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Designing optimal urban transport strategies: The role of individual policy instruments and the impact of financial constraints

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Abstract

This paper presents a methodology for the design of optimal transport strategies and the case study results of the methodology for the City of Edinburgh, using the two multi-modal transport/land-use models MARS and TPM. First, a range of policy instruments are optimised in turn and their relative impacts explored. Second, optimisations with and without financial constraints are performed and compared. Although both models produce similar optimal policies, the relative contribution of the instruments differs between models as does the impact on outcome indicators. It is also shown that by careful design it is possible to identify a strategy which costs no more than the do-minimum but which can generate substantial additional benefits. The optimisation methodology is found to be robust, and is able to be used with different transport models, and with and without financial constraints.

Keywords: Urban transport policy; Cost–benefit analysis; Optimisation

1. Introduction

The concept of integrated transport strategies is not new; many local authorities in the UK were developing them in the early 1990 s (May, 1991) and they were a key element in the first ECMT report on transport and sustainability (ECMT, 1995). However, few UK Local Transport Plans (LTPs) can be considered as truly 'integrated' as yet in their approach; they are limited in particular by the resources available, the unacceptability of demand management measures, the need to negotiate with operators on public transport service levels and fares, the lack of understanding of interactions between transport and land use, and the timescale for implementing innovative solutions.

There thus remain significant challenges, both in the short-term design of strategies and in the longer term fundamental understanding of their performance. Among the key issues are the need to understand how best to combine the wide range of different policy instruments; how to identify the optimal combinations of these, 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 our previous work where we have made significant advances in understanding the design of optimal transport strategies. In our initial research, the usefulness of optimisation methods to identify optimal transport strategies was shown (Fowkes, 1998). In the follow-up research, we studied the performance of transport policy packages with regard to the level of implementation OPTIMA (1998); FATIMA (2000), their financial feasibility and their transferability (May et al., 2000).

There have been relatively few similar research projects. The most relevant are TRENEN (Proost, 2000), which used a simple single-link model of a number of cities to identify optimal combinations; the ISGLUTI project which

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studied, but did not optimise, land use and transport strategies (Paulley and Webster, 1991); work by TRL with their Transport Policy Model, which indicated the relative merits of policies based on public transport and demand management in five UK cities, but made no attempt at optimisation (Dasgupta et al., 1994); and the PROPOLIS study (Lautso et al., 2004) where a comparative study of the performance of a range of policy instruments, and selected combinations, in seven European cities, was conducted using three different land use transport interaction models.

This paper is one of the several reporting on our work which aimed to cover these issues by making use of three time-marching models: MARS (Pfaffenbichler, 2003; Pfaffenbichler, 2003), TPM (TRL, 2001) and START-DELTA (Simmonds and Still, 1999). All three models were used to model Edinburgh in the UK. MARS and TPM also covered Leeds (UK) and Vienna (Austria), while TPM was used for another four UK cities: Dundee, Bristol, Exeter, and Preston. All models were applied with the same appraisal and optimisation framework to develop optimal policies. The aim of this paper is to present the methodology, describe two of the models used—MARS and TPM—and to present the case study results when applied to the city of Edinburgh. Each instrument is first optimised in isolation and its impact discussed in relation to a welfare-based objective and other outcome indicators. Then the paper discusses the results of optimising two packages of instruments using the same objective and compares the results between models.

In Section 2, we describe the appraisal methodology and outcome indicators used to compare the relative impact of the various instruments. We also give a qualitative description of the MARS and TPM models and outline the optimisation approach. Section 3 presents the case study results for Edinburgh from both models with the application of individual instruments, while Section 4 presents the optimal packages. Finally, in Section 5 we draw conclusions and discuss the implications for strategy design.

2. Methodology

In order to appraise different transport strategies, a set of objectives must be defined against which the policies are appraised. The objectives of our case study cities are based on suggestions made in the UK Government's White Paper on the Future of Transport (DETR, 1998a,b). Based on this, we agreed with the cities to use sustainability as an overarching objective, and took the six underlying policy objectives to be:

- protection of the environment
- safety and severity of traffic accidents
- economic efficiency
- equity and social inclusion
- contribution to economic growth
- intergenerational equity

Traditionally, strategies are assessed using a cost benefit analysis (CBA); however, the local authorities have more recently moved to a target-based approach in response to national guidelines for monitoring impacts. We have thus also developed an alternative approach to CBA which is based on goal achievement with respect to targets for indicators which reflect the policy objectives stated above. A full comparison of policies resulting from these two appraisal approaches is presented elsewhere (Emberger et al., 2003).

2.1. The CBA-based approach

To be able to work with these six objectives, we had to translate them into an objective function. The objective function tries also to balance the interests and needs between present and future generations (Minken et al., 2003). The objective function (OF) used is based on former research work carried out in PROSPECTS (May et al., 2003) and is implemented in both models. The OF consists of an economic efficiency term (the CBA part or core objective), and a term for monetised values for CO_2 emitted, local pollution, noise and accidents. All these costs are discounted over a 30-year evaluation period. Additionally, the needs of future generations may be considered through a weighting mechanism within the objective function. For the case of the City of Edinburgh presented here, we did not give extra weight to future generations so that results are more in line with current UK practice. It should be noted that economic growth is not represented within the objective function and that equity and social inclusion is only considered indirectly by looking at impacts on different modes. In mathematical terms, the objective function can be written as

$$OF = \sum_{t=1}^{30} \alpha_t [U_t + P_t + E_t]$$

where

OF is the objective function
U_t is the user benefit in year t
P_t is the net benefit of providers/operators, including the parking operator, toll operator, public transport (PT) operator, and the Government in year t
E_t is the external benefit from reductions in accidents, noise, emissions, and CO_2 in year t
α_t is the discounting factor in year t, $\alpha_t = 1/(1+r)^t$
r is the discount rate (taken as 3.5% to reflect UK practice)

The objective function is made up of the net present benefits of three sectors: users, providers, and externalities.

The user benefit includes users' money savings and time savings from the strategy; the providers' benefit equals revenues minus the operating and capital costs; the external benefits include those from reductions in accidents, noise, emissions, and CO_2. These benefits are calculated from the transport/land-use models and the appraisal framework.

The above OF and its components are used as a first means of comparing the relative impacts of the transport instruments. In addition, we discuss the cost implications of each instrument in terms of the change in present value of finance. The Present Value of Finance (PVF) of an instrument or set of instruments is defined as the net discounted financial benefit to government and other providers of transport facilities, both public and private, over a 30-year time horizon, relative to the do-minimum.

PVF is defined as:

$$PVF = \sum_{t=1}^{30} \alpha_t (R_t - C_t)$$

where

R_t is the revenue of providers/operators in year t

C_t is the cost of providers/operators in year t, including operating costs and capital costs.

2.2. Optimisation method

The above objective function can be used in an optimisation process whereby policy instruments are varied so as to maximise the OF value. We assume that the policy instruments can in the most general case be applied at any level in any one year ($t=1,2,\ldots,30$). Thus, for a single instrument there could in theory be 30 different levels in the optimal solution. In practice we have not attempted to solve this theoretical problem for a number of reasons:

- The optimal policy should be easily understood and easy to present to the public and other decision makers.
- Optimisation processes become harder to solve as the number of variables is increased with increased likelihood of finding local optima rather than a global optimum.
- Furthermore, each optimisation requires more computing time as the number of variables is increased.
- Some software packages used cannot represent instruments varying over time to such a fine degree and/or many more runs would be required which would be computer resource intensive.

Whilst some policy options, such as discrete measures being considered in only one year, can help cut down the problem, the most efficient and practical method for trimming the problem down is to limit the variation of all the instruments over the evaluation period.

The approach adopted here is the same as in PROSPECTS (Minken et al., 2003), i.e. to specify a piece-wise linear policy profile where policy instrument levels are optimised for two points in time, t_A the implementation year and t_L the long run year. Thus we need only specify the year of implementation, t_A, and the number of years until a long run value is to be expected. It is assumed that all policy instruments are 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. For the single instrument optimisation tests reported here we further limit the profile such that the policy is constant over time, i.e. the value used in the implementation year is equal to that used in the long run year and all other subsequent years. This allows a simple search technique to be applied to obtain the optimal single instrument values.

For the optimisation of packages of instruments, we optimise the OF subject to constraints on predefined ranges of instrument and also subject to financial constraints. The financial constraints may be imposed either on the PVF of all operators/providers, indicating that the strategy is self-financing, or on the PVF of the PT operator only, in which case the PT operator breaks even. The former allows for cross-subsidies between sectors whereas the latter ensures that the public transport sector is self-financing.

In this paper, both unconstrained and constrained optimisation problems are solved using the Downhill Simplex method (Nelder and Mead, 1965), via the AMOEBA routine (Press et al., 1990). To implement the constraint in the optimisation procedure, we add a penalty to the objective function whenever the PVF is negative. We have found that the optimisation method is robust, and able to be applied with different transport models, and with and without financial constraints.

2.3. Other transport-related indicators

Rather than simply compare instruments in terms of the objective function, we also compare the impact on certain key outcome and process indicators which describe how the transport system is responding. This analysis combined with the CBA analysis provides further understanding of the relative performance and value for money of the instruments. The indicators considered for the MARS model are the changes relative to the do-minimum in trip-km and average speed for all modes by peak and off-peak periods and cost of accidents and tons of CO_2 for private cars in peak and off-peak periods. Transport emissions for public transport are calculated off-line and included in the objective function (these are not significant except when frequencies are increased by a significant amount, thus we concentrate on car emissions which are affected by all instruments to some extent).

