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Transportation Research Part A 39 (2005) 548–565
TRANSPORTATION RESEARCH PART A
www.elsevier.com/locate/tra

Optimal land use and transport planning for the Greater Oslo area

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Received 30 August 2004; received in revised form 25 February 2005; accepted 26 February 2005

Abstract

The aim of this paper is to describe and apply a comprehensive framework to derive optimal and acceptable land use and transport strategies. The framework includes a constrained optimisation algorithm that approximates and maximises an objective function with respect to available land use and transport instruments and constraints. We apply the framework to Greater Oslo based on output from a land use and transport model for this area (RETRO). Available instruments are toll ring charges, public transport frequency and a discrete land use instrument. Constraints represent acceptable levels on the available instruments, and acceptable levels on equity between geographical zones, accident cost reductions and the financial balance of the actual strategy. Strategies are found in situations with increased and reduced fuel taxes, and the direct and indirect land use and transport effects of the optimal strategies are assessed.

Keywords: Location; Household; Travel; Objective; Approximation; Optimisation

1. Introduction

While developing land use and transport strategies, city planners need to consider objectives of increasing economic efficiency and reducing pollution, noise, accidents and climate costs. The

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0965-8564/$ - see front matter
doi:10.1016/j.tra.2005.02.007

objectives can be accounted for in terms of cost and benefits in an overall objective function. Strategies can be found that maximise the objective function with respect to available instruments. It is likely, however, that the optimal levels on the instruments would be politically unacceptable, and give effects in conflict with absolute goals of accident cost reductions, equity, financial balance etc. Thus, in practise we would look for strategies that maximises the objective function within the acceptable levels on the instrument values and under the constraints that actual goals are reached.

The aim of this paper is to describe and apply a comprehensive framework to determine optimal and acceptable land use and transport strategies. The main parts of the framework are: (1) A Land Use and Transport Integration (LUTI) model, (2) a cost benefit evaluation framework, and (3) an objective function OF based on the evaluation framework and a constrained optimisation algorithm that approximates and maximises OF with respect to available land use and transport instruments and constraints.

Greater Oslo is used as a case to demonstrate the framework. In 1998 the number of inhabitants was 0.5 million in Oslo city and 0.45 million in surrounding municipalities (Akershus county). Towards year 2015, it is expected that the population will grow by 70,000 people in Oslo and that there will be a need for 40,000 new residences (Municipality Plan for Oslo 2000). The expected high growth situation in Akershus implies a population increase of around 100,000 people (County Plan for Akershus 2000). This rapid development means that realized planning strategies can have considerable impact on travel behaviour and residential and workplace location in the area, which again will affects accessibility and environmental conditions.

The framework is used to find optimal strategies for situations with different levels on fixed fuel taxes and fuel combustion efficiency. Instruments available for optimisation comprise toll charges, public transport (PT) frequency, and a land use instrument. There are constraints on: the instruments, accident cost reductions, equity and finance. Herein, the RETRO model for Greater Oslo is used to assess land use and transport indicators in the evaluation framework. Graphical response surfaces and cost benefit tables enhance the insight and give a better foundation for deciding the right strategy to put into practise.

2. The RETRO model

Some existing LUTI models are made operational and solvable by interchanging data at an aggregate level, and by applying utility functions and transport submodels with simple structures. Other models are elaborate and well founded, but can have the drawback that model complexity makes them difficult to understand, collect data for and apply. The RETRO model is in the former of these categories. It is a real network LUTI model for the urban area of Greater Oslo, with sub models for *residential*—and *employment location*, *car ownership* and *travel behaviour*. Area units for residential, workplace, and transport purposes, are exogenously distributed to zones in RETRO. This is unlike most other LUTI models, where land development and land prices are endogenously determined.

RETRO consistently connects land use and an established four-stage transport model for peak and off peak trips. It is calibrated to equilibrium within and between the various markets (i.e., travel, residential—and employment location). The car ownership model was originally developed as part of the national model system for private travel (Ramjerdi and Rand, 1992), where fixed and variable car costs and real income are used as input. First the car ownership model is run and then the three other submodels are run sequentially and iteratively in a loop while interchanging data, where a method by Powell and Sheffi (1982) is used to guarantee convergence. About three iterations are needed to achieve convergence and equilibrium, where the travel model includes five inner iterations (between route choice (EMME/2) and travel demand). One RETRO run takes about 90 min on an Intel Pentium 4, 2.0 GHz CPU.

