Signal Priority near Major Bus Terminal

Case Study of Ruggles Station, Boston, Massachusetts

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Near major bus terminals, multiple bus arrivals per signal cycle and a convergence of buses from conflicting directions can make it impractical to apply signal priority logic that attempts to interrupt the signal cycle for each bus. This research explores signal control logic for reducing bus delay around a major bus terminal in Boston, Massachusetts, where the busiest intersections see almost four buses per signal cycle. With a traffic microsimulation to model a succession of signal priority tactics, a reduction in bus delay of 22 s per intersection was obtained, with no significant impact on general traffic. The general strategy was to provide buses with green waves, so that they are stopped at most once, coupled with strategies to minimize initial delay. The greatest delay reduction came from passive priority treatments: changing phase sequence, splits, and offsets to favor bus movements. Green extension and green insertion were found to be effective for reducing initial delay and for providing dynamic coordination. Dynamic phase rotation, from lagging to leading left, proved less effective. Cycle-constrained free actuation, in which an intersection has a fixed cycle length within which two phases can alternate freely, provided flexibility for effective application of early green and green extension at one intersection with excess capacity. Emphasis is given to the approach of providing aggressive priority with compensation for interrupted phases, highlighting the compensation mechanism afforded by actuated control with snappy settings and long maximum greens.

Giving priority to buses at traffic signals is a traffic management principle suited to achieving societal objectives of encouraging transit use, lowering transit operating cost, and improving transit service quality (*1*). At first glance, it would seem that, with some intelligent reallocation of time within a signal cycle, getting buses through signalizing intersections with near-zero delay should be possible; after all, they need only a few seconds of green, timed to match the moment of their arrival time.

However, where transit routes concentrate on approaching a bus terminal, bus volumes can become quite high, sometimes exceeding one bus per signal cycle. Priority logic that might work where bus arrivals are infrequent, interrupting the signal cycle for each bus and allowing several cycles for the intersection to recover, are impractical when bus arrivals become too frequent. Recovery is an important but often poorly conceived part of priority logic in which interrupted phases get a chance to clear built-up queues and, in a coordinated system, the signal returns to a background cycle (*2*). For example, in many applications priority requests are simply inhibited for a certain number of cycles or minutes after a priority interruption so as to ensure that other phases recover. This kind of blunt strategy limits the potential effectiveness of signal priority.

Further complicating matters, buses turning into and out of a terminal tend to belong to minor traffic streams not favored by arterial coordination plans and with long red periods. Where buses are part of the main arterial traffic flow, bus priority often benefits general traffic. In contrast, giving priority to buses by using minor phases can be detrimental to intersection capacity and, by interrupting coordination, risk queue spillback, hurting following buses as well as general traffic.

In addition, buses often approach the terminal from conflicting directions, so that priority given to one bus may delay another. Finally, the intersections near major bus terminals are often near saturation, offering little slack that priority logic can take advantage of.

Two cities in Europe with a reputation for aggressive transit priority underscore the challenge of giving signal priority near a terminal. Zurich's (Switzerland) trams experience nearly zero delay at most signalized intersections (*3*), with one notable exception: turning into and out of terminals, where conflicting tram lines with high frequency interfere with one another. And in Eindhoven, Netherlands, highly aggressive signal priority logic results in nearly zero delay for late buses at most intersections (*4*); however, no priority is applied where buses turn into and out of the central station.

This research addresses the questions: How effective can signal priority be near a major bus terminal? What signal priority strategies are likely to be most effective there? Because the answers can be very site specific, a case study approach is used, modeling traffic around Boston's Ruggles Station through microsimulation to see to what extent, at least in one case, giving priority to buses at traffic signals can reduce bus delay.

SITE DESCRIPTION

Ruggles Station, a major transfer center between bus, metro, and commuter rail, lies about 2 mi southwest of downtown Boston, on the edge of the Northeastern University campus. Buses arriving from the north and west use the station's main bus way entrance, while buses arriving from the south and east use a back entrance. All routes use the same busway exit, parallel to the main entrance, as shown in Figure 1.

Figure 1 also depicts the relevant part of the street network that was modeled, including turning movement volumes and volume–capacity (v/c) ratios for the morning peak hour. Bus volumes are shown in parentheses. Of the seven intersections shown, Intersections 2, 3, 5, and 6, the "primary intersections," are candidates for signal priority treatments. (Intersection 4 is an infrequently called midblock