Table 1
Comparison of MARS and TPM features for Edinburgh application

Model feature	MARS	TPM
Number of zones	25 zones: usually administrative boundaries	Three concentric zones: inner, outer, external
Modes of travel	Three modes: Car, Public Transport, Slow	Up to eight modes
Congestion effects	OD-specific speed-flow curves for commute trips. No speed effect for other trips (assumed to be in the off-peak)	Zone-specific speed-flow curves for peak and inter-peak for road modes, and over-crowding model for Public Transport modes
Generalised costs	In-vehicle time, money, access/egress, parking search time, wait times, change times	In-vehicle time, money, access/egress, parking search time, wait times
Journey purposes	Commute, other	Up to eight purposes
Time periods	Peak, off-peak	AM peak, inter-peak
Levels of car-ownership	0, 1	0, 1, $\geqq 2$
Demographics/household categories	Average household size, employed residents, cars per head, average income per zone	*Exogenous:* population, age group, household size, cars per head and employment; *Endogenous:* population age group segregated by car-ownership levels
Route choice	No	No
Mode/destination choice	Simultaneous	Simultaneous
Time of day choice	No	No
Demand response	Commute trips inelastic. Constant time budget	Elastic demand by journey purpose, mode, and car-ownership household category
Land use response	Yes	No, with exogenous land use factors

Traffic impacts reported for TPM include relative changes in person trips to reflect impacts of policies on mode shifts, in PCU-kms and average speed to reflect impacts on road congestion, and in bus occupancies to reflect impacts on bus patronage.

The above indicators are presented for each instrument for year 10 (2010) only, partly due to the amount of data produced and partly because 2010 is used to monitor progress of indicators against short run targets by local authorities.

2.4. The MARS and TPM models for the City of Edinburgh

In this paper we use two strategic models of Edinburgh, MARS and TPM, to model the transport policies and to output the indicators and OF used in the optimisation process. MARS (Metropolitan Activity Relocation Simulator) is a strategic, interactive land-use and transport interaction (LUTI) model. It was developed as a time-saving alternative to traditional four-step transport models, saving on run time by omitting the assignment stage and using area speed flow relationships in place of a full network. MARS can model the transport and behavioural responses to several demand and supply-side instruments. These impacts can then be measured against targets of sustainability. MARS assumes that land-use is not a constant but is rather part of a dynamic system that is influenced by transport infrastructure. The interaction process is modelled using time-lagged feedback loops between the transport and land-use sub-models over a period of 30 years. It should be noted that in our Edinburgh case study the land use responses to transport strategies are small and that we do not consider any land use policies here, i.e. we have ignored the impacts associated with changes in attractions and productions. For a full description of the MARS model, see Pfaffenbichler (2003).

TPM (Transport Policy Model) 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. In contrast to some large-scale spatially detailed transport models, TPM is a spatially aggregate modelling tool designed for ease of use, and with the ability to assess urban transport policy impacts rapidly and with very limited data requirements. For a full description of TPM, see TRL (2001). In this paper, the land use changes over time in TPM are exogenous inputs; 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.[1] In Paulley et al. (2004), a land use model has been integrated into TPM so that the impacts of interactions between transport and land use can be modelled.

Table 1 gives a comparison of the two models in terms of supply and demand representation.

The main differences between MARS and TPM are the number of zones, the segmentation of demand, and the assumption about constant travel time budget which constrains the demand response and modelling of land use responses. MARS is spatially more detailed with OD-specific speed-flow curves, TPM has only three zones but up to eight trip purposes and modes and greater detail in car-ownership/household categories and hence demand responses. TPM also has a public transport crowding model. Neither model includes route choice nor a time of

[1] http://www.tempro.org.uk/

Table 2
Overview of case study data

Model	Population (000 s)			Area (km^2)			Modal split (%)			Cars/1000 population	
Zone/mode	Inner	Outer	External	Total	Inner	Outer	Total	SL	PT	PC	All zones
MARS	n/a	n/a	n/a	1071.8	n/a	n/a	2305	22	25	54	371
TPM	58.0	393.5	2288.4	2739.9	28	352	n/a	13	23	65	342

SL: slow modes; PT: public transport; PC: private car.

day response, both performing simultaneous mode/destination choice.

Although both MARS and TPM were implemented for Edinburgh, they are based on different geographical areas. The MARS model for Edinburgh is made up of 25 zones with 14 zones representing the urban area and 9 larger zones representing the surrounding regions. TPM models Edinburgh using the three-zone system. The TPM inner zone covers the city centre of Edinburgh, and the outer zone (together with the inner zone) covers the City of Edinburgh district. The external zone covers a much larger area than that used in MARS but here only travel to and from the urban area is modelled.

Table 2 provides some basic information used in the models to describe the cities and modelled areas in terms of size, population and in modal split. Note that the modal split varies between models as TPM includes only slow mode trips that are substitutable by other modes, whereas the MARS model includes all slow mode trips. Note also that the external zone in TPM represents the catchment area of the majority of commuters travelling to or from the inner or outer zone; trips originating from the external zone and terminating at the external zone, or vice versa, are not modelled. Although the external zone can have a large population, the trip generation rates are much lower. Therefore, the number of trips generated from and attracted to the external zone is much smaller.

3. Relative impacts of single instruments

This section describes the tests conducted for single instruments and discusses the results in terms of relative impacts and make up of the objective function OF.

3.1. Tests conducted

Table 3 shows the single instruments tested, the area of application, the ranges tested and the optimum value within this range obtained via sensitivity tests for MARS and TPM. Note that in TPM, parking policies (charges and provisions) were not considered for optimisation in this study as their responses and hence impacts were thought to be similar to cordon charges. Also, TPM models fuel tax changes as a scenario variable rather than a policy lever.

3.2. Comparing the instruments in terms of CBA

Tables 4 and 5 show the CBA results with component parts and the PVF values for MARS and TPM tests, respectively.

First, it should be noted that we cannot compare the CBA results directly as the models were set up with different study areas and the instruments were therefore applied to different populations. However, if we look first at the optimal instrument values for common instrument tests we

Table 3
Tests conducted and optimum single instrument values

Instruments	Application	MARS range	Optimum MARS	TPM range	Optimum TPM
Fares peak	Study area	−50 to +100%	−50%	−50 to +100%	−45%[a]
Fares off-peak	Study area	−50 to +100%	−50%	−50 to +100%	−45%[a]
Frequencies peak	Study area	−50 to +200%	50%	−50 to +200%	140%
Frequencies off-peak	Study area	−50 to +200%	25%	−50 to +200%	80%
Cordon charge both periods	Cordon around zone 1	N/A	N/A	€0–8	€5.65
Cordon charge peak	Cordon around city centre	€0–6	€5.0	N/A	N/A
Cordon charge off-peak	Cordon around city centre	€0–6	€2.0[b]	N/A	N/A
Parking charge short stay	City centre	€0–6	€2.0[c]	N/A	N/A
Parking charge long stay	City centre	€0–6	€5.0[c]	N/A	N/A
Road capacity peak	Study area	−10 to +5%	5%	N/A	N/A
Road capacity off-peak	Study area	−10 to +5%	5%	N/A	N/A
Fuel tax	Study area	−50 to +200%	200%	N/A	N/A
Fuel efficiency	Study area	1% p.a.	1% p.a.	N/A	N/A
Smart card (bus speed increase)	Study area	N/A		0–5%	5%

[a] The optimum fare change for TPM lies on the −50% limit but tests were conducted in 15% steps.
[b] The optimum value of off-peak cordon charge in MARS is actually zero. The value €2 was used to provide a comparison with short stay parking charges.
[c] The long stay parking charge for MARS was set to be equal to the peak cordon charge to provide a direct comparison.

Table 4
Edinburgh: summary of MARS OF and its elements for individual instruments. (Units are €m discounted over the evaluation period)

	Peak fare	Off-peak fare	Peak frequency	Off-peak frequency	Peak Cordon charge	Off-peak Cordon charge	Parking long stay	Parking short stay	Road capacity peak	Road capacity off-peak	Fuel tax	Fuel efficiency per annum
Change in instrument level	−50%	−50%	50%	25%	5	2	5	2	5%	5%	200%	1%
Spatial coverage	Area	Area	Area	Area	Central	Central	Central	Central	Area	Area	Area	Area
OF	1162	407	156	51	374	−67	172	9	548	912	1178	239
PVF	−1217	−1485	−367	−177	1151	699	169	55	73	155	10,105	−553
User ben. Money PT	1437	1802	0	0	0	0	0	0	0	0	0	0
User ben. Money Car	88	0	28	0	−1272	−789	−135	−54	63	130	−10,133	666
User Ben. Time PT	329	0	378	227	234	0	68	4	203	244	393	−34
User Ben. Time Car	403	15	125	3	218	4	57	4	261	501	504	-46
User Ben Time NM	0	0	0	0	0	0	0	0	0	0	0	0
PT capital	0	0	−22	0	0	0	0	0	0	0	0	0
PT operating	0	0	−454	−301	0	0	0	0	0	0	0	0
PT fares (operator)	−1082	−1389	133	141	134	18	40	3	44	97	476	−35
Parking revenue	−2	−3	0	−1	−18	−14	144	53	2	4	−10	1
Net toll revenue	0	0	0	0	1082	723	0	0	0	0	0	0
Govt. capital	0	0	0	0	0	0	0	0	−1	−1	0	0
Govt. revenue	−133	−93	−24	−16	−43	−29	−14	−1	29	55	9639	−519
Local externalities	47	48	4	8	13	11	5	0	−46	−99	163	14
CO_2	74	26	−13	−11	28	8	8	1	−7	−20	144	192
OF/OF-fuel	98.7%	34.5%	13.2%	4.3%	31.7%	−5.7%	14.6%	0.8%	46.6%	77.5%	100.0%	20.3%

can see that both models suggest significant reductions in fares in both the peak and off-peak periods, bounded by the lower limit. It should be noted that both models assume that operating costs do not vary with patronage; TPM does, however, include a user cost in the form of an overcrowding model.

