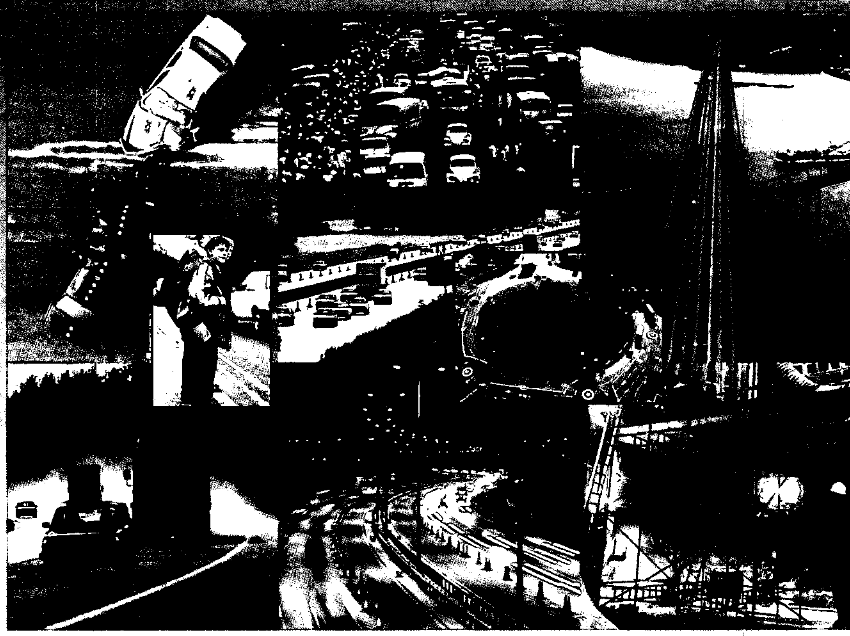

Bus priority approaching a roundabout: The Doncaster bus advance area

by A J Astrop and R J Balcombe

An executive agency of
THE DEPARTMENT OF TRANSPORT

TRL Report 194

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BUS PRIORITY APPROACHING A ROUNDABOUT: THE DONCASTER BUS ADVANCE AREA

by A J Astrop and R J Balcombe

Prepared for: Project Record: UG14 Innovative Bus Priority Measures
Customer: Driver Information and Traffic Management Division, DOT (C N Cheney)

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CONTENTS

EXECUTIVE SUMMARY

It is standard practice for bus lanes to be terminated some distance before major junctions in order to allow traffic other than buses to diverge and make full use of junction capacity. Buses emerging from a bus lane may therefore have to queue with other traffic before reaching the junction, and may not easily be manoeuvred into correct positions for turning there.

One innovation proposed to overcome this problem is the "bus advance area" between the end of the bus lane and the junction. Non-priority traffic entering the bus advance area can be controlled by special signals, creating gaps in the traffic flow during which buses can proceed unhindered from bus lane to junction.

At a signal-controlled junction the special signals are known as "pre-signals" and may be linked with the junction signals in order to minimise delays to non-priority traffic, which simply queues at the entrance to the bus advance area, rather than at the junction. An alternative application of the concept is on the approaches to roundabout junctions. The first trial of such an arrangement, on Cleveland Street in Doncaster, is the subject of this report.

A bus advance area was created on the approach to the Cleveland Street/ Trafford Way roundabout, where buses emerging from the near-side bus lane need to be in the middle lane of the carriageway in order to continue straight on or to turn right. New traffic signals at the Cleveland Street/Union Street junction regulate entry into the bus advance area from the bus lane, the non-priority lanes in Cleveland Street, and Union Street. This signal allows buses to leave the bus lane while other traffic is held back.

To maximise the potential benefit of the bus priority measures, bus detectors were installed at two strategic locations within the bus lane. When a bus is detected the general traffic is held on a red signal while the queues at the roundabout disperse. The bus can then enter the bus advance area on a green signal and manoeuvre into the correct lane without being hindered by traffic.

The bus lane was created some time before the traffic signals were put into operation on 16 May 1994, providing an opportunity to compare journey times of buses and other traffic through the system by means of "before" and "after" surveys. Measurements were also made of numbers of passengers in buses and other vehicles, and the punctuality of bus services.

For buses travelling along Cleveland Street, the effect of installing the signals at the end of the bus lane has been a marginal reduction (of about six seconds) in mean journey times during morning peak and off-peak periods, but the change is statistically significant only for off-peak journeys. However, this relatively small advantage has been obtained at considerable cost, in the form of additional delays to non-priority traffic of the order of 35 seconds per vehicle. There have been some benefits to both buses and other traffic emerging from a side-road into the main road, as a result of a side-road stage in the bus advance area signal cycle, but these are much too small to offset the disbenefits to main-road non-priority traffic.

Delays to non-priority traffic are larger than would be expected at an isolated signal junction with a similar proportion of green time, and a similar cycle time. There appear to be two reasons. First, the irregular operation of the signals, which respond to an effectively random pattern of bus arrivals, is likely to cause over-saturation and disproportionate delay when main road green stages are cut short or missed. Second, bunching of the traffic by the signals may cause intermittent overloading of the roundabout entrance, causing additional delay.

The Doncaster arrangement may not be the best possible example of a bus advance area on a roundabout approach, because of the complication of the side road. Estimates have therefore been made of how a similar scheme, identical save for the absence of a side road, might perform. Without a side road, sufficient additional green time could be made available to buses to eliminate the need for any buses to stop at the end of the bus lane (about 30 per cent have to stop under the current arrangement); there would still be surplus green time which could be used to reduce delays to other traffic. Alternatively, all the surplus green time could be allocated to non-priority traffic, without delaying buses any more than under the current arrangement. Each of these hypothetical arrangements is found to result in nett disbenefits (compared with the situation before the signals were introduced), but to a lesser extent than that observed with the current arrangement.

These results suggest that consideration should be given to an alternative form of bus advance area operation on roundabout approaches. Signals might be arranged so that non-priority traffic was interrupted only when the queue at the roundabout entrance exceeded a reasonable length, then some element of queue relocation might be achieved, without excessive additional delay. This could produce gaps in the traffic between the end of the queue and the bus lane, which buses could enter while non-priority traffic was held. At other times, when queues were shorter, buses should be able to merge with other traffic and join them, so there would be no need to impose signal control on buses.

The success of such an arrangement is likely to depend strongly on the correct design of the system, including the length of setback between the bus lane and the roundabout entrance, the lengths of queues which would trigger signal changes, detector positions etc. Modelling techniques recently developed at TRL to determine the optimal setback for a conventional (unsignalled) bus lane on a roundabout approach, which incorporate ARCADY software and some queuing theory, could possibly be extended to provide a theoretical evaluation of this form of bus advance area, prior to either track experiments, trials on public roads or both.

BUS PRIORITY APPROACHING A ROUNDABOUT: THE DONCASTER BUS ADVANCE AREA

ABSTRACT

Bus advance areas have been proposed as a means of reducing delays to buses when negotiating conventional setbacks between the ends of bus lanes and road junctions. They operate by holding non-priority traffic at pre-signals, allowing buses free passage. The first such bus advance area on the approach to a roundabout junction was installed in Doncaster in May 1994.

