BUS-ACTUATED SIGNAL CONTROL AT ISOLATED INTERSECTIONS – SIMULATION STUDIES OF BUS PRIORITY

by

R A Vincent, B R Cooper and K Wood

Any views expressed in this Report are not necessarily those of the Department of the Environment or of the Department of Transport

Public Transport Division
Transport Operations Department
Transport and Road Research Laboratory
Crowthorne, Berkshire
1978
ISSN 0305—1293
Ownership of the Transport Research Laboratory was transferred from the Department of Transport to a subsidiary of the Transport Research Foundation on 1st April 1996.

This report has been reproduced by permission of the Controller of HMSO. Extracts from the text may be reproduced, except for commercial purposes, provided the source is acknowledged.
Normal traffic signal operation can be modified to give buses priority, if buses are detected separately from other vehicles. A computer simulation has been used to estimate benefits to buses and disbenefits to other traffic when using various forms of priority control superimposed upon the normal UK vehicle-actuated signal operation. All the cases simulated were for two-stage signals controlling crossroads-type intersections with buses on the major road only.

The facilities considered are: a 'priority call' which regains the green for buses approaching a red signal, and a 'priority extension' which maintains an existing green. The priority call curtails the green time on the non-priority stage, and various methods are considered for alleviating disbenefits to this traffic. Simulation results form the basis for guidance in the use of different methods of priority control with various traffic conditions, bus detector locations and bus flows.

Appropriate priority control can usually achieve delay savings for bus passengers which total more than the increase in delay to other travellers. It is less easy to attain a net benefit if equipment costs and the high time-value of non-priority vehicle occupants such as commercial vehicle drivers are taken into account.

1. INTRODUCTION

This Report describes the use of a computer simulation to investigate ways of using selective detection (SD) equipment and associated signal control logic to give priority to buses at isolated signal-controlled junctions. To date, such equipment is believed to have been used only on a limited, experimental, basis to give buses priority, the well-known example in the UK being that in Derby¹. Approved SD equipment is now available for general use, and the simulation results given here are intended to aid in its application and to indicate the likely effects on buses and other traffic. The Department of Transport has issued a Technical Memorandum* giving recommendations for the use of selective detection, many of which are based upon these simulation studies.

All the examples considered here were simulations of simple major/minor cross-roads controlled by 2-stage traffic signals, and with buses on the major road only. The signal operation was basically the

---

standard UK, vehicle-actuated, control using ‘System D’ inductive loop detectors, and superimposed upon this were the following main forms of bus priority:

a) a ‘priority extension’ facility whereby buses can maintain a green signal; used on its own or with other facilities.

b) a ‘priority call’ facility* which regains the green for buses; used alone or with other facilities.

c) two techniques to recompense the non-priority stage after its curtailment by a priority call.

In general, the priority measures considered reduce delay to buses on the main road, but increase delay to other traffic, particularly that on the minor road, when compared with normal, no-priority, signal operation. Consequently, the basis adopted for comparing the various examples simulated has been their effect on total passenger delay at an intersection. In practice, the objective may be to minimise total passenger delay, or to maximise benefit to buses consistent with no increase in this total delay. Another possibility is the use of cost/benefit analysis in which changes in vehicle operating costs and the costs of delays to occupants are assessed separately for different classes of vehicle. Whichever criterion is used, the results presented here are sufficiently detailed to allow relevant deductions to be made.

2. THE SIMULATION MODEL

Briefly, the simulation attempts to model the behaviour of individual vehicles as they approach and pass through an intersection operating basically under ‘D-system’ vehicle-actuated signal control. The various bus priority measures are superimposed upon this normal operation. Thus, for an example where buses were first detected at 150 m before the stop-line the detectors used were normally as below.

<table>
<thead>
<tr>
<th>O</th>
<th>O</th>
<th>X</th>
<th>O</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12m</td>
<td>24m</td>
<td>25m</td>
<td>39m</td>
<td>50m</td>
<td>75m</td>
<td>100m</td>
<td>125m</td>
</tr>
</tbody>
</table>

Detector location as used in the simulation

Each of the bus detectors can extend the green by the same amount. This has been set at 5 seconds with the 25m detector spacing used, on the assumption that it is desirable to get a bus through the junction, even in a slow moving queue (5 m/sec). A ‘priority maximum running period’ — the maximum amount by which priority extensions can extend the green time beyond the normal maximum — was specified for all priority runs. It was set to the total time needed for a bus travelling at 5 m/sec to pass from the outer detector to the stopline; eg 30 seconds where the outer detector was at 150m.

* The term ‘priority call’ used in this report is equivalent to the ‘priority change’ facility referred to in the Department of Transport Technical Memorandum.
Only the first detector (outer) crossed by a bus was able to insert a demand for the priority call facility. This was done by analogy with the normal D-system. Subsequently it was decided that the equipment would be simpler if all bus detectors inserted such demands. The effect of this discrepancy is discussed in Section 6 along with other factors influencing the results but not studied fully.

The priority call facility will result in the non-priority stage being cut short. Two main ways of making amends for this have been studied: (a) an inhibit placed on the priority call facility during the non-priority stage green following any granted priority call; this prevents two successive curtailments of the side-road green but does not give any extra side-road green; (b), as (a) but the side-road green immediately following a granted priority call is allowed to run beyond the normal maximum green if traffic requires this; the extra amount (compensation green) was set at the average time lost by the side-road due to the priority call facility — this approximates to half the normal side road green. These two facilities are subsequently referred to as (a) inhibit and (b) compensation.