Both models suggest significant increases in bus frequencies. The increases suggested by TPM are far greater than those suggested by MARS as the combined effect of reduced wait times and reduced overcrowding results in significantly higher time savings for public transport users. The optimal cordon charges from TPM and MARS are similar (around 5€).

Looking at the MARS results in more detail, taking the overall effect on the OF value first, we can see that peak fare reductions of 50% are almost equivalent in OF terms to increasing fuel tax by 200%—note that fuel tax increases affect both periods whereas the majority of other instruments are applied to either the peak or off-peak period. The area-wide road capacity improvements also provide significant increases in the OF value. It should be noted that if fare reductions or road capacity changes were applied to both periods simultaneously then the combined OF values would be greater than for the fuel tax increase of 200%.

Although we can say that peak fare reductions give a similar OF value to fuel tax rises and as such would be judged as similar by an optimisation routine, there are obvious and significant differences in the impacts on various groups. For example with fare reductions in the peak, there are money (1.4 billion euro) and time benefits (328 million euro) to public transport users and the public transport operators incur the costs of fare reductions (in excess of 1.0 billion euro). The shift towards public transport use also brings congestion relief and hence time benefits to car users (403 million euro). When the fuel tax is increased there are significant money losses to car users (over 10 billion euro), some seven times greater than the money benefit to public transport users with the 50% fare reduction in the peak, whilst the time benefits to both public transport and car users are only 23% higher than with a fare reduction of 50%. With the fare reductions the PVF is in deficit by 1.2 billion euro which must come from other sources, e.g. the tax payer, whereas with the increased fuel tax there is a surplus of 10 billion euro over 30 years which could be used to invest in transport, other sectors such as health and education or to reduce other taxes.

Looking at the TPM results in more detail, when public transport fares are reduced, car users' journey time is reduced because of a shift of car users to public transport

Table 5
Economic benefits of individual policies for Edinburgh (€m) for policies obtained from sensitivity analysis using TPM

Policy instruments	Fares AM	Fares IP	Frequency AM	Frequency IP	Cordon Charge	Bus speed
Optimal policy values	−45%	−45%	140%	80%	€5.65	5%
OF	563	97	1305	148	695	419
All operators' benefits (PVF)	−587	−197	−902	−197	910	11
User benefits						
Money savings						
Private transport modes	89	2	189	2	−1382	29
Public transport modes	481	277	0	0	0	0
Time savings						
Private transport modes	452	5	784	3	761	153
Public transport modes	−34	−45	1040	334	66	166
Total user benefits	987	239	2013	339	−553	348
Operators' benefits						
PT operator	−439	−197	−506	−197	118	58
Parking operator	−97	0	−310	0	−365	−32
Toll operator	0	0	0	0	1227	0
Government	−52	0	−85	0	−71	−16
External benefits						
Accident and noise benefits	42	23	60	11	92	15
Environmental benefits	24	6	5	−10	52	10
Total external benefits	66	29	65	2	142	24
CO_2 benefits	97	24	129	6	198	35

Note: The notations used in the labels for policy instruments are: Fares: fares policy; Frequency: frequency policy; Bus speed: bus speed increase representing Smart Cards policy which reduce boarding times; AM: AM peak; IP: inter-peak.

and the accompanying reduction in overall road traffic. Thus we see positive private transport 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. Hence, there are negative PT mode time savings. 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.

Increases in peak frequencies give the best overall result in terms of OF value for TPM. This is due mainly to the significant user benefits for both car and public transport users coupled with money benefits for car users. As frequencies are increased, wait times and overcrowding costs are reduced which cause a large shift from car to public transport. This in turn gives rise to significant congestion relief for both modes.

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. On the other hand, the cordon charge reduces public transport users' time costs due to congestion relief. The cordon charge is the only policy that can generate a significant positive PVF though it causes the total user benefit to fall. It also generates the largest external benefits.

In terms of relative impacts of the two models from the sub-set of common instruments, fare reductions were the best performing instrument for MARS, followed by changes in capacity and peak cordon charges, with changes to frequencies performing poorly in comparison. This contrasts with the TPM relative performance whereby changes in peak frequencies outperform all other instruments, followed by cordon charges and fare reductions. The relatively strong performance of frequency and poor performance of the fare reductions can be explained in part by the inclusion of the overcrowding effect in TPM which outweighs the in-vehicle time benefits due to congestion relief.

3.3. Comparing impacts on indicators

Fig. 1a–e shows the percentage changes for a number of key indicators split by peak and off-peak for each instrument test for MARS. Fig. 2a–d shows the traffic impacts of the optimal individual policies for each policy instrument in terms of relative changes in number of trips, PCU-km, road

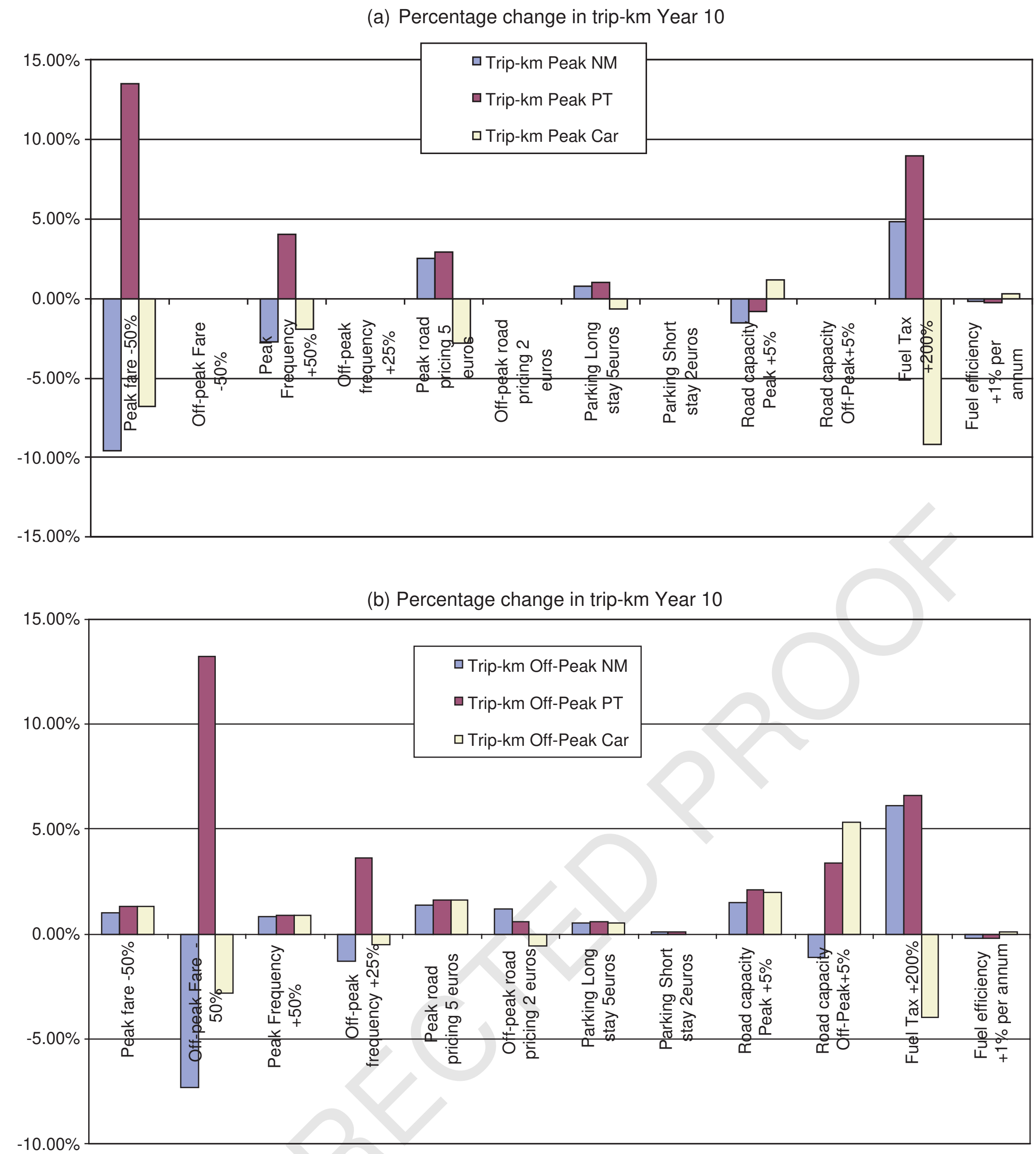

Fig. 1. MARS: Percentage change (a) in trip-km in the peak period—year 10; (b) in trip-km in the off-peak period—year 10; (c) in average speeds in the peak—year 10; (d) in cost of accidents by period—year 10; (e) in tons of CO_2 emitted by period in year 10.

speed, and bus occupancy for TPM. The traffic impacts shown are for year 10. The optimal individual policy values can be found in Tables 4 and 5.

Taking the common instruments first, both models include fare reductions of around 50%, which result in similar impacts in terms of car use (−5 to −6%) and public transport use (10 to +14%). However, the speed increases are greater for TPM than for MARS and TPM predicts a 10% increase in average bus occupancies which is not modelled in MARS.

