Conditional Bus Priority at Signalized Intersections: Better Service Quality with Less Traffic Disruption

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Abstract:

Conditional priority for buses at signalized intersections means that late buses are given priority, while early buses are not. This scheme is method of operational control that can improve service quality by keeping buses on schedule. An implementation in Eindhoven, the Netherlands, is described. Results show the strong improvement in schedule adherence, compared to when there is no priority. An experiment at an intersection measured traffic impacts under three scenarios: no priority, absolute priority, and conditional priority. Compared to no priority, absolute priority caused severe increases in delay, while conditional priority had almost no impact.

PRIORITY CONTROL AT SIGNALIZED INTERSECTIONS

Giving priority to transit vehicles at signalized intersections is one of the most powerful strategies for improving transit service that operates at grade or in mixed traffic. Advances in technology continue to create new and less costly means of providing priority, while increasing traffic congestion and concerns about air quality, livability, and the cost of rail construction make the need for transit priority ever more pressing. Priority at signalized intersections has been practiced and studied in the U.S. at least since the seventies *(1)*. In Europe, transit priority began even earlier, and is common in countries such as Switzerland, Germany, and the Netherlands *(2)*. Current interest in bus priority in the U.S. is high, spurred on by the Federal Transit Administration's Bus Rapid Transit Initiative *(3)* and by the intelligent transportation systems (ITS) community *(4, 5)*.

Transit priority strategies at signalized intersections can be classified along three broad dimensions.

- First is the distinction between *active* and *passive* priority. Active priority involves detecting and responding to transit vehicles in real time, while passive priority involves such measures as favorable cycle lengths, green splits, and progression *(6, 7, 8)*.
- Second, priority strategies can be categorized as giving *full*, *partial,* and *relative priority.* Under full priority, which is common in Europe, the traffic control program seeks to give the transit vehicle zero-delay service. Under partial priority, which is more common in the U.S. *(9)*, only the least disruptive priority tactics such as green extension and early green start are allowed, usually with rather stringent limits on extension lengths. Under relative priority, transit vehicles compete with other traffic for green time and permission to get priority. Transit vehicles are given a greater weight to account for their high passenger load *(10)*, but may be denied priority depending on competing traffic volumes or queues.
- A third dimension is the choice between *unconditional* and *conditional* priority. Unconditional priority means that every transit vehicle is given priority. We use the term *absolute priority* to refer to full, active, unconditional priority. Conditional priority, which has been implemented in both the U.S. *(5)* and in Europe, means that transit vehicles request priority only if they are behind schedule. In this paper, we shall use the term conditional priority to mean conditional full priority. It should be noted that others have used the term "conditional" to refer to schemes where priority is granted depending on competing traffic (volumes or queue lengths); we classify these schemes as relative priority.

OPERATIONAL CONTROL AND SERVICE RELIABILITY

Early applications saw transit priority primarily as a means of improving speed, which reduces operating cost and passenger riding time, and therefore used absolute priority to get the maximum speed improvement. Researchers noted that by reducing intersection delays, a major source of randomness in operations, service reliability improved as well *(11).*

Service reliability has long plagued the transit industry, and many transit agencies and researchers have sought methods of operational control that will improve punctuality (schedule adherence) and regularity (keeping the proper headway) (e.g., *12, 13*). Poor service reliability increases waiting time and crowding, drives up operating costs as recovery time and frequencies are increased to compensate for uncertain running times and fluctuating loads, and is seen by customers as one of the greatest sources of dissatisfaction. However, apart from priority at signalized intersections, the only control tactic that has proven viable in improving service reliability is holding early vehicles at control points, a practice that is customary at many transit agencies. (Other suggested strategies, such as inserting a reserve bus, have very limited applicability.) However, holding is a one-sided control strategy – it can be applied to early vehicles, but does nothing for late vehicles, except for the indirect effect of keeping the vehicles ahead of them from running early.

In contrast, conditional priority – giving priority at signalized intersections to late vehicles, but not to early vehicles – offers a means of operational control that tends to directly correct both early and late schedule deviations. Vehicles that are ahead of schedule are denied priority, and will tend to be delayed at traffic signals, while late vehicles are given priority and thus pushed ahead. This gives transit operations the kind of “push-pull” control needed to keep it on schedule.