Before and after measurements have shown that the bus advance area has resulted in small reductions in delays to buses (by comparison with a conventional bus lane arrangement) but at the expense of substantial delays to other traffic. This results partly from the necessity to provide a signal stage for side-road traffic to enter the main road at the start of the bus advance area. However, it is estimated that even without the side-road complication delays to non-priority traffic would outweigh benefits to bus passengers. The irregular signal cycle (actuated by a random pattern of bus arrivals) and bunching by the signals of traffic at the roundabout entrance are significant causes of delay. An alternative form of operation is proposed.

1. INTRODUCTION

It is standard practice for bus lanes to be terminated some distance before major junctions in order to allow traffic other than buses to diverge and make full use of junction capacity. Buses emerging from a bus lane may therefore have to queue with other traffic before reaching the junction, and may not easily be manoeuvred into correct positions for turning there.

One innovation proposed to overcome this problem is the "bus advance area" between the end of the bus lane and the junction. Non-priority traffic entering the bus advance area can be controlled by special signals, creating gaps in the traffic flow during which buses can proceed unhindered from bus lane to junction.

At a signal-controlled junction the special signals are known as "pre-signals" and may be linked with the junction signals in order to minimise delays to non-priority traffic, which simply queues at the entrance to the bus advance area, rather than at the junction. A number of such pre-signals are the subject of TRL studies (the first of which has been reported by Astrop and Balcombe, 1995) commissioned by the Department of Transport.

An alternative application of the concept is on the approaches to roundabout junctions. The first trial of such an arrangement, on Cleveland Street in Doncaster, is the subject of this report.

2. BACKGROUND TO THE SCHEME

At peak times, buses travelling into Doncaster town centre from Balby onto Cleveland Street were suffering considerable delay due to traffic congestion, particularly at the Cleveland Street/ Trafford Way roundabout. In order to improve bus journey times a bus lane was installed in the left lane of the carriageway on Cleveland Street, for almost its entire length from its southern end to Union Street, leaving two lanes open to non-bus traffic (figure 1).

A bus advance area was created on the approach to the Cleveland Street/ Trafford Way roundabout, where buses emerging from the near-side bus lane need to be in the middle lane of the carriageway in order to continue straight on or to turn right. New traffic signals at the Cleveland Street/Union Street junction regulate entry into the bus advance area from the bus lane, the non-priority lanes in Cleveland Street, and Union Street. This signal allows buses to leave the bus lane while other traffic is held back.

To maximise the potential benefit of the bus priority measures, bus detectors were installed at two strategic locations within the bus lane (figure 1). When a bus is detected the general traffic is held on a red signal while the queues at the roundabout disperse. The bus can then enter the bus advance area on a green signal and manoeuvre into the correct lane without being hindered by traffic.

To achieve this it was necessary to simplify traffic flows by prohibiting left and right turns from Cleveland Street into Union Street. Instead, the junction opposite St. James Street is now used for access into St Sepulchre Gate West.

The bus lane was created some time before the traffic signals were put into operation on 16 May 1994, providing an opportunity to compare journey times of buses and other traffic through the system before and after this date and assess the effectiveness of the bus advance area[1].

1 There was no opportunity to assess the effect of the bus lane alone, since the scheme was brought to the notice of the Department of Transport too late for a survey before construction of the bus lane was commenced.

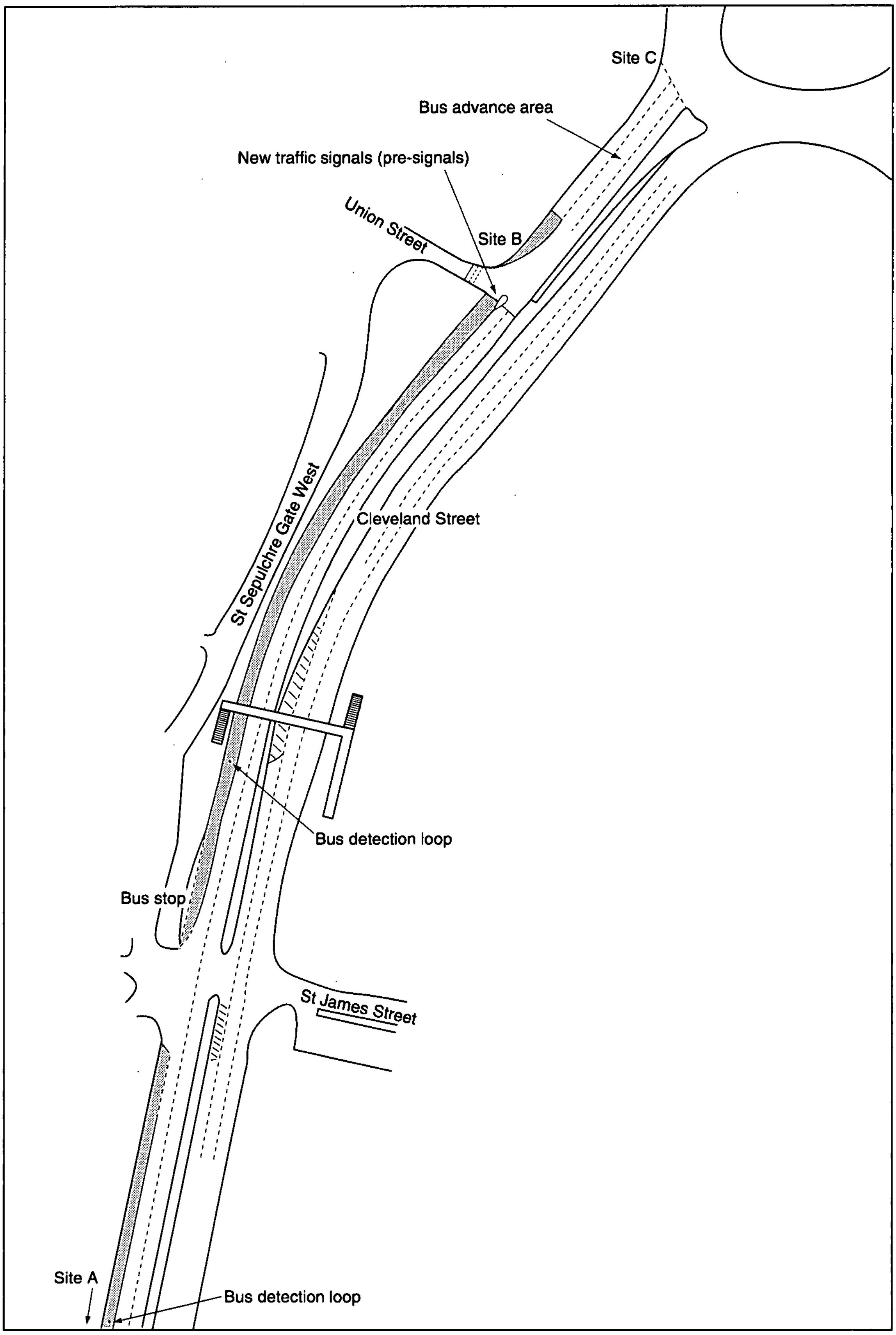

Fig. 1 Cleveland Street bus lane

3. METHOD

The main purpose of this study was to discover whether the addition of a bus advance area to a bus lane approaching a roundabout was effective in reducing delays to buses, improving the reliability of bus services, and whether other traffic was adversely affected.