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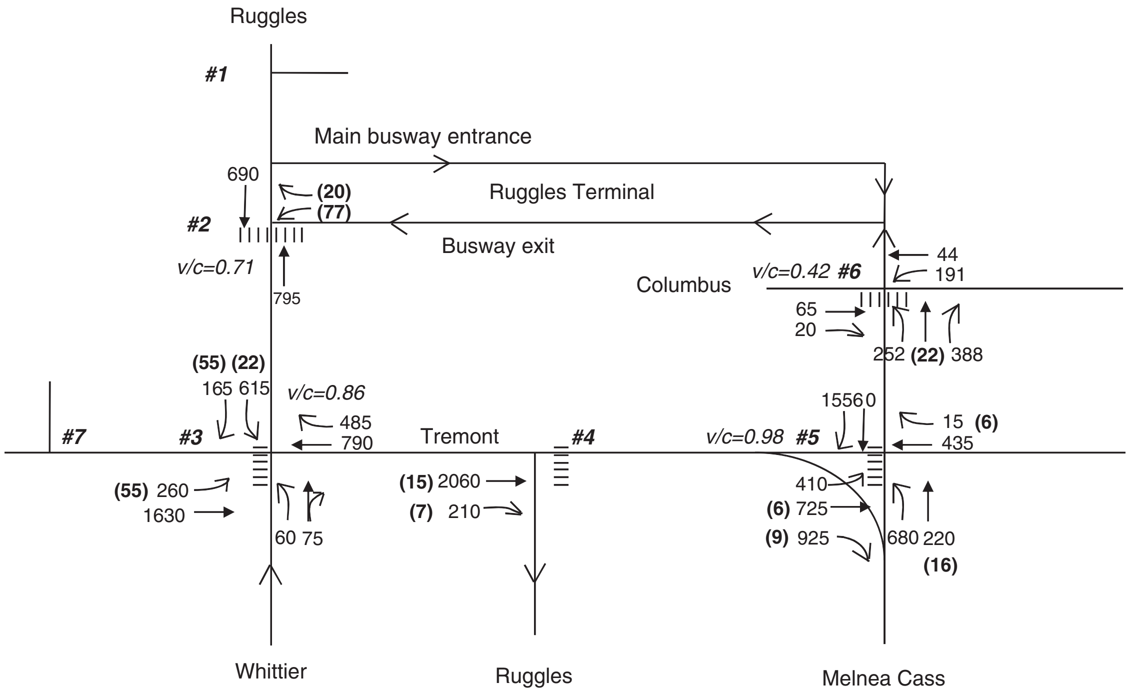

FIGURE 1 Street network indicating intersection numbers, morning peak hour traffic (bus) volumes, and v/c ratios.

pedestrian crossing; Intersections 1 and 7 were included to provide properly platooned traffic inputs). Of the primary intersections, Intersections 3 and 5 are highly saturated and Intersection 6, at the back entrance, has a lot of excess capacity.

Figure 2 shows morning peak hour bus flows into and out of the station by direction, the busiest being the west with 55 buses per hour. Intersections 2 and 3 see almost four buses per signal cycle. At Intersection 3, while buses represent only 3% of the vehicular traffic, bus passengers account for 37% of the people passing through the intersection, underscoring the social imperative of transit priority. Buses going to and from the north are essentially unaffected by traffic signals near the station and are therefore not targets of this research.

For directions other than north, 148 of the 154 buses entering or leaving the station pass through two primary intersections in the

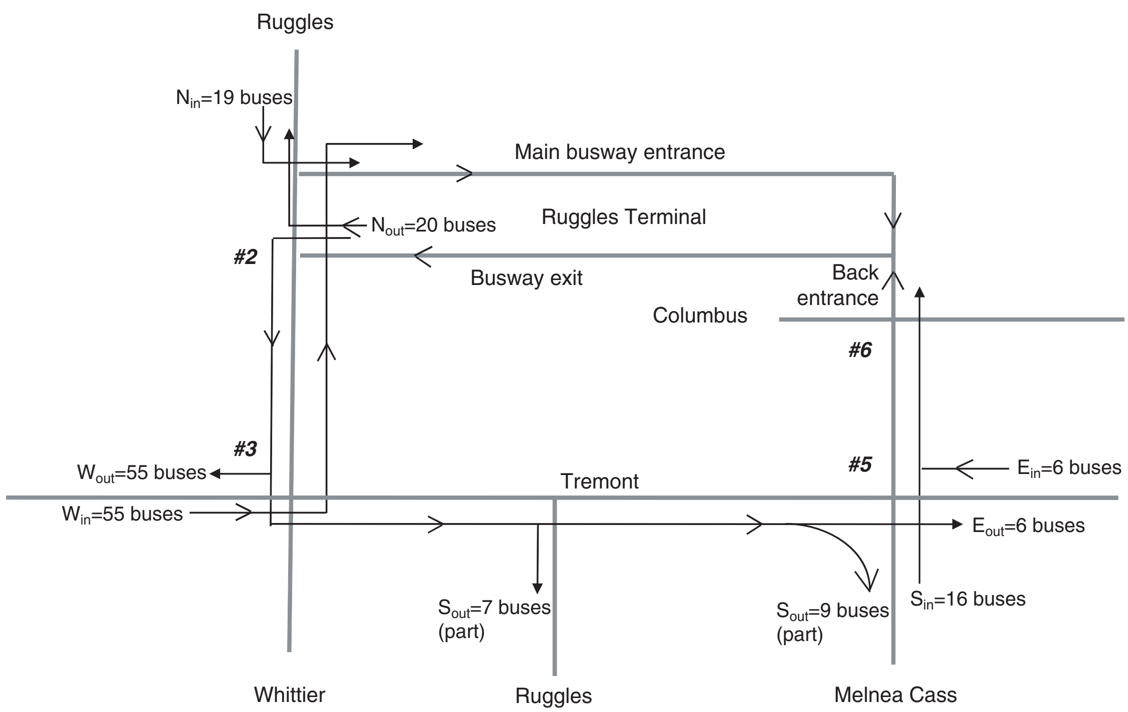

FIGURE 2 Bus flows by direction.

modeled zone, while six pass through three intersections. There are no bus stops in the modeled zone other than the terminal.