Similarly, both sets of tests include a peak cordon charge of around 5€. Again this produces similar changes in car use and public transport use with greater increases in speed for TPM—almost +30% in the central zone and +8% for the urban area compared to 3.8% for the study area in MARS.

As the optimal frequencies are far higher in TPM than MARS, the impact on mode shift is as expected much greater, with public transport trips increasing by 37% for a 140% increase in frequency compared to a 4% increase in patronage for a 50% increase in frequency with MARS as shown by the changes in trip-km.

Within the MARS set of tests, the fare reductions and fuel tax increases impact significantly on trip-km and hence on mode share. The main difference between fare reductions

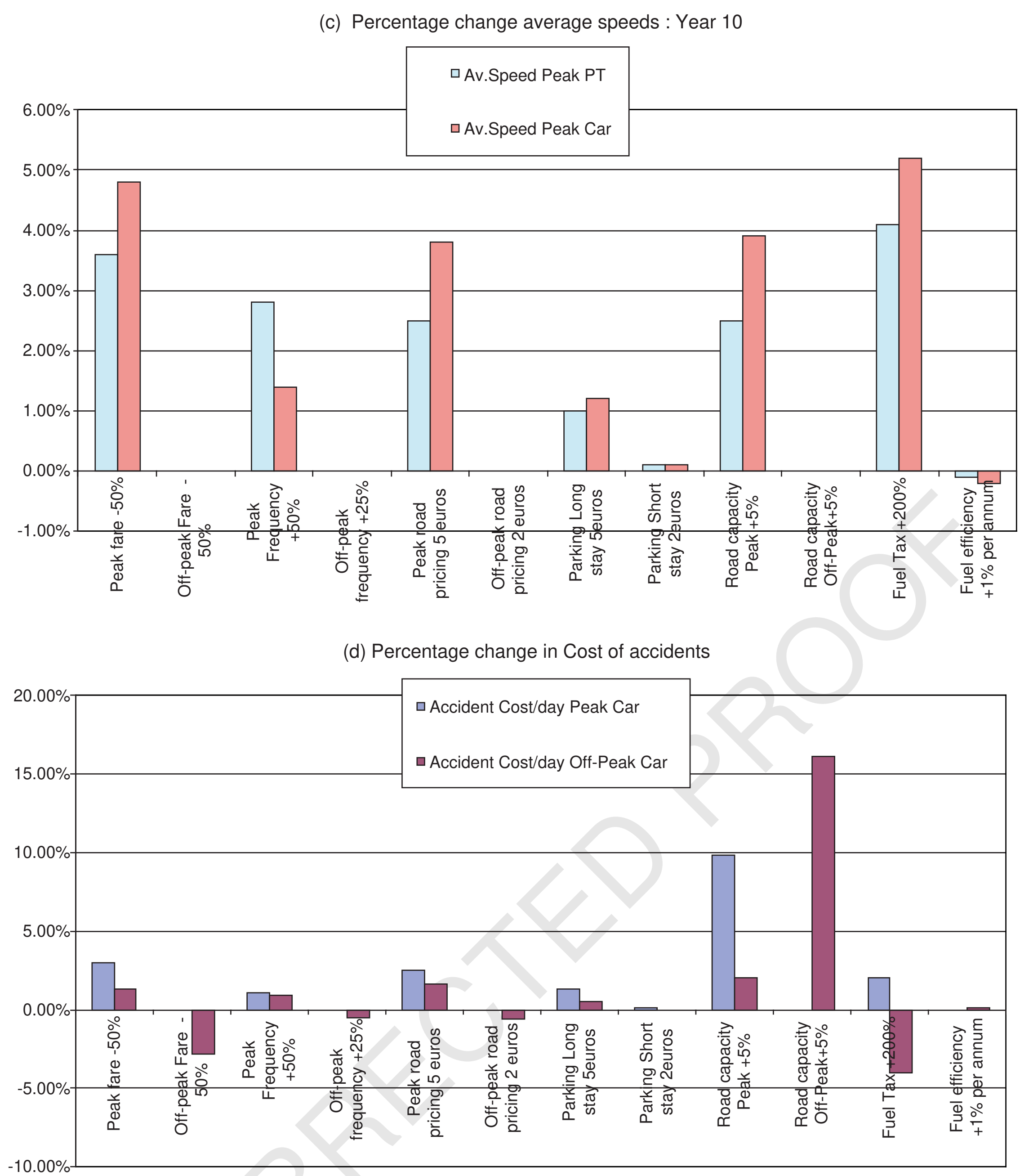

Fig. 1 (*continued*)

and fuel tax is that fare reductions attract new users from both car and slow modes whereas increased fuel tax reduces car use while increasing both public transport and slow mode trip-km.

Increasing road capacity by 5% increases the average speed of both motorised modes (by less than 5%). The net effect is to increase car use at the expense of slow modes. The increase in speeds and trip-km results in significant increases in the cost of accidents.

All instruments which affect the peak increase the cost of accidents in the peak due to increased speeds. In addition, increases can occur in the off-peak as a result of increased car use (taking up the additional time budget).

CO_2 emissions are reduced where speeds are increased and car use reduced which means that fuel tax and fare reductions produce significant reductions in CO_2. Increased fuel efficiency results in lower fuel consumption and hence lower emissions in year 10. Although not shown here these impacts become more significant over time as the fuel efficiency is assumed to increase at 1% per annum.

Perhaps, the most interesting result is for peak cordon charging around the city centre which produced a relatively

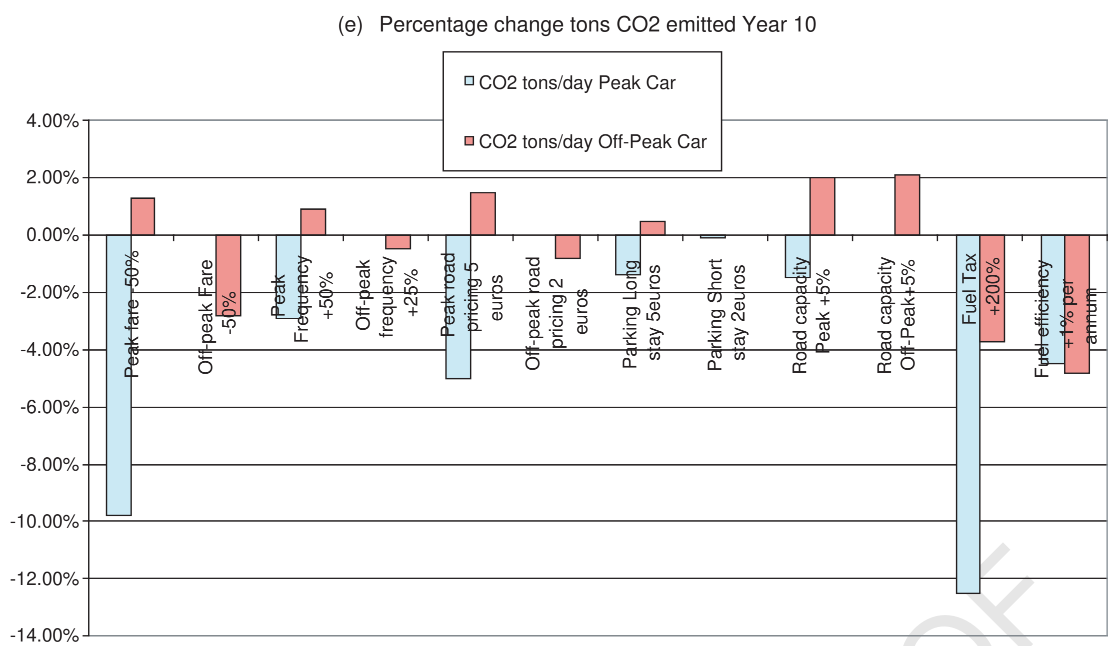

Fig. 1 (*continued*)

large reduction in car use in the peak compared to the area of implementation or size of the cordon. This is because there are around 20% of workplaces within the cordon and any through traffic is also charged.

Within the TPM tests, PT fare and frequency policies in the AM peak have little effect on traffic in the inter-peak. This is because departure time choices are not modelled; there are interactions of trips between time periods only in the parking model where the parking utilisation in the AM peak affects the places available in the inter-peak. Another point to note is that Fig. 2d shows 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