Conditional priority makes operational control a primary objective, rather than a fringe benefit, of priority at signalized intersections. While absolute priority improves schedule adherence somewhat by eliminating intersection delay, schedule deviation has other causes which are not corrected by absolute priority – early and late dispatching from the initial stop, other traffic delays, and randomness in passenger arrivals and service times. Many Dutch tram and bus lines have had absolute priority for years, but still suffer persistent problems with schedule adherence. For example, the Amsterdam trams, which have absolute priority at most of their signalized intersections, still have to plan their service needs to accommodate 150 percent of the expected peak load because of widely varying headways.

Moving from absolute to conditional priority involves a small sacrifice in operational speed to get a large improvement in punctuality. For example, on Line 1 in Eindhoven, scheduled running time (one way) during the a.m. peak was reduced from 24 min to 20 min when absolute priority was installed. When the system was changed to conditional priority, scheduled running time had to be raised to only 21 min. Thus, conditional priority preserves most of the speed advantage of absolute priority, while adding the advantages of strong punctuality control. The net effect, we believe, is better service quality. At the same time, conditional priority has another advantage over absolute priority – it interferes less with traffic.

LIMITING IMPACT TO OTHER TRAFFIC

Priority interruptions for transit vehicles usually have a negative impact on other traffic. Of course, traffic in the same stream as the priority vehicle or in a compatible stream may benefit, but the net effect is usually a decline in capacity and overall level of service. The impact on other traffic depends on the tactics used by the signal controller in granting priority, the tactics used to recover from interruptions, and the frequency of priority interruptions. Green extension is the least disruptive priority tactic, which accounts for its popularity in partial priority systems, as compared to tactics such as skipping and truncating phases. Recovery tactics, especially in coordinated networks, have received less attention than priority strategies. They remain a pressing research need, since they can influence vehicular delay as much as priority tactics.

The frequency of priority interruptions is important because the intersection may need some time to recover, i.e., to clear queues that built up during a priority interruption, or to return to a background cycle that provides progression. If interruptions occur too frequently, the intersection may not get a chance to recover, and cycle failures (failures to clear queues) will be common. For this reason, some relative priority schemes inhibit priority requests for either a fixed period of time after an interruption, or while there are long queues. With conditional priority, the frequency of interruptions will be naturally reduced. Conditional priority systems can also be tailored to minimize their impact at critical intersections by varying the 'lateness' criterion (the number of seconds late a bus must be before it gets priority) from intersection to intersection. By using a larger lateness criterion at the busiest intersections, the likelihood of interruption at those intersections goes down. Of course, the likelihood of interruption at the succeeding intersections will go up. By the same token, using a smaller lateness criterion at one or two intersections upstream of a critical intersection will lessen the likelihood that a bus arrives late and therefore requests priority at the critical intersection.

PREREQUISITES FOR CONDITIONAL PRIORITY

Implementing conditional priority requires tracking bus location, comparing it against the schedule to determine schedule deviation. Tracking can be based on global positioning or wayside devices that use low power radio or infrared communication. One system architecture has the tracking done by on-board computers, who communicate their schedule deviation to the traffic control system. Another is for the tracking to be done centrally at a transit control center using and automatic vehicle location system. The transit control center then communicates schedule deviations to the traffic control system. Both alternatives are recognized in the National ITS Architecture *(4)*. Experience in the Netherlands points to the advantages of decentralized control, and emphasizes that where possible, responsibility to maintain the system should lie with those who benefit the most, the transit agency or its supervising public authority *(14).*

Proper application of conditional priority also requires carefully tailored schedules and a cooperative process that engages bus operators and supervisors. If schedules are too tight, buses will always be running late, and the system will function like absolute priority. If the schedules are too loose, buses will tend to run early, and the system will function as though there was no priority. This is exactly what happened in an early application of conditional priority on tram lines 1 and 9 in the Hague. They had the same scheduled running time for the entire day, with the result that during the peak they always ran late, and off-peak they ran early. In both cases, the control margin needed for conditional priority to keep the vehicles on schedule was lost. A good schedule should provide a control margin at each intersection, meaning that the probability that a bus will be late is neither too close to zero nor too close to one. This requires collecting a lot of data on schedule deviations and adjusting schedules to maintain the proper control margin at each intersection. More detail on constructing timetables that support operational control and on the organizational process of implementing conditional priority at a transit agency is found in Muller *(15)*.

