A METHOD FOR THE DESIGN OF OPTIMAL TRANSPORT STRATEGIES

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Abstract

This paper is concerned with the design of optimal transport strategies. The aim of the research is to identify the best ways of achieving multi-modal integration and to determine the roles of public transport provision and demand management. In this paper, we present a methodology for the optimisation of integrated transport strategies and show the results of case studies for six UK cities: Leeds, Edinburgh, Dundee, Bristol, Exeter, and Preston, with an emphasis on the analysis for the city of Edinburgh. In the optimisation method presented, the objectives of the strategies are quantified by an objective function consisting of a set of indicators that measure a strategy's performance. At the heart of the optimisation is a strategic transport model which evaluates a transport strategy over a 30-year period. The levels of the policy measures in a strategy, such as public transport fares and frequency, and road charges, are adjusted such that the objective function is optimised. Two different types of analysis are performed: sensitivity tests around individual area-wide policies to identify optimal values of individual policies, and the optimisation of packages of transport policies. The effects of spatial variations of the public transport policies are also investigated.

Keywords: Transport strategy; Optimisation
Topic area: H10 Urban Transport Policy

1 Introduction

The UK 1998 Transport White Paper advocated the use of integrated transport strategies, including transport infrastructure, management and pricing measures as well as land use interventions, as ways of achieving the Government's objectives in urban areas (DETR, 1998). That approach was subsequently reinforced in the Government's guidance on the Local Transport Plans (and their equivalents) which all local authorities outside London submitted in 2000 (DETR, 1999) and in the revised version of Planning Policy Guidance 13: Transport (DETR, 2001).

Among the key issues in the concept of integrated transport strategies are the need to understand how best to combine the wide range of different policy instruments; how to identify the optimal combinations of them, given that most can vary substantially in the ways in which they are implemented; how to reflect constraints of finance, institutional responsibilities, technology and public acceptability in their design; how to develop implementation sequences which enhance their performance; and how far it is possible to transfer strategy specifications from one city to another.

These issues have been addressed in a number of previous publications where there have been significant advances in understanding the design of optimal transport strategies. In initial research a regression-based methodology was developed for determining the optimal combination of policy instruments, using the predictions from a conventional transport model (Fowkes *et al.*, 1998). The method was subsequently applied to nine

European cities, each with its own model, and some conclusions were drawn about the relative merits of different policy instruments (May *et al*., 2000).

The methodology presented here is a further development where we incorporate, in addition to the transport system, the development in land use over time. For this purpose, we use "time-marching" or dynamic land use / transport models which run the transport and land-use sub-models alternately to simulate the future developments of cities over a 30-year period. Thus the models can provide information about the impacts of transport strategies. This information is then used to assess the transport strategies against city-specific objectives within an appraisal framework. An automated optimisation process is used to identify an optimal policy package.

The work reported here was conducted under a UK EPSRC research project. In Stage 1 of the project we have developed two approaches to rank, and therefore optimise, the transport strategies. The first is based on the modified Cost Benefit Analysis (CBA) approach as developed by Minken *et al*. (2003), the second is the Indicator / Target (I/T) approach based on the level of goal achievement in a set of targets specified for objective indicators. The CBA-based approach and the I/T optimisation approach have been implemented in Stage 1 of the project and the results have been reported elsewhere (Emberger *et al*., 2003). Further work carried out in Stage 1 includes the study of temporal and spatial variations in policy instruments.

For case studies the method has been used in eight cities, employing three different land use / transport models: START/DELTA (Simmonds, 1999), Metropolitan Activity Relocation Simulator (MARS) (Pfaffenbichler, 2003; Pfaffenbichler and Shepherd, 2003), and Transport Policy Model (TPM) (TRL, 2001), all operating at different levels of detail.

In this paper, we present the methodology for the optimisation of integrated transport strategies and show the case studies' results for six UK cities: Leeds, Edinburgh, Dundee, Bristol, Exeter, and Preston, with an emphasis on the analysis for the city of Edinburgh. We shall report only the TPM results, and we shall concentrate on the CBA optimisation approach, though we shall present the values of I/T objective function values that result from this CBA optimisation, and discuss them where appropriate. Two different types of analysis are performed: sensitivity tests around individual area-wide policies to identify optimal values of individual policies, and the optimisation of packages of transport policies, including Public Transport (PT) fares and frequency policies, and central-area cordon charges. The effects of spatial variations of the PT policies are also investigated.

The next section describes the methodology for the integrated transport approach. Section 3 describes the land use / transport model TPM for the six cities. The sensitivity analysis and the optimisation results are discussed in sections 4 and 5, respectively. Finally, section 6 draws conclusions.

2 Methodology for the design of optimal transport strategies

2.1 The integrated approach for transport strategies

The integrated approach is designed to help city authorities to identify their city-specific optimal land use and transport strategies to meet their future needs and targets. The concept is to connect a state-of-the-art transport policy appraisal framework with a dynamic land use and transport interaction model and an automated multidimensional optimisation technique. This approach enables city authorities in collaboration with transport planners to simulate future developments of cities and regions and provide guidance for the implementation of optimal transport and land use policy packages.

