

APPENDIX A: DESIGNING CORDONS

A-1 MOTIVATION

As a result of interest in the development of integrated transport strategies where policy instruments are combined to complement each other and to achieve improved performance against a set of policy objectives, May *et al* (2005) applied an optimisation procedure to identify optimal strategies for packages of urban transport improvements to achieve various policy objectives. One of the conclusions of this study was that well performing strategies for a given set of European cities tended to include peak period cordon charges to enter the city centre. These cordon charges charge traffic for crossing the boundary into the charged area and this boundary serves to separate the charging area from the rest of the network.

The performance of any road pricing cordon or boundary will be affected by the combined effects of a reduction in traffic entering the area and an increase in traffic bypassing it. While congestion will be reduced within the area, it might well be aggravated outside it. Since these conflicting impacts will depend on both the topology of the road network and the pattern of demand for its use, it is difficult to offer general advice on cordon location. All that is known is that the benefits of road pricing, usually measured in terms of welfare economic impacts, are critically dependent on the choice of cordon (May *et al*, 2002).

Yet it has been observed that there has actually been very little technical advice on the best location for such boundaries. Most designs are based on a mix of professional and political judgment, with little or no assessment of whether alternative locations would be more effective.

A-2 A GENETIC ALGORITHM BASED APPROACH

This section presents a computational method based on the concept of Genetic Algorithms (GA) for directly optimising the charging cordon design so as to maximise the scheme benefits. It summarises the method, named GA-AS, as developed in Sumalee (2004a).

The problem of cordon design is very complex, since it involves an interaction between the scheme design by the planner and the possible responses of travellers. The problem can be categorised as a Mathematical Program with Equilibrium Constraint (MPEC), which is one of the most challenging optimisation problems. In addition, the topological requirement for the charged links to form a closed cordon imposes further complexity. This combination precludes the application of a conventional gradient-based optimisation algorithm.

Instead, the concept of Genetic Algorithms (GA) has been adopted. The basic idea of the GA approach is to code the decision variables of the problem as a finite string, called a 'chromosome', and calculate the fitness (objective function value) of each string. Chromosomes with a high fitness level have a higher probability of survival. The surviving chromosomes then reproduce and form the chromosomes for the next generation through the 'crossover' and 'mutation' operators. The flowchart of the GAAS is shown in Figure A-1 below.

In this framework, the travellers' responses to the scheme have been calculated by SATURN (Van Vliet 1982), which is a steady-state equilibrium assignment model that predicts route choice and traffic flows on a road network, based on the generalised costs of travel, and takes account of delays due to capacity constraints. The output from SATURN gives the equilibrium flows, which can then be used to evaluate the performance of different scheme designs. The GA will act as a planner in this framework to improve the scheme designs so as to maximise a given objective.

For the optimal cordon problem, each chromosome in GA represents a uniform charge level for a specific charging cordon. Thus, to apply GA to the charging cordon design problem, we need to develop a chromosome scheme which represents a closed cordon and preserves its formation, even after the genetic operators (i.e. mutation and crossover) are applied.

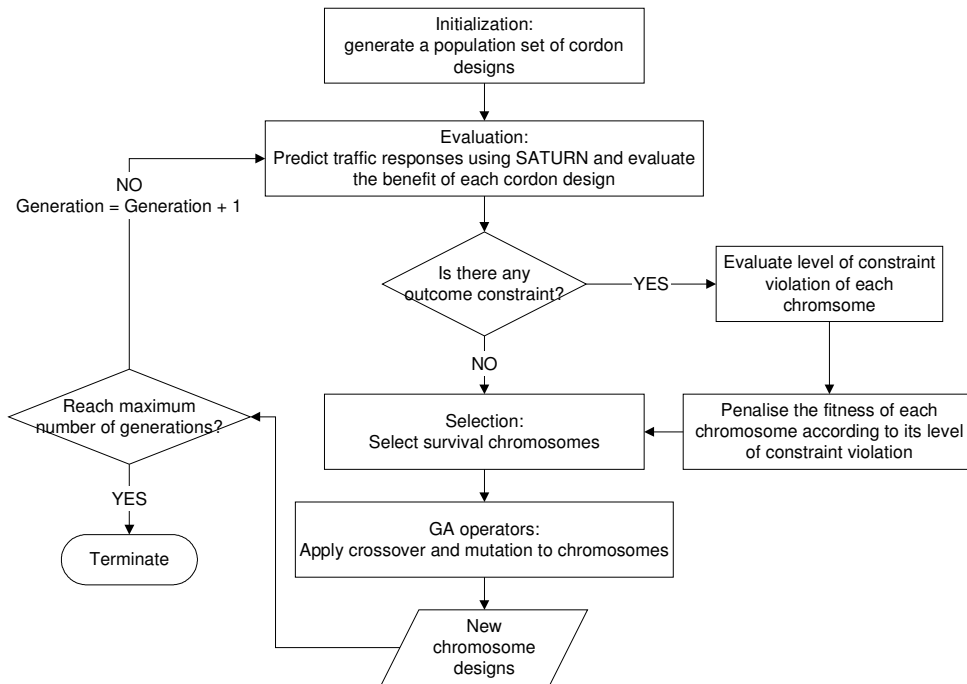


Figure A-1 Flow Chart of GA-AS

(Source Sumalee *et al* (2005))