THE EINDHOVEN BUS PRIORITY SYSTEM

A comprehensive program of transit improvements, including conditional priority on bus lines, is underway in Eindhoven, a city of 300,000 inhabitants in the southeast of the Netherlands. The Traffic and Transportation Engineering Laboratory of the Delft University of Technology provides technical support, including research and development of methods and software tools. To date, the conditional priority system is fully operational on Line 1, which runs from the central station to the northern edge of the city, offering 10 min service during the day. Local buses are all equipped with on-board computers that track vehicle location using VECOM™ two-way communication loops connected to traffic signal controllers, and dead reckoning between loops. The on-board computers record trip time events in detail, such as times when the vehicle stops or opens and closes its doors, together with time and location stamps. The data is automatically uploaded each evening to a computer at the Delft University Traffic and Transportation Engineering Laboratory, where it is reduced by a program called TRITAPT *(Trip Time Analysis for Public Transport)* to stop module records (a stop module is a bus stop and the interstop segment preceding it) and stored in a database. Thus, detailed operation data is available from nearly every trip, every day. TRITAPT then produces useful reports of schedule deviation, delays, recommended running times, and so forth *(16, 17)*.

The on-board computers also monitor schedule deviation in real time, displaying it in units of 10 s on a small screen visible to the operator. On lines without conditional priority, these displays help the operators know when they should try to “kill time” and when to speed up. About 300 m upstream of each controlled intersection, buses communicate their identification, desired direction (through, left, right), and on-time status (early / on time / late) to the local controller via a VECOM loop. "On time" is defined as ±10 s from the scheduled time at the loop. Controllers can be set to give buses priority (a) regardless of on-time status (absolute priority), (b) only if it is not early, or (c) only if it is late.

Buses on Line 1 operate in mixed traffic. Giving a bus priority therefore means giving priority to a regular vehicle stream. In this sense the priority system acts like an electronic bulldozer, pushing ahead any cars that are queued up in front of a bus – a very different kind of operation than if transit vehicles operate in their own right of way. In response to the priority request, the controller will estimate the arrival time of the bus, add an estimated amount of time to clear the queue ahead of it, and ensure that the light is green for the bus stream, if possible. The controller will truncate and skip conflicting streams as well as extend green on the priority stream. Safety constraints ensure that any green period, once started, must last at least 6 s, and that clearance times (yellow and all red) are enforced. VECOM loops at the stopline serve as exit detectors, which terminate the priority call.

SCHEDULE ADHERENCE RESULTS

A TRITAPT schedule deviation report for a typical day is shown in Figure 1. Each broken line shows the schedule deviation of a trip on Friday, May 29, along the route (stop codes such as NS are given on the horizontal axis) for Line 1 inbound. Not counting the last stop (a turnaround with no passengers boarding and often no alightings), it shows that buses were rarely more than 60 s early or more than 120 s late. Throughout the line, the distribution of schedule deviation remains tight. It should be noted that this level of punctuality is achieved in spite of imperfect dispatch control – departures from the first stop are evenly distributed over a range from 0 to 120 s late.

A contrasting picture comes from a summary of operations just three days earlier, when the conditional priority system was not operational because the timetable in the on-board computers had expired, and the new timetable had not yet been loaded. (This underscores the importance of system maintenance.). The schedule deviation report, given in Figure 2, shows much larger schedule deviations as the natural processes causing randomness were not checked by the conditional priority system.

To get a feeling for the human impact of the conditional priority system, we rode Line 1, standing next to the operator where we could see the schedule deviation display. If the bus was late as it approached red light, one could observe the light quickly turning green so that the bus could proceed unimpeded. If the bus was early, no such priority was given. During the entire trip, the bus was never more than 60 s late or 30 s early. When questioned, the operator told us that the conditional priority system was so popular with the operators that the union had agreed that no operator should get to serve on Line 1 more than half a day. Whereas on other lines the operators have continually adjust their driving behavior to stay on schedule, the conditional priority system on Line 1 keeps the bus on schedule automatically, making the operating task far more relaxed.