The optimisation process needs to be preceded by a series of initial setup steps. The setup process involves a series of initial preparations in close collaboration with the cities. Firstly, we have to identify the objectives and targets of the cities. Then we look for an agreement on a city-specific appraisal of impacts and realise this through a translation of their objectives into a so-called objective function. Then we define a set of policy instruments and their city-specific ranges. In the next step we define city-specific scenarios concerning their objectives, growth rates, economic development and so on. Based on that information we are able to set up the land use / transport model for the city. This model includes all city-specific information, such as the zoning system, inhabitants, workplaces, and housing.

The land-use / transport model is the core the optimisation method. It evaluates the impacts of a transport strategy over a 30-year period. The model takes as input the changes in transport policies along with all the transport demand and supply data and the socio-economic data, and produces as outputs information on changes in the objective indicators, such as travel demand, traffic volume, road speeds, traffic accidents, noise and emissions, and so on. These are fed into the appraisal framework to generate the objective function. The land use / transport model TPM is described in detail in section 3.

Figure 1 shows how the different parts in the methodology are woven together and depicts at the same time the requirements of the integrated approach. Once the setup is complete the optimisation process can begin, which is expressed by the loop of arrows in the figure. Starting with an initial set of transport policies, the loop “Land use / transport model → Appraisal of strategy → Objective function → New policies” is performed until the objective function cannot be improved by adjusting the policies in the policy package or the strategy.

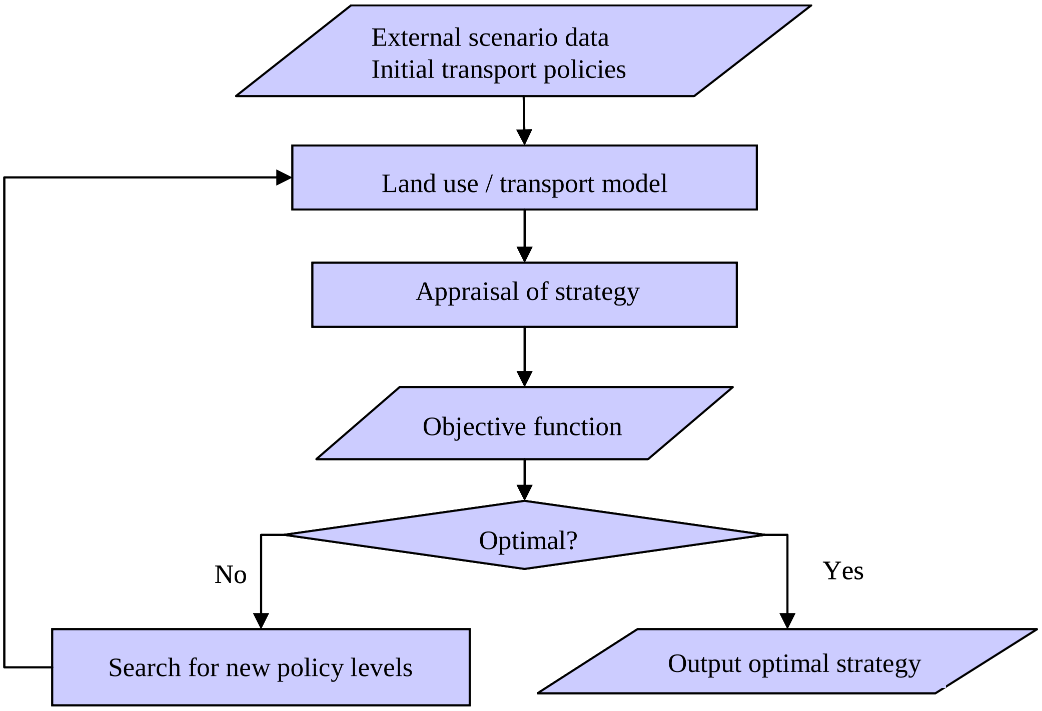


Figure 1: The integrated approach for transport strategies

2.2 The appraisal framework

To be able to identify the optimal transport strategies, a set of objectives against which the different strategies are appraised had to be defined. The objectives of all the cities are based on suggestions made in the UK Government's White Paper on the Future of Transport (DETR, 1998). Based on this, we agreed with our partner cities to use sustainability as an overarching objective, and formed six underlying policy objectives:

- economic efficiency

- liveable streets and neighbourhoods
- protection of the environment
- equity and social inclusion
- safety and severity of traffic accidents
- contribution to economic growth.

The objectives as they are set out above are abstract concepts; it is difficult to measure the performance of a strategy against them. Therefore, we convert the six objectives into an objective function (*OF*). The *OF* ranks all possible policy combinations in respect of their contribution to the overall objective of sustainability and is used as the criterion for the optimisation process.

Traditionally, transport strategies are assessed using a cost benefit analysis. However, the local authorities have more recently moved to a target-based approach partly in response to national guidelines for monitoring impacts and partly due to the lack of available monetary values for some of the indicators proposed in the New Approach To Appraisal (NATA) (DETR, 2000). Thus, in addition to the CBA approach, we have also developed an alternative, namely, the Indicator / Target (I/T) approach which is based on goal achievement with respect to targets for indicators which reflect the policy objectives stated above. The CBA-based approach and the I/T-based approach are outlined in turn below.