Since bus-actuated signal-control has been little used to date, it has been possible to validate the simulation results against data from only very few real cases, and these relate to situations where priority produced relatively small benefits for buses. Nevertheless, the validations which have been carried out, and which are reported in detail elsewhere, give confidence in the model as a tool for comparing control methods.

3. THE RANGES OF VARIABLES STUDIED

Four cases involving different traffic flows, saturation flows, cycle times etc were studied; these are detailed in Table 1.

TABLE 1

<table>
<thead>
<tr>
<th>Simulation Case No.</th>
<th>Traffic flow (veh/hour) on each approach</th>
<th>Saturation flow (veh/h of green)</th>
<th>Signal cycle time (seconds)</th>
<th>Maximum Green Times (seconds)</th>
<th>Degree of saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main Rd</td>
<td>Side Rd</td>
<td>Main Rd</td>
<td>Side Rd</td>
<td>Main Stage 1</td>
</tr>
<tr>
<td>1</td>
<td>1200</td>
<td>900</td>
<td>3300</td>
<td>1800</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>600</td>
<td>3300</td>
<td>1800</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>600</td>
<td>2300</td>
<td>1800</td>
<td>117</td>
</tr>
<tr>
<td>4</td>
<td>1200</td>
<td>600</td>
<td>2550</td>
<td>1800</td>
<td>89</td>
</tr>
</tbody>
</table>

In all the cases chosen, the degree of saturation of the intersection was greater than 80 per cent such as is found in busy urban situations. This was done to concentrate on situations where the effect of the priority operation would be most likely to cause appreciable delay to non-bus traffic and where the difference between various control methods was therefore expected to be critical. The signal settings were calculated on the basis given in Reference 2 (pp 57–58). For each of the cases, up to 5 different priority control methods were studied:

* Optimum cycle time is slightly longer. A maximum practical cycle time of 120 seconds is usually recommended, and is used here.
Method A: priority extension only
Method B: priority extension + priority call + inhibit
Method C: as Method B, + compensation
Method D: priority call + inhibit
Method E: as Method D, + compensation

Five different bus detector arrangements were studied with 25m between detectors in all cases; 6 bus detectors with the first located at 150m from the stop-line, 5 detectors with first at 125m, 4 with first at 100m, 3 with first at 75m and 2 with first at 50m. No examples with only one bus detector at 25m from the stop-line were studied since it was considered that queueing vehicles would commonly prevent the bus from reaching the detector and thereby from gaining priority. Four bus flow rates were considered: 20, 40, 60 and 80 buses/h in total for both directions on the main road. This gives a theoretical maximum of 400 examples to consider. In practice, some were omitted, mainly with Methods D and E, leaving about 330 examples run. Each example was simulated for sufficient real time to allow about 80 buses to pass through the intersection, i.e., 1–4 hours depending on bus flow.

For all examples of a given case (as in Table 1) and for a given bus flow, the same patterns of bus and other vehicle arrivals were used. The bus arrivals were specified to conform to a basic regular headway, with deviations from this schedule similar to those measured in actual bus surveys. For non-bus traffic it is less easy to define a simple arrival pattern which can be considered representative of real conditions generally. For most of the simulation runs, individual vehicle arrivals were randomly generated using a binomial probability process which also maintained the specified average arrival flow. Some extra runs using more bunched arrivals are considered in Section 6.

4. RESULTS FOR INDIVIDUAL CASES

Results from individual computer runs in which bus priority signal control was simulated were first compared with an average result obtained from four runs with different bus flows under normal, no-priority, signal operation. Thus, the reduction in average delay per bus (measured in seconds) and the increase in total delay to other traffic (measured in vehicle-hours per hour) were calculated for each priority run. For each of the cases studied (Table 1), the relationships between these two quantities and the independent variables ‘bus flow’ and ‘outer detector position’ were determined by separate multiple linear regressions. Priority control methods A, B, and C were investigated in this way. Control methods D and E — priority call + inhibit, and priority call + compensation — were not included in this analysis as they were clearly inferior to the Methods B and C in which they were combined with the extension facility. The results did, however, serve to show that the effects of the priority call and the priority extension facilities were approximately additive. They also showed that control method E — priority call + compensation — could in certain circumstances result in a net disbenefit to buses, since buses could on average be delayed for longer by the compensation to the side road, than they gained from the priority call.

The partial regression lines in Figures 1–4, diagrams (a)–(d), illustrate how the average saving per bus and the loss to non-bus traffic depend on (i) the two-way bus flow, when the outer detector position (D) is held constant at 100m, and on (ii) the detector position, when the bus flow (q_b) is fixed at 50 buses/hour. Where a line is shown with a zero slope, this indicates that the contribution which the independent variable makes to explaining the variability of the results, is not significant at the 10 per cent level. This
does not mean that a relationship does not exist, merely that it is not proven\(^\dagger\). Figures 1–4 also show, in
diagrams (e) and (f), the net reduction in passenger delay with the various control methods and with
different values of \(q_b\) and \(D\). These two diagrams are not themselves regression lines, but are calculated
from the previous diagrams (a), (b), (c) and (d), assuming an average bus occupancy of about 33 passengers
(ie 25 times the assumed occupancy of 1.3 for non-bus vehicles).

Further results are quoted in Table 2 in which delays and changes in delays due to the priority control
are averaged over all bus flows and all detector positions. The bus passenger flow quoted, which will just
give a net saving in overall passenger time, is calculated for an average of 50 buses/h. Equivalent values for
other bus flows can be calculated from the bus gains and other vehicle losses in Figures 1–4. Where the
total non-bus delay increases by no more than 1 veh-h/h, no great significance should be placed on the
passenger flow quoted in the final column.