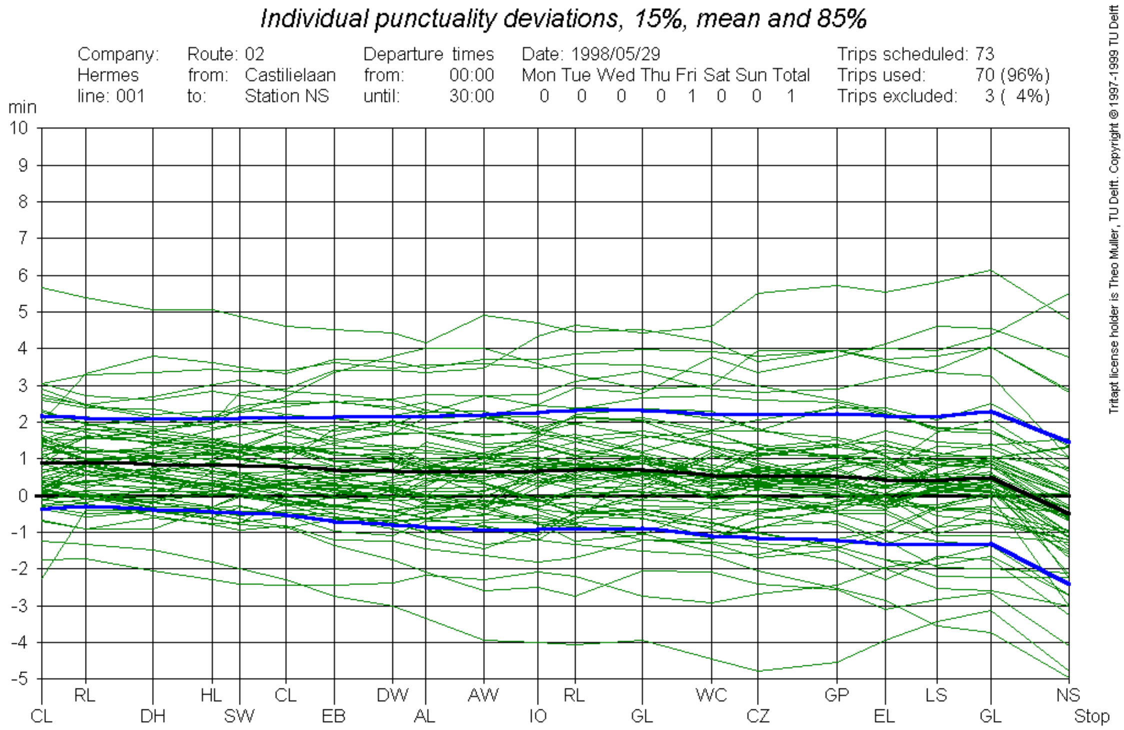

Figure 1: Schedule deviations on Friday, May 29 with conditional priority

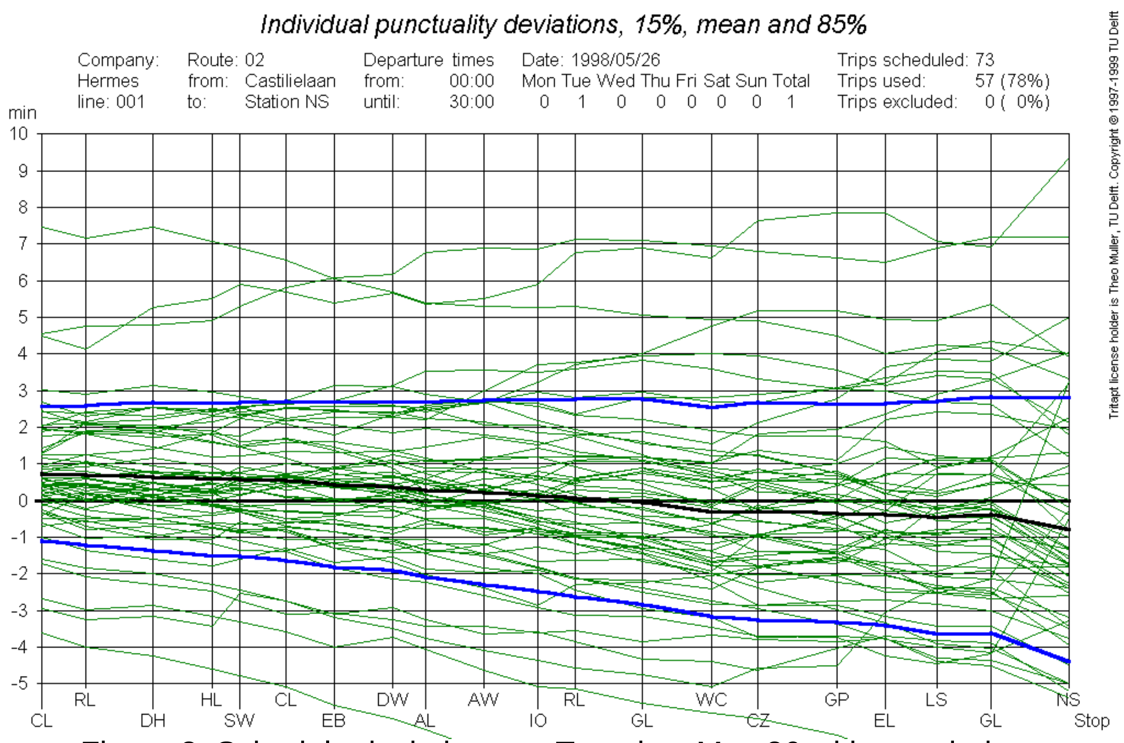

Figure 2: Schedule deviations on Tuesday, May 26 without priority.

EXPERIMENT AND SITE DESCRIPTION

To evaluate the traffic impact of conditional priority, an experiment was conducted on May 26, 27, and 29 (Tuesday, Wednesday, and Friday), 1998 at the busiest intersection along Line 1. Here, the Ring Road crosses Montgomery Laan, the north-south radial avenue that carries Lines 1 (with 10 minute service) and 9 (with 30 minute service). Traffic was observed each day from 7-11 a.m. and 2-6 p.m. With the cooperation of the city traffic department, the controller was set to operate with the no priority for buses Tuesday morning and Wednesday afternoon; with absolute priority on Tuesday afternoon and Wednesday morning; and with conditional priority (the normal mode) on Friday. There were no special events or unusual weather during the observation period.

No bus lines operate on this segment of the Ring Road, which has more traffic than Montgomery Laan. All four approaches have two through lanes, a protected left turn lane, and a separate bicycle path and sidewalk. Clearance times (yellow plus all red) are rather long – about 6 s – due to the wide intersection layout, with an additional 2 s of all-red time imposed on the northbound and eastbound through traffic streams, where bicycles get a 2 s advance green to reduce conflicts with right turning traffic. Both northbound and southbound directions use far-side stops.

When there are no priority interruptions, the controller follows a fixed-time plan with protected, lagging left turns. Cycle time and green splits vary by time of day. The cycle and offsets are set so as to produce a green wave for the Ring Road in the westbound direction. If a priority request arrives from a bus on a traffic stream whose light is red, conflicting streams will be truncated (subject to a 6 s minimum green), and the priority stream