The objective function used in the CBA approach is based on former research work carried out in an EC project, PROSPECTS, (May *et al*., 2003). The *OF* consists of an economic efficiency term, a carbon dioxide (CO_2) costs term and a term for monetarised values for local pollution and accidents. All these costs / benefits are discounted over a 30-year evaluation period. The economic efficiency term incorporates both transport user benefits and the operator / provider benefits. The user benefits for the households are calculated using the "rule of a half" or logsum formulas and including time and money savings from changes in land use and transport (Minken *et al*., 2003). The operator / provider benefits are derived by annual revenue minus cost including operating and capital costs as well as taxes for all firms, operators and entrepreneurs.

In the I/T approach, we use indicators as ways of quantifying objectives or sub-objectives. In the Local Transport Plans a large number of different indicators are presented to assess the implemented strategies. Such a large number of indicators cannot be used for an appraisal of policy strategies for several reasons. One problem is that if too many indicators are used, an information overload for decision makers occurs, and a single indicator has only a minor weight in the overall appraisal framework. Another problem is the issue of double counting. For example, changes in modal split figures contribute to more than one of the objectives mentioned above.

To avoid these problems we decided to use only outcome indicators (indicators measuring part of the outcome of a strategy) and match them against our objectives. Five indicators were selected: transport access, accidents, travel time, noise, and emissions. These indicators cover all objectives except for the objective “contribution to economic growth”. In addition, we added a CO_2 emissions indicator to take into consideration the overall objective of sustainability and the reduction of global warming.

The indicator / target-based approach compares the different transport policy packages in terms of their potential “goal achievement”. Therefore it is necessary to set targets for all of the indicators that have been chosen. These targets stem either from existing Local Transport Plans, or from nationwide targets (*e.g.*, DETR, 2000a) or were set by expert judgement to demonstrate the approach. A target for an indicator is expressed in terms of the relative changes in the indicator. The goal achievement is defined as the ratio of relative changes in an indicator from the implementation of the strategy over the target for the indicator, and is set as 1.0 if the target is fully achieved. The objective function is a weighted sum of the goal achievement and thus has a maximum value of 5.0.

2.3 The optimisation routine

An integrated transport strategy consists of a package of transport / land use policy instruments, which comprises the choice of policy instruments themselves, the level or the intensity of each policy – which may be specified by time of day – and the time-scale of implementation over the 30-year appraisal period. Here, we shall consider only transport policies in the optimisations, including changes in public transport fares and frequency, and the introduction of cordon charging. Note that there are also other possible policy levers, such as parking charge policy, and fuel duty policy, though they were not selected for optimisations. The levels of these policies are fixed at their do-minimum value in the optimisations.

In searching for the optimal transport package, each of the policy instruments in the package could, in principle, be varied in each year of the 30-year appraisal period. If this was permitted, the number of variables in the optimisation problem would have been too large for efficient optimisation. Suppose there are n policy instruments in a package. Then the policy space in which the optimal is sought would be $30n$-dimensional.

In order to make the optimisation problem manageable, we adjust the values of the policy instruments only in two of the 30 years: a short term year 2006 and a long term year 2016, given a base-year of 2001. In other words, the search for the optimal policies is performed with respect to the policy levels in the two years. The policy levels of each policy instrument for all other years are determined by a specifying a time profile over the 30 years, given the levels of the policy in the short-term and long-term years. It is assumed that all policy instruments were at the do-minimum level from 2001 to 2005. Between 2006 and 2016, the policy instrument values are changed linearly between their values in those two years. From 2016 to 2030, all policy instruments are held at their 2016 levels.

Having selected the policy instruments and the time profile over the 30-year period, the remaining problem is to find the levels of the different policies that lead to the maximal objective function.

3 The land use / transport model TPM for the six UK cities

TPM is a multi-modal strategic transport model developed at TRL for forecasting the impact of transport policies, individually or in combination, at a town or city-wide level, taking into account changes in socio-economic conditions. It involves trip generation, trip distribution and modal split processes. Road capacity constraint is modelled through the use of area-wide speed-flow relationships. For bus and rail, capacity restraint is modelled through the use of overcrowding models. An equilibrium between demand and supply is sought in the model. TPM is spatially highly aggregate, with three zones, one representing the city centre, one the rest of the city and one for external areas. On the other hand, TPM can model up to eight modes of travel, eight journey purposes, three car-ownership household categories, and two times of day. Generalised cost elements modelled in TPM include time costs (access, egress, waiting time and in-vehicle time) and money elements (public transport fares, central area parking costs and cordon charges). For more detail see TRL(2001). For the work presented in this paper, the land use changes over time are exogenous inputs to TPM; they are not responsive to changes in transport costs and accessibilities in the model. The changes in population and car-ownership over the 30 years are taken from the UK multi-modal transport studies database TEMPRO. A land use model will be developed and integrated into TPM so that the impacts of interactions between transport and land use can be modelled.

As mentioned above, TPM models an urban area using a system of three zones: an inner zone representing the central area, an outer annular zone representing the surrounding built-up area, and an external zone that may be the origin of trips into the other two zones, or the destination of trips from them. The inner zone is defined as that spatial area which is ‘controllable’ by the local authority, typically in terms of parking policy and charges, and where a cordon can be readily defined. The outer zone encompasses the remainder of the built-up area or conurbation. The exact location of the boundary is clearly open to interpretation, but it should include the area generally accepted to be part of the structure of the town or city. The external zone represents the catchment area of the majority of commuters travelling to or from the inner or outer zone. TPM performs detailed calculations of the movements between and within the inner and outer zones; trips originating from the external zone and destinating in the external zone, or vice versa, are not modelled. Note that the external zone can be very large and can have a larger population compared with the inner and the outer zones. The number of trips generated from and attracted to the external zone depends not only on population but also on trip generation rates which are lower in the external zones (because only trips from and to the external zone that interact with those of that the inner and outer zones are included).