### TABLE 2

Average results for the three main priority control methods

<table>
<thead>
<tr>
<th>Priority control</th>
<th>Case No.</th>
<th>Bus delay without priority (seconds)</th>
<th>Reduction in delay per bus with priority (seconds)</th>
<th>Reduction in standard deviation of bus delays** (seconds)</th>
<th>Change in delay on main-road with priority (seconds)</th>
<th>Increase in delay on side-road with priority (seconds)</th>
<th>Increase in total non-bus delay at junction (veh-h/h)</th>
<th>Bus passenger flow to give net time gain (pass/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Extension only</td>
<td>1</td>
<td>37</td>
<td>6</td>
<td>1</td>
<td>−1½</td>
<td>2½</td>
<td>½</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>1½</td>
<td>1</td>
<td>−½</td>
<td>1</td>
<td>~0</td>
<td>~ 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>27</td>
<td>4½</td>
<td>1</td>
<td>−½</td>
<td>2</td>
<td>½</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>18</td>
<td>3</td>
<td>1</td>
<td>−½</td>
<td>2</td>
<td>½</td>
<td>600(^\dagger)(^\dagger)</td>
</tr>
<tr>
<td>B Extension + call + inhibit</td>
<td>1</td>
<td>37</td>
<td>18½</td>
<td>6½</td>
<td>−6</td>
<td>55*</td>
<td>24</td>
<td>6100</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>5½</td>
<td>4</td>
<td>−1½</td>
<td>6</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>27</td>
<td>12</td>
<td>5½</td>
<td>−6</td>
<td>35½*</td>
<td>8</td>
<td>3200</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>18</td>
<td>8½</td>
<td>5½</td>
<td>−2½</td>
<td>18½*</td>
<td>5</td>
<td>2700</td>
</tr>
<tr>
<td>C Extension + call + compensation</td>
<td>1</td>
<td>37</td>
<td>7½</td>
<td>−1½</td>
<td>+4½</td>
<td>13½*</td>
<td>10</td>
<td>6200</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>4½</td>
<td>3½</td>
<td>−½</td>
<td>3½</td>
<td>1</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>27</td>
<td>5</td>
<td>1</td>
<td>+½</td>
<td>13</td>
<td>4½</td>
<td>4100</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>18</td>
<td>6</td>
<td>3</td>
<td>+½</td>
<td>6</td>
<td>2½</td>
<td>2000</td>
</tr>
</tbody>
</table>

Notes: ** Some additional benefit may be attributable to a control method if it reduces the variability
of bus delays, since this can lead to improvements in regularity and hence benefits to bus
users and operators. The value to be placed on such changes in the variability of delays is
likely to vary widely depending on the circumstances; a rough-and-ready rule with some
theoretical justification is to equate a one second reduction in the standard deviation of delay
with a one second reduction in mean delay.

* In these examples, the priority control increased the degree of saturation on the side-road
to between 95 and 100 per cent; this is an unstable situation which could result in still
greater increases in delay than those given here.

\(^\dagger\)\(^\dagger\) This value assumes the zero slope referred to in the footnote below.

\(^\dagger\) Although the negative slope of line A in Figure 3c is statistically significant at the 10 per cent level, it is
thought intuitively unlikely that such a slope is meaningful in practice. If the slope is assumed instead to
be zero, then the derived line in Figure 3e would have a shallower positive slope than that shown, and the
reduction in total passenger time would vary between about 0–3 passenger hours per hour.
It should be noted that the disbenefit to non-bus traffic with Methods A and B occurs almost entirely on the minor road, while traffic on the main road, flowing with the buses, usually receives small benefits. In contrast, with Method C, the compensation facility often results in disbenefits to main-road as well as side-road non-bus traffic. The increases in total non-bus traffic delays referred to in this Report are the net increases resulting from changes on both main and side roads.

5. COMBINED RESULTS FOR ALL FOUR TRAFFIC SITUATIONS

Further regression analysis was carried out for each priority control method using as input data the pooled information from all four junction cases. Again, the dependent variables were the reduction in average bus delay (in seconds) and the total disbenefit to other traffic (in vehicle-hours per hour). The independent variables were:

i) D, the position of the outer bus detector (metres)
ii) q_b, the two-way bus flow (buses per hour)
iii) either c, the cycle time (seconds) or MRR, the main-road red time (seconds).

The inclusion of factor (iii) took account, to some extent, of the difference in the degree of saturation in the four cases. The two alternative factors were highly correlated and only 'MRR' was included in the final regression equation for each control method, since this explained more of the variability than 'c'. The regression equations are summarised in Table 3.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Dependent Variable</th>
<th>Regression Equation</th>
<th>% Variability Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MEAN SAVING PER BUS (seconds)</td>
<td>0.037D +0.10MRR -4.8</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>MEAN LOSS TO NON-BUS TRAFFIC (veh-h/h)</td>
<td>-0.031q_b +1.9</td>
<td>27</td>
</tr>
<tr>
<td>B</td>
<td>MEAN SAVING PER BUS (seconds)</td>
<td>0.036D -0.031q_b +0.32MRR -6.6</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>MEAN LOSS TO NON-BUS TRAFFIC (veh-h/h)</td>
<td>0.077q_b +0.56MRR -22</td>
<td>59</td>
</tr>
<tr>
<td>C</td>
<td>MEAN SAVING PER BUS (seconds)</td>
<td>0.035D -0.078q_b +0.069MRR +2.8</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>MEAN LOSS TO NON-BUS TRAFFIC (veh-h/h)</td>
<td>0.034q_b +0.21MRR -7.9</td>
<td>82</td>
</tr>
</tbody>
</table>
The coefficients included in Table 3 are all significantly different from zero at the 5 per cent level. Where a coefficient is omitted, then it is not significant at the 10 per cent level.