The existing signal-timing plan provides arterial coordination for Tremont Street through Intersections 7, 3, 4, and 5, with a 100-s cycle. In the coordinated–actuated logic used in Boston, coordinated phases have a fixed ending time in the cycle and no detectors. Other phases have detectors and end either by gapping out or after a maximum green. Any slack time due to gap-out goes to the coordinated phase, allowing it to begin the next cycle early. Minor phases may be skipped if there is no call.

Intersection 2 (station exit) has three signal phases: Ruggles Street (the coordinated phase), pedestrian only, and busway. If the pedestrian phase is not called, the coordinated phase runs longer, until the scheduled end of the pedestrian phase. Intersection 6 (back entrance) is not part of the current coordination plan; it operates on a 90-s cycle without actuation. More detail on signal-timing plans, including time–space diagrams showing current and proposed coordination plans can be found elsewhere (*5*).

SIMULATION MODEL

The network shown in Figures 1 and 2 was modeled by using VISSIM (*6*), a microscopic traffic simulation model. Signal control logic was programmed with VAP, VISSIM's language for coding signal control. Traffic counts were taken from a recent master plan study done for Northeastern University. Signal-timing plans were obtained from the city of Boston and field verified.

To calibrate, saturation flow rate and vehicle discharge per cycle were measured for Intersection 2's eastbound left (EBL) phase, which is fully saturated during the morning peak. VISSIM's Wiedeman model parameters a_x, b_{add}, and b_{mult} were adjusted to match the saturation flow rate within recommended parameter ranges. To match the number of vehicles discharged per cycle, the first second of yellow on the EBL approach was represented as green to reflect the well-known phenomenon of Boston driving in which drivers, especially bus operators, intentionally delay their reaction to the onset of yellow on oversaturated approaches. The model was then verified by following the approach of Park and Schneeberger (*7*) for comparing field-measured and simulated travel time distributions on a path from Intersection 7 to the terminal via Intersections 2 and 3, with excellent agreement (there is a bimodal distribution reflecting cycle overflow at Intersection 2). More detail on calibration and validation can be found in Cesme (*5*).

SIGNAL CONTROL STRATEGIES FOR TRANSIT PRIORITY

Because the busiest intersections see as many as four buses per cycle, it is impossible to eliminate bus delay at signals unless buses are platooned to follow green waves. The first goal of the research was to prioritize streams of buses so that, while buses may be stopped at the first signal they encounter, they should proceed without delay through the next intersections. This stop-once approach scales up well to high bus volumes. Because of the limited scope of this study, the cycle length and offsets were held fixed with respect to external downstream intersections rather than using an acyclic approach such as recommended by Janos and Furth (*8*).

Six general signal control strategies, applied in one or more control tactics or logics, were employed to give buses priority.

Minimize Initial Delay

Four tactics were applied to minimize delay to buses at the first intersection in the network that they encounter:

- Green extension offers a high payoff to a benefited bus. Because it applies only to buses arriving in a small window within the signal cycle, it will not be requested frequently, even when bus volumes are moderately high, thus limiting its impact on other traffic. At Intersection 3, it was applied with substantial benefit to EBL buses. As described later, this tactic was also used to provide dynamic coordination for southbound left (SBL) buses at the same intersection, and for northbound (NB) buses at Intersection 6.
- Green insertion was also applied at Intersection 3 for EBL buses, which would otherwise face a long red period. In a normal cycle, EBL has a leading phase; with green insertion, a lagging phase is inserted as well in response to a bus detection. This tactic reduced bus delay at Intersection 3 substantially; however, because benefited buses then found themselves outside the main stream for which a green wave was provided (described later), this benefit was partially offset by delays at the following intersection.
- Early green, a tactic that applies to buses arriving on red and during the early part of green, is not an appropriate strategy for a phase with very frequent bus arrivals at an intersection near saturation. Unlike green extension, early green offers a relatively small benefit to a large fraction of buses. It targets buses arriving during the red period and the saturated part of the green, which typically represent most of the signal cycle, so that at intersections with high bus volume it will be requested nearly every cycle, making it tantamount to changes in split and offset that are better handled by deliberately adjusting splits and offsets. However, early green was applied with good results at Intersection 6, the back entrance, which has a lot of excess capacity and sees less than one bus per cycle.
- Phase rotation, in which a phase is shifted from lagging to leading (or vice versa) to shift a green period to match a bus's arrival time, can reduce bus delay with virtually no capacity impact. It was applied at Intersection 5 to benefit northbound through (NBT) buses, shifting the NB phase from lagging to leading on detection of a bus predicted to arrive before the normal green start. However, the delay reduction at Intersection 5 was small and was largely offset by increased delay at the following intersection because it took buses out of the coordination plan.

