes. All other inputs were as before.

Predictions from placing the bus stop in in-line fashion are shown in row 7 of Table 1. By comparing these against predictions in row 1, note how the higher bus flows reduced system exit flow, from 1,409 vph to 1,392 vph. This is no surprise. The greater number of dwelling buses interrupted car flows more often, to the system's detriment. Average travel times for cars and buses rose accordingly.

The higher bus flows might induce an engineer or planner to use the relatively large 10-second duration for the special greens—to accommodate the greater frequency of bunching, whereby multiple buses use a single display of the special green. Predictions in row 8 of the table caution against this move. The data unveiled damage beyond any in previous tests. Once again, the better option would be to do nothing at all.

3.3. Congestion Level

Travel times thus far predicted were, of course, sensitive to the site's level of congestion. Lesser queue expansions would mean lower travel times, in part because the cross-modal influence would be less dramatic. Qualitatively speaking, however, findings seem rather invariant to congestion level. To illustrate, the bus stop remained on Link 1 and bus demand was returned to 12/hour. Car demand in the first hour, λ_1, was reduced from 1,600/hour to 1,500/hour. Residual queues as a result expanded only upon the site's five downstream-most links (i.e., half the expansion of previous tests). Car demand, λ_2, remined unchanged at 1,420/hour.

Test results are shown in rows 9–12 of the table. Row 9 holds predictions for an in-line bus stop, to be compared against those in row 1. Note how exit flow is virtually unchanged (i.e., it changed by only 2 vph). Car and bus travel times are now lower, of course, because congestion has been lessened. Converting the stop to an off-line one (see row 10) did not quite restore exit flows to capacity in this instance. This is only because residual queues dissipated before the last vehicles had exited the system, so the critical bottleneck was not saturated with flow for the entire simulation period. Comparisons of rows 10 and 11 show that buses are once again served almost equally by the off-line stop and by a 75-meter bypass with 5-second special greens, but that the latter produce greater VHT and PHT. Use of a 10-second special green would again be worse than doing nothing. Note that from a qualitative perspective, there is nothing new to report here.

3.4. Bottleneck Capacity

We find one circumstance for which a bypass can be the preferred treatment for a bus stop located just upstream of the critical bottleneck: when the capacity of that bottleneck is so low that its discharge headways approach in size the voids created by bypass special greens. To illustrate, we reduce the critical bottleneck's capacity from 1,420 vph to 1,200 vph, such that the average discharge headway of 3 seconds comes rather close to the voids created by a 5-second special green. First-hour car demand, λ_1, was diminished to 1,400/hour, so that residual queues again occupied Links 1–10 at the end of hour 1. Car demand, λ_2, was diminished to 1,200/hour to arrest the queues' expansion. All else was as in the previous test. The bus stop remained on Link 1, of course. Predictions are shown in rows 13–16 of Table 1.

Note that exit flow with an in-line bus stop (1,192 vph in row 13) was only slightly less than the bottleneck capacity of 1,200 vph. This is because the latter reflects an already-large discharge headway. Rows 14 and 15 reveal that a 75-meter bypass with 5-second special greens now saved buses 0.5 minutes of travel time, on average, as compared to an off-line stop. The voids created by a 10-second special green were still large enough to do substantial damage (see row 16).

In a sense, the findings of this section confirm what was said of section 3.1: it's all about exit flows. This time around, a well-managed bypass on Link 1 could be viewed as the best option for bus-favoring intervention, because it only modestly degraded the critical bottleneck's already-low discharge flow.

3.5. Sprawling Cities and Signal Coordination

For a penultimate test, all values of car and bus demand and of the critical bottleneck's capacity were returned to the original ones used in section 3.1. The site's bus stop was returned to Link 2, again 36 meters upstream of Intersection 2, and a single alteration was made: the physical length of Link 2, and only of Link 2, was expanded from 120 to 200 meters. The intent was to illustrate how bypasses can be of greater benefit to buses when placed on long links; for example, commensurate with what is found in sprawling cities that developed around the automobile.

Note from row 17 of the table that the in-line bus stop produced results comparable to those shown in row 5. The only differences (0.1 minutes in average car and bus travel times) occurred because the site was made modestly longer. Row 18 holds the predictions for when a 200-meter bypass was added to Link 2. A shorter bypass may have sufficed, and findings were invariant to the special green durations. Note how the bypass reduced average bus travel time from 13.9 minutes (row 17) to 12.3 minutes (row 18). The savings of 1.6 minutes is twice that of what occurred when a bypass was placed on a 120-meter-long Link 2 (see again rows 5 and 6 of the table). On the longer 200-meter link, the bypass enabled buses to advance ahead of a larger number of cars. Cars on the 200-meter link were forced to wait two cycles before entering downstream Intersection 2 because the longer link now held a longer car queue. Thanks to the bypass, buses on that link waited no more than a single cycle.