Bus delay is reduced with all three control methods by installing the outer bus detector further from the stop-line; the average time saved by increasing D from 50 m to 150 m is 3½ seconds per bus. There is no corresponding, significant, effect on other-traffic delay, (see coefficients of D in Table 3). The siting of detectors further than 150 m from the stop-line was not considered as it was likely to be beyond the capabilities of the equipment.

There is a marked dependence of bus gain and other vehicle loss on the bus flow for both Method B and Method C forms of control. As bus flow increases the disbenefit to other traffic increases while the benefit to individual buses falls. However, the total benefit to buses will often rise since the number of buses receiving benefit increases. Reference to the coefficients of \( q_b \) will clarify the different effects of Methods B and C. Bus saving decreases more rapidly with increasing bus flow for Method C, where buses are disbenefited to a greater extent by the compensation facility than for Method B where only the inhibit operates. Conversely, other-traffic loss increases less rapidly with increasing bus flow for Method C due to the extra compensation, which is not given for Method B. For Method A the average saving per bus is seen to be independent of bus flow: this seems reasonable, but the disbenefit to other traffic apparently decreases with increasing bus flow, and this is intuitively unreasonable. The equation concerned does, however, explain only a small proportion of the variability in the simulation results and great reliance should not therefore be placed upon it.

The coefficients of the 'main-road red' term in the equations should also be treated with some caution as the range studied is fairly small (32–74 seconds) and the cases studied may not be a representative sample in terms of the relationship between main-road red and degree of saturation. Nevertheless, it is clear that the disbenefit to non-bus traffic increases very sharply as MRR increases for Method B. This is due to the loss of green to the non-priority stage caused by the priority-call facility. The degree of saturation is thereby increased on the side road and, for large values of MRR, this will result in large unstable delays. The same appears to be true, to a lesser extent, for Method C. For buses, the average saving increases with increasing MRR, but the increase is small with Method C since the compensation facility causes long delays to some buses which cancel-out some of the benefits.

Broad conclusions as to the suitability of the different control methods are therefore:

Method A can be used in all cases. It gives limited average benefits to buses (0–8 seconds) although the buses actually gaining priority extensions benefit by much more than this. There is little disbenefit to other traffic (mainly less than 1 veh-h/h).

Method B gives larger benefits to buses (4–24 seconds) but also larger losses to non-bus traffic (1–24 veh-h/h). Total passenger delay is likely to show a consistent reduction only for cycle times up to 1 minute (up to about 1½ minutes for the lower bus flows).

Method C produces smaller benefits for buses (0–14 seconds) than Method B, but also less disbenefit to other traffic (1–14 veh-h/h). It appears to be potentially most useful where cycle times are around 1½ minutes and where Method B might cause too great a non-bus disbenefit. It will probably then achieve somewhat greater bus gains than Method A while still giving some net passenger time savings. A technically simpler and cheaper alternative to Method C is considered in Section 6 of the report.
6. THE EFFECTS OF SUBSIDIARY FACTORS

Delays to buses and other vehicles may be influenced by a wide variety of factors; those considered most relevant in the context of bus priority control were studied in the main series of simulation runs and the results presented in the previous sections. Of the remaining factors, variations in many were judged unimportant and were not investigated, while some required further study before their relevance became clear; these latter cases are dealt with below.

6.1 Demands from all bus detectors

As mentioned in Section 2, the main series of simulation runs used only the outer bus detector to generate demands for a priority call. Two other possibilities are that all detectors could place demands or that only one or more of the inner detectors (nearest to the stop-line) could do so. Some eight extra simulation runs for Case 4 with 40 buses per hour were made to investigate both these options. Using all detectors to control the signals in the same way is the easiest technical solution, and results from the extra simulation runs showed that this causes no statistically significant disbenefits compared with either of the more complex arrangements: it is therefore to be preferred.

6.2 Bus-detector spacing

The spacing between adjacent bus detectors was chosen to be 25 m for the main simulation series. It is important from the cost point of view to know whether this spacing is reasonable; the larger the detector spacing, the cheaper is the equipment, but the less efficient is the signal control.

Two extra simulation runs were made using 50 m detector spacing for Case 1 with 40 buses per hour. The bus priority extension time was also doubled to 10 seconds in order to cater for a slow moving bus (5 m/s), as before. Compared with the equivalent runs using 25 m spacing, non-bus traffic delays increased overall, with side road traffic suffering extra delays which were only partly compensated by savings on the main road. This effect would be expected from the less efficient signal operation with fewer detectors; they would tend to give longer green extensions than necessary for buses on the main road. On this evidence, supported by some theoretical comparisons using Webster’s formula\(^2\), it would seem sensible to use the 25 m spacing for intersections with high degrees of saturation and hence long cycle times. For short cycle times as in Case 2, the wider detector spacing would cause a much smaller increase in overall vehicle delay and the equipment cost saving would probably outweigh the disbenefit (see Section 7.3).

