Published paper
S.D. Clark, A.D. May, F.O. Montgomery (1995) *Priority Management for Urban Arterials. Transferability of Techniques: York/Selby Road.* Institute of Transport Studies, University of Leeds, Working Paper 463

UNIVERSITY OF LEEDS
Institute for Transport Studies

ITS Working Paper 463 *ISSN 0142-8942*

December 1995

PRIORITY MANAGEMENT FOR URBAN ARTERIALS

TRANSFERABILITY OF TECHNIQUES

YORK/SELBY ROAD

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This work was undertaken on a project sponsored by the Engineering and Physical Sciences Research Council (Grant Ref: GR/J09390)

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ABSTRACT

This paper describes the background and methodology employed in research funded by EPSRC to assess the effect of individual traffic control measures, both in isolation and in combination upon urban arterials. The aim of the project was to test the transferability of the techniques developed in a DRIVE II project, PRIMAVERA, to a range of different types of urban corridor. Measures can be classed into three broad categories: Congestion Management, Public Transport Priority and Traffic Calming. The scope of these measures is wide, some operating at a junction level whilst others affect the whole network.

Measures from these areas are applied to a sophisticated microsimulation model of four urban arterial corridors: three in Leeds and one in Leicester. The effects of the application of individual and integrated measures are assessed in terms of their efficiency, environmental and safety impacts using a form of Multi-Criteria Analysis. Travel time and other monetary costs are also taken into consideration.

This paper reports the results for the A64 York and A63 Selby Road which are the main arterial routes to the east of Leeds.

1 DESCRIPTION

The network of roads which form the York Road and Selby Road arterials function as the main corridor to the east of Leeds, linking the Outer Ring Road into the City Centre (see figure 1 for a schematic representation of the network). The outer section of this corridor forms a triangular road network, with the Ring Road running north to south along a 2km stretch, the York Road, north east to south west for 2.75 km and the Selby Road east to west for 3km. The land use surrounding this triangle is mainly residential. The York and Selby roads merge 2.75km from the City Centre. The stretch of road west of this merge point operates as an urban clearway with a high capacity, high speed limits and very little opportunity for on-street parking. Severe congestion occurs on the network both in the am peak inbound direction (which can continue until 10:00) and the pm peak.

The dominant route through the network is along the A64 York Road from the Outer Ring Road to the City Centre. Much of the A64 is dual carriageway with either a grass median, a metal fence or a combination of the two separating the two carriageways. A small number of U-turning points are provided on the sections from timing points 1 to 5, but none after this point. Timing point 1 is a four arm roundabout. The initial section of road from points 1 to 2 is single carriageway with one lane in each direction and a number of minor giveway junctions onto the arterial. A service road runs parallel to the arterial in the outbound direction. Timing point 2 is a four arm roundabout which forms the first significant merge point in the network, the greatest competing flow with the arterial being the two lane link to the east (Cross Gates Road) . West of this point the arterial is always at least two lanes wide in each direction and the degree of side street access is minimal. Point 3 is a signalised junction, with strong arterial flows in the peaks but significant cross arterial flows after the am peak from a retail park at the northern arm of this junction. Point 4 is a complex junction which functions as a signalised roundabout. Its staging sequence is given in the upper portion of figure 2. Inbound between points 4 and 5 there are three lanes of traffic, the kerb-side of which is a reserved bus lane, with a set-back, during the am peak period. The outbound direction is two lanes. Point 5 is a staggered junction with the staging given in the lower portion of figure 2. A right turn ban is in force from the side-streets. West of this point there are no further side-streets onto the arterial, with long sections of the arterial being elevated. Between points 5 and 6 both directions have two lanes. Below point 6 is a roundabout with some of its arms forming slip roads off and onto the arterial. The section between points 6 and 7 has three lanes in each direction. This presents a merge problem travelling outbound where the number of lanes reduces from three to two at timing point 6. At point 7 the inner two lanes of the arterial are elevated and form the start/end of the city's Inner Ring Road and are regulated as a Motorway. The kerb-side lane forms a two lane slip road into a staggered signalised junction.

On the A63 Selby Road, timing point 8 is a three arm roundabout. The initial section from points 8 to 9 to 10 has a single lane in each direction, with many side streets which give way to traffic on the arterial. Timing points 9 and 10 are signalised, point 9 is a staggered junction and the area around point 10 is a busy local shopping area. The stretch from 10 to 4 is two lanes in both directions, with a narrow railway bridge at point 4. The flows under the bridge are tidal, as can be seen in the signalling diagram for this point in the upper portion of figure 2.

The stretch of the Outer Ring Road between points 1 and 8 is two lanes in both directions.

The land use surrounding the outer sections of both arterials is mainly residential. Towards the inner section from points 5 to 7, the land use is more mixed with a combination of residential and light industrial units.

In the morning peak a great deal of congestion occurs on the whole of the network. The only free-flowing sections are on the Outer Ring Road. The flows at various points in the network are given in figures 6 and 7. During the inter-peak period, which starts at around 10:00, the traffic begins to move freely with little or no oversaturation in the network. The pm peak period is not modelled as part of this study.

For the purpose of this study the two time periods considered are the am peak period, 0730 to 0900 and the inter-peak period, 1000-1500. The reason for the selection of the inter-peak period is to provide a differing set of less congested conditions in which to evaluate measures.

2 MEASURE SELECTION

A meeting was held with two members of the project team and a representative from Leeds City Council (LCC). The meeting started by LCC outlining their long term plans for this corridor.

Two primary concerns need to be borne in mind when looking at measures for application here. The first is that the westerly section of the corridor is already very urbanised and it is thought that any additional traffic would cause very little additional harm to the physical/visual environment. In contrast the two outer arms of the corridor are environmentally sensitive, being surrounded by mainly residential properties. Any measure which is able to relocate queues from the outer arms of the corridor into the inner sections is likely to be well received.

The Outer Ring Road is managed by the Highways Agency and as such should not be adversely affected by any measures on the A64/A63, which are both managed by LCC.

The A64/A63 is under active consideration for the implementation of a guided bus scheme along the extensive central reservations that currently exist.

There is a proposal to build a section of the M1/A1 link to the immediate south of this corridor. If this project is completed it is hoped that traffic, especially heavy goods traffic, will divert from the A64/A63 corridor onto this new road. This would give greater scope for enhancing the bus priority and pedestrian facilities on the A64/A63.
Bearing these themes in mind, the following measures (from those listed in Clark et al, 1995), were identified as being worthy of consideration for the A64/A63. Most of the measures are applicable in both the am peak and the inter peak periods. Where they are suitable for only one of these time periods then this is explicitly stated. The short code used in later sections to refer to this measure is given at the end of the description.