In TPM the base year is 2001 for each of the six cities. The 30-year period over which the objective functions are evaluated therefore runs from 2001 to 2031. Table 1 provides some basic information used in the model to describe the cities and modelled areas, including the size of the study areas, population, car-ownership, and modal splits in the base year. Note that TPM includes only slow mode trips that are substitutable by other modes rather than all slow mode trips.

Table 1: Overview of the data used for each of the cities in the case studies

Data	**Zone**	**Bristol**	**Dundee**	**Edinburgh**	**Exeter**	**Leeds**	**Preston**
Area (km^2)	Inner	5.31	1.54	28.27	3.14	11.46	3.14
	Outer	221.67	77.00	351.86	60.48	215.52	60.48
Population (thousands)	Inner	5.116	0.495	58.000	4.071	31.609	6.119
	Outer	543.227	145.050	393.500	108.094	561.684	139.634
	External	424.452	435.464	2288.400	100.417	1529.924	2919.466
	Total	**972.795**	**581.009**	**2739.900**	**212.582**	**2123.217**	**3065.219**
Cars per head	Inner	0.431	0.276	0.414	0.337	0.257	0.202
	Outer	0.414	0.308	0.373	0.407	0.374	0.367
	External	0.436	0.417	0.335	0.484	0.409	0.422
Mode split (%)	**Modes**	**Bristol**	**Dundee**	**Edinburgh**	**Exeter**	**Leeds**	**Preston**
	Car	71.63	62.09	51.64	73.55	64.61	74.67
	Motorcycle	1.35	0.00	0.00	0.00	0.00	0.00
	Bus	9.53	14.80	34.68	5.53	20.60	12.05
	Rail	2.20	1.08	1.62	0.00	2.11	1.69
	Taxi	1.50	0.00	0.00	0.00	0.00	0.00
	Cycle	2.16	2.46	1.18	1.04	0.47	3.21
	Walk	11.63	19.56	10.88	19.87	12.21	8.37

4 The optimal individual policies

Optimal values of each individual policy are identified by a one-dimensional search scheme or a sensitivity test. Sensitivity tests were performed around individual area-wide policies, and for each of the six cities. The tests generate a large amount of information. Therefore, we shall draw some general conclusions from all cities' results, and discuss the results in detail only for the City of Edinburgh.

4.1 Sensitivity test method

Sensitivity tests are performed by varying a single policy instrument at a time, by a certain step size and within a reasonable range, while all other policy instruments have their values fixed at zero (thus they are kept constant at the base year values). The values of the policy that is being altered are set to be equal at both the implementation year (2006) and the "long run year" (2016), leading to a flat instrument profile from 2006 to the threshold year of 2031. This procedure is carried out for each of the different policy instruments in turn. The ranges over which individual policies are altered are as follows.

(1) Area-wide PT fares in AM peak and Inter-Peak (IP) are varied within the range [0%, –50%] in steps of 15%.

(2) Area-wide PT frequencies in AM peak and IP are varied within the range [0%, 200%] in steps of 20%.

(3) A central area cordon charge is varied within the range [0p, 500p] in steps of 50p.

4.2 General conclusions for all cities

The optimal individual policies for the six cities are listed in Table 2. The following conclusions can be drawn from the sensitivity tests for all cities.

(1) As PT fares are reduced, the value of OF_{CBA} increases. The optimal values of fare reductions for all cities are achieved at the boundary of the fare policy range tested. Note that the optimal values are -45% simply because the incremental step is 15%. Further tests outside the test range specified show that an optimal value of fare reduction must eventually be reached – beyond this optimal point, buses will be entirely filled with passengers and a fares policy alone cannot improve the OF_{CBA} without the additional introduction of frequency increases.

(2) A reduction in PT fares or an increase in PT frequencies in the AM peak produces much larger values of the CBA objective function, OF_{CBA}, than in the IP period because there are normally larger numbers of car trips in the AM peak than in the IP, and thus there are greater benefits to be gained by PT operators for a given percentage of mode shift by car users onto public transport.

(3) There exist optimal values for the frequency policy within the range tested. The optimal values are different for different cities. It seems that the optimal value of the frequency policy depends on the specific value of the base year number of bus-kms. The larger the base year value of bus-kms, the more expensive it would be to increase the PT frequency by a fixed factor. Therefore, the optimal frequency changes tend to be smaller in such large bus-km cases.

(4) There exist optimal cordon charges within the range tested. The optimal value depends on the congestion level in the central area. A cordon charge is effective only when the road is congested in the do-minimum case. In Exeter, the roads in the central area are not congested in the base case, and so introducing a cordon charge leads to negative OF_{CBA} values.