The "before" survey was carried out between 5 and 7 May 1994, and the corresponding "after" survey between 7 and 11 June 1994.

In each survey the following data were collected: bus, goods vehicle and car journey times, vehicle occupancy levels and traffic flows.

On Weekdays data were collected in the morning peak (0730-0930) and between 1015-1230. On Saturday, the data collection times were 0830-1030 and 1100-1300.

Observers were positioned at a number of locations around the system (see figure 1) to record partial registration plates (i.e. numbers and year letters) and the times at which they passed. Data were recorded for a random sample of vehicles, this could then be grossed up to provide an estimate of traffic flows. The observers were briefed to select vehicles with registration numbers ending 1, 2 or 3. The NOPCOP number plate comparison program (Lucas 1986), which matches partial numberplates between designated origin and destination points, was used to calculate both bus and car journey times.

All buses were recorded, and their service numbers were also noted.

Bus occupancy surveys for routes 79, 156, 157, 159, 455, 456, X78 were undertaken, with the number of passengers on board being recorded as the bus left the last bus stop on Cleveland Street (see figure 1). It was not possible accurately to determine the number of passengers on the bus by roadside observations; enumerators therefore had to board the bus to count the number of passengers. To limit the cost of this exercise, counts were made on a sample of buses. The bus service number and the departure time from the bus stop were also recorded.

Car occupancy counts were undertaken at site A as shown in figure 1.

Finally, observations were made on 9 January 1995, from 0730 to 0930 and from 1015 to 1230, of the traffic signal stages, numbers of buses passing through the junction without delay, and delays to buses which had to stop at the signals.

4. JOURNEY TIMES

4.1 BUSES

Table 1 shows mean journey times for buses measured in the two surveys. Bus journey times along Cleveland Street (from A to C) during the morning peak on weekdays seem to have been marginally shorter in the second survey, but the difference is only significant at about a 12 per cent confidence level and Table 2 shows the number of buses observed at different points. Off-peak bus times from A to C were significantly shorter (at the 2 per cent confidence level). By contrast, Saturday buses appear to have been significantly slower during the after survey (at the 0.5 per cent confidence level). However, both bus journey times and traffic flows (tables 1 and 4) were substantially less on the Saturday of the before survey than on the after survey Saturday, or any weekday, so that we cannot be certain whether this comparison is valid.

To some extent the advantage buses derive from free passage through the advance area may be offset by additional delay at the new signals at the Union Street junction: before the signals were installed, traffic emerging from the side road had to give way to traffic on the main road, so that buses emerging from the bus lane would not normally have had to wait for side road traffic. Although the bus lane green stage of the signals is initiated by vehicle detectors in the bus lane[2], any buses arriving just after the end of green stage may be delayed for at least part of a cycle. Our observations indicate that the green stage for the bus lane constitutes 13.3 per cent of the cycle time on average, and that 69 per cent of buses travel from the bus lane to the advance area without any delay. On the other hand, 31 per cent of buses are delayed, by an average of 13.4 seconds each, so the average delay over all buses is 4.2 seconds.

Buses emerging from Union Street seem to have had slightly shorter journey times from B to C, but the differences have no statistical significance, as the number of buses using this route was too small to provide a sufficient sample for precise measurement. However, it is not unreasonable to assume that there would have been reductions in bus journey times similar to those observed for other traffic between B and C (table 3).

4.2 NON-PRIORITY TRAFFIC

Average journey times for non-priority traffic are shown in table 3. On weekdays average journey times along Cleveland Street (A-C) in the morning peak have increased by 64.3 per cent, and off-peak times by 58 per cent, despite slightly smaller traffic flows (table 4). Saturday journey times appear to have increased even more, but this may be a result of the anomalously low traffic flows on the first Saturday, discussed in section 4.1.

2 Occasionally a green stage is initiated by the passage of a vehicle other than a bus, using the bus lane legally (e.g. bicycle or emergency vehicle) or illegally (including cars temporarily straying into the bus lane near the detector).

TABLE 1

Before and after bus journey time comparison

	Before	After	Before	After
	A-C (main road buses)			
	0730-0930		1015-1230	
Tuesday		79.9		63.1
Thursday	81.8	85.1	71.0	66.5
Friday	94.1	82.4	69.0	65.0
Mean	88.2	82.6	70.0	64.9
Standard error	2.9	2.1	1.7	1.3
	0830-1030		1100-1300	
Saturday	50.7	67.9	63.6	75.8
Standard error	1.8	3.5	2.6	3.4
	B-C (buses from Union Street)			
	0730-0930		1015-1230	
Tuesday		33.4		26.7
Thursday	28.0	35.1	33.8	30.4
Friday	48.3	44.7	26.5	26.0
Mean	39.3	37.5	29.5	27.9
Standard error	5.0	4.3	2.9	1.8
	0830-1030		1100-1300	
Saturday[3]		21.3		38.9
Standard error		1.5		8.5

3 Data on journey times between B and C in the before survey were lost because of computer failure

There are two factors which may explain this additional delay. The first is delay to traffic at the new signals where the flow of non-priority traffic on Cleveland Street may be interrupted to allow other traffic to emerge from Union Street, or buses to leave the bus lane. In the morning peak, the non-priority signals on Cleveland Street are red for about 53 per cent of the time, and, in 10 per cent of cycles are red for 53 seconds or more. The second factor is the bunching of traffic by the new signals: platoons of traffic released by the signals may overload the roundabout entry, causing excess delay there, but the roundabout may have unused capacity at other times. These factors are discussed more fully in appendix A.

Traffic from Union Street (B to C) has experienced a slight (but significant at the 0.2 per cent confidence level) reduction in journey times on weekdays, both in the peak and later in the morning. This may be because times spent queuing for the green stage of the signal are less than those previously spent waiting for gaps in the main traffic flow along Cleveland Street. Furthermore, traffic from Union Street which needs to be positioned in the central or off-side lane at the roundabout can now perform this manoeuvre while main road traffic is held at the signals.

5. ADHERENCE TO BUS SCHEDULES

One of the possible benefits of bus priority measures is an improvement in bus reliability, resulting from buses being subject to less unpredictable delay when they are not subject to hindrance by congested traffic. Such improvements can affect both bus passengers, who may be able to allow for less contingency time in planning their journeys, and bus operators, who may be able to schedule buses and drivers more efficiently.