It is to be expected that rotation from lagging to leading left should be ineffective where bus volumes are high, because it is similar to early green in that it will be requested by a high fraction of buses and yields a relatively small benefit per requesting bus. Rotation from leading to lagging, a tactic not tested in this study, is more appropriate for intersections with high bus volumes, being similar to green extension in that it is targeted to buses arriving within a relatively small part of the signal cycle (after the normal phase), and is therefore requested by a small fraction of buses but yields a large benefit to affected buses.

Fixed and Dynamic Coordination for Buses

Through a combination of passive and active priority tactics, this research aimed to give buses a green wave so that they would have to stop at most once within the network.

Passive priority measures do not depend on a bus being detected, and therefore apply every cycle, making them amenable to serving high volumes of buses. Two passive priority measures were used. The first was changing the coordination plan to give progression to bus movements. Through changes to both the phase sequence at Intersection 2 and the offsets between Intersections 2 and 3, it was possible to provide green waves for buses through Intersections 2 and 3 without interfering with the existing progression along Tremont Street. However, possibilities are limited when buses approach an intersection from conflicting directions. At Intersection 5, some inbound buses arrive from a NB approach while others arrive on an EB approach, making it impossible to create a passive green wave through Intersections 5 and 6 for both streams of buses.

The second passive priority change was preventing a minor phase from being skipped to reduce variability in offsets. At Intersection 3, the lightly used NB phase usually has a split of 10 s, but it can also consume 0 s when skipped for lack of demand and 20 s when there is a pedestrian call. This variability makes it difficult to coordinate Intersection 3's EBL, which begins just after the NB phase, with downstream Intersection 2. By putting the NB phase on minimum recall, it is never skipped, changing the range of its green time demand to 10–20 s, a range small enough that it could be accommodated in our coordination plan.

Where passive priority is unable to give buses a green wave, we used green extension (for Intersection 3 SBL and for Intersection 6 NBT) and early green (for Intersection 6 SB through) to create green waves, an outcome we call dynamic coordination. Dynamic coordination was often needed when an active priority tactic such as green extension released a bus from an upstream intersection outside the normal green wave.

Aggressive Priority with Compensation

In many priority applications on coordinated arterials in the United States, there is no mechanism for compensating interrupted phases, so priority interruptions can result in the building of large queues. In reaction, many priority schemes are cautious (e.g., prohibiting priority calls in successive cycles or inhibiting priority when cross-street occupancy exceeds a threshold) and sometimes result in such small benefits to public transport that the investment becomes questionable. If instead, signal control logic has mechanisms for compensating interrupted phases, it can be more aggressive in favoring buses and thus far more effective.

In the signal control logic proposed around Ruggles Station, compensation comes from using actuated control with long maximum greens and snappy settings. Snappy settings (for this application, short extension increments) extend the green only while a queue is discharging near the saturation flow rate. With the combination of snappy settings and long maximum greens, a phase shortened by a priority action in one cycle can usually get enough green time in the next cycle to recover in the next cycle. With snappy settings, long maximum greens have little impact on other phases because those maximums will not be used except when an unusually long queue has developed. They also avoid wasting green time during periods of unsaturated flow, so that slack time is available for phases needing it either to favor a bus movement or to recover from an interruption.

Queue Management

For buses, the coordination plan should aim to minimize delay. For general traffic, the first goal should be to manage queues to keep fluid the road sections used by buses and to prevent spillback, with its catastrophic effect on intersection capacity. Reducing delay for general traffic is a secondary objective, one that often follows automatically from effective queue management.

The proposed coordination plan manages queues by (*a*) maintaining existing offsets for the main traffic movements, (*b*) adjusting other offsets to eliminate a routine source of spillback on Ruggles Street northbound between Intersections 3 and 2, and (*c*) eliminating routine overflow queues on Intersection 3's EBL approach. By increasing EBL's maximum green from 17 to 21 s, oversaturation for this phase was essentially eliminated, reducing average delay for this movement (which includes 55 buses per hour) by more than 40 s. Thanks to snappy detector settings, the average reduction in green time available to other phases was only 1.4 s per cycle.

There was a concern that aggressive priority tactics favoring EBL buses at Intersection 3, which "borrow" green time from the westbound (WB) movement, might reduce WB capacity so much that queues might spill back into Intersection 5. Therefore, the model included a spillback detector that, when triggered, would inhibit phase insertion at Intersection 3. With today's morning peak hour volumes, that spillback detector was never triggered; however, sensitivity tests showed that it would be triggered if traffic volumes increased by 10%.