Based on Sumalee (2004a), the concept of a “branch-tree” was used to encode a closed cordon into a chromosome format. The “branch-tree” is simply a mathematical representation of the links which form a closed cordon. The crossover operation is defined as an exchange between a valid pair of sub-branches from mated chromosomes which will automatically ensure the formation of a charging cordon for the new chromosome. The mutation is based on the branching in and branching out operations as applied to a branch-tree to reduce or widen the coverage of a particular part of that cordon.

The detail of the branch-tree structure and its associated crossover and mutation operators can be found in Sumalee (2004 a,b). This algorithm is also able to optimise the location of a double cordon scheme.

GA-AS can be extended to deal with outcome constraints (e.g. minimum desired revenue level or minimum reduction in total travel time) on the optimal cordon design problem. The mechanism used to handle the constraints is via a penalty function method which is a commonly used method to handle constraints in evolutionary computation methods. Thus the algorithm generates potential solutions without considering the constraints and then penalises those violating the constraints by decreasing the fitness of the chromosomes thereby reducing its chance of survival in the next generation (analogous to the survival of the fittest concept in Darwinian evolution theory). In this way, a constrained problem is transformed to an unconstrained problem by associating a scalar penalty with all constraint violations.

GA-AS was applied to a typical European city (Sumalee 2004a,b). In that study, where the objective was to maximise economic welfare, the benefits of the three judgemental cordons (Figure A-2) was compared with the optimal single cordon found by the GA-AS (Figure A-3).

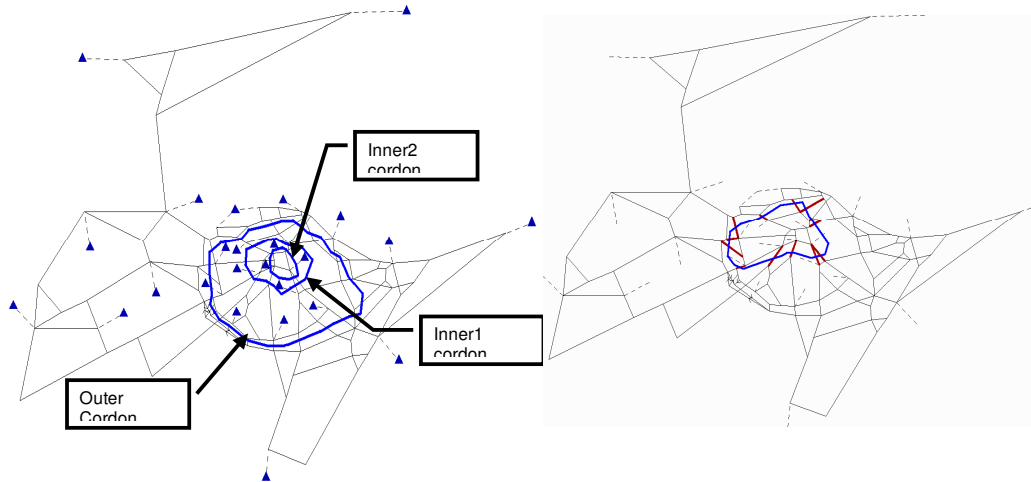


Figure A-2 Network with three Judgemental Cords **Figure A-3 Location of the Optimal Cordon OPC**

Table A-1 summarises the benefits found. Benefits are computed net of operating cost of toll points (assuming £100 per toll point per peak hour of operation). Figure A-3 shows the optimal single charging cordon (denoted as OPC) found by the GA-AS procedure. OPC is larger than the judgmental cordons and extends further to the west where congestion is more serious. The net benefit generated by OPC is £7.21k per peak hour which is 80% higher than the benefit produced by the Inner2 cordon and over three times the benefit of the other two judgmental cordons. This result clearly indicates the potential loss of scheme benefit by relying on professional judgment.