In order to assess any change in reliability resulting form the scheme, actual times at which buses passed point C were recorded during the surveys, and compared with scheduled times. A notional allowance of two minutes has been made to represent the journey time over the short distance (about 400m) between point C and the bus station, which is the point referred to in timetables. The services surveyed were:

18	18B	20	22	73	74	79	156	157
159	162	195	196	222	223	293	294	296
297	453	454	455	456	X78	456		

TABLE 2

Bus counts (buses per hour)

	Before	After	Before	After
	Site A (south end of Cleveland Street)			
	0730-0930		1015-1230	
Tuesday		32		41
Thursday	34	35	44	43
Friday	38	35	45	45
	0830-1030		1100-1300	
Saturday	41	33	36	38
	Site B (Union Street)			
	0730-0930		1015-1230	
Tuesday		6		6
Thursday	6	6	5	6
Friday	6	5	6	6
	0830-1030		1100-1300	
Saturday		7		5
	Site C (Cleveland St/Trafford Way roundabout)			
	0730-0930		1015-1230	
Tuesday		41		49
Thursday	40	43	50	50
Friday	41	39	53	52
	0830-1030		1100-1300	
Saturday	44	48	43	45

Observations were made on Thursday, Friday and Saturday (5 to 7 May 1994), and Tuesday, Thursday, Friday and Saturday (7, 9 to 11 June 1994), and the results are shown in table 5.

The mean differences, obtained by subtracting scheduled from observed departure times, and then averaging over all observations, indicate the average lateness of buses. Because of the somewhat arbitrary adjustment described above, the actual values shown should not be taken as absolute measures of punctuality, but differences between the two surveys are revealing. Weekday bus services appear to have been more punctual, on average, after the introduction of the bus advance area, but Saturday timings may have deteriorated slightly. It is unlikely however that these relatively small changes in deviations from schedule would have been noticed by passengers, particularly in view of the large standard deviations recorded which were much the same in both surveys. Standard deviations of differences from schedule were much the same before and after, indicating no obvious change in regularity.

The apparent changes in punctuality appear to be much greater in magnitude than bus time savings along Cleveland Street resulting from the bus advance area (table 1). Changes in traffic conditions on other parts of bus routes between the two surveys seem to be the most likely reason.

6. VEHICLE OCCUPANCIES

6.1 BUSES

Mean numbers of passengers counted on buses leaving the last stop in Cleveland Street (figure 1) are shown in table 6.

6.2 NON-PRIORITY VEHICLES

Mean numbers of occupants of cars and goods vehicles counted at site A are shown in table 7.

TABLE 3

Journey times for non-priority traffic

	Before	After	Before	After
	A-C (main road)			
	0730-0930		1015-1230	
Tuesday		97.0		79.4
Thursday	59.3	100.0	49.8	79.7
Friday	73.5	106.3	43.8	81.7
Mean	67.2	101.6	46.8	80.4
Standard error	0.9	1.1	0.5	0.8
	0830-1030		1100-1300	
Saturday	36.7	72.8	46.7	88.3
Standard error	0.7	1.5	1.3	1.9
	B-C (from Union Street)			
	0730-0930		1015-1230	
Tuesday		27.5		20.7
Thursday	36.3	30.7	25.8	24.5
Friday	38.9	34.8	24.3	22.9
Mean	37.8	31.1	25.1	22.7
Standard error	1.5	1.0	0.7	0.5
	0830-1030		1100-1300	
Saturday[4]		19.4		27.3
Standard error		1.5		1.8

4 Data on journey times between B-C in the before survey were lost because of computer failure

7. TIME SAVINGS

Time savings for different types of road user have been estimated for the morning peak and the off-peak period for traffic travelling along Cleveland Street (A-C) and from Union Street (B-C)[5]. In each case the mean time saving per vehicle is multiplied by the mean number of travellers (per hour) which is derived from the statistics in tables 2 and 6 (for buses) or 3 and 7 (other vehicles). Estimates have been limited to weekdays, because of the incompleteness of Saturday data. The results are shown in table 8.

Both peak and off-peak there are small savings to bus passengers, whether travelling all along Cleveland Street or joining it from Union Street (B-C), and to occupants of other vehicles emerging from Union Street. These are heavily outweighed by the loss in time (negative savings) for occupants of non-priority vehicles on Cleveland Street (A-C). It is not possible to make such detailed estimates for Saturday traffic, but the overall effect is likely to be similar (or slightly worse if the apparently anomalous bus journey times in table 2 are taken at face value).

While this negative result is disappointing, it does not automatically imply that the concept of bus advance areas on approaches to roundabouts is fundamentally unsound. In this particular example the simple concept of a bus advance area has been compromised by the presence of the side road, which has to be allocated green time which could otherwise be used for main road traffic. It is therefore of interest to attempt to explain the effect of this complication on the performance of this particular scheme, and then to make a hypothetical evaluation of a similar arrangement without a side road. These ideas are discussed in the following two sections.

8. DELAYS AT ACTUAL JUNCTION (WITH SIDE ROAD)

8.1 DIRECT DELAY BY SIGNALS

There are two lanes with a total width of 6.1m at the junction stop line. According to the findings of Kimber *et al* (1986) the saturation flow may be estimated at 3980 vehicles per hour (see appendix A for details).

5 Traffic from A to C has been taken as that counted at C less that counted at B - which is taken as the flow from B to C

TABLE 4

Non-priority traffic counts (vehicles per hour)

	Before	After	Before	After
	Site A (south end of Cleveland Street)			
	Before	After	Before	After
	0730-0930		1015-1230	
Tuesday		1312		912
Thursday	1352	1294	1096	1111
Friday	1565	1539	1129	1196
	0830-1030		1100-1300	
Saturday				
	Site B (Union Street)			
	0730-0930		1015-1230	
	Before	After	Before	After
Tuesday		212		215
Thursday	210	204	301	209
Friday	215	217	250	277
	0830-1030		1100-1300	
Saturday		219		225
	Site C (Cleveland St/Trafford Way roundabout)			
	0730-0930		1015-1230	
	Before	After	Before	After
Tuesday		1412		1151
Thursday	1442	1304	1378	1192
Friday	1645	1454	1352	1034
	0830-1030		1100-1300	
Saturday	904	1294	756	1237

The mean traffic flow recorded during the morning peak in the "after" survey was some 1380 vehicles per hour (table 4). Observations (appendix B) made on 9 January 1995 revealed that during the morning peak (0730-0930) there were 129 green signal stages, with a total duration of 3413s, for non-priority traffic on Cleveland Street. This implies a mean cycle time of 55.8s and a mean green time of 26.5s.

The mean delay per vehicle at the junction may be estimated at 15.3s, using these measurements and equation 4 of appendix A (derived by Vincent *et al*, 1980). This is rather less than half the additional delay of 34.4s caused by the traffic signals, according to our observations (table 8).

This discrepancy may be explained, at least in part, by the variability in the lengths of the green and red stages, which are illustrated in figure 2. The distribution of red time has a marked bimodal characteristic, with red stages being relatively short when only side road traffic has to be accommodated, but much longer when a bus lane stage is required. Abnormally long red stages will cause longer-than-average traffic queues to form, and short green stages may be insufficient for queues to clear the junction. Delays are therefore likely to be greater than predicted by equation 2, but at present we have no means of quantifying this effect.