Queue Storage (AM). The two arms of the corridor, the A64 (points 2-3-4) and the A63 (point 9-10-4), both have long queues during the morning peak period. Currently the queues on the two arms are balanced in terms of the saturation at junction 4. The queues are not however balanced in length with the total extent of the queue being greater in duration on the A63. This measure redistributes an amount of green time away from the A64 and to the A63 in order to reduce the queues on the later. The maximum amount of time which could be transferred is 5 seconds per cycle. In one application of the measure the existing assignment (which was calculated using the original green split) is used with the new green split and in another application a re-assignment is performed with the new green split. Without reassignment the flows into timing point 4 are A64 : 1322 and A63 : 1777, whilst with reassignment the flows are A64 : 1271 and A63 : 1782. Clearly the effect is to reduce the flow on the A64 to reflect the reduced green time whilst the flow on the A63 has remained almost constant. Thus the effect of extra green time on A63 will not be negated by additional traffic flows. (QS without re-assignment; QS(I) with re-assignment)

Longer cycle times (AM). Currently the junctions at timing points 3, 4, 5, 7, 9 and 10 operate on a variety of cycle times (between 60 and 90 seconds) during both the morning and inter-peak periods. In order to derive the optimal TRANSYT (Vincent et al, 1980) timings for the network a common cycle time was required. The choice for the optimal cycle time to use was made with reference to the CYOPT facility in TRANSYT 9. The time selected for the am peak was 88 seconds and the time for the inter peak period was 72 seconds. In view of the requirement that queues should be relocated from the outer arms to the inner section of the corridor, the cycle times at the above mentioned junctions were increased to 104 seconds during the morning peak. (LC)

Coordination for buses. This measure calculates green split and junction offset timings to match better with the behaviour of buses as they travel along the arterial. Usually this requires greater offsets between junctions to account for the greater journey times which buses experience. The attempt at coordination is in both directions, along the 3-4-5-7 and the 10-4-5-7 routes. (CB)

Selective vehicle detection. Three junctions in the inbound direction were equipped for selective vehicle detection. These correspond to timing points 9 (both junctions) and 3. (SVD)

Guided bus. As mentioned above, this corridor is a candidate for the implementation of a guided bus scheme. The guideways would be implemented along the central reservations of the A64 and A63. For this measure two-way Guideways were implemented on routes 3-4-5 and 10-4-5. To fully implement Guideways in the central reservation and still allow existing traffic movements it was necessary to signalise a number of priority junctions. The major change was at a junction between timing points 4 and 5. In order to allow right turning traffic to turn safely at this junction the signal plan shown in figure 3 was adopted. Stage 2 was necessary to avoid east to north turners having to cross three traffic streams (westbound Guided Bus, eastbound Guided Bus and eastbound traffic).

Simpler plans were necessary at two intermediate junctions between timing points 10 and 4. In many cases the Guided Buses constitute an additional traffic stream at the existing junctions in the network. This means that it is usually necessary to incorporate an additional stage in the cycle to allow for the passage of Guided Buses. This stage and its associated inter-green period can have a significant effect on the efficiency of the junction. There are cycles when this stage is required and others when it is not. Unfortunately it was not possible to incorporate this form of demand dependency in NEMIS. Thus the Guided Bus stage runs during every cycle for a fixed duration, irrespective of the demand from Guided Buses. Clearly a better approach would be to make the stage demand dependent and of variable length. (GB)

Zero bus lane setback (AM). There is already a reserved bus lane with a 100m set-back between timing points 4 and 5, operational in the am peak. This measure eliminates the set-back, taking the bus lane to the junction stopline. Modifications are required to the stages at timing point 5 in order that left turners do not conflict with kerb side buses. The approach adopted is to modify the stages in figure 2 to hold back buses during stage 1, and insert a stage between 1 and 2 which holds back general traffic in order to allow buses to exit the link without conflicts. Once again this new stage, 1b, is called every cycle rather than when demanded. (ZB)

Reduce bus lane setback (AM). The set-back for the reserved bus lane between timing points 4 and 5 is reduced from 100m to the distance required to accommodate the average number of left turners per cycle. On average there will be 10 vehicles wishing to turn left, and assuming that each vehicle requires 6m of queue storage stage then this setback should be 60m. No changes are required to the signalling arrangements. (BS)

Reduced dwell time at stop. A 20% reduction in the dwell time at every stop in the network is implemented. (TS)

Remove bus laybys. The time taken for a bus to enter and leave a layby can add a significant amount of time to its journey. This can be the case where the layby is close to a queue of traffic, the bus being unable to pull out because of the stationary traffic. Also in free-flow conditions, especially along a road section with high speeds, the bus may not be able to find a suitable gap. To improve the journey time for buses, seven of the ten bus laybys which fall into either of the above categories are removed. (BL)

Bus Pelican. There is a bus layby immediately upstream of a Pelican in the section of road between timing points 4 and 5. The movement of the bus layby to downstream of the Pelican will enable any bus to leave the layby in the shadow of a pedestrian green man. (BP)

Calmed offsets (IP). The road sections between points 3-4-5 and 10-4-5 are given offsets which are suitable for a progression speed of 12m/s. The maximum speed of vehicle on these road sections is limited to a maximum of 12m/s to correspond with these offsets. (CO)

Platoon formation (IP). The signalling of an additional junction, 150m upstream of timing point 10 will allow the control of the section of road between the two signalised junctions. The aim of this control is to create well defined platoons of vehicles which provide significant gaps in the traffic stream to allow pedestrians to cross the road. This is especially welcome on this section of road since it is surrounded by shops on both sides of the road. (Hopkinson et al, 1989) (PL)

Physical calming. The physical calming of the sidestreet network surrounding the outer arms of the corridor is implemented. The calming involves a reduction in both flows and maximum speeds on these roads. (PC)