Table A-1 Comparison of the performance of different charging regimes for the test network

Charging regime	Optimal toll	No. of toll points	Gross Social welfare benefit (£k/hour)	Net Social welfare benefit (£k/hour)	% of benefit compared to OPC
Inner1 cordon	£0.50	9	3.00	2.10	-71%
Inner2 cordon	£0.75	7	4.69	3.99	-45%
Outer cordon	£0.75	20	3.96	1.96	-73%
OPC	£1.50	13	8.51	7.21	-
D-OPC	£1.25	38	19.08	15.28	+112%



Figure A-4 Location of the Optimal Double Cordons (D-OPC)

GA-AS was used in the fourth test to find an optimal double-cordon scheme (D-OPC) (Figure A-4). The benefit generated by D-OPC is £15.28k per peak hour which is more than double of the benefit from the OPC.

A-3 A “SHORT CUT” APPROACH

While the Genetic Algorithm approach described above has been shown to be capable of generating significantly improved cordon designs, it is analytically complex, and has yet to be tested on the road networks of other cities or with other models. The UK Department for Transport was interested in providing guidance to local authorities on road pricing design (DfT, 2008), and commissioned work on a short cut method which could be applied more rapidly on a wider range of network models. The aim of the short-cut approach was to improve on the judgmental designs by using some theoretical modelling whilst reducing the number of simulations required by the GA based approach. As such it was not designed to find an optimal closed cordon design but it was expected to improve performance over the judgmental approach.

Previous work on the GA approach had included as a benchmark the system optimal or “first best” solution whereby all links were tolled to give the system optimal or maximum welfare gain (Sheffi, 1985). The top-15 links are links that have the highest marginal cost as calculated via the “first best” system.

Table A-2 Relative performance of OPC and SLA cordons

Cordon	Optimal toll	Cost of operation per peak hour (£k)	Gross total benefit per peak hour (£k)	% of gross total benefit compared to first-best	Net benefit per peak hour (£k)	Flow crossing top 15 links	Proportion of total flow on top 15 links	Proportion of top 15 gross benefits
Top 15 links	Varied	1.50	19.46	52.3%	17.96	66759	100%	100%
OPC	£1.50	1.30	8.51	22.9%	7.21	34389	51.5%	43.7%
SLA-single	£0.75	1.60	7.94	21.3%	6.34	51278	76.7%	40.8%
First-best condition	NA	35.00*	37.19	100.0%	2.19*	ALL	100%	N/A

* notional figures based on 350 links being charged

Further investigations showed that the percentage of first best benefits achieved versus the number of links tolled at the system optimal level (added in order of decreasing charges) formed a curve as shown in Figure A-5. Similar curves were also found for networks of other British cities which have many more links and many more origin-destination pairs than the test network shown here. These curves proved useful in defining how many links (the top X links) should be used in the design process. The number of links used should be manageable whilst still achieving a significant proportion of the first best benefits. In general less than 10% of the links are required to achieve around 60-70% of the first best benefits.

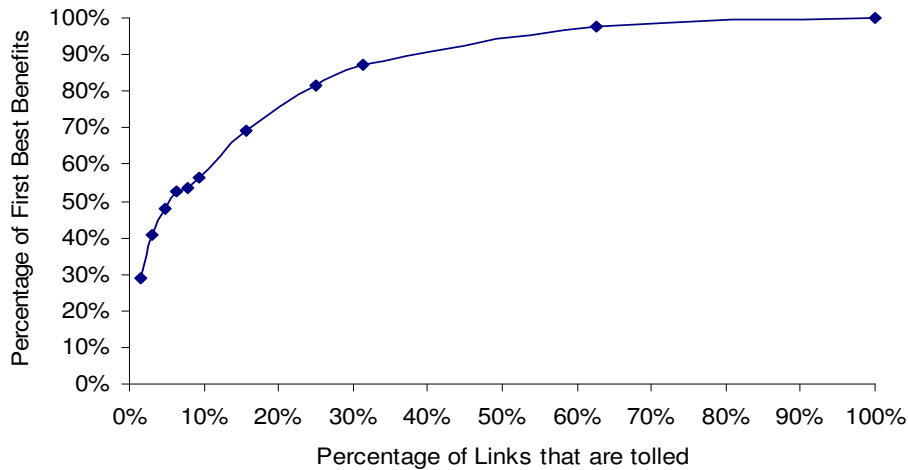


Figure A-5 Percentage of first best benefits versus percentage of links tolled

As these limited point charges on the highest charged links from the system optimum could out-perform the closed cordons it was thought that using these links may prove beneficial in designing a new closed cordon. Figure A-6 shows the position of these top 15 “highest tolled” links for the test network. As can be imagined it would be difficult to find a closed cordon which is not unduly complex which passes through all these links. However, it was realised that it was not essential to include the top links in the cordon; instead the cordon charge should be imposed on the principal path flows through these high cost links. The higher the proportion of high cost flows covered by the cordon the higher the potential benefits of that cordon location. This led to the idea of using a select link analysis to aid the cordon design process.