6.3 Free-running speeds of simulated vehicles

The average free-running speed used generally was 50 km/h. It was suspected that the benefit obtainable by buses from the priority extension facility might be greater at lower speeds (see Appendix 2(a)). To test this, some 15 repeat runs were made with a lower free-running speed (35 km/h) on the bus approach. In cases with long cycle times (1, 3 Table 1) the lower speed resulted in extra bus savings of 2–3 seconds per bus for all 5 detector arrangements; other-traffic delays were not significantly altered. For the short-cycle case (2, Table 1) the results were inconclusive. These results do not alter the order of merit of the main control methods (A, B and C) since the priority extension is used in all three.
6.4 Maximum green settings

In all the simulation runs considered previously, the maximum green times used to control the vehicle-actuated operation of the signals were set to values calculated for optimum fixed-time control as in reference 2. To check on the effect of using longer maximum times than these, as might be done at sites where flows fluctuate widely during the day, a series of simulation runs was made based on Method B for Case 2 with 40 buses/hour.

Results showed that both buses and other traffic suffered increasingly long delays as maximum green times were increased. Thus, although buses benefited much as before from the priority control relative to no priority with the same maximum settings, their delay was longer than necessary due to the non-optimum settings. In terms of passenger delay for the particular case studied, the increase of one-third in maximum green times resulted in a net loss of about 2.5 passenger-hours per hour (there were proportionately larger disbenefits for longer maximum settings). There is thus a strong case with both priority and conventional control for using maximum times calculated as the optimum according to reference 2. If average traffic flows change substantially during the day, it would be worthwhile to consider installing a time switch to change settings as appropriate, before considering the question of priority control.

It may in some situations prove impractical to change settings to match changes in traffic conditions, and signals will thus be operated on non-optimum settings for parts of the day. The results given in this Report relate strictly to optimum settings and should not be assumed to apply otherwise.

6.5 Compensation using the standard maximum-green facility

Results presented in Sections 4 and 5 show that the compensation facility used in Method C is likely to be beneficial in only a limited range of conditions. Methods A or B will often be more appropriate and they require less complex equipment to operate the priority control. It was desirable therefore to seek another, simpler, method to repay the green time which a non-priority stage loses when it is curtailed by the priority-call facility. A method which seemed potentially suitable makes use of the maximum green timers which are fitted as a standard feature to vehicle-actuated controllers. If the normal maximum green \( g_2 \) on the non-priority stage is set to a larger value \( g_2 + \Delta g_2 \) then, in all those cycles without a priority call, the stage is able to regain some of the lost green time. This contrasts with the compensation in Method C which is given only in the cycle immediately following a priority call. The new method was designated as Method B2 since the same priority facilities are used as in Method B, but with the modified maximum green setting.

The method was investigated theoretically and with the simulation; details are given in Appendix 1.

The general trend of results makes it clear that Method B2 is preferable to Method C: it produces net passenger delays which are similar or possibly marginally better; the delay to buses is often a few seconds less at the expense of extra delay to side-road traffic; the standard deviation of bus delays is usually less; and the Method B2 is simpler to implement. Nevertheless, Method B2 can only be considered a suitable control option in the same limited situations as have previously been quoted for Method C.

6.6 Method B without the inhibit facility

The inhibit facility prevents the priority call operating during two successive cycles by inhibiting the second call. This facility may be an unnecessary complication if priority calls in adjacent cycles are unlikely.
Simple probability calculations similar to those in Appendix 1 suggest that the inhibit may reasonably be dispensed with if bus arrivals average less than about one bus per two cycles. Extra simulation runs with Case 2 confirmed this.

6.7 Alternative patterns of traffic arrivals

The delay experienced by traffic arriving at a traffic signal is known to depend on the precise pattern of the arrivals — whether traffic is more or less bunched. Delay is least with perfectly regular arrivals (ie constant headways) and increases with the degree of bunching (see, for example, reference 5). A quantity which is used to help describe the nature of the arrival pattern is:

\[ I = \frac{\text{variance of number of vehicles arriving per unit time}}{\text{mean number of vehicles arriving per unit time}} \]

The larger the I factor is, the more bunched are the traffic arrivals. The main series of simulation runs used arrivals having I values of about 0.6–0.8*. Some extra runs using arrivals with I of 1.4–1.6* were made to check whether the effects of the priority were altered.

Results with Method A gave savings to buses which were generally as large or larger than those obtained previously, and the savings in overall passenger delay were also similar or smaller. The extra benefit with high I values was most pronounced for cases 1 and 3 with high degrees of saturation. Bunched traffic arrivals with Method B (or B2) produced little change in bus benefits but caused extra disbenefits to side-road traffic compared with earlier results; only for Case 2 does Method B seem likely to result in overall net passenger-time savings and then not consistently.

Thus, Method A is confirmed as being suitable for use with both the bunched and more regular traffic. With Method B disbenefits to non-priority traffic, due to curtailment of the side-road green and consequent increase in the degree of saturation, are emphasised by more bunched arrivals.

7. COSTS AND BENEFITS OF PRIORITY CONTROL

It would be impractical to apply comprehensive cost/benefit analysis to every situation simulated and, even for individual cases, numerous assumptions would need to be made. This section therefore restricts itself to a general commentary, taking costs and benefits at early 1976 values.

7.1 Equipment costs

The approximate cost for slot-cutting and cable laying for detectors is £2/metre. Thus for each detector loop covering one wide lane or two normal lanes on an approach, and assuming 25 m loop spacing, the cost will be about £100. Standard equipment will soon be available and the cost of each detector equipment capable of driving at least 3 and probably more loops may be about £150. Thus, roughly, each loop and detector costs up to £150. There will also be the cost of extra signal-controller equipment. At present this can only be guessed at, but it is unlikely to be less than £400 per intersection. Bus-borne equipment costs are similarly unknown, but might be about £50 per bus.