8.2 SECONDARY EFFECTS AT THE ROUNDABOUT

The interruption of the flow of the main stream of traffic along Cleveland Street may affect the operation of the roundabout. Instead of traffic arriving at the roundabout in a reasonably steady stream, well within the design capacity,

TABLE 5

Adherence to bus timetables

Period	Mean Difference (sec)		Standard Deviation		Sample Size	
	Before	After	Before	After	Before	After
0730-0930						
Tuesday	No Data	112	No Data	215	No Data	74
Thursday	189	11	262	196	74	81
Friday	123	67	235	245	71	72
1015-1230						
Tuesday	No Data	71	No Data	264	No Data	107
Thursday	192	64	262	247	97	108
Friday	131	39	260	266	112	104
0830-1030						
Saturday	7	67	243	280	85	86
1100-1300						
Saturday	57	88	260	287	96	97

TABLE 6

Bus occupancies

O-D	Time	Day	Passenger/Bus	
			before	after
A-C	0730-0930	Tue		19.4
		Thu	18.5	20.0
		Fri	19.5	22.2
	1015-1230	Tue		25.9
		Thu	25.4	20.6
		Fri	24.8	25.3
	0830-1030	Sat[6]	23.4	21.9
	1100-1300	Sat	26.9	21.0

6 Saturday counts made on 26 March 1994

it may be bunched by the action of the signals. This bunching may be sufficient to overload the roundabout entry for part of the time, with capacity being under-utilised at other times.

We have attempted to investigate this possibility by using the ARCADY model to predict delays at the roundabout under conditions of uniform flow, and with the entry periodically interrupted. Since the flows of traffic using other arms of the roundabout are not known, we have used a plausible range of values. The results of this exercise (described in appendix C) suggest that additional delays at the roundabout might be in the range of about 3 to 6 seconds per vehicle, depending on traffic flows on other arms of the roundabout. This may in practice be an overestimate, since in its present form the ARCADY software will treat units

TABLE 7

Non-priority vehicle occupancies

O-D	Time	Day	Passenger/Vehicle before	Passenger/Vehicle after
A-C	0730-0930	Tue		
		Thu	1.27	1.45
		Fri	1.43	1.43
	1015-1230	Tue		
		Thu	1.63	1.70
		Fri	1.64	1.55
	0830-1030	Sat[7]	1.89	1.82
	1100-1300	Sat	1.98	2.00

7 Saturday counts made on 26 March 1994

TABLE 8

Weekday time savings

		Passengers Per hour	Time saving Per vehicle (s)	Total time savings (person hours/h)
Peak (0730-0930)				
A-C	Bus	723	5.6	1.12
B-C	Bus	113	1.8	0.06
A-C	Other	1743	-34.4	-16.66
B-C	Other	295	5.7	0.47
Total				-15.01
Off-Peak (1015-1230)				
A-C	Bus	1065	5.1	1.51
B-C	Bus	141	1.6	0.06
A-C	Other	1707	-33.6	-15.93
B-C	Other	421	2.4	0.28
Total				-14.08

of time no smaller than one minute, so that alternate green and red times of one minute must be used to simulate the effect of a signal which is green for approximately 50 per cent of the time. A shorter cycle time is likely to cause less bunching, and cause smaller delays. Nevertheless, it seems likely that interruption of smooth traffic flow into the roundabout may make a considerable contribution to the observed delays.

9. DELAYS AT SIMPLE BUS ADVANCE AREA (WITHOUT SIDE ROAD)

In this section we attempt to estimate delays to buses and other traffic in the hypothetical case of a bus advance area

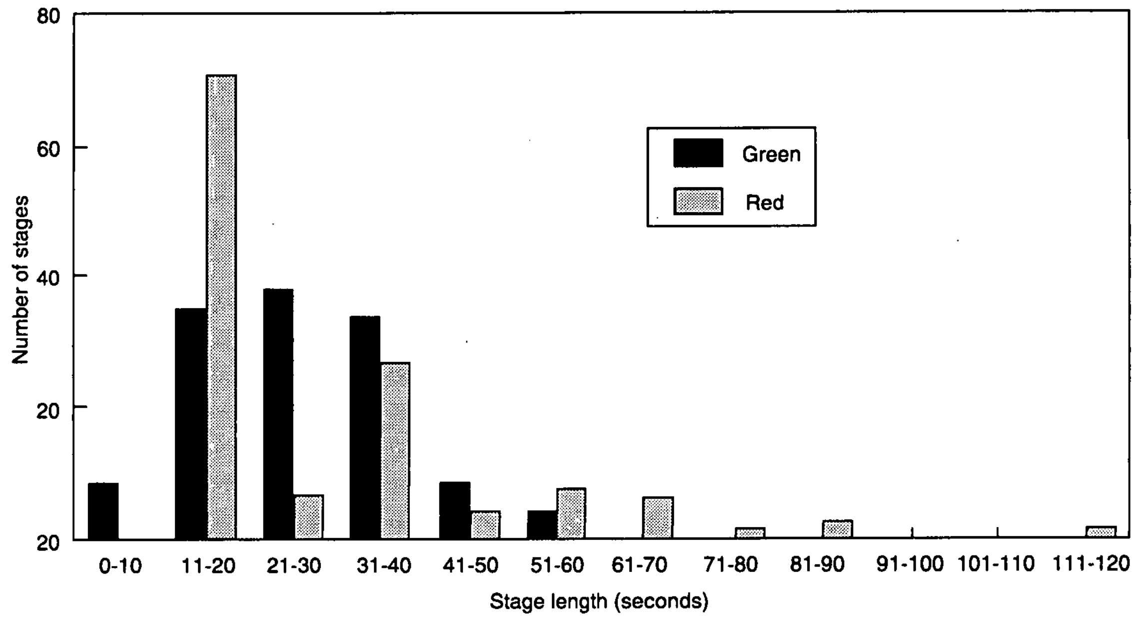

Fig. 2 Non-priority signal settings - Cleveland Street 0730-0930

exactly like that studied in this report, except for the omission of the side road entry. This is not to suggest that traffic management measures involving the closure of Union Street in Doncaster would be feasible or desirable, but it is used simply as a device to give some indication of how bus advance areas might work in conjunction with roundabouts in more straightforward situations. In this hypothetical arrangement, the green time (and the associated inter-green time) provided for side road traffic could be reallocated to the bus lane, or non-priority traffic on the main road, or partly to both. In practice there would be no merit in allocating all the available green time for buses: we show in section 9.1 that a partial allocation to the bus lane would be sufficient to allow all buses to move into the advance area without interruption. The consequences of allocating all the available green time to non-priority traffic is explored in section 9.2.