Maximize Capacity

Slack capacity allows more flexibility for priority interruptions. One opportunity to increase capacity arose: replacing an all-pedestrian phase at Intersection 2 with a pedestrian phase concurrent with the busway exit, along with a leading pedestrian interval and substantially longer walk interval to maintain pedestrian safety and improve pedestrian level of service.

Flexible Signal Control

With flexible control logic, it becomes easier to accommodate and recover from priority interruptions. At Intersection 6, which has a lot of excess capacity, a control logic was created that can be called "cycle-constrained free actuation." To prevent queue spillback on the short block between Intersections 5 and 6, it maintains the coordination cycle of 100 s and places the low-volume EB phase at a fixed point in the cycle, where it will not interfere with the main traffic and bus progression. The remaining two conflicting phases, NBT and left (NBTL) (used by buses) and WB and northbound right (NBR), were allowed to alternate freely within the remaining part of the cycle by using standard actuation logic. The simulation showed that the freely actuated phases were realized between one and three times per cycle, providing a flexibility that allowed early green and green extension requests by NBT buses to be acted on almost immediately while also providing a natural means of compensation to WB traffic, whose delay was actually reduced because of the shorter red periods.

Simulation Results

Simulation results are based on at least five replications of 1 h of simulated time (after a warm-up period) by using steady-state morning peak hour demands. Additional replications were performed as necessary to reduce the coefficient of variation of average bus and traffic delay to 0.2.

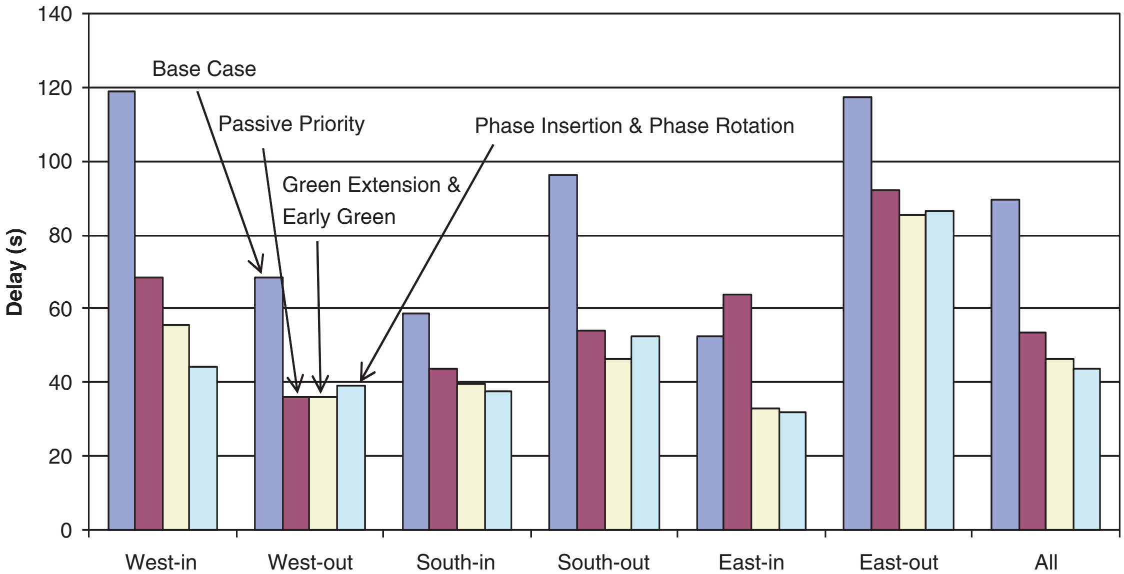

FIGURE 3 Average bus delay by direction with successive implementation of priority schemes.

Bus Delay Reduction

Figure 3 shows the impact of priority on networkwide bus delay, with buses grouped by direction. Overall, average delay per bus falls from 90 to 44 s. Because each bus passes through two or more intersections in the network, average delay per intersection has been reduced from 44 to 22 s. The most dramatic improvement is for the 55 buses per hour entering the terminal from the west; their average delay networkwide falls from 119 to 44 s. For the bus routes coming to or from the west, route cycle time falls by 1.75 min, which on some routes may be enough to reduce the needed fleet size.

If one assumes an average bus occupancy of 20 persons, a passenger value of time of $10/h, a bus operating cost of $120 per vehicle hour, and that the annual benefits will be four times the morning peak hour benefit for 250 days/year, an annual operating cost savings of $240,000 and an annual travel time benefit of $400,000 are predicted. The reduction in average delay to passengers, accompanied by an improvement in service reliability because the incidence of long delays is dramatically reduced, will attract more transit users, with additional concomitant societal benefits.