will turn green after the appropriate clearance time. If the priority stream was not next in sequence, intervening streams are skipped, and the priority stream's green ends as soon as the bus passes the stopline (subject to a 6 s minimum). Service then goes to the stream that was next in sequence when the priority call was received, and continues in the regular sequence. If the priority stream is green when the priority request is received, the green will be extended until the bus passes.

Priority interruptions invariably cause the traffic control program to get behind in its cycle. In order to return to the background cycle (the cycle used for progression on the Ring Road), the controller follows a "hurry" tactic, giving streams minimum (6 s) green times until the program catches up.

To measure vehicular delays, video cameras were mounted on four utility poles, one for each approach, giving a view from the stopline upstream to an approach entry point located beyond where the queue normally reaches. Teams of two students reduced the data by replaying the videotapes and using a computer program that records the moment at which any key is pressed. The students hit designated keys each time a vehicle passed the entry point, the through / right stopline, and the left stopline. Each four-hour observation period began with a car that entered an approach when there was no queue, so that if cumulative arrivals and departures are plotted as a function of time, the total time spent in the approach would equal the area under between the cumulative arrival and departure curves. Because this type of analysis is sensitive to miscount errors, checks on the number of cars "trapped" between the entry line and stopline were made approximately every three minutes by direct counting, stopping the videotape if necessary. If the difference between the cumulative arrivals and departures at that moment did not match the trap count, the videotapes were replayed, using slow motion when necessary, and the entry / exit records corrected.