* These values have been chosen as broadly representative of the extremes met in practice at isolated intersections at least 300 m distant from other signals. The time unit used in the definition of I was 10 seconds.
7.2 Benefits and disbenefits

The reader wishing to predict the effects of bus priority at a particular intersection may be helped by Appendix 2; this gives approximate, theoretical, estimates of savings in delay to buses for a range of bus flows and other conditions. The values are in reasonable agreement with the simulation. No equivalent, simple method has been found for predicting disbenefits to other traffic, but the simulation results in this report provide a rough guide to these.

For each 5 seconds reduction in average delay to buses, with an average bus passenger flow of 1000/h for 10 hours/day and 300 days/year, then the benefit from passenger time saved valued at £0.40/h would be about £1,700 pa. For other traffic, taking 1.3 passengers/vehicle, a loss of 1 veh-h/h for the same number of hours would represent a loss of £1,600 pa (all occupants' time valued at £0.40/h); this loss would roughly double if the time of commercial vehicle occupants and about 20 per cent of car occupants are valued at their higher, working-time rates. Benefits would accrue to people waiting at bus stops and to the bus operator if the variability of bus journey times was improved. Precisely how much is very dependent on the case, but as mentioned before a rough and ready rule is to equate a 1 second reduction in mean delay with a 1 second reduction in the standard deviation of delays. Further benefits can be achieved if savings accumulate sufficiently to allow the operator to reschedule and run the service with fewer buses. Theoretically, ignoring discontinuities due to only being able to deal in whole buses, there would be a benefit of about £700 pa for a 5 second reduction in delay per bus with a flow of 40 buses/hour. (This assumes that the cost saved per bus removed from all-day service is about £12,000 pa; running costs transfer to the remaining buses).

7.3 The value of extra detectors

The variation in benefits and disbenefits is fairly consistent for different cases and control methods, so it is possible to evaluate whether it is worth using extra detectors to detect the buses further from the stop-line.

Detecting at 150 m instead of 50 m saves about 3½ seconds per bus and generally reduces variability: say a total benefit equivalent to about 5 seconds per bus. For the figures above, this is worth about £1,700 pa in bus passenger time saved, with a further potential saving of £700 pa to the operator. Disbenefits to other traffic are less clear; the overall regression equations in Table 3 show no disbenefit with earlier detection, but one of the results for individual cases (Figure 2d) does indicate larger delays. A loss of 0.5 veh-h/h associated with the bus detection at 150 m instead of at 50 m would cause disbenefits of about £800—£1,600 pa depending on the proportion of travellers working. The extra equipment cost would be for 8 extra detectors at 25 m spacing (2 approaches) totalling about £1200 and requiring at least a £120 pa net benefit to justify it. This would seem to be comfortably available in the case considered, particularly as the evidence for other traffic disbenefits is weak. Thus, if it has been decided that priority is justified at a particular junction, then it is worth detecting buses as early as possible allowing for physical constraints such as bus-stops, other intersections etc, up to the 150 m limit considered in this Report.

7.4 Summary

The total roadside equipment costs, assuming that bus detection starts at 150 m before the stop-line, might be approximately £2,000 per intersection. On-bus equipment costs will depend on the size of fleet concerned, and would allow priority to be given at several intersections if required. Costs might be in the range £250—£1,000 per intersection assuming 5—20 buses would be equipped per intersection offering
priority. These total costs of up to about £3,000 per intersection would usually be justified by net passenger time savings of the magnitude shown for the most successful control method in each of Figures 1-4, (e) and (f), assuming time is valued at £0.40/h for all travellers. When work-time rates are used to value delay to commercial vehicle drivers etc, then disbenefits increase to an extent whereby the cost/benefit result could be marginal or perhaps against using the bus priority signal control.

8. CONCLUSIONS

A computer simulation has been used to investigate various methods of traffic signal control which give priority to buses. The cases studied were all of the cross-roads type intersection controlled basically by vehicle-actuated, 2-stage, signal equipment and with buses on the major road only; priority control was superimposed upon signals otherwise timed according to standard UK practice (reference 2). For these conditions the following conclusions were reached:

1) A control method (A), which allows detected buses to maintain an existing green signal by means of a 'priority extension' facility, can give net savings in passenger time in nearly all likely circumstances. Average delays to buses are, however, reduced by only small amounts: 0-8 seconds in the cases considered, the greater saving being achieved when cycle times are long. Those buses actually gaining the priority extensions will have much larger savings than these averages, while the remainder receive no benefit.

2) Another method (B), which includes an additional priority call facility to obtain the green for buses approaching a red signal, achieves greater average savings for buses but often at the expense of large disbenefits to non-bus traffic. The method will usually give net passenger-time savings if the signals are operating on a short cycle time of up to about 1 minute, or possibly up to about 1½ minutes if the bus flow is small — about 20 buses/hour.

3) The priority call facility curtails the green time available to the non-priority stage. It will generally be necessary to inhibit the priority call to prevent its operation during the cycle following a granted priority call. If bus arrivals average no more than about one every two cycles, the inhibit may be unnecessary.

4) A method (C) which allows the non-priority stage a longer-than-normal green during the cycle after it has been curtailed by a priority call, appears to offer no advantages over a simpler technique (Method B2) whereby the standard maximum-green timer for the non-priority stage is set to a longer-than-normal value. Suitable values are tabulated in the appendix to this report. The use of this method (B2) marginally extends the range of conditions for which the priority call (Method B) is suitable.