3 MEASURE INTEGRATION

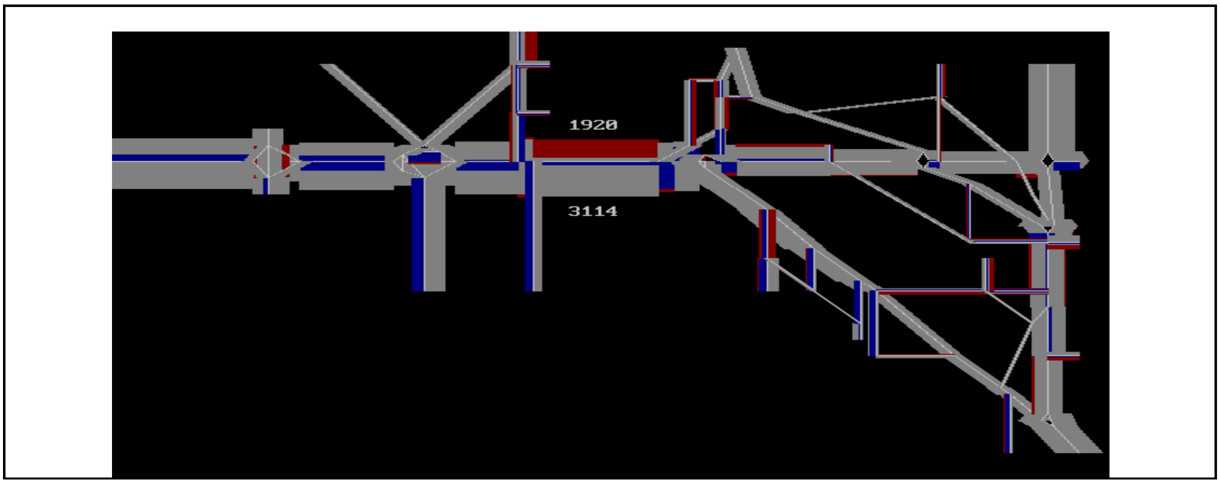
In order to ensure a broad coverage of evaluation results each measure needs to be applied in as wide a variety of circumstances as resources allow. This variety will come from a combination of measures from differing areas (for example from congestion management and from bus priority). Clearly some of the measures are mutually exclusive and so cannot be considered in an integrated approach. Coordination for buses and calmed offsets cannot be implemented at the same time and three bus measures: zero bus lane setback, reduced bus lane setback and guided buses are incompatible.

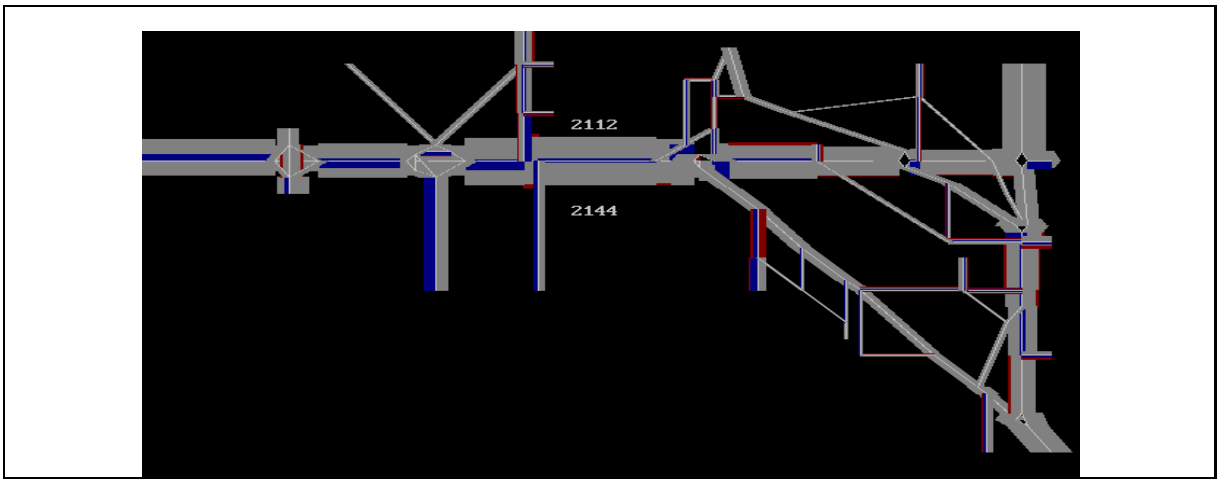
4 CALIBRATION RESULTS

The following calibration results are from the supplied traffic database.

Automated Traffic Count sites are available for a number of links on both the arterial roads within the network and also some of the connecting network. Figure 1 shows these sites. From the simulation two sets of flows are available:

Assigned : These are the flows taken from the OD matrix and assigned, using Wardrop's Equilibrium Assignment, to the links in the network. These flows can be thought of as the demand flows. The assigned flows along every link in the corridor are represented in figure 4 for the am peak period and figure 5 for the inter peak period. The numbers associated with selected links denote the hourly,





assigned, flows in vehicles per hour.
Simulation : These are the actual outflows which occur during the simulation. These flows can be less than the assigned (capacity less than demand) or, less frequently, more than the assigned (unmet demand in the initial ½ hour period being processed in the following 1 hour).

Figure 6 shows the correspondence between observed, assigned and simulated flows for the am peak period. The level of agreement between observed and simulated flows is poor at important sites in the inbound direction. Note that for site 256038 the assigned and simulated flows are twice those observed. It is possible that the observed flow is anomalous since for the 0700-0800 and 0900-1000 hours the hourly flow is near 1200. Clearly the observed flow is not free-flow but congested, whilst it is nearer free flow in the model. Several attempts were made to try and improve on these results, but without success.

Figure 7 shows the correspondence between Observed; Assigned and Simulated flows for the inter peak period. The level of agreement is good, with the only potential problem being 9350 inbound and J396 outbound.

The comparison of moving observer journey times for the am peak are given in table 1. The observed journey times are from a moving observer study conducted in April and May 1992. The modelled journey times are from journeys by fixed route vehicles in the simulation network. Table 2 gives similar data for the inter-peak.

Journey times	Observed **mean**, (sd), n	Modelled **mean**, (sd), n	Journey times	Observed **mean**, (sd), n	Modelled **mean**, (sd), n
1→2	**542** (91) 6	**136** (2) 15	7→6	**64** (8) 6	**79** (2) 24
2→3	**195** (155) 6	**117** (24) 13	6→5	**75** (16) 6	**75** (12) 22
3→4	**194** (83) 6	**266** (112) 13	5→4	**80** (25) 6	**105** (14) 12
4→5	**126** (39) 12	**196** (36) 26	4→3	**49** (13) 12	**71** (17) 12
5→6	**58** (12) 12	**68** (7) 26	3→2	**80** (13) 12	**59** (4) 12
6→7	**99** (26) 12	**117** (22) 26	2→1	**81** (15) 12	**69** (2) 12
8→9	**257** (55) 6	**56** (20) 14	4→10	**119** (10) 6	**129** (6) 11
9→10	**442** (127) 6	**287** (65) 11	10→9	**120** (25) 6	**90** (11) 12
10→4	**400** (75) 6	**481** (144) 12	9→8	**94** (23) 6	**47** (6) 12