In a final test, the physical length of Link 2 remained as above, as did all other inputs, save for the site's signal coordination. Zero offsets were left in place for the signals at Intersections 10–15, while those at Intersections 1–9 were re-sequenced as per a strategy known as "backward coordination" (Daganzo & Lehe, 2016; Sadek et al., 2022). In short, arterial offsets for these latter signals were synchronized to the backward waves that propagate through queues. As a result, green times at Intersections 1–9 were initiated each cycle only after residual queues on the respective links downstream were moving forward. Very importantly, those residual queues now filled larger portions of their links as a result of the backward strategy.

By filling links nearly to their brims, residual queues spread to fewer links in a system. For our site, the number of links occupied by residual queues dropped from 10 to 8. As a practical matter, the altered coordination strategy reduced the locations where bypasses (or other bus-favoring interventions) would be needed. Other practical implications are discussed in Chapter 4.

Chapter 4. Conclusions

Simulations show that the bus bypass in AASHTO's guidebook (AASHTO, 2014) becomes a concern when placed immediately upstream of a critical bottleneck in a congested network, even though this is where queues are likely to be most persistent in real-world settings. In these cases, the voids in car flow periodically created by special greens propagated through the critical bottleneck, thus reducing its long-run average exit flow. We therefore found that a bypass placed in this fashion could in some cases benefit buses relative to a similarly placed in-line bus stop. But this was only the case when the special green time was kept small (i.e., 5 seconds), and benefits were diminished by the cross-modal influence of degraded car flows. A bypass proximate to the critical bottleneck worsened the situation for both buses and cars whenever the special green time was set to 10 seconds, such that the voids created in flow grew large.

High bus flows were shown to exacerbate the concerns outlined above, and those concerns remained when the site's level of queueing was cut in half. A bypass proximate to the critical bottleneck could be viewed as a preferred option only when that bottleneck's capacity was so small that its discharge headways approached the size of the voids created by special greens. But this finding also means that the damage done by a poorly placed bypass would be worse than those predicted herein, had the critical bottleneck's capacity been higher than those presently studied.

It thus seems a good idea to avoid placing a bypass too close to a critical bottleneck. For bus stops that are proximate to these bottlenecks and that cannot be moved, converting an in-line stop to an off-line one appears a better option, even though buses were delayed when exiting the stop and reentering traffic. This simple alternative still performed as well, or better, for buses than did a bypass; and by honoring the constraint to do no further harm to car flows, it did a better job of reducing VHT and PHT systemwide. If funds and need exist, installing a bypass on one or more congested street links further upstream could further benefit buses. Findings show that this upstream placement saves bus delay as likely intended. This is largely because the well-placed bypass did not degrade congested car flows by diminishing the system's exit flows. The voids created by the special greens were fully compressed when they encountered residual queues on the link downstream. We found that placing the bypass 100 meters upstream of the critical bottleneck was sufficient to achieve full compression for both durations of the special green that were tested. Thus, we envision that in most cases (unless the block length is extremely short) placing the bypass one intersection upstream of the bottleneck would be enough to eliminate the problem.

Benefits to buses were found to grow when a well-placed bypass was installed on a longer street link. The longer link and its suitably lengthened bypass enabled buses to enter the downstream intersection after circumventing greater numbers of cars and shortened the time that buses waited at that intersection. In the present case, travel time savings to buses more than doubled by installing the bypass on a link that was two-thirds longer than the original. It thus seems that bypasses can be more effective in cities with longer street links, such as those in the western United States and parts of Asia, for example. The finding also means that for sites with varying block lengths and all else equal, it may be beneficial to prioritize longer links when deciding where to install bypasses.

We also found that backward signal coordination reduces the number of links affected by connected queues, consistent with Daganzo and Lehe (2016). This outcome reduces the number of a network's links in need of bus-favoring interventions.

There are, of course, caveats attached to our findings partly because they come with all the uncertainties inherent in simulations. The magnitudes of all impacts predicted herein might be different from those observed in the field, and those magnitudes will be case-specific. We suspect that our findings are qualitatively reliable, however, largely because they confirm that the success of a mobility intervention rests upon its effect on a site's critical bottleneck(s), and because the present story is much like what is already known regarding freeway incident management. Our findings therefore come as little surprise in retrospect and should largely hold for complex, real-world systems despite the idealizations adopted herein. Moreover, real-world complexities may amplify present concerns but will not negate them; see Daganzo (1998) for discussion on this matter.

Complexities might also make difficult the task of identifying critical bottlenecks in real-world networks. And precisely how many links upstream a bypass can be placed without degrading system outflow is likely to be case specific and involve complexities of its own. Perhaps the present findings will motivate the efforts needed to confront these real-world challenges.

To what extent practitioners need this motivation is impossible for us to say. The lessons of the present work might already be understood and incorporated into practice. Then again, the absence of relevant discussion in the AASHTO Guidebook (AASHTO, 2014) seems to us a troubling and perhaps telling omission. The present findings may will lead to more guidance in future editions of the Guidebook. This would be one way in which this study might contribute to the field.

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