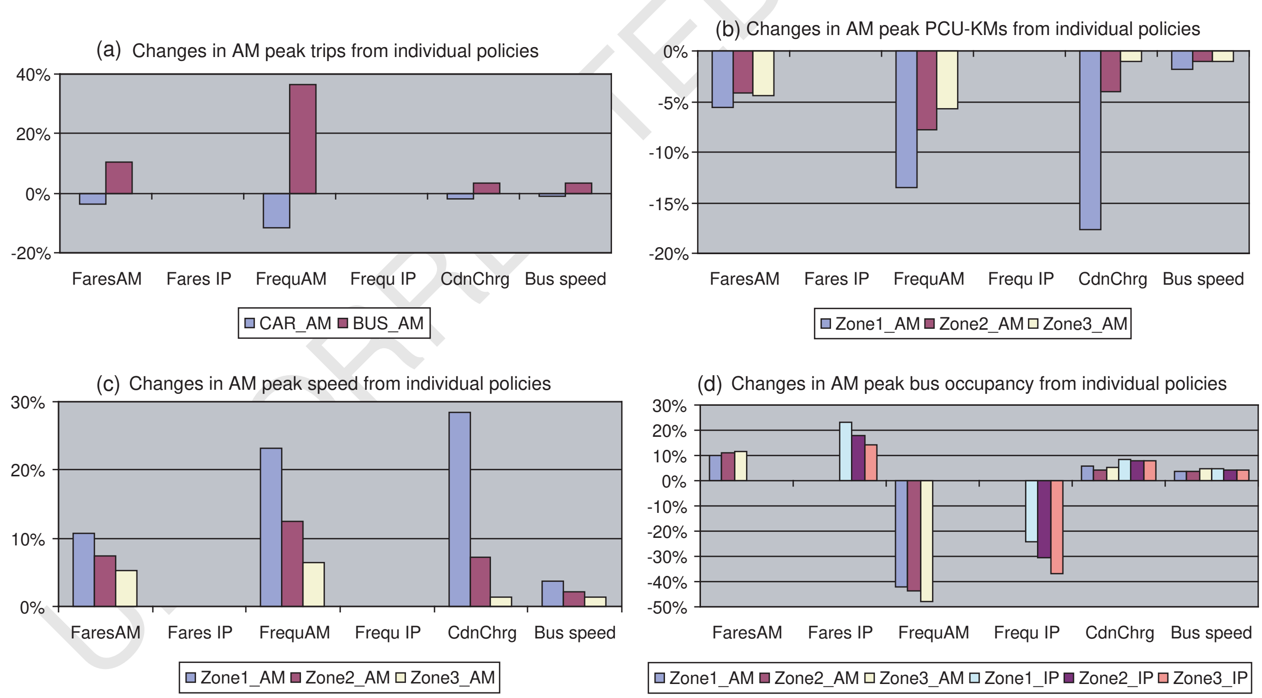

Fig. 2. TPM: Percentage changes in (a) the number of trips; (b) total PCU-kms by zone; (c) road speeds by zone; (d) bus occupancies. The notations used in the labels for policy instruments are: Fares, PT fares policy; Frequ, PT frequency policy (applied to bus mode only); CdnChrg, Cordon charge in zone 1; Bus speed, bus speed increase representing SMART CARDS policy; AM, AM peak; IP, inter-peak.

can increase bus patronage and hence bus occupancies, beyond a certain level these frequency increases will lead to buses becoming less full.

For TPM, all of the individual optimal policies reduce car trips and increase bus trips. This has the effect of reducing the total PCU-kms (through the reduction of car traffic) and increasing the average road speed. For MARS all policies except road capacity increases and increased fuel efficiency reduce car use in the peak, whereas car use in the off-peak may increase if time is saved in the peak through the constant time budget which reallocates time saved to non-essential trips.

Finally, there are some patterns which emerge, some of which are due to the model assumptions:

- Off-peak instruments do not affect the peak as there is no link back to the peak.
- Peak instruments can affect off-peak travel through the constant travel time budget in MARS—if time savings arise in the peak then additional trips or trip-km will appear in the off-peak.
- In the peak there exists a speed-flow relationship in both models and so externalities can vary with both trip-km and speed—the most obvious being changes in costs of accidents in MARS which can be seen to increase if speeds increase even with decreased flows. For TPM the number of accidents does not vary with speed.
- In the off-peak, there is no speed-flow relationship for MARS and only a small change in speed for TPM due to lack of congestion, so in general local emissions and accidents in the off-peak are related to car trip-km changes.

These differences in the relative performance of instruments between models (set up for the same city) both in terms of CBA and other indicators could have serious implications for policy makers. If funds are limited and the appraisal mechanism used is based on CBA then the TPM may favour increases in peak frequencies over peak fare reductions whereas the MARS model would favour changes to fares and other instruments before changes to frequencies. If, on the other hand, a target-based approach were used, then as the changes in outcome indicators were greater for TPM than for MARS targets would be met more easily.

4. Optimisation of policy packages

Three policy instruments are included in the transport strategies for the City of Edinburgh in both MARS and TPM: PT fare changes, PT frequency changes, and cordon charges. In addition, low-cost road capacity changes are considered in the MARS model. 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 (zones 1, 2 and 12 in MARS and zone 1 in TPM). Also, each instrument is allowed to vary by time of day—AM peak and inter-peak—again with the exception of the cordon charge in TPM, where the same cordon change is applied in both the AM peak and inter-peak. 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 do-minimum. Finally, in TPM, the fares policy is applicable to both bus and rail while the frequency policy is applicable only to bus.

The following two packages of transport policies are defined:

- *Package 1:* bus frequency and cordon charge policies in both MARS and TPM, and capacity improvements in MARS only.
- *Package 2:* as for Package 1 but including the optimisation of PT fare changes.

The PT fares policy is excluded in Package 1 because local authorities do not have influence over PT fares. Thus, Package 1 corresponds to the current institutional arrangement while Package 2 the future institutional arrangement.

It is necessary to define the ranges within which each policy instrument could be adjusted for optimisation. These were based on practical and acceptability constraints and on discussions with the cities. The upper and lower policy bounds that were applied during the optimisation procedures are as follows:

- PT fares: −50 to +100%
- PT frequency: −50 to +200%
- Cordon charge: 0 to 10€
- Road capacity: −20 to +5%

As has been mentioned, two types of financial constraints are considered, as follows:

- The whole strategy should be self-financing.
- The PT operator should at least break-even at the evaluation discount rate.

Both constraints are considered in the MARS and only the first constraint is modelled in TPM, although some constrained solutions are found by sensitivity analysis rather than by running a constrained optimisation.

4.1. The Edinburgh optimisation analysis using MARS

4.1.1. Package 1—unconstrained solutions

Table 6 shows the percentage changes in peak and inter-peak PT frequencies in year 2006 and year 2016, the peak and inter-peak cordon charge in euros in years 2006 and 2016, and the percentage change in road capacity for all periods and all years for the optimal policy set—note that

Table 6
Package 1 optimisation results for MARS with and without finance constraints

Optimisation number/code	Frequency AM 2006 (%)	Frequency AM 2016 (%)	Frequency IP 2006 (%)	Frequency IP 2016 (%)	Road Price AM 2006 (€)	Road Price AM 2016 (€)	Road Price IP 2006 (€)	Road Price IP 2016 (€)	Road capacity all periods and years (%)	objective function (€m)	PVF (€m)	PT operator's PVF (€m)
S1	25	50	30	40	3.2	5.75	0.0	0.0	5	2067	798	−222
S1–S2	25	50	30	40	3.2	5.75	0.0	0.0	0	569	551	−379
S1b	20	23	20	23	3.2	5.75	0.0	0.0	5	2013	1073	4.4
S1–S2b	10	11	10	11	3.2	5.75	0.0	0.0	0	467	1002	3.0

the upper bound of 5% for road capacity change is always met so the presentation is simplified to one column. The final three columns show the objective function value, the change in PVF and the change in value of finance for the public transport operator.

The optimal unconstrained solution S1 consists of a 5% increase in road capacity across the whole study area, which is the upper bound for this instrument; increases in PT frequencies in both periods which increase over time; and the introduction of peak period cordon charges which also increase over time. Note that there are no charges in the inter-peak as the model assumes that there is no congestion in the inter-peak - hence the optimal charge should be zero.

As the road capacity change is on the upper bound, test S1–S2 was conducted to show the effect of removing the additional area-wide road capacity, i.e. it is assumed that capacity is unaltered over the period of study. The objective function value drops by 72% which shows the important contribution that road capacity improvements make. The road capacity improvement here is an area-wide policy. Other tests (Emberger et al., 2004) have shown that applying a 5% increase in capacity to radial movements contributes only 3.5% of the area-wide capacity improvements.

4.1.2. Package 1—finance-constrained solutions

For the unconstrained optimal solution, there is no problem with the first financial constraint; the revenues collected from the cordon charge outweigh the capital and operating costs associated with the PT frequency changes and for the low cost road capacity changes.

However, for the optimal strategy S1 the PT operator loses in the region of €222m over the evaluation period and in the case with no change in road capacities (S1–S2) the operator loses around €379m. Thus, there is a significant subsidy requirement to support the increased PT frequencies in both cases.

The obvious way to reduce the cost to the operator is to reduce the increase in frequencies. A number of sensitivity tests were conducted, with road cordon charges and capacity changes set as before, to find where the break-even point occurred for the PT operator. Thus, we have not optimised the objective function with a finance constraint, though this is possible; we have simply looked for where the constraint is binding by varying the levels which affect the finance for public transport operators. Table 6 shows the highest scoring combinations which just break-even; these are coded S1b and S1–S2b for the cases with and without capacity changes.

Note that in the first case with capacity increases, the long run change in frequency is +23%, whereas with no capacity increases the long run change is only +11%. This is because the public transport users benefit from the increased speeds due to increases in road capacity which bring a greater mode shift to public transport from slow modes which, in turn, pays for additional services. Note also that the strategy S1b provides the best financial return (with the highest PVF) and with no subsidy required to PT operators.

In the 'with capacity' case (S1b) the break-even constraint has only reduced the objective function value by around 3% (€54m), whereas in the 'no capacity change' case (S1–S2b) the objective function value is reduced by €102m or 18%. This is due to the greater operator losses in the initial unconstrained optimum without capacity changes compared to those with capacity changes, which have to be recouped by a greater reduction in services.

4.1.3. Package 2—unconstrained solutions

Table 7 shows the optimisation results for Package 2. Note that the fare changes are optimal at the lower bound of −50% for both periods and all years.

S2 has increases in PT frequencies of 60%—higher than for Package 1. This can be explained by the fact that the fare reductions attract more users who then benefit from the reduced wait times and hence justify greater increases in service levels. However, the objective function is relatively insensitive to changes in frequencies and the fare and road capacity changes contribute over 80% of the final value. This confirms that fare reductions and capacity changes dominate the solution and are in this case on their lower and upper bounds, respectively. The addition of fare changes increases the objective function value from S1 by 75%.