Table 1 : Observed vs modelled am car journey times (s)

Journey times	Observed **mean**, (sd), n	Modelled **mean**, (sd), n	Journey times	Observed **mean**, (sd), n	Modelled **mean**, (sd), n
1→2	**90** (11) 4	**72** (3) 15	7→6	**58** (10)	**83** (3) 24
2→3	**71** (7) 4	**79** (15) 14	6→5	**65** (16)	**85** (12) 23
3→4	**55** (23) 4	**96** (17) 15	5→4	**72** (11)	**109** (21) 12
4→5	**72** (12) 8	**64** (10) 30	4→3	**53** (9)	**80** (14) 13
5→6	**52** (4) 8	**66** (3) 28	3→2	**58** (14)	**64** (2) 13
6→7	**104** (37) 8	**109** (17) 30	2→1	**77** (8)	**70** (2) 12
8→9	**72** (16) 4	**75** (22) 15	4→10	**92** (20)	**124** (6) 11
9→10	**124** (10) 4	**70** (5) 15	10→9	**141** (27)	**90** (21) 11
10→4	**104** (16) 4	**138** (24) 15	9→8	**50** (3)	**61** (14) 11

Table 2 : Observed vs modelled inter peak car journey times (s)

The greatest level of disagreement occurs during the am peak period at the outer edges of the network.

Table 3 presents the results for bus journey times in the am peak period. The observed data were collected using number plate matching techniques over two days (D1 and D2). There is a large difference in the two observed journey times and frequencies for the 10→4 journey.

Bus journey times	Observed (D1) **mean**, (sd), n	Observed (D2) **mean**, (sd), n	Modelled **mean**, (sd), n
2→4	**441** (58) 25	**400** (52) 8	**420** (145) 22
4→7	**415** (72) 31	**310** (83) 32	**411** (33) 29
10→4	**466** (129) 23	**305** (72) 7	**453** (135) 13

Table 3 : Observed vs Modelled am Bus journey times (s)

Unfortunately no observed bus journey time information is available for the inter peak period. The modelled journey times are, however, presented in table 4. Both the journey times and the number of completed journeys, in relation to those scheduled, look reasonable.

Bus journey times	Observed (D1) **mean**, (sd), n	Observed (D2) **mean**, (sd), n	Modelled **mean**, (sd), n
2→4	N/A	N/A	**247** (30) 16
4→7	N/A	N/A	**377** (25) 25
8→4	N/A	N/A	**197** (11) 17

Table 4 : Observed vs Modelled inter peak Bus journey times (s)

5 CBA RESULTS

The cost benefit analysis results, relative to the base case of a TRANSYT base plan are given in figures 8 and 9.

The corresponding mean Cost Benefit and upper and lower limits are given in table A1 of appendix A. Table A2 of appendix A also lists the individual results. The codes used to denote each measure are given in section 2.

In the discussion which follows a *significant* result is one where the 95% confidence interval for the measure does not overlap with that of the TRANSYT base case. A difference without this qualification term is just an observation on the direction of movement.

Most of the individual measures produce a decrease in the operating cost of the network, although none of these decreases is significant. For those measures which produce an increase, the increase is significant. These measures are related to bus priority schemes, Guided Bus (GB), Zero Bus lane setback (ZB) and reduced Bus Setback (BS). This feature is carried through to the integrated measures, where those combined measures which involve any of these three measures have a significant increase in costs, with the exception of the reduced bus setback and reduced time at stops which produce an insignificant increase over the TRANSYT base case.

Table 5 ranks the top seven of the measures which gave the greatest reduction in costs, both in individual simulation runs and on average. In total 17 measures gave a reduction in the average cost; 16 gave a reduction for simulation run one; 15 for run two; 13 for run three and 16 for run four.

Run	1	2	3	4	5	6	7
Average	LC+CB	QS	LC+SVD	QS(I)+CB	QS+SVD	QS(I)+BP	TS+BP
1	QS(I)+CB	QS(I)	LC+SVD	CB	QS	LC+CB	TS
2	TS+BP	QS(I)+CB	LC+CB	QS+CB	QS	LC+SVD	BL
3	LC+CB	QS	QS+SVD	LC+SVD	TS+BP	QS(I)+CB	QS+CB
4	QS(I)+SVD	LC+CB	QS	LC+SVD	LC	BL	TS+BL

Table 5: Ranking for improvement in CBA for first seven measures on A64 am peak

The combined measure of a longer cycle time with coordination for buses ranks in the top seven in four of the above cases whilst in the fifth case it ranks number 8. A large number of the measures involve some form of differing queue storage plans (ie QS or QS(I)). The congestion measures which appear to be of benefit are either longer cycle times or differing queue storage. The bus priority measures which give benefit are coordination for buses, selective vehicle detection and reduced time at stop. No calming measures feature in this top seven.

In order to establish whether these features are significant and consistent across all the simulations a regression of the CBA figure on dummy variables indicating whether that particular measure was part of the package is appropriate. Regression of the cost variable on the measure indicator variables produces the following equation and associated t-ratios:

$$\begin{array}{l} CBA = 51178 + 7072\,GB + 5842\,BS + 3041\,ZB + 1465\,PC \\ \qquad\quad (302)\quad (14.70)\quad (12.14)\quad (6.32)\quad (3.35) \end{array} \qquad (1)$$

The explanatory power of this equation is high, with an R^2_{adj} figure of 93.7%. None of the coefficients associated with significant parameter estimates are negative.

Figure 9 presents the Cost Benefit results for the inter-peak. The corresponding mean Cost Benefit and upper and lower limits are given in table B1 of appendix B. Table B2 of appendix B also lists the individual results. The codes used to denote each measure are given in section 2.

The operation of the TRANSYT base plan appears to increase the cost of the network in comparison to the existing on-street plan. This surprising result may be due to the use of a 72 second cycle time in the TRANSYT plan, rather than the mixture of cycle times in the range 60 to 90 seconds which are used in the inter-peak on-street plan.

The reduced time at stop (TS), removal of bus laybys (BL) and bus pelican arrangement (BP) have, nevertheless, given a decrease in operating costs. However, none of the decreases are significant. The physical calming of side streets has also produced a reduction. This effect may be the result of traffic being moved off the side streets and onto the under capacity arterial roads where it can be more efficiently controlled.

The guided bus measure has produced a significant increase in operating costs, for much the same reasons as outlined in the morning peak period. Calmed offsets (CO) and platoon formation (PL) in Halton village have also produced significant increases in the operating cost. Those combined measures which use one or more of these three measures also produce a significant increase in operating costs.