9.1 INCREASED GREEN TIME FOR BUSES

According to observations made on 9 January 1995, the amount of green time (and associated inter-green time) allocated to the side road between 0730 and 0930 is 1955s. The delay to buses which do not arrive at the signal during green stages amounts to only 334s. Without the side road all of this delay could have been eliminated by extending green stages or advancing their initiation by the amounts of time buses were actually delayed. This would have resulted in the running together of what were separate green stages for buses, resulting in a total of 61 bus stages over the two hours, instead of the actual 67; the number of main road stages would also have been reduced to 61 from 129. Since there would have been fewer stages, the amount of inter-green time required would also have been less, allowing the total green time for non-priority traffic to be increased from 3413 to 5337s. The mean cycle time would have become 118.0s and the mean green time 87.5s.

With these mean signal settings the average delay per vehicle is estimated (using equation 2) as 7.2s, less than half the amount estimated in section 8.1 for the actual signal arrangements.

However, the reasons postulated in section 8 for the discrepancy between estimated and observed delays may also apply in this case: there are still irregularities in signal cycles, and there would still be interruption of the flow into the roundabout. It is arguable that these effects would be relatively less important with the increase in capacity for general traffic making the system less sensitive to perturbations of this kind, but no rigorous method of quantification is available at present. It is probably safe to assume that at worst the extra delay attributable to these reasons would be in the same proportion to that estimated by equation 2; at best the extra delay might be negligible. Thus the overall delay per vehicle might be in the range 7.2 to 16.2s, compared with the 34.4s actually observed.

The effect on buses is easier to assess. The observations of 9 January 1995 showed that 25 of the 80 buses using the bus lane between 0730 and 0930 were delayed at the signals by a total of 334s - an average delay of 4.2s per bus. This delay could be eliminated if, in the absence of the side road, the signals were operated as suggested here. However, there would be a further gain: in addition to the time spent waiting at the lights, time spent braking and accelerating would be avoided. For an individual bus cruising at 20 mile/h (32km/h), the time lost through decelerating to rest, and accelerating to cruising speed again (both at a rate of 1 m/s^2) is about 9s. The additional gain per bus, if no buses have to stop is thus 2.8s per bus. The overall effect would be that buses would gain an average of 12.6s (observed saving of 5.6s (table 8) + 4.2s + 2.8s). Bus passengers would therefore save 2.5 person hours per hour (cf 1.12 person hours per hour, table 8)

Delays to occupants of other vehicles on the main road would also be reduced from 16.66 to somewhere between 3.5 and 7.8 person hours per hour.

In practice these estimates may be somewhat over optimistic for two reasons. First, they are based on the assumption that the traffic signals could be made to respond perfectly to the requirements of buses, with green stages being started and stopped exactly when needed, so as not to delay buses or other traffic unnecessarily. Second, the comparisons made here depend on the assumption that there was no side road traffic which could have impeded main road traffic before the signals were installed. These effects are however likely to be marginal, so the estimates given above should be a reasonable indication of the effectiveness of the bus advance area in this hypothetical situation. While the overall result is less unfavourable than that actually observed, disbenefits to people in non-priority vehicles would still seem to outweigh benefits to bus passengers by a substantial amount.

The balance of benefits and disbenefits is dependent on relative volumes of bus passengers and other road users. Greater volumes of bus passengers would enjoy a greater collective benefit from the arrangement considered here, but this would be offset by further delays to other people, as more green time would need to be allocated to the bus lane. For the sake of illustration, we make the assumption that doubling the number of buses (and passengers) using the system would necessitate an overall increase in bus green time to 2000s over the peak period, and an increase in the number of signal cycles to 100[8]. This produces a mean cycle time of 72s, and a mean green time of 45s for non-priority traffic. The average delay estimated from equation 4 is 9.4s, but the variability in cycle times and the effect of bunching at the roundabout might increase this estimate to 21s. Thus the benefit to bus passengers would become 5.06 passenger hours per hour (double the previous value), while the disbenefit to other road users would increase to between 4.5 and 10.2 passenger hours per hour. It thus seems possible that a suitable bus advance area might produce overall net benefits with higher bus passenger flows, but our evidence is not strong enough to provide proof of this proposition.

9.2 ADDITIONAL GREEN TIME FOR NON-PRIORITY TRAFFIC

An alternative method of arranging the signals in the absence of the side road would be to allocate all the surplus green (and inter-green) time to non-priority traffic, without altering the bus lane stages. This, by definition, will have no effect on delays to buses.

This would increase the total green time available to non-priority traffic by some 310s over two hours, compared to the arrangement described in section 9.1, but the number of priority green stages would revert to the original 67. Thus the mean cycle and green times would reduce to 107.5 and 84.3s respectively, but the proportion of green time would increase. The mean delay to non-priority traffic is then estimated (using equation 2) to be 4.9s, which for reasons described in section 8 might be increased to 11.0s. Disbenefits to occupants of non-priority vehicles would thus be in the range 2.4 to 5.3 person hours per hour, compared with bus passenger benefits which would remain at 1.12 person hours per hour. Compared with the arrangement in section 9.1 (enough green time to buses to eliminate bus delays at signals) the gain to non-priority traffic marginally exceeds the loss to bus passengers.

10. DISCUSSION

While our observations do not provide evidence with which to evaluate the new Cleveland Street bus lane, they show clearly that the addition of signal control at the end of the bus lane has produced a nett disbenefit, with small time savings for bus passengers being heavily outweighed by increased delays to other road users.

This result in itself does not demonstrate a fundamental flaw in the principle of bus advance areas on approaches to roundabouts: in this case the incorporation in the signal cycle of a stage for side-road traffic has been a major factor in delaying main-road traffic. This poses the question of whether any signal arrangement could be devised which would be an improvement on the unsignalled bus lane in this location. While it is possible to propose alternative solutions, major modelling exercises and the collection of considerably more data would be needed to predict their effectiveness. However, we shall return to this question presently.

It is possible, however, to make some estimate of how a bus lane approaching a roundabout in a simpler location, without the complication of a side road, might be improved by signal control. It has not been possible within this study to develop rigorous modelling techniques, but the judicious combination of tested models and plausible assumptions produces a range of likely outcomes. These suggest that in conditions similar to those found in Cleveland Street, the addition of two stage signals, interrupting main road traffic only when buses need to leave the bus lane, would result in a nett disbenefit (albeit smaller than that observed in this study). The balance of advantage to bus passengers and disadvantage to others might be shifted if bus and bus passenger flows were much higher, but the case is not proven.

8 The actual quantities required would depend on the distribution of the additional buses over the peak period. The values assumed here seem plausible, but in practice might be subject to considerable variation.

This leads to the question of whether there might be some compromise solution which would give some advantage to buses without a disproportionate increase in delays to other traffic. This may have been achieved with bus advance areas on approaches to signal-controlled junctions, although the only complete study so far is complicated by the effects of other bus priority measures installed simultaneously in the Shepherd's Bush area (Astrop and Balcombe, 1995). Nevertheless, there is reason to believe that delays to non-priority traffic can be minimised by linking the phasing of pre-signals to that of the signals at the main junction, effectively displacing the queue without increasing its length and the associated delays.