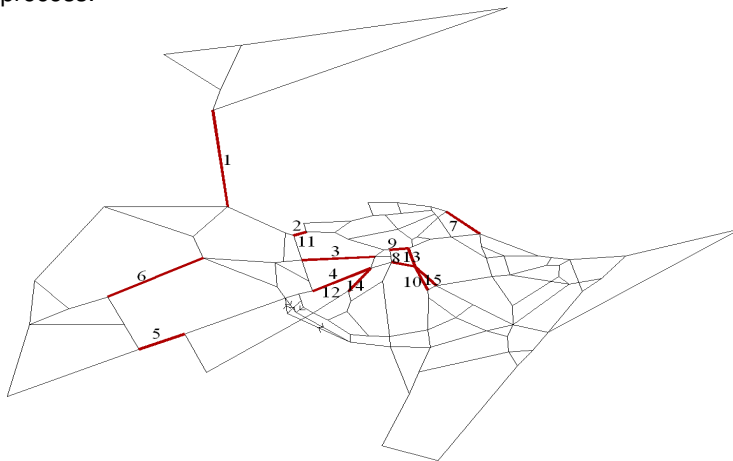


Figure A-6 Location of Top 15 with the Highest Marginal Cost (Numbered in Rank Order)

Select link analysis (SLA) is available in many commercial traffic assignment packages such as EMME/2 or TRANPLAN and is an easy to use option within SATURN. Basically select link analysis shows the paths used by all flows through a set of links. First a select link analysis is performed for the top X links (in this case 15 as shown in Figure A-7). Next the path information is used to aid in the design of a new cordon on screen, trying to capture as much of the flow from the SLA as possible. A further select link analysis is performed on the new cordon and this is cross-matched with the top X links to determine the proportion of flow covered. Cordons with a high proportion of flow covered are taken to the next stage which is to run the simulation for various charge levels to optimise the uniform charge around the cordon.

This heuristic process can be summarised as follows:-

1. Compute the system optimum and calculate first-best benefits.
2. Sort the system optimal charges in descending order and apply those charges using an increasing number of links, creating a graph of relative benefits versus number of links charged.
3. Use the graph from Step 2 to select a sub-set of Top X links and produce a visual output of these links.
4. Carry out a select link analysis with these links to show, using bandwidths, where the flows come from/go to through these top X links.
5. Draw a cordon or set of cordons either on-line or off-line which “catch” a high proportion of the flows from the top X links.
6. Optimise the charge level for the cordon by plotting benefits for a set of uniform charge levels.
7. Repeat 5-7 until a satisfactory cordon design is achieved.

An example of the single cordon produced by the above approach is shown in Figure A-8. As shown in Table A-2, this single SLA cordon achieved 21% of the first best gross benefits while the GA optimised single cordon OPC achieved 22% of the same benefits. Thus the method has delivered gains in welfare which are comparable to those produced by a much more time consuming and complex approach.

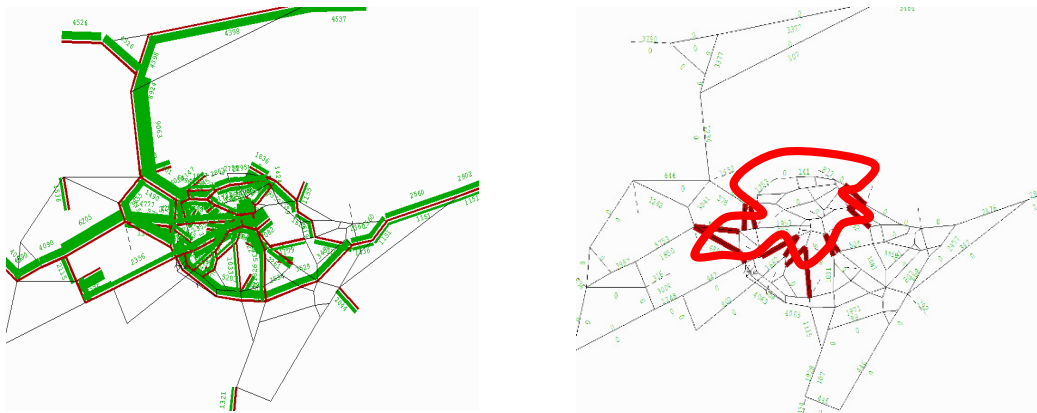


Figure A-7 Top 15 Links and Figure A-8 Single Cordon developed using Bandwidths from Select Link Analysis the Select Link Approach

More recent work for the UK Department for Transport (Shepherd *et al* 2006) has proven the method to be effective for much larger networks of other English cities. Some limitations were however found to arise from the differing ways in which buffer networks had been specified. Improved approaches are currently being developed. As well as reducing analysis time, the SLA approach has the advantage over the GA optimisation approach of involving the planner directly in drawing potential cordons, thus enabling local knowledge to be applied.