Average total vehicular delay for an approach was found by dividing the total time spent in the system (the area between the cumulative arrival and departure curves) by the number of passing vehicles, and subtracting the normal passage time. Normal passage time was taken as the average passage time of several sample vehicles that passed through the intersection unimpeded. *Total* vehicular delay should be distinguished from *stopped* delay, a measure commonly used to determine intersection level of service. When an approach is not oversaturated, total delay is about 30 percent greater than stopped delay *(18)*. As delays increase due to cycle failures, the difference becomes smaller. Because it was not possible to distinguish vehicles upon arrival by intended turning movement, average delays could only be measured by approach.

In addition to observing traffic, the signal system behavior was tracked since traffic impacts due to transit priority are due primarily to the way the controller responds to priority requests. Taps to the green signal head leads were fed into a computer to record the moment at which each signal's green time began and ended. The computer is housed in a special-purpose data collection van owned by Delft University's Traffic and Transportation Engineering Laboratory, and is capable of recording data from 128 input channels.

TRAFFIC IMPACT

In Figure 3, average vehicular total delay is given by hour under the three scenarios.

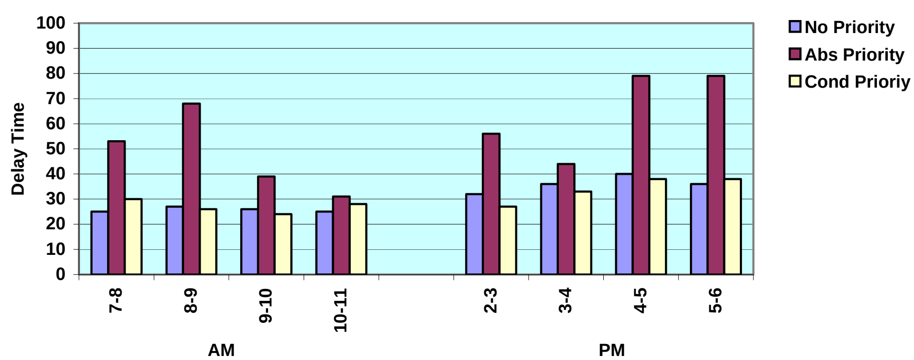

Figure 3: Average Vehicular Total Delay, All Approaches combined

The general pattern is striking: compared to no priority, vehicular delays under conditional priority are about the same, while absolute priority causes large increases in delay. Total delay increased by 40 s per vehicle in the three busiest hours when buses were given absolute priority, while conditional priority caused no significant change in delay. Traffic volumes during the observation period, shown in Figure 4, slightly favor conditional priority, but not enough to account for the enormous difference in impact between absolute and conditional priority.

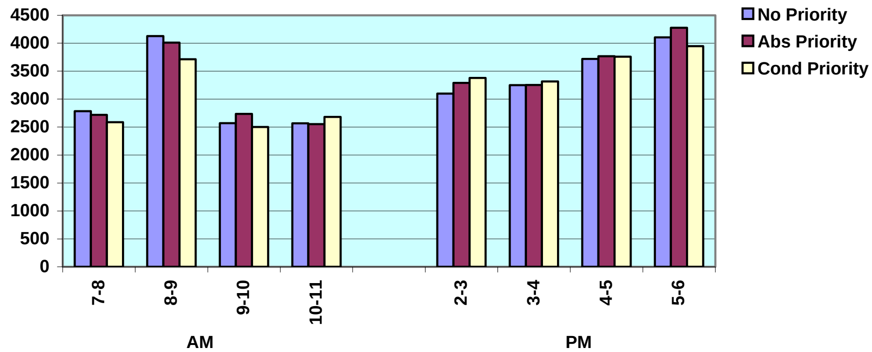

Figure 4. Traffic Volumes during observation periods

Impacts are shown by approach in figure 5, the corresponding traffic volumes in Figure 6.