Table 2: Optimal individual policies for six UK cities

City	Fares AM	Fares IP	Frequency AM	Frequency IP	Cordon Charge
Bristol	-45%	-45%	40%	20%	250p
Dundee	-45%	-45%	60%	40%	150p
Edinburgh	-45%	-45%	140%	80%	350p
Exeter	-45%	-45%	80%	60%	100p
Leeds	-45%	-45%	200%	140%	300p
Preston	-45%	-45%	100%	0%	200p

4.3 Detailed sensitivity test analysis for Edinburgh

Detailed sensitivity test results for Edinburgh are summarised in Table 3 and Figure 2. Table 3 shows the optimal individual policy values together with the economic impacts, while Figure 2 shows the traffic impacts. In Table 3, in each column, the policy value for which results are presented is the optimal point for that particular instrument within the range over which it was tested. This optimal point is either at the boundary (or, more precisely, at the closest point to the boundary that was tested) or in the interior of the test range. The following conclusions may be drawn from Table 3 on the economic impacts of individual policies.

(1) When PT fares are reduced, car users' journey time is reduced because of a shift of car users to public transport and the accompanying reduction in overall road traffic. Thus we see positive private transport time savings. However, PT users' (perceived) journey time is increased due to overcrowding effects on PT modes. Hence, there are negative PT mode time savings. For bus users, reducing fares has two effects: it increases bus running speed due to congestion relief and it also increases bus occupancies and crowding, which, in turn, means an increase in passengers' perceived travel times. For the levels of fares reduction shown here, the overcrowding effects are dominant and bus users incur increased time costs. Further examination of the test results has shown that when the fares reduction is smaller, increase in bus running speed dominates, and bus users' time cost is reduced.

(2) As the PT frequency increases, journey times for both car users and PT users are reduced. Also, the PT operator gains an increased revenue, though incurs the cost of capital investments and increased operating costs. When applied individually and within the ranges tested, increasing the frequency during the AM peak is the most effective policy because it gives the highest *OF* value.

(3) With the introduction of a road charging policy, car users' journey time is reduced significantly but they have to pay highly for the benefits that they receive. For Leeds, a cordon charge increases PT users' time costs due to crowding while in Edinburgh a cordon charge reduces PT users' time costs due to congestion relief. See point (1) for explanations.

(4) Of all the singly-applied instruments, only cordon charge alone can generate a positive Present Value of Finance (*PVF*).

(5) When applied alone, none of the policy instruments could meet all the targets of the I/T objectives because the values of the I/T objective function, $OF_{I/T}$, are all smaller than 5.0.

Figures 2a-2d show the traffic impacts of the optimal individual policies for each policy instrument in terms of relative changes in number of trips, PCU-km, road speed, and bus occupancy. The traffic impacts that are shown are those for the year 2010. The optimal individual policy values can be found in Table 3.

The traffic impacts of each individual policy depend mainly on whether it can reduce car trips. Any policy instrument that can reduce car trips also reduces car person-kms, car vehicle-kms, and the total PCU-kms, and leads to an increase in average road speeds through a reduction in congestion. Note that the PT fares policy is applied to both bus and rail travel while the PT frequency policy is applied to buses only. As a result, a reduction in fares would increase both bus trips and rail trips while an increase in frequency would attract more trips to bus only (from rail as well as from other modes). A few more points can be drawn from the test results:

(1)PT fares and frequency policies in the AM peak have little effect on traffic in the IP, and vice versa.

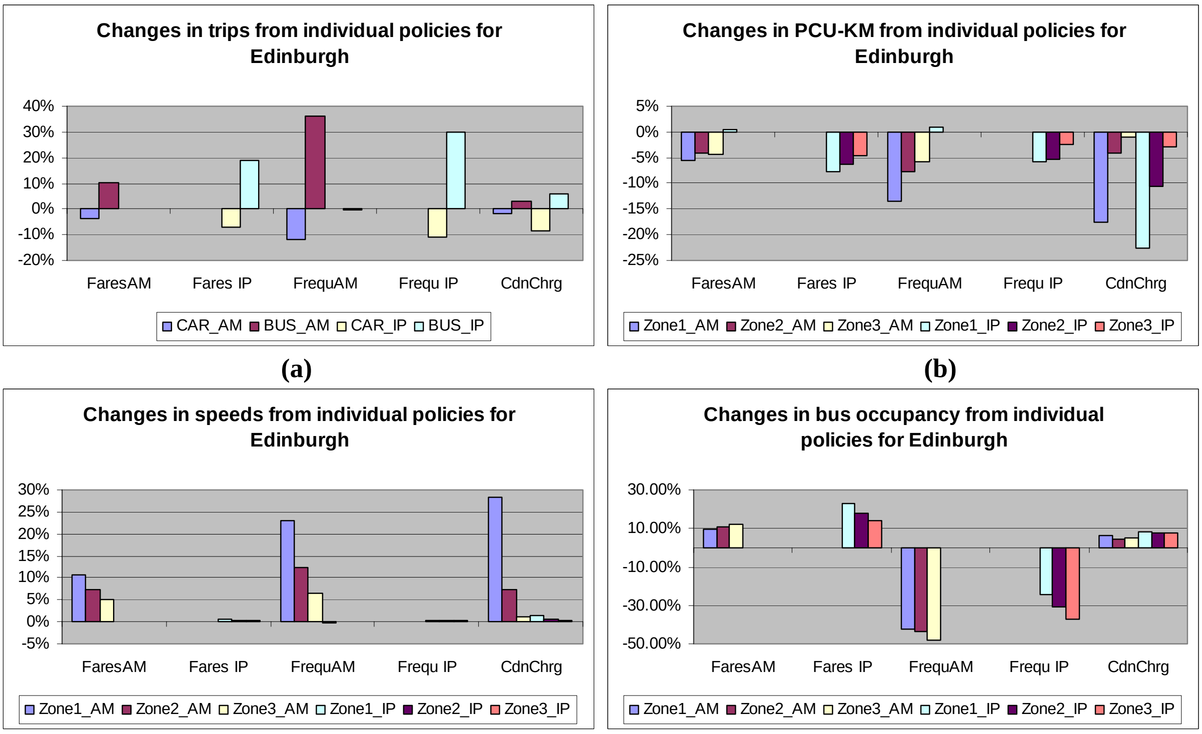
(2)The responses of relative changes in the number of bus trips to changes in bus fares are stronger in the IP than in the AM peak. This is expected because in the AM peak a relatively large proportion of car trips are work trips which are less sensitive to costs and are less likely to shift from car to buses. For the same reason, the responses of relative changes in the number of car trips to the introduction of a cordon charge are larger in the IP than in the AM peak.