Results presented in Figure 3 are for successive stages of implementation, so that incremental benefits of more advanced strategies can be isolated. "Base case" represents the existing operation. "Passive priority" represents changes to splits, offsets, and phase sequence, as well as the bringing of Intersection 6 into coordination. The research found that 79% of the overall improvement could be gained through passive priority treatments, highlighting the importance of creating a timing plan that favors buses. In the next stage of implementation, green extension (Intersection 3's EBL and SBL and Intersection 6), early green (Intersection 6), and cycle-constrained free actuation (Intersection 6) were added, contributing to 16% of the overall improvement. The final 5% of overall improvement comes from adding phase insertion (Intersection 3's EBL) and phase rotation (Intersection 5's NB left).

Effectiveness of Active Priority Tactics

To examine more carefully the effectiveness of different active priority tactics, Table 1 shows the net change in delay per targeted bus by means of different tactics applied in succession, with passive priority

TABLE 1 Change in Bus Delay for Targeted and Other Bus Streams

	Change to Targeted Streams (s/bus)			Change to Other Streams (s/bus)			Net Change per Targeted Bus (s/bus)	
Intersections 2 & 3								
Green extension	W-in −12.9	S-out −7.7	E-out −6.3		W-out −0.1		−11.4	Main entrance
Phase insertion		W-in −11.4		S-out 6.4	E-out 0.8	W-out 3.4	−4.4	
Intersections 5 & 6								
Priority actuation	S-in −3.9		E-in −30.9		—		−13. 0	Back entrance
Phase rotation		S-in −2.1			E-in −1.2		−2.3	

NOTE: Negative changes indicate a reduction in average bus delay, while positive changes indicate an increase in delay.

improvements as the baseline. "Targeted buses" are those susceptible to the treatment. For example, when examining the impact of phase insertion for EBL buses at Intersection 3, only buses belonging to this EBL stream are counted as targeted buses. "Net change in delay" accounts for the change in delay to not only the targeted buses but to all buses at all intersections, thus accounting for the (often negative) impacts that priority to one group of buses has on other buses, and to changes in delay at downstream intersections that may result from altering a bus's position in the coordination plan.

Two active priority tactics proved quite effective. One was green extension, applied at Intersection 3 for EBL buses, which reduced delay by 11.4 s per targeted bus. The other, labeled "priority actuation" in Table 1, is the combination of cycle-constrained free actuation with green extension and early green applied at Intersection 6, which yielded a net reduction in delay of 13 s per targeted bus. Phase insertion (also applied to Intersection 3's EBL buses) was moderately effective, reducing net delay by 4.4 s per targeted bus beyond the gain already obtained by using green extension. Phase rotation at Intersection 5, which changed a lagging left to leading, yielded an incremental reduction in net delay of only 2.3 s per targeted bus. As mentioned earlier, phase rotation from lagging to leading was expected to be relatively ineffective compared with rotation from leading to lagging.

Compensation Mechanisms

To examine more closely the compensation mechanisms afforded by actuated control, green time distributions for Intersection 3's EBL green are shown in Figure 4 for different stages of priority implementation.

In the base case, with a 17-s maximum green, EBL maxes out in nearly every phase, resulting in an average green time of 16.4 s. When EBL's maximum green is extended to 21 s, the frequency of max-out falls to about 50% and average green rises to 17.8 s. The small change in average green arises because vehicles served in one cycle do not need to be served in the next, so long greens in one cycle tend to lead to short greens in the next. This reallocation of 1.4 s of green time from WB through (WBT) to EBL yielded a huge reduction in vehicular delay to EBL (from 99.5 s to 64.0 s) due to reduced incidence of cycle overflow, while increasing WBT delay by only 1.2 s.

When green extension is applied, buses extend the green in 21% of the cycles, with an extension of up to 10 s; however, average green time increases by only 0.3 s to 18.1 s because the extension period serves cars as well as buses.

On request, green insertion provides a secondary EBL phase with a minimum green of 8 s and maximum green of 15 s. The length of the secondary phase is governed by a bus checkout detector. The primary phase remained subject to green extension. Simulation showed that a secondary phase was inserted in 39% of the cycles; however, the total amount of green time consumed by EBL (primary and inserted phases combined) rose by only 1.0 s, to 19.1 s, because green time spent during a secondary phase reduced the need for green time in the following primary phase.

With the coordinated actuated logic used, the aggressive priority tactics favoring EBL "borrow" all of their time from the WBT phase. Compared with the passive priority case, WBT's average green falls