4.1.4. Package 2—finance-constrained solutions

The unconstrained optimum resulted in fare reductions of 50% and increases in PT frequency of 60%. The large fare reductions and increases in frequency mean that both financial constraints are broken this time. Various

Table 7
Package 2 optimisation results for MARS with and without finance constraints

Optimisation number/code	Fare change AM 2006 (%)	Fare change AM 2016 (%)	Fare change IP 2006 (%)	Fare change IP 2016 (%)	Frequency AM 2006 (%)	Frequency AM 2016 (%)	Frequency IP 2006 (%)	Frequency IP 2016 (%)	Road price AM 2006 (€)	Road price AM 2016 (€)	Road price IP 2006 (€)	Road price IP 2016 (€)	Road capacity all periods and years (%)	Objective function (€m)	Present value of finance (€m)	PT operator's PVF (€m)
S2	−50	−50	−50	−50	60	60	60	60	5.0	6.0	0.0	0.0	5	3604	−2556	−3297
S2b	−5	−5	−5	−5	5	5	5	5	5.0	6.0	0.0	0.0	5	2038	1178	0
S2-pvf-opt	−50	−49	−12	−38	2	50	7	16	4.3	8.2	2.7	4.4	3.3	3020	258	−1995

sensitivity tests were conducted by varying fares and frequencies around the S2 solution to lower costs to operators.

S2b is the solution which ensures that the PT operator breaks even. Notice that the fare reductions are now only 5% and the frequency changes are only +5%. The costs of the frequency changes are balanced by increased fare revenues (despite the 5% reduction in fares). Since the road cordon charges were not revised downwards this solution results in a large PVF overall. Fares are then reduced further to find where the PVF constraint is just broken.

S2-pvf-opt shows the optimised result where all variables are allowed to vary. This solution shows that re-optimising the road prices upwards in the peak and introducing them in the off-peak allows us to retain the 50% fare reductions in the peak, and to retain most of the fare reduction in the off-peak. The long-term frequency increases are similar to the unconstrained levels but the increases are delayed to help meet the PVF constraint—discounting seems to play a role here. With all instruments allowed to vary, the PVF-constrained optimum reduced welfare by only €402m or 11%.

4.2. The Edinburgh optimisation analysis using TPM

4.2.1. The optimal transport strategies

As with the MARS model, two packages of transport policies with and without fares changes, and with and without financial constraint are identified. Optimal strategies obtained for Edinburgh in Packages 1 and 2, with and without the constraint that PVF ≥ 0, are listed in Table 8.

Consider first the unconstrained optimisations. In general terms, the optimal strategy in Package 1 is to increase bus service levels and to apply a cordon charge to the central area. When the PT fares policy instruments are introduced in Package 2, the optimal strategy is to reduce them. The fare reductions are either at, or very close to, the lower bound of −50%.

It is interesting to compare the optimal strategies within Package 1 to those in Package 2. The bus service level increase in Package 2 is greater than in Package 1. 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.

When the financial constraint is included in the optimisation of Package 1, we see that PT frequencies are increased by much smaller percentages than in the unconstrained case. Cordon charges are higher when satisfying the financial constraint than when the constraint is not applied. In the optimal strategy of Package 2, where fares policies can be varied, the constrained solution has smaller fare decreases than the unconstrained solution. In 2006, AM peak fares are actually raised by 36% relative to the do-minimum case and remain higher than in the do-minimum for virtually all of the period from 2006 to 2016.

Table 8
Optimal transport strategies with TPM for the two packages with and without financial constraints

Policy	Year	Time	Unconstrained Package 1	Constrained Package 1	Unconstrained Package 2	Constrained Package 2
Fares (%)	06	AM	–	–	−46	36
Fares (%)	06	IP	–	–	−48	−40
Frequency (%)	06	AM	127	89	188	70
Frequency (%)	06	IP	103	77	198	65
Cordon charge (€)	06	All	1.84	3.95	2.42	2.84
Fares (%)	16	AM	–	–	−50	−2
Fares (%)	16	IP	–	–	−49	−31
Frequency (%)	16	AM	123	68	120	66
Frequency (%)	16	IP	98	69	104	67
Cordon charge (€)	16	All	4.02	5.18	2.23	5.48

The reason is that fares are raised to help meet the financial constraint. This will be confirmed in the next subsection. By comparing the two financially constrained optimal strategies, we can see that the PT frequency and cordon charge are very much the same. Therefore, one cannot expect much reduction in fares when fares are allowed to change. We can also compare the constrained Package 2 strategy with the unconstrained strategy. The frequency increases in the constrained strategy are only one-third of those in the unconstrained strategy. The cordon charge is applied only in the central area. Therefore, the only way to reduce the financial requirement is to increase fares. Again, this will be discussed further in the next subsection.

4.2.2. *Impacts of the optimal strategies*

The optimal transport strategies maximise objective achievements by reducing total traffic volumes (vehicle-km) and so increasing road speeds. Fig. 3 shows relative changes in person trips by mode which result from the constrained and unconstrained optimal strategies of the two packages. The results are given for the mid-term year of 2010.

The first point to note from the figure is that all strategies reduce car trips and increase bus trips. There are larger mode shifts to buses from cars in Package 2 than in Package 1 in the unconstrained strategy packages, as can be expected from the differences in the optimal strategies of the two packages—there is a 50% reduction in PT fares and a much higher frequency increase in Package 2. This is true only in

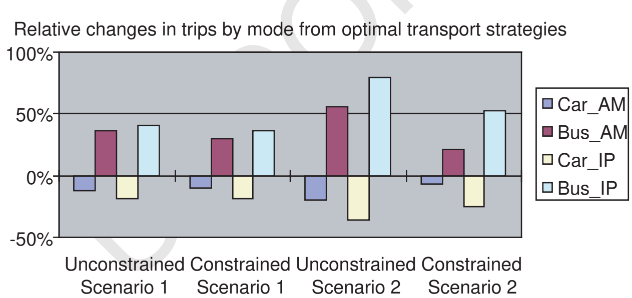

Fig. 3. Relative changes in person trips by mode in 2010 from optimal transport strategies for the two policy packages with and without financial constraints—TPM.

the inter-peak in the constrained cases, however. The bus patronage is actually lower in the AM peak in Package 2 than in Package 1. This is simply because buses are made less attractive by increased fares in Package 2. The effect of the constraint is that the smaller increase in PT service levels in the constrained case leads to a smaller shift away from car in both time periods.

The economic impacts of the optimal strategies are summarised in Table 9. Note that the figures listed in the tables 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 all cases. Note also that each optimisation is listed in one column of the table.

Table 9
Economic impacts of optimal transport strategies with TPM for the two policy packages with and without financial constraints

Benefits (€m)	Unconstrained Package 1	Constrained Package 1	Unconstrained Package 2	Constrained Package 2
Car user money saving	−553	−921	−95	−950
PT user money saving	0	0	965	139
Car user time saving	1006	997	1171	955
PT user time saving	1415	1068	1623	1002
Parking operator revenue	−626	−634	−782	−568
PT operator revenue	556	469	−373	353
PT operator cost	−1108	−706	−1318	−652
Toll operator revenue	760	1026	503	1010
Toll operator cost	−44	−44	−44	−44
Government revenue	−110	−108	−137	−100
External benefit	387	432	574	455
Objective function	1685	1577	2085	1598
Total user benefits	1868	1144	3663	1145
Value of finance	−571	2	−2152	0

Consider first the optimal strategy of the unconstrained Package 1 scenario. The strategy brings about time savings for both car users and PT users, though for car users, the package involves a monetary cost from road charging. The PT operator gets increased revenue from increased PT patronage, but the revenue is outweighed by increased capital and operating costs due to bus frequency increases. The toll operator, on the other hand, enjoys a relatively large profit from the road charging. Note that the reduction in parking operator's revenue is due to reduced car trips.

With reduced fares in the unconstrained Package 2 scenario, there is a relatively large increase in PT users' money savings and time savings compared with Package 1. The benefits for car users are also larger. As a result, the total road users' benefits are much larger than those in the unconstrained Package 1. However, the PT operator incurs a large loss of revenue due to reduction of fares. The capital and operating costs for the PT operator are also larger compared with Package 1 due to a larger increase in bus frequencies. As a result, the Package 2 strategy is more expensive than that of Package 1, with much lower values of finance. On the other hand, the objective function is increased by 24%, indicating clearly the benefits to be gained from a fares reduction.

In the absence of the financial constraint, neither of the two strategies is self-financing. When financial constraints are imposed, the values of the objective function for the constrained strategies were lower than for the unconstrained strategies. This can be explained by examining the main elements that constitute the objective function.

For both constrained policy packages, the user benefits are reduced in comparison with the unconstrained strategies. Higher cordon charges lead to lower money savings for private transport mode users, while less intensive fare reduction strategies lead to substantially lower money savings for public transport users in Package 2. There are lower time savings for all road mode users. This occurs because of the smaller mode shift from car to public transport that results from smaller fare decreases and fewer bus services. These two points lead to total user benefits that are much lower for each package's constrained solution than for its unconstrained one. The reduction in user benefit is particularly stark in Package 2. Also in the constrained cases, total operator revenues increase considerably. This increase is most noticeable in Package 2 where the PT fares were increased in the AM period. Operator costs, both capital and operating, are lower in the optimal strategy with the finance constraint. Once again, this is due to the lower number of additional PT services introduced in the constrained optimal strategy. Thus, the net benefit for PT operators is increased.