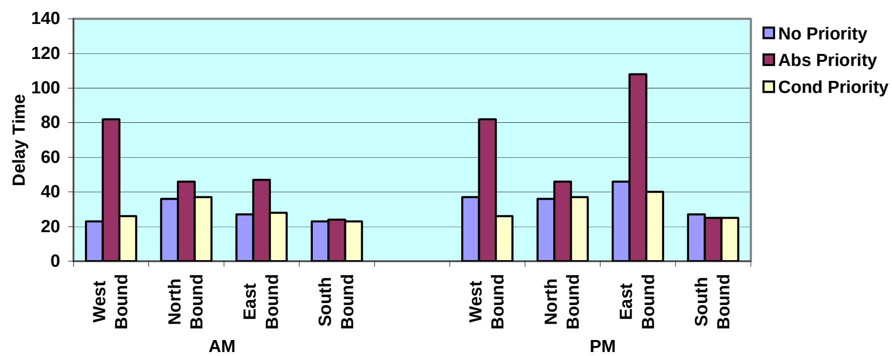

Figure 5. Delay times per approach

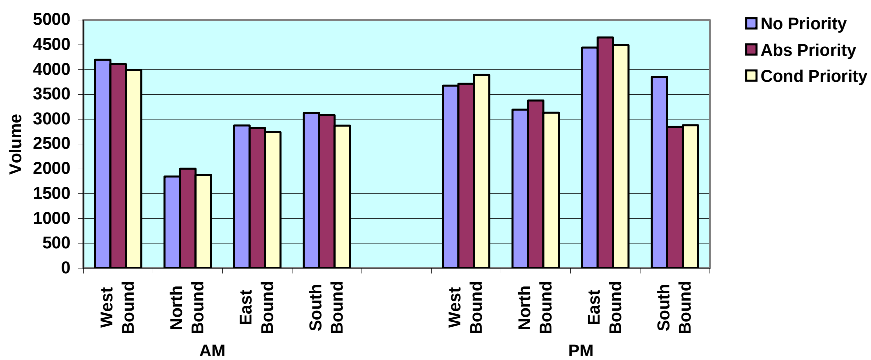

Figure 6. Volumes per approach

The Ring Road (eastbound and westbound approaches) clearly suffers the most from absolute priority, since it conflicts with the priority streams. Even though absolute priority favors the northbound and southbound directions, their average delays show a small overall increase compared to no priority. What can be seen here is that there is not simply a tradeoff between the priority road and the cross street. The priority interruptions reduce overall efficiency, so that while the priority road's level of delay remains largely unchanged, the cross street suffers severely.

The changes in delay under the different priority scenarios can be explained primarily by changes in capacity resulting from priority interruptions. The tactics used for giving priority and for returning to the background cycle result in extra phases for the north-south through traffic, requiring more phase changes with their corresponding lost time. Because lost time at this intersection is large, the impact is sizable. In the critical conflict group, the lost time rises from 29 percent of each cycle under no priority to 39 percent under absolute priority during both the a.m. and p.m. observation periods. In contrast, conditional priority causes lost time increases of 4 and 2 percent of the cycle in the two periods, respectively. Because of the priority given to the north-south street, it is able to maintain its share of the green time, with lost time taken mostly out of the cross street green time. An indication of how approach capacity changed is shown in Figure 7, where relative capacity is the number of seconds of green weighted by the number of lanes, scaled to equal 100 for the base case (no priority).

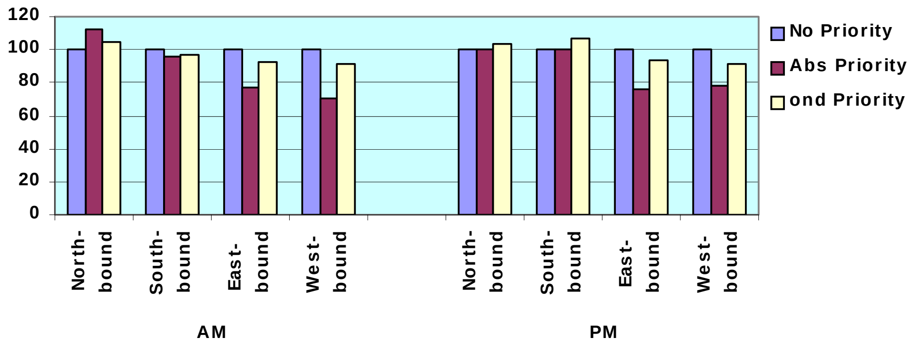

Figure 7. Relative Capacity under Different Priority Schemes

While northbound and southbound capacity hardly changed under absolute priority, the eastbound and westbound approaches lost over 20 percent of their capacity. The impact of conditional priority is much smaller – the eastbound and westbound approaches lose only about 5 percent of their capacity.