Table 6 ranks the measures which gave the greatest reduction in costs, both in individual simulation runs and on average.

Run	1	2	3	4	5	6	7
Average	BP+TS	TS	BL	LGT	BP	PL	TS+SVD
1	BP+TS	BL	TS	LGT	BP	PC	TS+SVD
2	TS	BL	LGT	BP+TS	BP	PC	

3	BL	TS+SVD	TS	LGT	BP+TS		
4	BP+TS	TS	BP	BL	PC	LGT	TS+SVD

Table 6: Ranking for improvement in CBA for measures on A64 inter peak

Various bus priority measures appear consistently in this table, a feature found in the am peak results given above.

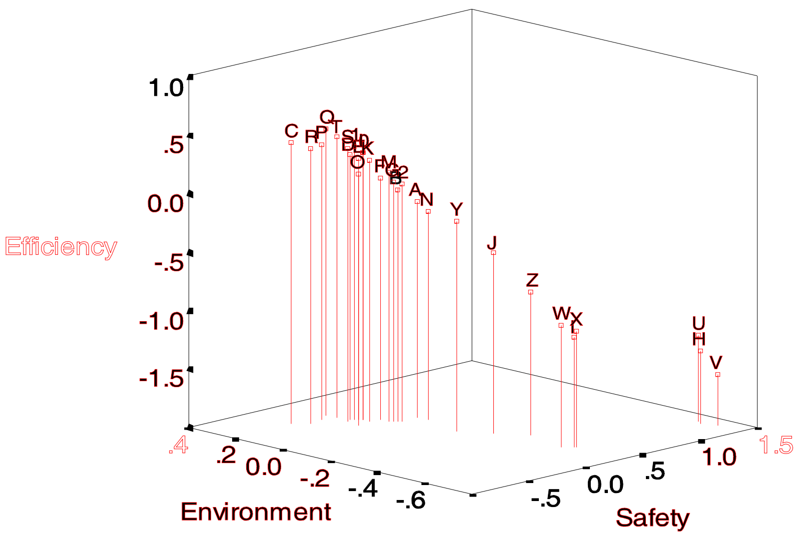
A regression equation for the CBA of the inter peak period is

$$CBA = 29694 + 3355\,GB + 1340\,CO + 1191\,PL \qquad £$$
$$(229) \quad (9.79) \quad (5.17) \quad (3.47)$$

The explanatory power of this equation is high, with an R^2_{adj} figure of 84.9%. None of the parameter estimates is negative which suggests that none of the measures produces a consistent, significant reduction in the operational cost of the arterial.

6 MCA RESULTS

A 3D scatter plot of each measure's score on the efficiency, environment and safety scales for the am peak produces figure 10. The plotted point for each measure is the centroid of the cluster of four points obtained from the four simulation runs. Detailed data are given in appendix A.
A64 am peak key:



A :LGT
B :TRA C :QS D :QS(I) E :LC F :CB
G :SVD H :GB I :ZB J :BS K :TS
L :BL M :BP N :BC O :QS+CB P :QS(I)+CB
Q :LC+CB R :QS+SVD S :QS(I)+SVD T :LC+SVD U :GB+TS
V :GB+PC W :ZB+TS X :ZB+PC Y :BS+TS Z :BS+PC
0 :TS+PL 1 :TS+BP 2 :BL+BP

There is evidence of a linear relationship between the three sets of scores. A high efficiency score is associated with a high environmental score but a low safety score. The small cluster to the bottom right of this plot is composed of guided bus (H), guided bus with reduced time at stops (U) and guided bus with physical calming (V).

Tables 7, 8 and 9 rank those seven measures which score highest on each of the individual scores. In total 16 measures gave a positive average efficiency score; 16 gave a positive score for simulation run one; 14 for run two; 16 for run three and 15 for run four.

Run	1	2	3	4	5	6	7
Average	LC+CB	QS	LC+SVD	QS(I)+CB	QS+SVD	QS(I)+SVD	TS+BL
1	LC+CB	TS+BP	QS(I)+CB	QS+SVD	QS	TS	LC+SVD
2	QS	LC	BL	QS+SVD	QS+CB	TS+BL	QS(I)
3	QS(I)+SVD	LC+SVD	LC+CB	TS+BP	BL	QS+SVD	BP
4	TS+BP	TS+BL	LC+SVD	LC+CB	QS(I)+SVD	QS(I)	QS

Table 7: Ranking for positive scores on efficiency for first seven measures on A64 am peak

In total 17 measures gave a positive average environment score; 14 gave a positive score for simulation run one; 15 for run two; 16 for run three and 14 for run four.

Run	1	2	3	4	5	6	7
Average	LC+CB	QS	QS+SVD	QS(I)+CB	LC+SVD	QS(I)	QS(I)+SVD
1	LC+CB	TS+BP	QS	QS+SVD	QS(I)+CB	LC+SVD	TS
2	LC	QS	QS+SVD	BL	QS+CB	QS(I)	TS+BL
3	QS(I)+SVD	LC+CB	LC+SVD	QS+SVD	QS(I)+CB	BP	BL
4	TS+BP	TS+BL	LC+SVD	QS(I)+CB	LC+CB	QS	QS(I)

Table 8: Ranking for positive scores on environment for first seven measures on A64 am peak

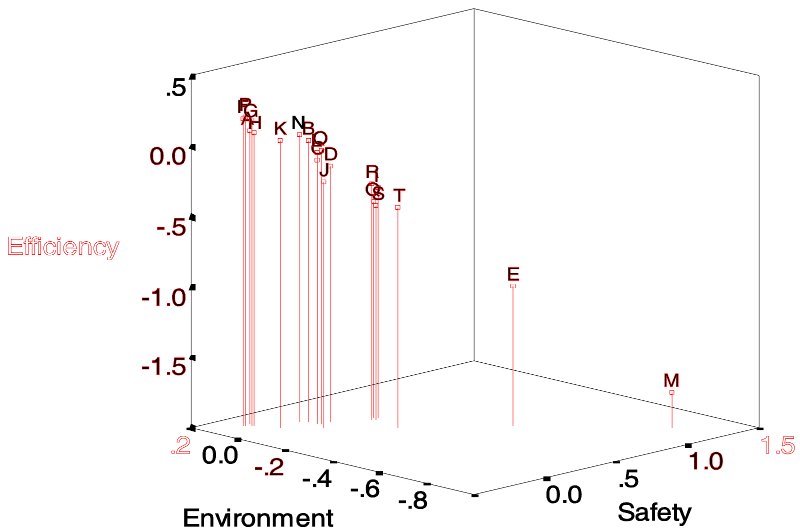
In total 12 measures gave a positive average safety score; 15 gave a positive score for simulation run one; 15 for run two; 12 for run three and 13 for run four.