5) When using priority control, it is important to use the standard methods in reference 2 to produce basic cycle time and maximum green times (albeit that the non-priority maximum green may be then lengthened if using Method B2). Use of unnecessarily long maximum green settings will cause extra delay and will nullify some of the benefits of priority.

6) The priority-call facility reduces not only the average delay to buses, but also the variability of these delays. The priority extension has little effect on variability.
7) Over the range studied, detecting buses further from the stop-line increases benefits to buses with little evidence of disbenefit to other traffic. Detection at 150 m in advance — the technical limit of the equipment — rather than at 50 m, saves an average 3–4 seconds per bus.

8) Since traffic conditions often vary widely throughout the day, it may be worthwhile to install a time switch to change from one form of priority control to another as appropriate.

9) While it is usually possible to give buses priority and to achieve a reduction in total passenger delay at the intersection, it may sometimes be difficult to attain an excess of benefits over costs if the high time-value of non-priority vehicle occupants such as commercial vehicle drivers is taken into account.

9. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Public Transport Division of the Transport Operations Department of TRRL.

Data on measured I values (Section 6.7) was made available to TRRL by research staff at the Imperial College of Science and Technology, London. The help of Messrs Crompton, Goldschmidt, and Gilbert is gratefully acknowledged.

10. REFERENCES


Fig. 1 SIMULATION RESULTS FOR CASE 1
Fig. 2  SIMULATION RESULTS FOR CASE 2
Fig. 3  SIMULATION RESULTS FOR CASE 3
Fig. 4 SIMULATION RESULTS FOR CASE 4
As a first step in testing-out Method B2, a theoretical study was undertaken to try to determine suitable values for $\Delta g_2$, depending on the particular situation at a junction. Making some simplifying assumptions, it is possible to calculate the probability that a priority call will occur during a cycle, and also the average amount by which the non-priority green is then curtailed. Hence, a value for $\Delta g_2$ can be found which over many cycles allows the non-priority stage to regain (during cycles without priority calls) the same amount of green time as is lost by curtailment.

Definitions:

- $B$ = total priority bus flow per hour
- $g_1$ = maximum green time (seconds) on priority stage 1
- $g_2$ = basic maximum green time (seconds) on non-priority stage 2
- $g_2 + \Delta g_2$ = lengthened non-priority maximum green time (seconds)
- $I_{12}$ = intergreen time between $g_1$ and $g_2$ (seconds)
- $r$ = period during which a priority call can be initiated (seconds)

Assuming that the signals are operating to maximum green times with the lengthened green for the non-priority stage, then $r = I_{12} + (g_2 + \Delta g_2)$. The expected number of bus arrivals during one period $r$ is:

$$p = e^{-r \cdot B/3600}$$

(1-p) is therefore the probability of one or more buses arriving during $r$; this causes a priority call unless the inhibit is operating. If we assume that of all cycles:

- proportion $\alpha$ are normal (i.e. uninfluenced by priority control)
- proportion $\beta$ have a priority call during $r$
- proportion $\gamma$ have an inhibit since they follow a priority call cycle,

it can then be shown that:

$$\alpha = \frac{P}{2-p} \quad \text{and} \quad \beta = \gamma = \frac{1-p}{2-p}$$

When Stage 2 is curtailed by a priority call, the average green can be shown to be cut to approximately

$$\frac{g_2 + \Delta g_2}{2}.$$  

Compared with $g_2$, which is average time required by stage 2 with no priority, the loss is

$$g_2 - \frac{g_2 + \Delta g_2}{2} = \frac{g_2 - \Delta g_2}{2}$$

during proportion $\beta$ of all cycles.

To regain this loss during the remaining cycles,

$$(\alpha + \gamma) \Delta g_2 = \frac{\beta (g_2 - \Delta g_2)}{2}$$
For a particular case, equations 1, 2 and 3 can be solved by successive approximations to give $\Delta g_2$. Table 4 below gives $\Delta g_2$ for various combinations of bus flow (B) and stage 2 basic green ($g_2$), the latter being calculated using the procedure given in reference 2.

**TABLE 4**

Extra maximum green time (seconds) to compensate non-priority stage when using priority control method B2

<table>
<thead>
<tr>
<th>Non-priority basic green ($g_2$)</th>
<th>Total buses per hour (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>60</td>
<td>8</td>
</tr>
</tbody>
</table>

The above theory takes no account of cycle time since a certain proportion of cycles involve the green being cut on stage 2, and the remainder give the same amount of green back. The result is the average green ($g_2$) as required by the Webster formula\textsuperscript{2} and hence cycle time is on average unaltered.

A limited series of simulation runs were made to test Method B2. In Case 1, it was clearly unsuitable, as expected, due to large net disbenefits in passenger time only slightly less than those found with Method C (Figure 1). No reruns were made for Case 2, since the simpler Method B was already known to be acceptable (Figure 2). In Case 3, a few runs with 60 buses/h indicated that Method B2 might possibly break-even in passenger-time terms but only with very high average bus occupancy (50+), and with an outer detector at 150 m giving maximum benefit to buses; otherwise, there will probably be net disbenefits slightly smaller than shown in Figure 3(e) for Method C. Previous results had shown Method C to be most viable in Case 4 so reruns covering all 4 bus flows and 3 outer detector positions were made with Method B2. The net passenger time results were nearly identical with those in Figure 4 for Method C.
12. APPENDIX 2

ESTIMATES OF DELAY SAVINGS TO BUSES WITH PRIORITY SIGNAL CONTROL

The tables quoted in this appendix are derived theoretically making several implicit simplifying assumptions. They should be treated as a rough guide only. The priority extension and the priority call facilities are treated separately; it is assumed that their effects are additive.

a) Priority Extension Facility

\( \lambda_1 \) is the proportion of the cycle time which is green for the priority stage. \( T \) is the average time taken by buses to travel from the outer bus detector (furthest from the stop line) to the stop line, during the last part of the bus stage green when a priority extension is likely to be of benefit.