2.1. Travel behaviour

RETRO assesses route, mode and destination choices and trip frequency, for periods with peak and off peak traffic load. The three last dimensions are described with a nested logit model (Ben-Akiva and Lerman, 1985) for travel within and between the 27 city districts of Oslo and the 22 municipalities of Akershus. Calculation of mode choice probability (car, public transport or walk/bicycle) between zones is found by a multinomial logit formulation with generalised travel costs plus elements dependent on individual's characteristics. A corresponding logsum C'_{id} with scale parameter μ^m for the aggregated travel cost of travelling from zone i to zone d is used as the lower nest in the logit formulation for the probability that an individual in zone i travels to destination d

$$P_{id} = \frac{\mathrm{e}^{(A_d + C'_{id})\mu^d}}{\sum_e \mathrm{e}^{(A_e + C'_{ie})\mu^d}}$$

where μ^d is a scale parameter and A_d is the average attraction utility of visiting destination zone d (includes indicators for the number of work places, public and private services and shopping centres).

A geometric distribution (Bhattacharyya and Johnson, 1977) is used to represent the marginal probability that an individual make q trips from zone i (Ben-Akiva and Lerman, 1985, p. 125). By assuming that the utility of making a q'th trip from zone i is equal for all q, the expected value of q becomes $E_{iq} = \exp\left(\mu \cdot \left(V_q + V_{ia}\right)\right)$. Here μ is a parameter, V_q depends on the characteristics of the individual and the logsum

$$V_{ia} = (1/\mu^d) \ln \sum_d \mathrm{e}^{(A_d + C'_{id})\mu^d} \tag{1}$$

expresses the average peak or off peak attraction—and access utility of mode and destination choices of trips from origin zone i. Total trips is found by weighing the modelled travel demand of a representative sample of individuals by the sample enumeration technique as described by Ben-Akiva and Lerman (1985).

A dispersion matrix is used to spread the total trips between the 49 greater origin and destination zones in Greater Oslo to corresponding trips between 438 smaller origin and destination zones covering the same area. The trips between the 438 zones is used in the fixed assignment algorithm of the EMME/2 software (INRO) for calculation of route choice and transport costs in the expected transport networks for road and public transport around 2015. The transport costs are then aggregated to costs between the 49 zones before they are used in assessments of travel demand and land use. The transport model is calibrated to the situation around 2015. Parameter estimates were found in earlier work (see Vold, 1999).

2.2. Residential location

The principle for determination of the housing rents in MEPLAN, TRANUS and DELTA, is to adjust the housing rents such that the share of residents in the zones stay within upper and lower limits (Echenique et al., 1990; De la Barra, 1989; Simmonds and Still, 1998). This pricing mechanism is also used in UrbanSim—except for hedonic elements in the underlying price of land (Wadell, 2000). This way of determining the prices is not required in RETRO's residential location submodel, since there are explicit constraints with upper and lower limits for the share of households in the zones. Upper u_i and lower limits l_i are set such that the share of households in the zones cannot be increased or decreased by more than 15% relative to a base case situation. These upper and lower limits are assumed to reflect the planner's preferences and choice.

The residential location model is consistently connected with the nested logit representation of travel behaviour by integration of peak periods attraction—and access utility V_{ia} (Eq. (1)) in the housing rent. Disutility is also integrated in the housing rent in terms household density $d_i(h_i) = \zeta \cdot (H \cdot h_i)/\mathrm{RH}_i$, where h_i is the share of the total number of households in the study area that is located in zone i, H is the total number of residences in Greater Oslo, RH_i is the area units regulated for housing supply in zone i, and ζ is a parameter. Finally, the zone specific constants ϕ_i accounts for housing standards and historic scarcity of housing within the zone. Thus housing rent capitalises zone characteristics by the hedonic price function $q_i(\mathbf{h}^{k+1}, \mathbf{h}^k) = d_i(h_i^{k+1}) + V_{ia}(\mathbf{h}^k) + \phi_i$ where the parameter values represent the household's expected willingness to pay. Here $\mathbf{h}^{k+1} = [h_1^{k+1}, \ldots, h_{49}^{k+1}]$ and $k+1$ is the iteration index for elements that are updated as part of the residential location model and k for elements that are calculated in the previous iteration and already applied as input in other submodels. Housing provider's provision of residences is found by solving the optimisation problem:

$$\max_{\mathbf{h}^{k+1}} V(\mathbf{h}^{k+1}) = \max_{\mathbf{h}^{k+1}} \sum_i [q_i(\mathbf{h}^{k+1}, \mathbf{h}^k) \cdot h_i^{k+1}]$$

$$\text{s.t.} \quad l_i \leqslant h_i^{k+1} \leqslant u_i \quad \forall i$$

$$\sum_i h_i^{k+1} = 1$$

where shadow prices represent extra costs of providing land for houses that are either sufficiently positive or negative to ensure that the exogenously set upper and lower limits for the shares of households in the zones are not violated. Hence the representation of residential location in RETRO is based on the assumption that the households always move to the houses provided by the housing providers, who maximise the profit by adjusting the distribution of houses in accordance with household's expected willingness to pay. The pool of out-migrants is subdivided to zones with in-migration according to the share of people that move into the respective zones. The socio-economic profile of the in-migrants to any zone corresponds to the socio-economic profile of the pool of out-migrants. Clearance of the housing market is ensured since altered distribution of houses would violate the upper or lower limits or reduce the profit. The C-version of the constrained optimisation algorithm DONLP2 (7/99), developed by P. Spellucci, Technical University at Darmstadt, is applied to solve the optimisation problem. The global optimum is always found since V is convex wit respect to $\mathbf{h}^{k+1}$.

In order to apply the method of maximum likelihood to estimate the hedonic price function representing the resident's willingness to pay, we introduce a multinomial logit model for the representative household's *preferences* for locating. Since all zone characteristics are capitalised in the housing rent the likelihood function becomes

$$L = \prod_i \left[\frac{\exp(\mu^h(-q_i(\tilde{h}_i) + d_i(\tilde{h}_i) + \widetilde{V}_{ia}))}{\sum_k \exp(\mu^h(-q_k(\tilde{h}_k) + d_k(\tilde{h}_k) + \widetilde{V}_{ka}))} \right]^{\tilde{h}_i} = \prod_i \left[\frac{\exp(\mu^h(-\phi_i))}{\sum_k \exp(\mu^h(-\phi_k))} \right]^{\tilde{h}_i} \tag{2}$$

where $\tilde{h}_i$ is the share of households in zone i in 2015 according to official statistics and $\widetilde{V}_{ia}$ is fixed at attraction and access utility in the base case situation. To ensuring a perfect fit between model output h_i for the base case and $\tilde{h}_i$, we apply the estimation criteria that $\hat{\phi}_1, \ldots, \hat{\phi}_n$ solve

$$\begin{aligned} &\max_{\mathbf{h}} \; V(\mathbf{h}, \phi_1, \ldots, \phi_n) = V(\tilde{\mathbf{h}}, \phi_1, \ldots, \phi_n) \\ &\text{s.t.} \quad l_i \leqslant h_i \leqslant u_i \quad \forall i \\ &\sum_i h_i = 1 \end{aligned} \tag{3}$$

By dual formulation, it is easily shown that first order conditions for a solution to (3) are given by

$$\phi_i = h_i \cdot \frac{\mathrm{d}(\mathrm{d}_i(h_i))}{\mathrm{d}h_i} + \mathrm{d}_i(h_i) + \widetilde{V}_{ia}|_{h_i=\tilde{h}_i} \quad \forall i \tag{4}$$