The green time and lost time analysis suggests some improvements to the traffic control program. First, a recovery strategy involving long cycles, rather than hurrying through 6 s phases with 6 s lost time between phases, would limit the capacity loss, which is critical in the peak hours. Second, the recovery strategy should seek to balance the green time loss between the approaches, rather than take all the green time away from the cross street. Third, the recovery strategy should aim first to prevent cycle overflows (queues remaining when the light turns red), and only after that aim to maintain progression, as progression is meaningless when there are cycle overflows.

BUS DELAYS

To get a more detailed view of the success of the priority system in giving unimpeded service to priority buses, bus delays in the stop modules that include the study intersection approaches were analyzed for the observation periods using data from the on-board computers and TRITAPT software. "Delay" is defined by TRITAPT as time spent standing still or at speeds of less than 5 km/h, excluding time spent at bus stops. While delay is most likely to occur at the intersection, it could also include delay elsewhere in the stop module. Average delays under the three priority scenarios are shown in Figure 8.

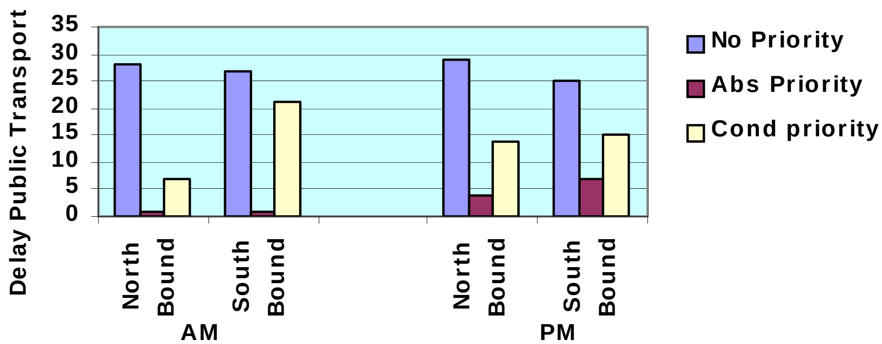

Figure 8. Average transit delay

When there is no priority, buses are delayed an average of 27 s, falling to 3 s when buses have absolute priority. Thus, absolute priority comes close to achieving its goal.

Average delay under conditional priority lies in between, with greater reductions northbound than southbound. This difference can be explained partly by the fact that northbound, a higher proportion of vehicles arrive late (because of the proximity of the central station terminal, from which buses are often dispatched one or two minutes late). We also found that the conditional priority system is not as effective at giving zero-delay service to priority vehicles as absolute priority. While over 90 percent of the buses got zero-delay service under absolute priority, only 45 out 61 late buses (74 percent) got zero-delay service under conditional priority, and several late buses had delays of over 30 s. It seems that some system improvement may be needed to either the schedule deviation tracking system, the controller, or communication links between them in order to achieve the goal of near-zero impedance for late vehicles.

CONCLUSIONS

Conditional priority – giving full priority at signalized intersections to transit vehicles that are behind schedule – is an effective and practical strategy for improving service reliability on urban bus routes. Its technological practicality and effectiveness in keeping buses on schedule are clear in the Eindhoven project. Its political practically is demonstrated by our findings, taken from the busiest intersection along the route with conditional priority, that the gains in operational quality for public transport come at nearly no cost to other vehicular traffic. In contrast to absolute priority, conditional priority causes substantially less traffic disruption, while improving service quality.

Our findings also highlight areas in which further attention is needed in designing and implementing priority systems. Better traffic control algorithms are needed to help the system recover from priority interruptions. Careful attention after implementation is needed to ensure that the priority system is functioning as designed.

Finally, this project highlights the importance to public transportation of having the support of the municipal traffic engineering department. In Eindhoven, the city traffic engineering department is committed to the public transportation improvement program. It is involved not only in providing priority to buses at signalized intersections, but also (in other sectors of the city) in converting general traffic lanes to bus lanes, in metering traffic on oversaturated roads used by buses, and in implementing parking restrictions in the city center. Conditional priority for transit can only succeed with the support and active involvement of both the transit agency and the city traffic engineers.

ACKNOWLEDGEMENTS

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