Table 5 gives an approximate estimate for the saving due to the priority extension, averaged over the total priority bus flow; the actual buses gaining the priority will save an amount approximately equal to the average non-green time on the priority stage.

<table>
<thead>
<tr>
<th>( T ) (seconds)</th>
<th>( \lambda_1 ) .2</th>
<th>.3</th>
<th>.4</th>
<th>.5</th>
<th>.6</th>
<th>.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>11</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>13</td>
<td>11</td>
<td>9</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

As might be expected, buses save more the longer the normal red time for buses, and they save more the earlier they are detected (thereby increasing \( T \)).

The formula used to derive Table 5 is: Delay saving = \( \frac{(t-2)}{c} \cdot (c-g_1) \) seconds/bus where \( c \) is cycle time and \( g_1 \) is priority stage maximum green as in reference 2. The proportion of buses benefiting from a priority extension is taken as \( \frac{(t-2)}{c} \) allowing for traffic treating the first 2 seconds of amber as being effectively green. The saving for buses gaining a useful extension is \( (c-g_1) \) approximately.

b) Priority Call Facility at 2-stage signals (with the inhibit facility).

\( B \) buses/h is the total bus flow on the priority stage.
\( g_2 \) (seconds) is the maximum green time on the non-priority stage.

Table 6 gives an approximate estimate for the saving due to the priority call, averaged over all buses.
### TABLE 6

Average delay saving (seconds) per bus on priority stage, due to priority call facility (cycle time = 100 sec only)**

<table>
<thead>
<tr>
<th>$g_2$ (seconds)</th>
<th>B buses/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td>60</td>
<td>16</td>
</tr>
</tbody>
</table>

Note** Table 6 delay savings are for a signal cycle time of 100 seconds *only*; to obtain savings where another cycle time (c sec) is in use, multiply saving from Table 6 by 100/c.

Benefits *per bus* decrease with increased bus flow, since more buses arrive during an inhibit cycle and cannot gain priority; nevertheless, *total* bus benefit increases. Also, as the non-priority green increases for a given cycle time, bus savings increase since the priority call cuts short a longer red period on the priority stage.

The formula used to produce Table 6 is: \[ \text{Delay saving} = \frac{3600}{\beta} \cdot \frac{1}{c} \cdot \frac{g_2}{B} \] where $\beta$ is given by equation 2 in Appendix 1. The proportion of buses gaining a priority call is taken as $3600 \cdot \beta/c \cdot B$ and the average saving per benefited bus as $g_2/2$.

Note: This theory assumes that the signal stages are running to maximum green times as calculated from Webster's formulae, except when a priority call or extension is operating. If the signals are operating to substantially shorter green times on average, then lesser values should be used for $g_1, g_2$ and $c$ when estimating $\lambda, \beta$ and using the tables.
ABSTRACT

Bus-actuated signal control at isolated intersections — simulation studies of bus priority:
R A VINCENT, B R COOPER and K WOOD: Department of the Environment Department of Transport, TRRL Laboratory Report 814: Crowthorne, 1978 (Transport and Road Research Laboratory). Normal traffic signal operation can be modified to give buses priority, if buses are detected separately from other vehicles. A computer simulation has been used to estimate benefits to buses and disbenefits to other traffic when using various forms of priority control superimposed upon the normal UK vehicle-actuated signal operation. All the cases simulated were for two-stage signals controlling crossroads-type intersections with buses on the major road only.

The facilities considered are: a 'priority call' which regains the green for buses approaching a red signal, and a 'priority extension' which maintains an existing green. The priority call curtails the green time on the non-priority stage, and various methods are considered for alleviating disbenefits to this traffic. Simulation results form the basis for guidance in the use of different methods of priority control with various traffic conditions, bus detector locations and bus flows.

Appropriate priority control can usually achieve delay savings for bus passengers which total more than the increase in delay to other travellers. It is less easy to attain a net benefit if equipment costs and the high time-value of non-priority vehicle occupants such as commercial vehicle drivers are taken into account.

ISSN 0305—1293

ABSTRACT

Bus-actuated signal control at isolated intersections — simulation studies of bus priority:
R A VINCENT, B R COOPER and K WOOD: Department of the Environment Department of Transport, TRRL Laboratory Report 814: Crowthorne, 1978 (Transport and Road Research Laboratory). Normal traffic signal operation can be modified to give buses priority, if buses are detected separately from other vehicles. A computer simulation has been used to estimate benefits to buses and disbenefits to other traffic when using various forms of priority control superimposed upon the normal UK vehicle-actuated signal operation. All the cases simulated were for two-stage signals controlling crossroads-type intersections with buses on the major road only.

The facilities considered are: a 'priority call' which regains the green for buses approaching a red signal, and a 'priority extension' which maintains an existing green. The priority call curtails the green time on the non-priority stage, and various methods are considered for alleviating disbenefits to this traffic. Simulation results form the basis for guidance in the use of different methods of priority control with various traffic conditions, bus detector locations and bus flows.

Appropriate priority control can usually achieve delay savings for bus passengers which total more than the increase in delay to other travellers. It is less easy to attain a net benefit if equipment costs and the high time-value of non-priority vehicle occupants such as commercial vehicle drivers are taken into account.

ISSN 0305—1293