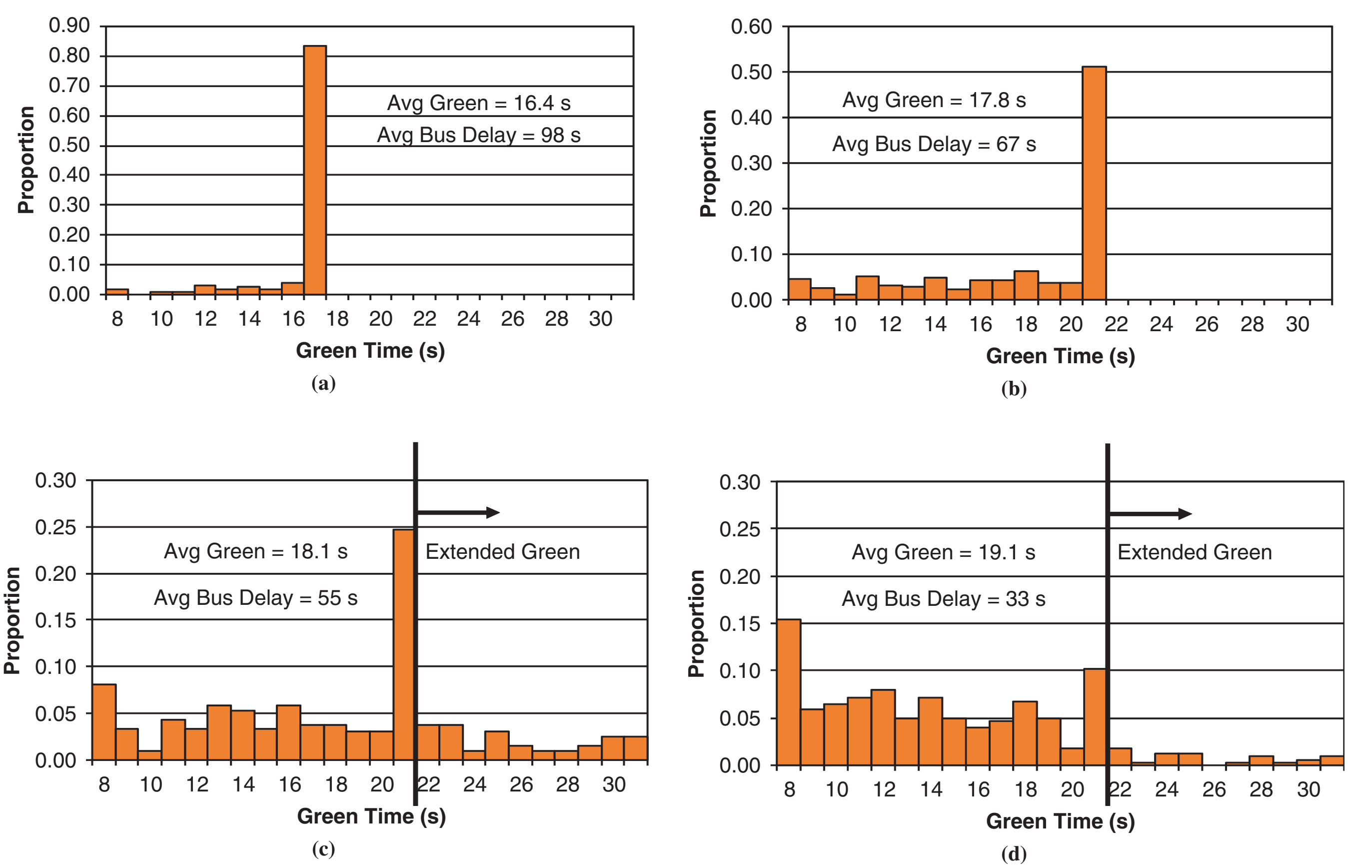

FIGURE 4 Green time distribution for Intersection 3 EBL with successively applied priority tactics: (*a*) base case, (*b*) passive priority, (*c*) green extension, and (*d*) phase insertion.

TABLE 2 Priority Interruptions and Incidence of 1, 2, and 3 Realizations per Cycle over 10 Simulated Hours at Intersection 6

Realization per Cycle	NBTL (used by bus)	WBL	Early Green	Green Extension
1	68	81	67	30
2	229	205		
3	53	63		
Average realizations per cycle	1.90 phases/cycle	1.89 phases/cycle	6.7 interruptions/h	3.0 interruptions/h

NOTE: WBL = westbound lane.

by 2.8 s when green extension and green insertion are applied. This 2.8 s can be decomposed into 1.3 s of increased green time for EBL plus 1.5 s of additional lost time (4 s per phase change, multiplied by 39% incidence of phase insertion). This loss in average green time increases WBT delay from 28 to 38 s. However, this increase is accompanied by a 20-s decrease in delay to EBL general traffic and a 34-s decrease in delay to EBL buses, making it a clearly positive tradeoff from a societal viewpoint.

Cycle-Constrained Free Actuation

Table 2 reports on the performance of the cycle-constrained free actuation logic programmed for Intersection 6, with green extension and early green for NBT buses. On average, the actuated phases (NBTL and WB left) were realized 1.9 times per cycle; in some cycles, they are realized only once and in a few cycles three times. The short red periods that result from multiple realizations and the compensation mechanism inherent in actuated logic generate low average delays to general traffic (14.9 s compared with 22.0 s in the base case). The flexibility in the logic allows bus requests to be served quickly, resulting in low average delay (7.4 s) for buses.