(3)All of the optimal values of the individual policies reduce car trips and increase bus trips (Figure 3a). This has the effect of reducing the total PCU-kms (through the reduction of car traffic) and increasing the average road speed (Figures 3b-3c).

(4)In Figure 3d it is seen that policies of reducing fares and introducing a cordon charge both lead to increases in bus occupancies, but increasing the frequency of buses has the opposite effect. Although increasing bus frequencies can increase bus patronage and hence bus occupancies, beyond a certain level these frequency increases will lead to buses becoming less full.

Table 3: Economic benefits of individual policies for Edinburgh (£m) for policies obtained from sensitivity analysis

Policy instruments	**Fares AM**	**Fares IP**	**Frequency AM**	**Frequency IP**	**Cordon Charge**
Optimal policy values	**–45%**	**–45%**	**140%**	**80%**	**350p**
User benefits					
Money savings					
Private transport modes	55	1	117	1	-857
Public transport modes	298	172	0	0	0
Time savings					
Private transport modes	280	3	486	2	472
Public transport modes	-21	-28	645	207	41
Total user benefits	612	148	1248	210	-343
Operators' benefits					
PT operator	-272	-122	-314	-122	73
Parking operator	-60	0	-192	0	-226
Toll operator	0	0	0	0	761
Government	-32	0	-53	0	-44
All Operators' benefits (PVF)	-364	-122	-559	-122	564
External benefits					
Accident and noise costs	26	14	37	7	57
Environmental costs	15	4	3	-6	32
Total external benefits	41	18	40	1	88
CO2	60	15	80	4	123
OF_{CBA}	349	60	809	92	431
$OF_{I/T}$	3.87	0.92	4.62	0.05	3.61



(a) (b)

(c) (d)

Figure 2. Traffic impacts of the individual policies listed in Table 3 for Edinburgh in the year 2010: (a) relative changes in number of trips; (b) relative changes in total PCU-kms by zone; (c) relative changes in road speeds; (d) relative changes in bus occupancies. The notations used in the labels for policy instruments are: “Fares”= PT fares policy; “Frequ”=PT frequency policy (applied to bus mode only); “CdnChrg”=Cordon charge in zone 1; “AM”=AM peak; “IP”=inter-peak.

5 The optimal strategy for the City of Edinburgh

5.1 Optimisation set-up

Three policy instruments are included in the transport strategies for the City of Edinburgh: PT fare changes, PT frequency changes, and cordon charges. All policy instruments, with the exception of the cordon charge, are area-wide policies: they are applicable to the whole study area. The cordon charge policy is applied within the cordon of the central area (zone 1). Also, each instrument is allowed to vary by time of day – AM peak and inter-peak – again with the exception of the cordon charge, where the same cordon change is applied in each time period. The cordon charge policy is specified in terms of absolute figures, such as £5. All other policies are in terms of relative changes. For example, a PT fare policy of –20% means that the fares are reduced by 20% relative to the base year. Finally, the fares policy is applicable to both bus and rail while the frequency policy is applicable only to bus.

Because local authorities do not have power over PT fare changes, optimisations of the *OF* by varying several policy instruments were carried out for two strategy scenarios:

- Scenario 1: bus frequency and cordon charge policies only.
- Scenario 2: as for scenario 1 but include optimisation of PT fare changes as well.

Optimisations were also conducted for two spatial aggregation levels: area-wide optimisation and zone-dependent optimisation. There were thus four types of optimisation carried out. In the zone-dependent optimisations, the PT fares and frequency policies are allowed to take different values in each zone as well as in each time period.