Run	1	2	3	4	5	6	7
Average	GB+PC	GB+TS	GB	BS+PC	ZB+PC	ZB	ZB+TS
1	GB+PC	GB+TS	GB	BS+PC	ZB	ZB+PC	BS
2	GB+PC	GB	GB+TS	ZB+PC	ZB+TS	BS+PC	PC
3	GB	GB+PC	GB+TS	BS+PC	ZB	PC	ZB+TS
4	GB+TS	GB	GB+PC	ZB	ZB+TS	ZB+PC	BS+PC

Table 9: Ranking for positive scores on safety for first seven measures on A64 am peak

There is a large degree of agreement between those measures which appear in tables 7 and 8. The change in queue storage (with or without re-assignment), a longer cycle time and reduced time at stops feature near the top, either in their own right or as combinations. The results in table 9 confirm the CBA analysis, guided bus (as implemented), zero bus lane setback, reduced bus setback and physical calming of the side streets have good safety implications in that they reduce speeds, although the first three achieve this by creating congestion in the network.

Figure 11 shows the three dimensional MCA scatter plot for the inter-peak. The detailed data are given in appendix B.



A64 inter peak key:

```
A  :LGT
B  :TRA C  :CB          D  :SVD E  :GB          F  :TS
G  :BL          H  :BP          I  :CO          J  :PL          K  :PC
L  :CB+SVD      M  :GB+PC       N  :TS+SVD      O  :BL+TS       P  :BP+TS
Q  :CO+SVD      R  :CO+TS       S  :CO+BP       T  :PL+PC
```

Two measures immediately separate out, guided bus with physical calming (M) and guided bus (E).

Tables 10, 11 rank those measures which score highest on each of the efficiency and environment scores. Very few measures produced a positive safety score. Thus the ranking in table 12 is from most negative to zero and an optimal measure will feature in tables 10 and 11 but not 12.

Run	1	2	3	4	5	6	7
Average	BP+TS	TS	BL	LGT	BP	TS+SVD	PC
1	BL+TS	CB+SVD	PC	BL	LGT	TS	BP+TS
2	BL	TS	BP	LGT	TS+SVD	BP+TS	
3	BP+TS	BL	TS+SVD	LGT	BP	PC	TS
4	TS	BP+TS	BP	PC	BL	TS+SVD	

Table 10: Ranking for positive scores on efficiency for first seven measures on A64 inter peak

Run	1/8	2	3	4	5	6	7
Average	TS	LGT	BP+TS	BL	BP	PC	TS+SVD
1	TS/ CB	BP+TS	LGT	BL	BP	TS+SVD	PC
2	BL	TS	LGT	BP	BP+TS		
3	LGT	BP+TS	BP	BL	TS	PC	TS+SVD
4	TS/ SVD	BP+TS	BP	LGT	TS+SVD	BL	PC

Table 11: Ranking for positive scores on environment for first seven measures on A64 am peak

Run	1/8	2/9	3/10	4/11	5/12	6	7
Average	BP+TS	BL	BP	LGT	PC	TS+SVD	PL
1	BP+TS/ CB+SVD	TS	PC	LGT	BP	BL	BL+TS
2	LGT/ TS+SVD	BL	BP	BP+TS	TS	PL	PC
3	BL/ BL+TS	BP+TS/ PL	LGT	TS	BP	PC	TS+SVD
4	TS/ PL	BP/ SVD	BP+TS/ CB	PC/ BL+TS	BL/ TRA	LGT	TS+SVD

Table 12: Ranking for negative scores on safety for first seven measures on A64 am peak

These results reinforce the conclusions from the cost benefit analysis. The bus priority measures have performed well (with the exception of the guided bus implementation) for the efficiency and environment impacts. No congestion management measures were applied in the inter peak period. Once again those measures which perform well in safety terms perform badly in terms of efficiency and the environment.

7 CONCLUSIONS

In the morning peak, changes in queue storage, the removal of bus laybys, reduced dwell time at bus stops and longer cycle times all improve efficiency, as do their combination with certain bus priority measures. Conversely, the three measures which substantially increase bus priority (guided bus and reduced and zero setbacks) all significantly reduce efficiency, both on their own and in combination with traffic calming measures. In the inter-peak, only reduced dwell time at stops improves efficiency; guided bus and certain combinations with traffic calming worsen it.

The environmental impacts are similar in direction to the efficiency ones, but of smaller scale. In the morning peak, only changes in queue storage and a combination of longer cycle time and bus coordination achieve environmental improvements, while the substantial bus priority measures, on their own and in combination with physical calming and, surprisingly, reduced time at stops, increase the environmental impacts. In the inter-peak, no measures improve the environment, and only guided bus and physical calming worsen it. It should be stressed that these are aggregate environmental indicators. Those measures which divert traffic from side streets will improve the environment there, but at the expense of a greater increase in emissions on the main roads.

The safety impacts are to a large extent the mirror image of the efficiency ones. In the morning peak, the three substantial bus priority measures and their combination with physical calming improve safety, while queue relocation worsens it. In the inter-peak guided bus alone and with calming measures improves safety, as does the use of calmed offsets. Reduced time at stops and two of the minor bus priority measures worsen it.

Most measures have an impact in the time periods in which they are applied. The only ones which have a limited impact are selective vehicle detection, coordination of buses and the relocation of one bus layby. Although the conditions are very different, the performance of all measures is generally consistent between the morning and inter-peak periods.

These results are generally as would be expected. The congestion management measures improve efficiency, as do the more limited bus priority measures. However, their environmental impacts are small, and their safety effects adverse, since they will facilitate higher speed travel. The traffic calming measures have, to a limited extent, the reverse effect; while they will generate environmental improvements on side streets, these are more than offset by increased emissions on the main roads.

The most important results are those for the more substantial bus priorities. Removing the setback on the key bus lane reduces efficiency and worsens the environment, as might be expected, but improves safety because speeds are lower. Even a reduction in the length of the setback has a similar, though less pronounced, effect. The guided bus measure has an even greater adverse effect. It appears that the loss of capacity for general traffic at junctions has more than outweighed the benefits to buses. It may be, of course, that an alternative design would have been more successful, but this result does point to the difficulty of introducing guided bus into heavily congested corridors.