Delay to General Traffic

Impact on general traffic delay, overall and by origin–destination (O-D) pair within the network, is shown in Figure 5. Some dramatic improvements result for the O-D pairs using Intersection 3's EBL phase and for O-D pairs ending on Ruggles Street, thanks to the changes in split at Intersection 3, elimination of the all-pedestrian phase at Intersection 2, and changes in offset that help eliminate overflow queues and spillback. Negative impacts are small and scattered. Over the network, passive priority reduces general traffic delay by 5 s per vehicle, and active priority increases average delay by less than 1 s per vehicle.

CONCLUSION

Near major bus terminals, multiple bus arrivals per signal cycle and bus arrivals from conflicting directions make it difficult to apply the kind of priority tactics that work well when bus arrivals are relatively infrequent. However, while it may be impossible to eliminate all signal delay to buses, this case study shows that substantial reduction is possible by applying multiple and intelligent tactics that focus

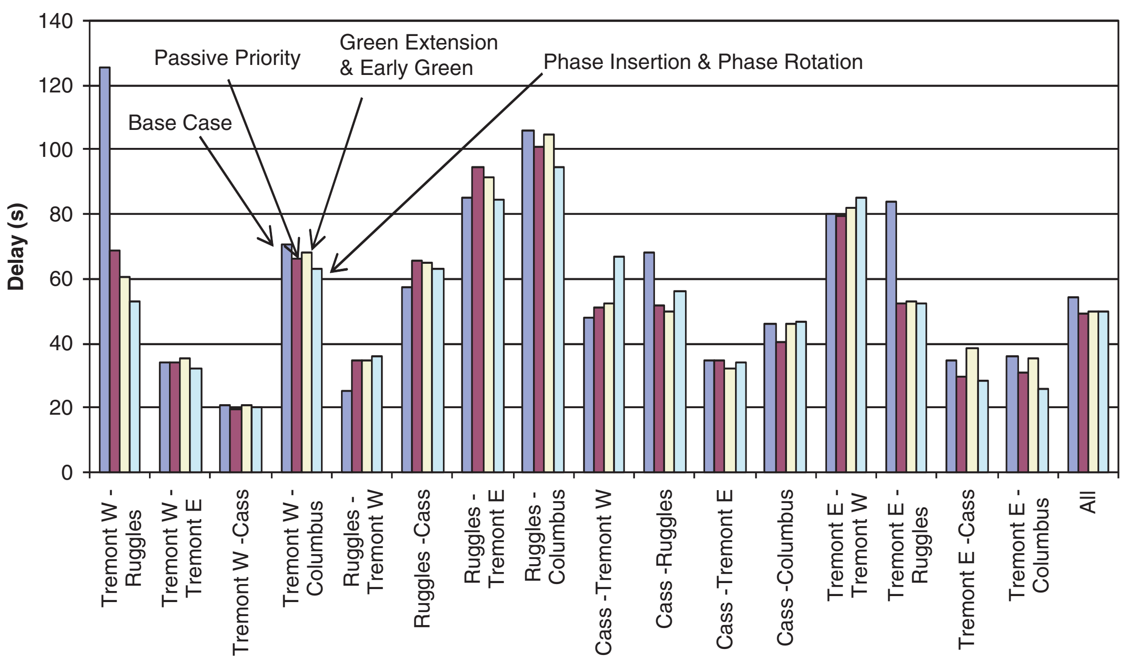

FIGURE 5 Average traffic delay by O-D pair with successive implementation of priority schemes.

not only on individual buses but also on streams buses through several intersections. Overall, average bus delay fell from 90 to 44 s, for a savings of 22 s per bus per intersection.

Passive priority treatments—providing splits and offsets that favor buses—can be very effective at reducing bus delay when an existing coordination plan does not favor bus movements. Overall, 79% of the total delay reduction was obtained by passive measures alone. Much of the benefit came from a longer maximum green that reduced overflow delays for a left-turn movement; another large part came from improving coordination so that most buses were stopped at only one of the two intersections through which they passed.

Green extension and phase insertion proved to be effective active priority tactics. They were used to reduce initial delay as well as to provide dynamic coordination. Phase rotation proved to have limited effectiveness in this study. Early green is not effective where bus volumes are high but proved effective at one intersection with about 0.5 bus per cycle.

Actuation, with generous maximum greens balanced by snappy settings that end a green period after the queue is discharged, provides a mechanism for compensating interrupted traffic streams and thus prevents the buildup of large queues. With effective actuation, time borrowed from conflicting phases to advance a bus in one cycle through green extension or insertion can be (largely) returned in the following cycle, when the prioritized phase needs less green time. Compensation allows more aggressive priority tactics and settings to be used, with greater overall benefit.

Cycle-constrained free actuation can be an effective signal control strategy at undersaturated intersections, combining the benefits of fixed coordination with those of free actuation. The flexibility afforded by free actuation is especially beneficial for accommodating active priority interruptions.

The estimated economic benefits of transit priority in this case study—$240,000/year in operating cost savings, $400,000/year in travel time savings, and improvements in service quality that are likely to attract new passengers—indicate that society would benefit from increased investment in intelligent, aggressive transit signal priority.

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