Optimisations carried out here are unconstrained in the sense that there are no constraints on the outputs, such as finance constraints, or barriers for implementation. However, in order for the optimisation algorithm that we used to work properly, it is necessary to impose upper and lower bounds for each policy instrument. The upper and lower policy bounds that were applied during the optimisation procedures are as follows:

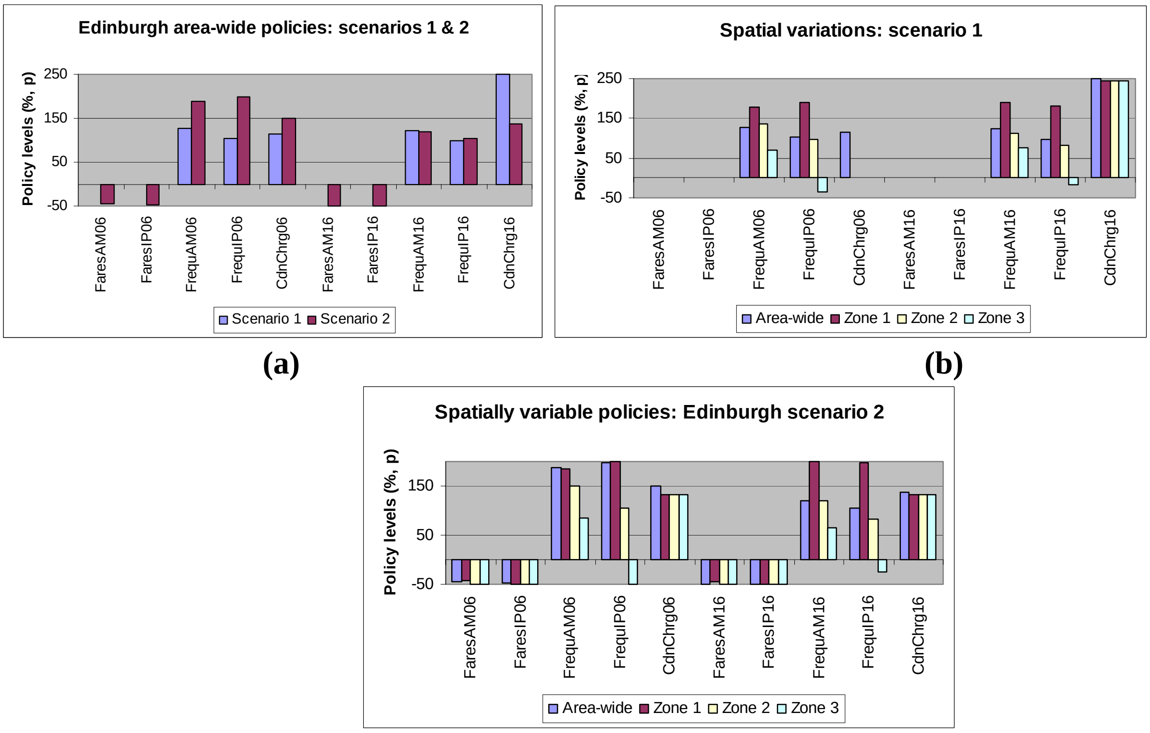
- The PT fares policy was permitted to vary between –50% and +100%
- The PT frequency policy was permitted to vary between –50% and +200%
- The cordon charge was allowed to vary from 0p to 620p (0 to 10 euros)

The optimal strategies and their economic and traffic impacts are discussed in the following two subsections, respectively.

5.2 The optimal strategies

The optimal strategies for the two scenarios, and for the two spatial aggregation levels are demonstrated in Figures 3a-3c. Figure 3a compares scenarios 1 and 2 for area-wide optimisations and Figures 3b-3c show the effects of allowing spatial policy variation in the optimal strategies.

In general terms, the optimal strategy is to increase bus service levels and to apply a cordon charge to the central area. When bus and rail fares are available for optimisation in scenario 2, then the optimal strategy is to reduce them. For both area-wide and zone-dependent policy applications, the fare reductions are either at, or very close to, the imposed lower bound of –50%. The situation is slightly different in the case of bus frequency policies. For area-wide policy application, the optimal strategy involves bus frequency policies in scenario 1 that are substantially different from this upper bound.



(a) **(b)**

(c)

Figure 3. Optimal transport strategies for Scenarios 1 & 2 and for the two spatial aggregation levels. The notations used in the labels for policy instruments are: “Fares”=PT fares policy; “Frequ”=PT frequency policy; “CdnChrg”=Cordon charge in zone 1; “AM”=AM peak; “IP”=inter-peak; “06”=year 2006; “16”=year 2016.

When policies are permitted to be zone-dependent, the overall picture is still one in which PT fares are to be reduced, bus frequencies are to be increased and cordon charges are to be applied. The bus frequency increase tends to be larger in the inner zone (zone 1) and smaller (or a decrease rather than an increase) in the external zone (zone 3).

It is interesting to compare the optimal strategies within scenario 1 to those in scenario 2. The introduction of a fares policy seems to have the effect of requiring increased bus service levels in the AM peak. This can be understood in terms of the fare reductions leading to greater bus patronage and hence a need for more buses to avoid overcrowding and to ensure that all new passengers may be accommodated.

5.3 Economic and traffic impacts of the optimal strategies

The economic and traffic impacts (in terms of mode shifts for cars and buses in the year 2010) of the optimal strategies are summarised in Table 4 and Figure 4, respectively. Note that the figures listed in Table 4 are in terms of benefits (discounted values and relative to the do-minimum) through the implementation of the optimal strategies. Thus, positive values imply benefits and negative values imply costs. In Table 4, the objective function has been divided into five parts: user benefits, all operators’ revenue and costs, external benefits and the CO2 benefits, such that the sum of rows 1 to 5 is equal to the *OF*. In addition, the *PVF* is the *net* benefit for all operators (the sum of rows 2 and 3).