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Appendix A: Results for am peak

Measure	MEAN	STDS	95% LL	95% UL	Eff	Env	Safety
LGT	52923	494	52136	53709	-0.14	0.00	0.17
TRA	52140	539	51283	52997	0.00	0.00	0.00
QS	50307	772	49078	51536	0.41	0.21	-0.49
QS(I)	50896	584	49967	51826	0.27	0.12	-0.17
LC	51125	955	49606	52644	0.23	0.11	-0.11
CB	51753	831	50431	53074	0.07	0.06	-0.02
SVD	51902	821	50595	53209	0.06	0.01	-0.02
GB	58651	298	58177	59125	-1.37	-0.65	1.31
ZB	57676	221	57325	58027	-1.06	-0.60	0.30
BS	54602	620	53616	55588	-0.45	-0.31	0.20
TS	51088	423	50415	51761	0.24	0.07	-0.10
BL	50759	532	49912	51606	0.29	0.10	-0.09
BP	51738	776	50502	52973	0.13	0.02	-0.02
PC	53388	534	52538	54238	-0.22	-0.04	0.19
QS+CB	51453	984	49887	53019	0.16	0.05	-0.24
QS(I)+CB	50499	722	49351	51647	0.36	0.18	-0.29
LC+CB	50101	872	48714	51489	0.46	0.21	-0.18
QS+SVD	50628	636	49616	51640	0.35	0.18	-0.38
QS(I)+SVD	50637	1288	48589	52686	0.33	0.12	-0.19
LC+SVD	50368	563	49473	51263	0.40	0.17	-0.18
GB+TS	58191	931	56710	59673	-1.26	-0.63	1.34
GB+PC	59372	352	58812	59932	-1.55	-0.71	1.34
ZB+TS	57289	1516	54877	59701	-0.96	-0.56	0.27
ZB+PC	57560	1268	55543	59577	-1.00	-0.61	0.31
BS+TS	53312	542	52450	54175	-0.19	-0.21	0.09
BS+PC	56206	1045	54544	57869	-0.77	-0.40	0.35
TS+BL	50759	532	49912	51606	0.29	0.10	-0.09
TS+BP	50647	881	49245	52050	0.34	0.12	-0.13
BL+BP	51907	853	50549	53264	0.03	0.00	0.05

Table A1: Mean Cost Benefit (Ecu); standard deviation of CBA and mean MCA

Measure	CBA	Efficiency	Environment	Safety
LGT	52354	-0.09	-0.02	0.17
	52809	-0.05	0.07	0.21
	52977	0.00	0.01	0.05
	53550	-0.42	-0.08	0.24
TRA	51764	0.00	0.00	0.00
	52588	0.00	0.00	0.00
	51592	0.00	0.00	0.00
	52617	0.00	0.00	0.00
QS	49649	0.45	0.24	-0.52
	49630	0.65	0.31	-0.56
	50916	0.18	0.10	-0.36
	51033	0.39	0.18	-0.53
QS(I)	51447	0.26	0.14	-0.23
	50229	0.32	0.13	-0.26
	51322	0.10	0.06	-0.03
	50588	0.40	0.17	-0.17
LC	51265	0.33	0.13	-0.16
	49910	0.54	0.31	-0.22
	52237	-0.09	-0.06	-0.01
	51088	0.13	0.06	-0.07
CB	51934	-0.09	0.02	0.05
	51754	0.13	0.09	0.02
	52667	0.04	0.01	-0.09
	50656	0.18	0.13	-0.06
SVD	51591	0.00	-0.02	0.04
	51130	0.12	0.05	-0.05
	51836	0.21	0.04	-0.02
	53054	-0.07	-0.01	-0.04
GB	58528	-1.20	-0.70	0.98
	59078	-1.38	-0.61	1.35
	58392	-1.35	-0.63	1.51
	58607	-1.54	-0.67	1.39
ZB	57734	-1.13	-0.63	0.34
	57670	-0.95	-0.53	0.22
	57916	-1.01	-0.60	0.29

	57385	-1.14	-0.64	0.36
BS	53985	-0.48	-0.30	0.25
	55269	-0.44	-0.34	0.14
	54981	-0.45	-0.31	0.21
	54173	-0.43	-0.31	0.20
TS	50725	0.38	0.14	-0.13
	51035	0.09	0.04	-0.03
	50899	0.21	0.06	-0.10
	51693	0.27	0.05	-0.14
BL	50757	0.22	0.06	-0.05
	50007	0.49	0.24	-0.14
	51130	0.37	0.13	-0.19
	51142	0.08	-0.02	0.02
BP	51409	0.03	-0.01	0.04
	52729	-0.09	-0.11	0.08
	50907	0.35	0.15	-0.10
	51906	0.22	0.06	-0.11
PC	52887	-0.03	-0.02	0.18
	52966	-0.27	-0.03	0.27
	53884	-0.41	-0.11	0.24
	53814	-0.17	-0.02	0.07
QS+CB	51391	0.06	0.01	-0.32
	50981	0.39	0.16	-0.38
	52847	-0.11	-0.08	0.04
	50594	0.29	0.11	-0.29
QS(I)+CB	50507	0.50	0.21	-0.40
	51375	0.23	0.13	-0.09
	50506	0.30	0.16	-0.33
	49607	0.42	0.21	-0.34
LC+CB	49572	0.63	0.31	-0.22
	50968	0.16	0.04	-0.05
	49161	0.58	0.28	-0.22
	50705	0.45	0.20	-0.24
QS+SVD	49864	0.45	0.21	-0.49
	50346	0.48	0.25	-0.48
	51179	0.36	0.20	-0.47
	51124	0.10	0.06	-0.10

QS(I)+SVD	50751	0.27	0.06	-0.21
	51831	0.20	0.02	-0.09
	48826	0.81	0.35	-0.35
	51142	0.05	0.06	-0.09
LC+SVD	51050	0.37	0.16	-0.21
	50605	0.20	0.07	-0.07
	49856	0.58	0.25	-0.23
	49960	0.46	0.21	-0.22
GB+TS	58715	-1.10	-0.58	1.07
	56824	-0.84	-0.57	0.77
	58388	-1.34	-0.60	1.39
	58838	-1.79	-0.79	2.13
GB+PC	59719	-1.68	-0.78	1.18
	59348	-1.73	-0.81	1.48
	59526	-1.43	-0.61	1.40
	58895	-1.36	-0.61	1.29
ZB+TS	55086	-0.57	-0.46	0.22
	58427	-1.11	-0.60	0.31
	58119	-1.00	-0.57	0.23
	57524	-1.15	-0.62	0.33
ZB+PC	57581	-0.95	-0.58	0.29
	58935	-1.46	-0.78	0.46
	55874	-0.46	-0.43	0.15
	57850	-1.12	-0.64	0.33
BS+TS	52871	0.00	-0.11	0.08
	52823	-0.22	-0.20	0.07
	53863	-0.41	-0.33	0.18
	53692	-0.14	-0.19	0.01
BS+PC	56287	-0.87	-0.44	0.46
	54969	-0.45	-0.26	0.27
	56054	-0.85	-0.41	0.38
	57516	-0.89	-0.47	0.29
TS+BL	51142	0.08	-0.02	0.02
	51130	0.37	0.13	-0.19
	50757	0.22	0.06	-0.05
	50007	0.49	0.24	-0.14
TS+BP	50331	0.52	0.25	-0.27