However, where the flow into a roundabout is affected not by signals, but only by other traffic, such synchronisation is more difficult, and without synchronisation traffic may be required to queue at the signals, and then again on the approach to the roundabout. However, if the signals were arranged so that non-priority traffic were interrupted only when the queue at the roundabout entrance exceeded a reasonable length, then some element of queue relocation might be achieved, without excessive additional delay. This could produce gaps in the traffic between the end of the queue and the bus lane, which buses could enter while non-priority traffic was held. At other times, when queues were shorter, buses should be able to merge with other traffic and join them, so there would be no need to impose signal control on buses.

The success of such an arrangement is likely to depend strongly on the correct design of the system, including the length of setback between the bus lane and the roundabout entrance, the lengths of queues which would trigger signal changes, detector positions etc. Modelling techniques recently developed at TRL to determine the optimal setback for a conventional (unsignalled) bus lane on a roundabout approach, which incorporate ARCADY software and some queuing theory, could possibly be extended to provide a theoretical evaluation of this form of bus advance area, prior to either track experiments, or trials on public roads if any authority were willing to experiment with such an arrangement in a suitable site.

It is also worth considering whether this modified form of bus advance area might usefully have been applied to the Cleveland Street site in Doncaster. If only non-priority traffic on the main road were signal controlled, traffic joining Cleveland Street from the side road (Union Street) would have to give way at the junction, instead of proceeding freely during its own green stage. Thus side road traffic would be performing the same manoeuvre as it did before the signals were put into operation, except that occasionally it would be able to emerge during a main road red stage. This arrangement would represent a solution intermediate between the before situation, with no signals, and the current system with its long delays to non-priority traffic. The benefit to buses should also be intermediate between the values found in this study, there would be some increased delay to side road traffic, but much less delay to non-priority traffic on the main road. Until suitable modelling methods are developed, it is not possible to estimate what the overall benefit might have been, and there is no opportunity to test the arrangement in practice, since the roundabout has now been equipped with traffic signals, for more general traffic management purposes.

11. CONCLUSIONS

The bus advance area at the Cleveland Street/Trafford Road roundabout in Doncaster has failed to produce any benefit over and above any which may have resulted from the creation of the bus lane. The gains to bus passengers have been only marginal, and heavily outweighed by losses to occupants of other vehicles.

A substantial part of the disbenefit can be attributed to the need, inherent in the current design, to provide a green signal stage for side road traffic. Attempts have been made to estimate how a bus advance area on a roundabout approach, on a similar site but without a side road might have performed. The results are somewhat speculative, since suitable modelling techniques have yet to be developed, but they seem to indicate that the type of arrangement used in Doncaster might produce little or no nett benefit.

An alternative arrangement is suggested, in which only non-priority traffic is signal controlled, and is held at the signal only when queues at the roundabout entrance become too long. This concept should preferably be tested by new modelling methods, before trial on public roads.

12. ACKNOWLEDGEMENTS

We are grateful to officers of the Metropolitan Borough of Doncaster who contributed, through discussions and the provision of information, to the design of the study, and to Keith Shorter, of Babtie Traffic and Transportation, who conducted the surveys on our behalf. Our thanks are due to Dr Iain York, of TRL, for the modelling described in appendix C.

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APPENDIX A: ESTIMATION OF DELAYS AT SIGNALS

A.1 SATURATION FLOW

Kimber *et al* (1986) analysed measurements made at 64 sites and derived a model to predict the saturation flow at isolated traffic signals. For a two-lane entry to a signal-controlled junction on a horizontal, straight road, with no opposing turning movements, this model predicts saturation flows:

$$s_1 + 1940 + 100\,(w_1 - 3.25) \quad (1)$$

and

$$s_2 + 2080 + 100\,(w_2 - 3.25) \quad (2)$$

where s_1 and s_2 are the saturation flows (vehicles per hour), and w_1 and w_2 the widths (metres) of the first and second lanes respectively).

Combining these equations yields, for the total saturation flow:

$$s = s_1 + s_2 + 4020 + 100\,(w_1 + w_2 - 6.50) \quad (3)$$

Since the width of the main-road non-priority stop line at the Cleveland Street/Union Street junction is 6.1m, the saturation flow is estimated at 3980 vehicles per hour.

A.2 VEHICLE DELAY

According to Vincent *et al* (1980) the average delay to vehicles on one approach to an isolated traffic signal may be estimated using the equation:

$$d = \frac{(c-g)^2}{2c\left(1-\frac{g}{s}\right)} + 15\frac{T}{Q}\left[(q-Q) + \sqrt{(q-Q)^2 + 240\frac{Q}{T}}\right] \quad (4)$$

where

g is the green time in seconds

c is the cycle time in seconds

s is the saturation rate of flow in vehicles per hour

Q (=gs/c) is the maximum throughput

q is the mean rate of flow in vehicles per hour over a time T minutes

When, as in the conditions observed in this study, T is large compared with $240Q/(q-Q)^2$, and $q<Q$, the second term approximates to $1800/(Q-q)$ and is independent of T.

APPENDIX B: SIGNAL OBSERVATIONS

Observations were made of timings of the signal stages at the Cleveland Street/Union Street junction between 0730 and 0930 and between 1015 and 1230 on 9 January 1995. Numbers of buses using the bus lane were also recorded, as were any delays to buses which had to stop in the bus lane and wait for green signals. The results of the morning peak observations are summarised in table B.1.

Also shown in table B.1 are distributions of green time for the hypothetical junction without a side road discussed in section 9. The third column represents the option where sufficient green time is allocated to the bus lane to allow all buses to emerge from it without delay. The total green time shown for the bus lane is slightly greater than the sum of the original green time and the original delay to buses; this results from the cancellation of main road stages which would otherwise be less than 8 seconds long. The fourth column assumes no change in the bus lane stages, with all the surplus green time made available by the removal of the side road allocated to non-priority traffic.

TABLE B.1

Signal timings

	Actual Junction	Hypothetical Juncyion without Side road	
		Increased green time for buses (s9.1)	All surplus green time allocated to non-priority traffic (s9.2)
Main road (non-priority traffic)			
Total green time	3413	5337	5647
Stages	129	61	67
Mean green time (g)	26.5	87.5	84.3
Mean cycle time (c)	55.8	118.0	107.5
Bus lane			
Total green	958	1321	958
Stages	67	61	67
Buses passing without delay	55	80	55
Buses delayed	25	0	25
Total delay to buses	334	0	334
Side Road			
Total green	1377	-	-
Stages	131	-	-
Inter green (total stages x 4.44)	1452	542	595
Total time (2h)	7200	7200	7200

APPENDIX C: EFFECT OF SIGNALS ON DELAYS AT ROUNDABOUT

C.1 INTRODUCTION

This appendix describes the results of a modelling exercise undertaken to investigate the likely magnitude of additional delays at the roundabout caused by interruption of the traffic flow by signals, as suggested in section 8.2. TRL's ARCADY software was used to estimate delays to traffic entering the roundabout, under the conditions obtaining in this study. Section 16.2 contains the assumptions that were made in order to fulfil the data requirements of ARCADY. The roundabout's parameters entered into ARCADY are in section 16.3. Section 16.4 contains the results of the ARCADY runs and section 16.5 presents the main conclusions.