We use Eq. (4) to substitute ϕ_i in the likelihood Eq. (2) and obtain estimates by numerical maximisation of $\ln(L(\mu^h, \zeta))$ with respect to μ^h and ζ. The estimate of $\hat{\zeta} = -2.14$ implies that people dislike to live close to other people. Thus increasing density has a negative direct effect on the housing rent. The relationship between estimates of the logsum parameters $\hat{\mu}^h = -0.0041$ and $\hat{\mu}^d = -0.0226$ and $\hat{\mu}^m = -0.0235$ are all theoretically sound (see Ben-Akiva and Lerman, 1985). A future version of RETRO should include a convex function for the utility of density in order to explicitly reflect that, in reality, neither too low nor too high density is optimal. This will change V into a non-convex form, which may necessitate replacement of the DONLP2 algorithm by a more robust optimisation algorithm, for instance the simulated annealing optimisation method (see e.g., Brotchie, 1987).

2.3. Employment location

The employment location submodel of RETRO could be formulated similarly to that of the residential location model. However, due to the historic development of the model, such an option was not available at the time when the present model application was performed. Instead the conventional multinomial logit model for employment location originally developed for the IMREL model was applied (Anderstig and Mattsson, 1991). Generally the model relocates workplaces to places where the accessibility to the workforce is high and land use indicators are favourable. The utility of locating in a zone j is represented by $M_j = \alpha \cdot A_j + \beta_0 + \sum_k \beta_k \cdot I_{kj} + \varphi_j$, where the accessibility to the work force $A_j = \ln[\sum_i h_i \cdot \exp(\hat{\mu}^m \cdot C'_{ij})]$ depends on the location pattern of the households h_i and travel costs $\hat{\mu}^m \cdot C'_{ij}$ from the residential location and transport model, respectively. Significant and positive estimates were obtained by linear regression according to Ben-Akiva and Lerman (1985, p. 120) for α and β_1, β_2 and β_3, respectively, for the numbers of students at high schools and universities in the zones and area units for workplace/business purposes in the zones. The residuals from linear regression were subsequently used as zone specific parameters φ_j to ensure a perfect fit between base case model output of the share of workplaces in zones for year 2015 and official forecasts. Upper w_j^u and lower w_j^l bounds for the change in the share workplaces in the zones were set at ±30%. The rent is assumed constant (equal to the zone specific parameter) except for the shadow costs incurred with scarcity (which make the market mechanism similar to many other LUTI-formulations).

3. The evaluation framework

Output of land use and transport indicators from RETRO are used in the evaluation framework, which is a computer program that determines the strategies' impacts *per year* in terms of economic efficiency EEF, pollution costs PC, noise costs NC, accidents cost AC, global climate costs related to CO_2 emissions CC, and equity K_a.

3.1. Economic efficiency

Economic efficiency is expressed as

$$\text{EEF} = B + (1 + \lambda) \cdot \text{PVF}$$

where B is the present value of benefits and $\text{PVF} = -I + f$ is the present value of finance, where I represents infrastructure investments and f is the financial benefits to transport service suppliers plus the financial benefits to the government including revenue from fuel taxes and annual car taxes. $\lambda \cdot \text{PVF}$ is the shadow price of public funds representing the net economic synergies of transferring money. The results in this paper are based on a zero shadow price of public funds.

The present value of the benefits $B = u + v$ includes the housing rent paid to the housing provider's, u, and household's benefits expressed according to DSC (2001) as $v = L + A + C$, where L is residential location utility, A is destination attraction utility and C is transport costs. Location utility L_i in zone i comprises the disutility d_i, housing rent q_i plus positive or negative shadow costs, ρ_i, if either the maximum or minimum share of households for the zone is reached. To calculate the overall level on these utility components relative to a base case situation, Neuberger's second method "the rule of half" was applied according to DSC (2001), i.e., $\Delta q = (1/2) \cdot \sum_i (H_i + H_{i,\text{base}}) \cdot (q_i - q_{i,\text{base}})$, where H_i and $H_{i,\text{base}}$ are the total number of households in zone i in Greater Oslo in the alternative and the base case situations. Corresponding formulas were used to assess Δd and $\Delta\rho$. Destination attraction utility for people from zone i is expressed according to Sweet (1997) by $A_i = (1/\mu^d) \cdot \ln[\sum_j \exp(\mu^d \cdot A_{ij})]$, where μ^d is a logsum parameter and A_{ij} is the attraction utility of zone j for people from zone i. Thus, net overall attraction utility becomes $\Delta A = (1/2) \cdot \sum_{i'} (T_{i'} + T_{i',\text{base}}) \cdot (A_{i'} - A_{i',\text{base}})$, where $T_{i'}$ is the total number of trips from a zone i'—internal or external to Greater Oslo. Net monetary costs for car drivers are obtained by