The financially constrained optimal strategies for Edinburgh save the transport operators money by cutting back on the introduction of additional PT services, and therefore on the capital and operating costs. However, the main source of the positive PVF seems to be the enormous increase in revenues that is generated by higher PT fares and a higher cordon charge. This is particularly the case in Package 2, in which the PT operator's revenue changes from negative to positive and the toll operator's revenue is doubled with the introduction of the constraint. Users are much worse off than in the unconstrained strategy; they are persuaded to switch modes more by the 'stick' of higher costs for private transport modes, rather than by the 'carrot' of better public transport.

5. Conclusions and implications for strategy design

This paper has investigated the contribution of individual policy instruments and the design of optimal policy packages by using two models of the same city to assess welfare gain using a comprehensive objective function. The two models produce consistent results for some conclusions, but differ in the predicted magnitude of effect for others.

Both models produce similar recommendations for change for individual instruments, with often similar optimal levels. Fares should be reduced towards the lowest level tested, of −50%. Public transport frequencies should be increased by 50% in the peak and 25% in the off peak according to the MARS model, but by around three times these levels according to the TPM model. Cordon charges of around €5 should be introduced to enter the city centre in the peak.

The models agree that peak period interventions are more effective than off peak ones, though neither model was particularly effective in modelling off peak cordon charges. The models differ in their assessment of the most effective individual policy instruments. The MARS model suggests that fares reductions and fuel tax changes produce the greatest welfare gain. Cordon charges are more effective than public transport frequency increases, and also more effective than parking charge increases. Low cost increases in capacity are shown to be beneficial overall, but to increase car use, and hence accident and emission costs. The TPM model suggests that peak period frequency increases are the most effective, and that cordon charges are more effective than fare reductions.

Both models indicate the same process for the achievement of welfare gain, with the principal benefit arising from travel time savings to users, and with substantial money transfers between users, operators and the government, depending on the nature of the policy instrument. The scale of impact was typically larger for the TPM model than the MARS model.

Optimal strategies were tested in six ways: a package of measures which excluded fares changes, which are currently outside local authority control in UK cities other than London; a package which included fares changes; two similar packages with constraints to ensure that the public transport operator breaks even; and two similar packages constrained to ensure that the overall transport system pays for the improvements made over a 30 year period.

The models agree that the unconstrained optimum strategy without fares changes involves increases in public transport frequency and the introduction of a cordon charge to enter the city centre. The MARS model suggests frequency increases of 50% in the peak and 40% off peak by 2016, while TPM suggests 120 and 100%. MARS advocates a cordon charge of €5.75, and TPM €4.00 by the same date.

The models also agree that, with fares allowed to be varied, they should be reduced by around 50% to achieve the optimum performance, with frequencies further increased. MARS suggests a 60% frequency increase by 2016, while TPM suggests an increase of around 200% by 2006, settling down to around 120% by 2016. The models differ in the assessment of the further changes needed in cordon charges; MARS proposes a modest further increase to €6.00, while the TPM suggests that the charge in 2016 could be reduced to €2.20. MARS suggests that the optimal strategy with fares changes included is 75% better than the strategy which excludes fares, while TPM estimates a 25% improvement.

The requirement for the public transport operator to break even is not surprisingly a more severe constraint on the optimal strategy which includes fares reductions. The MARS model suggests that in the first package, modest changes to frequency increases and cordon charges could enable the operator to break even with a reduction in welfare gain of only around 3%. Conversely in the second package the fares reductions and frequency increases have to be severely curtailed, losing over 40% of the strategy's benefits.

The requirement for the strategy overall to pay for itself is less demanding. For MARS the package without fares reductions requires no change, while that with a fares reduction requires a lower frequency increase and a higher cordon charge, resulting in a reduction of around 20% in welfare gain. For TPM, both packages again require lower frequency increases and higher cordon charges; these are achieved with reductions of under 10% in welfare gain for the package without fares reductions, and of around 25% for the package with fares reductions.

Generally, these results reiterate the importance to optimal strategies of fares reductions, frequency increases and road pricing found in earlier research. They thus strengthen the case for local authorities to be given powers to introduce road pricing and, in the UK outside London, to be given back the powers to influence public transport fares.

The financially constrained strategies demonstrate the important message that optimal transport strategies need not be expensive. Optimal strategies have been identified which pay for themselves in 30 years, and generate welfare gains of around €3000m, or €6000 per capita as predicted by MARS or around half these values as estimated by TPM.

The fact that the two models produced some differing results in terms of scale of impacts and relative importance of policy instruments introduces a cautionary note. Policy makers need to be aware of the assumptions underlying the models that they use. In this case, it appears that the principal differences arise from the inclusion of an overcrowding effect in TPM, and of higher levels of demand response generally in TPM than in MARS. Such models are reliable in indicating the direction in which policy should be taken, which is the most important message from this paper. The more detailed recommendations on scale of change need to be checked carefully before policy commitments are made.

References

Dasgupta, M., Oldfield, R., Sharman, K., Webster, V., 1994. Impact of Transport Policies in Five Cities. TRL, Crowthorne (PR 107).

DETR, 1998.Anon., 1998. A new deal for transport: better for everyone. TSO, London.

DETR, 1998.Anon., 1998. Understanding the new approach to appraisal. DETR, London.

ECMT, 1995.Anon., 1995. Urban transport and sustainable development. ECMT/OECD, Paris.

Emberger, G., May, A.D., Shepherd, S.P., 2003. Method to identify optimal land use and transport policy packages, Introduction of a Indicator/-Target based appraisal approach, Proceedings 8th International Conference on Computers in Urban Planning and Urban Management, CUPUM'03 SENDAI, Japan, 27 - 29 May 2003 2003.

Emberger, G., May, A.D., Shepherd, S., 2004. Methods to identify optimal land use and transport policy packages: a comparison of area-wide and spatially constrained policies, Paper presented at the 10th World Conference on Transport Research, Istanbul July 2004 2004.

FATIMA, 2000. Final Report. DG7 Urban Transport Research, 4th Framework Programme. EC, Brussels.

Fowkes, A.S., et al., 1998. A shortcut method for optimisation of strategic transport models. Transportation Research 32A (2).

Lautso, K., et al., 2004. Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability (PROPOLIS) Final Report to the European Commission.

May, A.D., 1991. Integrated transport strategies: a new approach to urban transport policy formulation in the UK. Transport Reviews 11 (2).

May, A.D., Shepherd, S.P., Timms, P.M., 2000. Optimum transport strategies for European Cities. Transportation 27, 285–315.

May, A.D., Karlstrom, A., Marler, N., Matthews, B., Minken, H., Monzon, A., Page, M., Pfaffenbichler, P.C., Shepherd, S.P., 2003. Developing Sustainable Urban Land Use and Transport Strategies-A Decision Makers' Guidebook, Institute for Transport Studies. University of Leeds, Leeds.

Minken, H., Jonsson, D., Shepherd, S.P., Jarvi, T., May, A.D., Page, M., Pearman, A., Pfaffenbichler, P.C., Timms, P., Vold, A., 2003. Developing Sustainable Urban Land Use and Transport Strategies - A Methodological Guidebook. Institute of Transport Economics (P.O.Box 6110 Etterstad, 0602 Oslo).

Nelder, J.A., Mead, R., 1965. A simplex algorithm for function minimization;. Computer Journal 7, 308.

OPTIMA, 1998. Optimisation of policies for transport integration in metropolitan areas. Final report. Office for official publications of the European Communities, Luxembourg.

Paulley, N.J., Webster, F.V., 1991. Overview of an international study to compare models and evaluate land use and transport policies. Transport Reviews 11 (3).

Paulley, N., Zhang, X., Ash, A., Emberger, G., Shepherd, S.P., 2004. The Design of Optimal Transport Strategies: The Impacts of Land Use and Transport Interactions. European Transport Conference, PTRC, Strasbourg.

Pfaffenbichler, P., 2003. The strategic, dynamic and integrated urban land use and transport model MARS (Metropolitan Activity Relocation Simulator): Thesis available from Technical University of Vienna.

Pfaffenbichler, P., Shepherd, S.P., 2003. A dynamic model to appraise strategic land-use and transport policies. European Journal of Transport and Infrastructure Research. Special Issue: Sustainable Transport, 2(3/4) (2003).

Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., 1990. Numerical Recipes. The Press Syndicate of the University of Cambridge pp. 289–293 (Reprinted).

Proost, S., van Dender, K., 2000. TRENEN II STRAN. Final report for publication. Leuven, Katholieke Universiteit.

Simmonds, D.C., Still, B.G., 1999. DELTA/START: Adding Land Use Analysis to Integrated Transport Models. Proc 8th WCT, vol. 4. Elsevier, Amsterdam.

TRL, 2001.Anon., 2001. TRL Transport Policy Model User Manual. TRL, Crowthorne.

Designing optimal urban transport strategies: The role of individual policy instruments and the impact of financial constraints.

S.P. Shepherd et al.

Proof corrections – 14/9/05

Please note the following corrections.

Page 2 line 126 the second reference should read "Pfaffenbichler and Shepherd, 2003". This addresses the reference issue.

Page 5 Table 2. The formatting of the headings are out of line. The first "total" should be under "population" and the second "total" should be under "Area" and "Modal split" should be above the three columns "SL, PT, PC" Table 2 should look like this :-

Table 2: Overview of case study data.

Model	**Population (000's)**				**Area (km^2)**			**Modal split*** **(%)**			**Cars / 1000 population**
Zone / Mode	**Inner**	**Outer**	**External**	**Total**	**Inner**	**Outer**	**Total**	**SL**	**PT**	**PC**	**All zones**
MARS	n/a	n/a	n/a	1,071.8	n/a	n/a	2,305	22	25	54	371
TPM	58.0	393.5	2,288.4	2,739.9	28	352	n/a	13	23	65	342

* SL = Slow modes; PT = public transport; PC = private car.