	51960	-0.05	-0.10	0.04
	50228	0.39	0.07	-0.12
	50072	0.50	0.25	-0.16
BL+BP	51006	0.30	0.13	-0.04
	52970	-0.33	-0.16	0.21
	51487	0.25	0.10	-0.10
	52165	-0.10	-0.07	0.13

Table A2: Individual Cost Benefit (Ecu) and MCA

Appendix B: Results for inter peak

Measure	MEAN	STDS	95% LL	95% UL	Eff	Env	Safety
LGT	29467	149	29230	29705	0.09	0.10	-0.25
TRA	29766	244	29377	30154	0.00	0.00	0.00
CB	30149	301	29669	30628	-0.13	-0.02	0.02
SVD	30257	347	29704	30809	-0.17	-0.05	0.07
GB	32158	184	31865	32450	-1.00	-0.47	0.65
TS	29253	76	29132	29374	0.18	0.11	-0.28
BL	29270	160	29015	29525	0.17	0.08	-0.27
BP	29519	79	29393	29645	0.08	0.08	-0.25
CO	30907	270	30477	31338	-0.36	-0.11	0.30
PL	30613	201	30293	30933	-0.25	-0.09	-0.04
PC	29634	41	29568	29699	0.04	0.01	-0.18
CB+SVD	30052	328	29530	30573	-0.07	-0.03	0.00
GB+PC	33940	1372	31757	36123	-1.75	-0.82	1.19
TS+SVD	29725	304	29241	30209	0.05	0.01	-0.05
BL+TS	30001	204	29676	30327	-0.05	-0.05	0.00
BP+TS	29240	170	28969	29511	0.20	0.10	-0.28
CO+SVD	31105	297	30633	31578	-0.45	-0.11	0.27
CO+TS	30911	334	30380	31443	-0.32	-0.11	0.25
CO+BP	31215	222	30861	31568	-0.47	-0.13	0.26
PL+PC	31157	211	30821	31492	-0.43	-0.24	0.23

Table B1: Mean Cost Benefit (Ecu); standard deviation of CBA and mean MCA

Measure	CBA	Efficiency	Environment	Safety
LGT	29346	0.19	0.12	-0.24
	29656	0.07	0.09	-0.30
	29518	0.11	0.13	-0.26
	29350	0.00	0.06	-0.19
TRA	29405	0.00	0.00	0.00
	29828	0.00	0.00	0.00
	29927	0.00	0.00	0.00
	29903	0.00	0.00	0.00
CB	30029	-0.05	0.01	0.00
	30589	-0.20	-0.09	0.07
	29906	-0.23	-0.02	0.05
	30071	-0.05	0.00	-0.03
SVD	29969	-0.26	-0.08	0.16
	30222	-0.07	-0.06	0.11
	30754	-0.28	-0.07	0.04
	30082	-0.05	0.00	-0.04
GB	32053	-1.19	-0.52	0.94
	32209	-0.91	-0.48	0.60
	31977	-0.87	-0.40	0.53
	32392	-1.04	-0.47	0.54
TS	29159	0.25	0.13	-0.32
	29328	0.23	0.11	-0.21
	29299	0.05	0.05	-0.22
	29226	0.20	0.15	-0.38
BL	29307	0.18	0.08	-0.22
	29074	0.28	0.13	-0.27
	29460	0.18	0.08	-0.40
	29238	0.04	0.04	-0.19
BP	29484	-0.05	0.05	-0.23
	29623	0.13	0.08	-0.23
	29530	0.11	0.08	-0.22
	29438	0.12	0.10	-0.32
CO	30974	-0.54	-0.17	0.40

	30582	-0.15	-0.06	0.25
	31231	-0.46	-0.14	0.34
	30842	-0.29	-0.09	0.22
PL	30912	-0.50	-0.18	0.07
	30489	-0.18	-0.06	-0.13
	30500	-0.16	-0.10	-0.04
	30550	-0.18	-0.05	-0.05
PC	29630	0.09	0.02	-0.29
	29585	-0.06	-0.04	-0.08
	29634	0.06	0.04	-0.13
	29686	0.07	0.03	-0.22
CB+SVD	30043	0.00	-0.02	-0.06
	30186	-0.09	-0.01	0.01
	29604	-0.08	-0.01	0.03
	30373	-0.10	-0.06	0.03
GB+PC	35959	-2.56	-1.09	1.22
	33326	-1.61	-0.80	1.32
	33561	-1.57	-0.76	1.06
	32915	-1.25	-0.64	1.16
TS+SVD	29297	-0.01	0.04	0.01
	30005	0.05	-0.04	-0.05
	29750	0.12	0.01	-0.09
	29848	0.04	0.04	-0.06
BL+TS	29964	0.00	-0.01	-0.14
	30262	-0.11	-0.10	0.23
	29765	-0.07	-0.04	-0.07
	30015	-0.03	-0.04	0.00
BP+TS	29132	0.28	0.13	-0.38
	29387	0.02	0.03	-0.21
	29058	0.32	0.11	-0.27
	29383	0.17	0.11	-0.26
CO+SVD	30915	-0.36	-0.05	0.24
	31146	-0.38	-0.12	0.24
	31508	-0.75	-0.20	0.38

	30852	-0.30	-0.08	0.23
CO+TS	30417	-0.32	-0.11	0.28
	31154	-0.35	-0.10	0.12
	31035	-0.29	-0.10	0.23
	31040	-0.32	-0.13	0.35
CO+BP	31392	-0.48	-0.16	0.33
	30905	-0.35	-0.06	0.21
	31358	-0.66	-0.20	0.32
	31203	-0.41	-0.11	0.18
PL+PC	31398	-0.46	-0.26	0.16
	31256	-0.39	-0.24	0.28
	30926	-0.32	-0.18	0.21
	31048	-0.56	-0.26	0.27

Table B2: Individual Cost Benefit (Ecu) and MCA