The major impacts of the optimal strategies are as follows.

(1) If the PT policies are varied across zones, then the PT operator can achieve similar revenues at a lower cost. As a result, a larger overall economic efficiency (measured by the values of *OF*) can be achieved.

(2) With reduced fares for the two spatial aggregation levels in scenario 2, the total road users’ benefits are much larger than those in the analogous situations in scenario 1. However, the scenario 2 strategies are more expensive with much lower values of finance.

(3) Varying PT policies across zones does not seem to make significant differences in mode shifts *in the study area as a whole*. However, further examination of the data show that it does make a difference to mode shifts locally in different zones. In other words, the mode shifts in each zone with the spatially-variable policies are significantly different from those with the area-wide policies.

(4) There are significantly larger mode shifts to buses from cars and other modes in scenario 2 than in scenario 1 (nearly 60% in the AM and 80% in the IP increases in bus trips in scenario 2), as can be expected from the differences in the optimal strategies of the two scenarios – there is a 50% reduction in PT fares and a much higher frequency increase in scenario 2.

Table 4. Economic benefits of the optimal strategies for Edinburgh in Scenarios 1 and 2, and with area-wide policies and zone-dependent variation of policy instruments.

	Benefits (£m)	**Area-wide optimisation: Scenario 1**	**Zone-dependent optimisation: Scenario 1**	**Area-wide optimisation: Scenario 2**	**Zone-dependent optimisation: Scenario 2**
1	User benefits	1158	1278	2271	2271
2	All operators' revenue	360	300	-489	-518
3	All operators' cost	-714	-658	-844	-692
4	External benefits	94	85	156	156
5	CO_2 benefits	146	136	200	196
6	OF_{CBA}	1045	1142	1293	1414
7	*PVF*	-354	-358	-1334	-1210

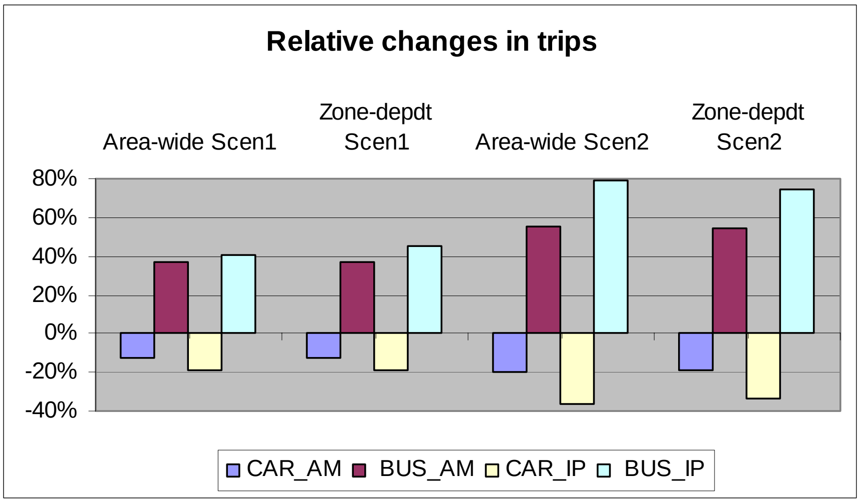


Figure 4. Traffic impacts of the optimal strategy: relative changes in car trips and bus trips in year 2010.

6 Summary

In this paper, we have presented a methodology to identify city-specific optimal Land Use and Transport strategies. The methodology has been applied to six UK cities using the TRL strategic transport policy model TPM.

In the first step, individual policies are tested for optimal levels. The model suggests reducing PT fares (to the imposed lower limit in almost all cases), increasing PT frequencies, and introducing cordon charges.

Having examined the individual policies, we then looked at the optimisations of two scenarios of policy combinations. For scenario 1, the model suggests an increase in frequencies (doubled) and a modest charge around the city centre. The strategies require significant funds to finance the larger increases in frequencies.

For scenario 2 the model predicts optimal fares to be around their lower bound *i.e.* a reduction of 50%. This increases the *OF* value significantly and increases the finance requirements compared with scenario 1 strategy. Reducing fares requires greater increases in frequencies. Cordon charges should be increased in the short term but reduced significantly in the longer term.

Finally we investigated the effects of spatial variations on optimisations. It was found that varying fares and frequency policies across zones allows the PT operator to achieve similar revenue (to that with area-wide policies) at a lower cost. As a result, the values of finance are higher and so is the overall economic efficiency (the *OF*).

As has been mentioned, the methodology presented here is based on the first stage of an EPSRC research project. The optimisations reported in this paper are unconstrained in that there are no constraints on the outputs, such as finance constraints, or barriers for implementation. Acceptability and feasibility have been assessed in later Stages of the project, where we impose finance constraints in searching for optimal strategies. In further work of the project, we have also tested whether different implementation sequences of policy instruments can help to mitigate acceptability barriers. Finally we focused on land use measures and their impacts and contribution to optimal and acceptable strategies. All these studies will be reported in the near future.

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of the cities involved. The conclusions are, however, our own, and do not necessarily reflect any of the cities' transport strategies.

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