Page 12 Table 6. The coding has been changed. Please revert to original coding of model runs by replacing "S1-S2" with "S1-2" and "S1-S2b" with "S1-2b" otherwise it looks as though we have subtracted a later model run named S2 from model run S1.

The references to the runs in the text should also be changed. These occur on lines 1258, 1277, 1302 and 1317.

Also in Table 6, capitalise the heading "Objective function".

Table 3 : Tests conducted and optimum single instrument values.

Instruments	**Application**	**MARS Range**	**Optimum MARS**	**TPM Range**	**Optimum TPM**
Fares peak	Study area	−50% to +100%	-50%	−50% to +100%	−45%***
Fares off-peak	Study area	−50% to +100%	-50%	−50% to +100%	−45%***
Frequencies Peak	Study area	−50% to +200%	50%	−50% to +200%	140%
Frequencies Off-peak	Study area	−50% to +200%	25%	−50% to +200%	80%
Cordon charge both periods	Cordon around zone 1	N/A	N/A	€0 to €8	€5.65
Cordon charge peak	Cordon around city centre	€0 to €6	€5.0	N/A	N/A
Cordon charge off-peak	Cordon around city centre	€0 to €6	€2.0*	N/A	N/A
Parking charge short stay	City centre	€0 to €6	€2.0**	N/A	N/A
Parking charge long stay	City centre	€0 to €6	€5.0**	N/A	N/A
Road capacity peak	Study area	−10% to +5%	5%	N/A	N/A
Road capacity off-peak	Study area	−10% to +5%	5%	N/A	N/A
Fuel tax	Study area	−50% to +200%	200%	N/A	N/A
Fuel efficiency	Study area	1% p.a.	1% p.a.	N/A	N/A
Smart card (bus speed increase)	Study area	N/A		0% to 5%	5%

*The optimum value of off-peak cordon charge in MARS is actually zero. The value €2 was used to provide a comparison with short stay parking charges.
**The long stay parking charge for MARS was set to be equal to the peak cordon charge to provide a direct comparison.
***The optimum fare change for TPM lies on the −50% limit but tests were conducted in 15% steps.

Table 4 : Edinburgh : Summary of MARS *OF* and its elements for individual instruments. (Units are €m discounted over the evaluation period)

	Peak Fare	**Off-peak Fare**	**Peak Frequency**	**Off-peak frequency**	**Peak Cordon charge**	**Off-peak Cordon charge**	**Parking Long stay**	**Parking Short stay**	**Road capacity Peak**	**Road capacity Off-Peak**	**Fuel Tax**	**Fuel efficiency per annum**
Change in instrument level	−50%	−50%	50%	25%	5	2	5	2	5%	5%	200%	1%
Spatial coverage	Area	Area	Area	Area	Central	Central	Central	Central	Area	Area	Area	Area
OF	1162	407	156	51	374	-67	172	9	548	912	1178	239
PVF	-1217	-1485	-367	-177	1151	699	169	55	73	155	10105	-553
User ben. Money PT	1437	1802	0	0	0	0	0	0	0	0	0	0
User ben. Money Car	88	0	28	0	-1272	-789	-135	-54	63	130	-10133	666
User Ben. Time PT	329	0	378	227	234	0	68	4	203	244	393	-34
User Ben. Time Car	403	15	125	3	218	4	57	4	261	501	504	-46
User Ben Time NM	0	0	0	0	0	0	0	0	0	0	0	0
PT Capital	0	0	-22	0	0	0	0	0	0	0	0	0
PT Operating	0	0	-454	-301	0	0	0	0	0	0	0	0
PT fares (operator)	-1082	-1389	133	141	134	18	40	3	44	97	476	-35
Parking revenue	-2	-3	0	-1	-18	-14	144	53	2	4	-10	1
Net Toll Revenue	0	0	0	0	1082	723	0	0	0	0	0	0
Govt.Capital	0	0	0	0	0	0	0	0	-1	-1	0	0
Govt. Revenue	-133	-93	-24	-16	-43	-29	-14	-1	29	55	9639	-519
Local externalities	47	48	4	8	13	11	5	0	-46	-99	163	14
CO2	74	26	-13	-11	28	8	8	1	-7	-20	144	192
OF/*OF*-fuel	98.7%	34.5%	13.2%	4.3%	31.7%	−5.7%	14.6%	0.8%	46.6%	77.5%	100.0%	20.3%

Table 5**:** Economic benefits of individual policies for Edinburgh (€m) for policies obtained from sensitivity analysis using TPM

Policy instruments	**Fares AM**	**Fares IP**	**Frequency AM**	**Frequency IP**	**Cordon Charge**	**Bus speed**
Optimal policy values	**–45%**	**–45%**	**140%**	**80%**	**€5.65**	**5%**
OF	563	97	1305	148	695	419
All Operators' benefits (PVF)	−587	−197	−902	−197	910	11
User benefits						
Money savings						
Private transport modes	89	2	189	2	−1382	29
Public transport modes	481	277	0	0	0	0
Time savings						
Private transport modes	452	5	784	3	761	153
Public transport modes	−34	−45	1040	334	66	166
Total user benefits	987	239	2013	339	−553	348
Operators' benefits						
PT operator	−439	−197	−506	−197	118	58
Parking operator	−97	0	−310	0	−365	−32
Toll operator	0	0	0	0	1227	0
Government	−52	0	−85	0	−71	−16
External benefits						
Accident and noise benefits	42	23	60	11	92	15
Environmental benefits	24	6	5	−10	52	10
Total external benefits	66	29	65	2	142	24
CO2 benefits	97	24	129	6	198	35

Note: The notations used in the labels for policy instruments are: "Fares"=fares policy; "Frequency"=frequency policy; "Bus speed" = bus speed increase representing Smart Cards policy which reduce boarding times; "AM"=AM peak; "IP"=inter-peak.

Table 6: Package 1 optimisation results for MARS with and without finance constraints.

Optimisation number / code	Frequency AM 2006 (%)	Frequency AM 2016 (%)	Frequency IP 2006 (%)	Frequency IP 2016 (%)	Road Price AM 2006 (€)	Road Price AM 2016 (€)	Road Price IP 2006 (€)	Road Price IP 2016 (€)	Road capacity all periods and years (%)	objective function (€m)	*PVF* (€m)	PT operator's *PVF* (€m)
S1	25	50	30	40	3.2	5.75	0.0	0.0	5	2067	798	-222
S1-2	25	50	30	40	3.2	5.75	0.0	0.0	0	569	551	-379
S1b	20	23	20	23	3.2	5.75	0.0	0.0	5	2013	1073	4.4
S1-2b	10	11	10	11	3.2	5.75	0.0	0.0	0	467	1002	3.0

Table 7: Package 2 optimisation results for MARS with and without finance constraints.

Optimisation number / code	**Fare change AM 2006 (%)**	**Fare change AM 2016 (%)**	**Fare change IP 2006 (%)**	**Fare change IP 2016 (%)**	**Frequency AM 2006 (%)**	**Frequency AM 2016 (%)**	**Frequency IP 2006 (%)**	**Frequency IP 2016 (%)**	**Road Price AM 2006(€)**	**Road Price AM 2016(€)**	**Road Price IP 2006(€)**	**Road Price IP 2016(€)**	**Road capacity all periods and years (%)**	**objective function (€m)**	**present value of finance(€m)**	**PT operator's *PVF* (€m)**
S2	-50	-50	-50	-50	60	60	60	60	5.0	6.0	0.0	0.0	5	3604	-2556	-3297
S2b	-5	-5	-5	-5	5	5	5	5	5.0	6.0	0.0	0.0	5	2038	1178	0
S2-pvf-opt	-50	-49	-12	-38	2	50	7	16	4.3	8.2	2.7	4.4	3.3	3020	258	-1995

Table 8. Optimal transport strategies with TPM for the two packages with and without financial constraints.

Policy	Year	Time	Unconstrained Package 1	Constrained Package 1	Unconstrained Package 2	Constrained Package 2
Fares (%)	06	AM	-	-	-46	36
Fares (%)	06	IP	-	-	-48	-40
Frequency (%)	06	AM	127	89	188	70
Frequency (%)	06	IP	103	77	198	65
Cordon charge (€)	06	All	1.84	3.95	2.42	2.84
Fares (%)	16	AM	-	-	-50	-2
Fares (%)	16	IP	-	-	-49	-31
Frequency (%)	16	AM	123	68	120	66
Frequency (%)	16	IP	98	69	104	67
Cordon charge (€)	16	All	4.02	5.18	2.23	5.48

Table 9. Economic impacts of optimal transport strategies with TPM for the two policy packages with and without financial constraints.

Benefits (€m)	**Unconstrained Package 1**	**Constrained Package 1**	**Unconstrained Package 2**	**Constrained Package 2**
Car user money saving	-553	-921	-95	-950
PT user money saving	0	0	965	139
Car user time saving	1006	997	1171	955
PT user time saving	1415	1068	1623	1002
Parking operator revenue	-626	-634	-782	-568
PT operator revenue	556	469	-373	353
PT operator cost	-1108	-706	-1318	-652
Toll operator revenue	760	1026	503	1010
Toll operator cost	-44	-44	-44	-44
Government revenue	-110	-108	-137	-100
External benefit	387	432	574	455
Objective function	**1685**	**1577**	**2085**	**1598**
Total user benefits	**1868**	**1144**	**3663**	**1145**
Value of finance	**-571**	**2**	**-2152**	**0**