$\Delta C_{\text{car,mon}} = (1/2) \cdot \sum_{i'j}(T_{i'j,\text{car}} + T_{i'j,\text{null,car}}) \cdot (C_{i'j,\text{car,mon}} - C_{i'j,\text{null,car,mon}})$. Time costs for car drivers, and monetary and time costs for *PT* travellers, are obtained correspondingly. Additional monetary cost for buying a car and other car costs that do not depend on distance are also accounted for.

3.2. Environmental and accident costs

Vehicle-specific distance and speed dependent emission functions from the MEET EU project (1999) are used to assess environmental costs of CO, VOC, NO_X, PM emissions (PC) and CO_2 emissions (CC) for all private gasoline and diesel cars. A constant relationship between CO_2 emissions and SO_2 emissions was assumed. The rate of emissions from cars with gasoline and diesel engines (0.09) was obtained from Bang et al. (1999). Costs of SO_2, NO_X, VOC and PM_{10} emissions were set according to Eriksen et al. (1999). Rosendahl's (2000) assumption on the shares of cars without studded tyres (10% in 1995/96 to 75% in 2015) and his assessment of marginal benefits of reductions were used in EMME/2 to respectively calculate the total production of road dust PM_{10} in Greater Oslo and costs of road dust of € 0.019 and € 0.0027 per vehicle km for 1998 and 2015.

Since it is irrelevant to calculate the local consequences of the CO_2 emissions, it is not unreasonable to assume that the CO_2 emissions costs corresponds to the national level CO_2 abatement costs to reduce the emissions taking place in year *i* to an acceptable level (e.g., according to the Kyoto agreement). We applied the estimate by Minken et al. (2001) that these cost amount to € 100 per ton CO_2 towards 2010 and increase linearly to € 200 in 2030.

Noise costs NC are assessed as a marginal noise cost per vehicle kilometre (from Eriksen et al., 1999) multiplied by total vehicle kilometres, except that the costs for bus and tram are slightly changed to make the differences between modes consistent with recent Swedish research.

Accident costs AC includes the number of accidents between cars, accidents where only soft travellers (walk/bicycle) are involved, and accidents where a soft traveller and a car are involved. Jansson's (1994) formula for the total change in accident costs was used. Jansson's model does not specify where pedestrians are walking, but expresses the conditions in terms of risk factors and transport activity. Risk factors were based on Elvik et al. (1997), risk elasticities on Elvik (1994) and Fridstrøm (1999, p. 150), and costs per accident on Elvik (1998) and Elvik et al. (1997).

3.3. Equity

To measure distributional impacts on household utility (i.e., equity) in a year *k*, we use the Kolm measure (Kolm, 1976),

$$K_{k,a}(\mathbf{x}) = \frac{1}{a}\log\left(\frac{1}{n}\sum_{i=1}^{n}\exp(a(\bar{x}_k - x_{i,k}))\right)$$

where n is the number of zones, and $a > 0$ is a transfer sensitive parameter which we have set at 0.0001 ($€^{-1}$), and $x_{i,k} = d_{i,k} + V_{ia,k}$ (€) is the utility changes *per household* in zone *i* in year *k*. Disutility, $d_{i,k}$, and accessibility, $V_{ia,k}$, are obtained from RETRO. Larger values of K_a are associated with reduced equity. The Kolm measure has the quality that equal absolute changes in utility for all population groups give no change in equity. This is different from the Gini measure (Dagum, 1987), where this would improve equity.