C.2 ASSUMPTIONS

It was assumed that the proportion of heavy goods vehicles in the flow from each arm were the standard default values contained in ARCADY and that they did not vary over time or turning movement.

It was assumed[9] that turning proportions did not vary over time and that they were as shown in table C.1.

C.3 ROUNDABOUT PARAMETERS

The geometric parameters calculated from a scale map (figure 3) of the Doncaster roundabout are shown in table C.2.

It was known from the survey that the flow through arm A (i.e. the one with the bus lane and signals) is 1350 pcus per hour. The flows through the other arms were unknown and so a range of flows have been tested in section C.4.

9 No measurements were made of movements on the different arms of the roundabout, so traffic flows have been assumed proportionate to the capacity of the arms.

TABLE C.1

Traffic turning proportions at roundabout

Arm cars are flowing from (see figure 3)	Arm cars are flowing to (figure 3) A	B	C	D
A	0.00	0.40	0.20	0.40
B	0.22	0.00	0.56	0.22
C	0.40	0.30	0.00	0.30
D	0.22	0.56	0.22	0.00

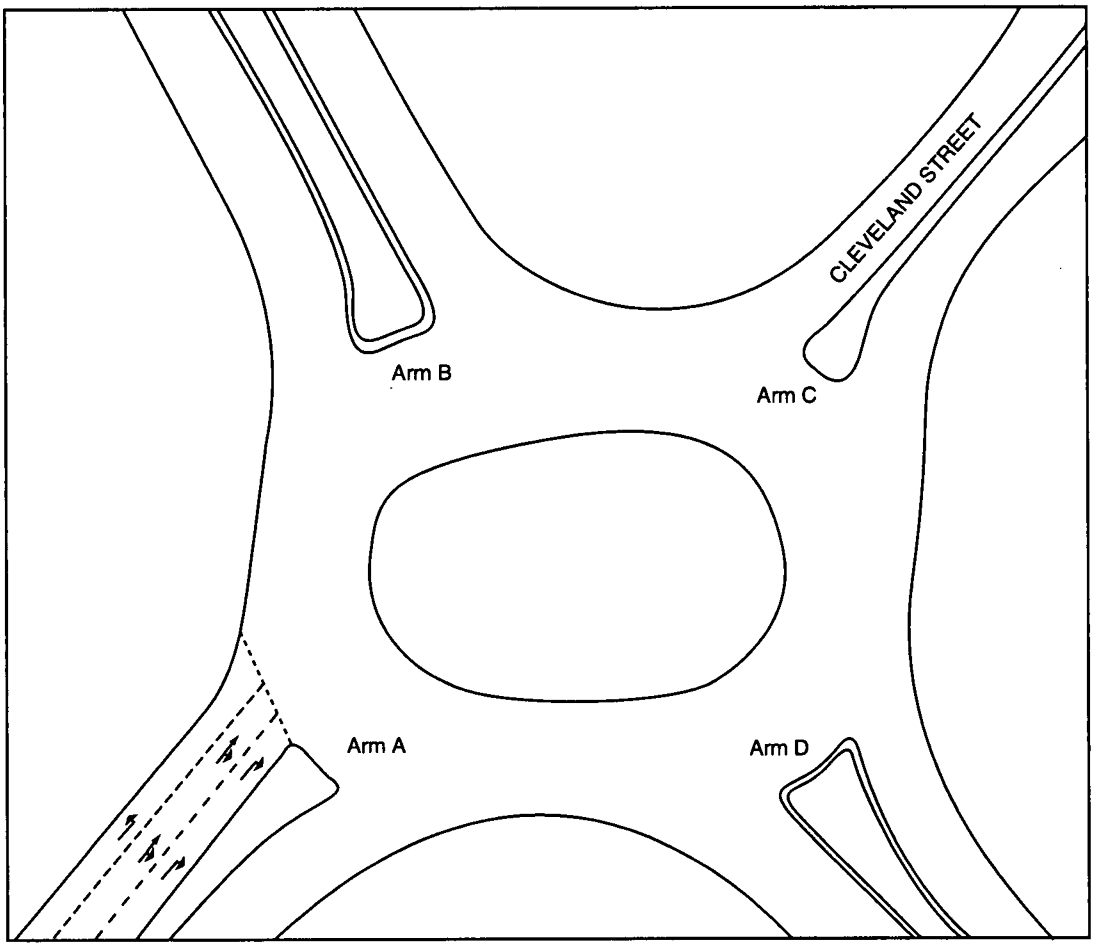

Fig. C.1 Roundabout details

C.4 ARCADY RUNS

In order to simulate the presence of traffic lights, ARCADY was run for a half hour period consisting of one minute intervals. The traffic lights were assumed to be green, and then red, during alternate one minute intervals. The model therefore simulated a fixed time signal with a two minute cycle split evenly between red and green time. It was not possible to simulate a smaller cycle time as the smallest interval in ARCADY is one minute. It was assumed that the flow through the arm was consistent and therefore 45 cars arrived at the roundabout during each green phase and none during a red phase. In the runs without the traffic lights the flow from the same arm was assumed to be 22.5 cars during each one minute interval.

The flow through each of the other arms varied according to the run performed. In each one the flow was steady and equal to the pcus per hour divided by 60 in each of the intervals.

The average time a car waits at the roundabout was calculated by summing the total vehicle minutes spent queuing

TABLE C.2

Geometric parameters of roundabout

Parameter	Arm A	Arm B	Arm C	Arm D
Approach road half width	11.00	7.00	5.25	6.00
Entry width	11.25	7.75	5.50	8.25
Average effective flare length	2.70	1.00	0.25	16.25
Entry radius	17.00	17.50	11.25	18.75
Inscribed circle diameter	33.50	33.5	32.20	32.50
Entry angle	20.00	27.00	9.00	28.00

in each of the thirty intervals and then dividing by the number of cars that arrived at the roundabout during the time period (i.e. 30 x 22.5). The results are shown in table C3.

C.5 CONCLUSIONS

Traffic lights setback on the arm of a roundabout have an adverse effect on the queuing time of traffic at the roundabout. In the runs performed they doubled, and in some cases almost tripled, the average queuing times.

The extra time that cars were queuing at the roundabout because of the effect of the signals varied between about 3 and 6 seconds.

TABLE C.3

Estimated vehicle delays

(i) Flow on arm C: 500 pcus per hour

Flow on arms B/D	Average time each car queues at roundabout (seconds) Without traffic lights	With traffic lights
400	2.64	5.99
500	2.87	6.52
600	2.93	7.31
700	3.16	7.99
800	3.41	8.77
900	3.68	9.69

(ii) Flow on arm C: 700 pcus per hour

Flow on arms B/D	Average time each car queues at roundabout (seconds) Without traffic lights	With traffic lights
400	2.75	6.38
500	2.90	6.92
600	3.16	7.71
700	3.40	8.50
800	3.66	9.41
900	3.92	10.34