4. Objective function and optimisation

A strategy is considered optimal if the levels on instruments available for optimisation $\mathbf{X}_{2015}$ maximises the objective function

$$\mathrm{OF}(\mathbf{X}_{2015}) = \sum_{k=1998}^{2030} \frac{1}{(1+r)^{k-1998}} \cdot (W_k(\mathbf{X}_{2015}) - W_{k,\mathrm{base}}),$$

within an acceptable solution area, where $W_k = \mathrm{EEF}_k + \mathrm{PC}_k + \mathrm{NC}_k + \mathrm{AC}_k + \mathrm{CC}_k$ represents overall welfare in year k of a strategy and the same formula for $W_{k,\mathrm{base}}$ represents overall welfare in base case. A 7% discount rate r was used, in accordance with official Norwegian guidance (NOU, 1997). Prices are real and fuel efficiency is unchanged during the base case situation. The base case is based on detailed county plans for regulation of residential areas—representing official forecasts for infrastructure development, demographic development and land use. We consider these plans as today's trend of development, which implies greater areas for residential purposes. It is assumed that base case levels on transport instruments resemble today's situation during the whole period.[1]

W_k and $W_{\mathrm{k,base}}$ are only evaluated for year 2015. Values from 1998 to 2014 are approximated by $W_k = (2015-1998)^{-1} \cdot (k-1998) \cdot W_{2015}$ and in years after 2015 by $W_k = W_{2015}$, i.e., we assume that the policies are gradually changed towards policies determined for 2015.

We assume that the instruments available for optimisation by local authorities in year 2015 are: $\mathbf{X}_{2015} = \{X_{2015,\mathrm{PTfreq}}, X_{2015,\mathrm{toll}}, X_{2015,\mathrm{land}}\}$ = {*Public transport (PT) frequency* ($X_{2015,\mathrm{PTfreq}}$), *Peak toll ring charges* ($X_{2015,\mathrm{toll}}$), *A discrete instrument that represents the choice between developments towards 2015 according to what the local authorities describe as today's trend of development and an alternative trend for development*[2] ($X_{2015,\mathrm{land}}$)}. To reduce the computation time and the complexity of this paper, we decided to keep other instruments available for local authorities at today's levels (e.g., parking charges, PT fares).

Whereas welfare and equity are quantifiable, there are no such measures for acceptability. A strategy is considered acceptable if land use and transport instruments and effects of the strategy are within specified constraints and otherwise unacceptable. Acceptable toll charges for this study are within the range (−100%, +200%) and PT frequency is within the range (−25%, +100%), relative to the base case situation in 2015. Moreover, acceptability is further emphasised by constraining accident costs (AC) to be 5% lower, and net present value of finance (PVF) and equity (K) to be no worse than in the base case situation in 2015. Hence strategies are considered optimal and acceptable if they solve the constrained optimisation problem.

[1] Today's toll ring charge is fixed one way at approximately € 1.5. The fixed off peak charge is reduced relative to today's situation to 10% of today's level by 2015, since this was found optimal in a related study (Vold et al., 2001).

[2] The alternative trend is based of alternative municipality plans that focus on possible exploitation of more areas for residential purposes in central districts (mainly station areas and areas along the sea-side). The increasing areas for residential purpose within Oslo are compensated by a corresponding reduction in Akershus counties.

$$\max_{\mathbf{X}_{2015}} \ \mathrm{OF}(\mathbf{X}_{2015})$$
$$\text{s.t.}$$
$$1.05 \cdot AC_{2015}(\mathbf{X}_{2015}) - AC^{\text{base}}_{2015} \leqslant 0$$
$$PVF_{2015}(\mathbf{X}_{2015}) - PVF^{\text{base}}_{2015} \geqslant 0$$
$$K_{2015,a}(\mathbf{X}_{2015}) \leqslant K^{\text{base}}_{2015,a}$$
$$0 \leqslant X_{2015,\text{toll}} \leqslant 3.0 \cdot X^{\text{base}}_{2015,\text{toll}}$$
$$0.75 \cdot X^{\text{base}}_{2015,\text{PTfreq}} \leqslant X_{2015,\text{PTfreq}} \leqslant 2.0 \cdot X^{\text{base}}_{2015,\text{PTfreq}}$$

In principle, we can apply a general optimisation algorithm to solve optimisation problems of this type. Such algorithms evaluate the objective function (OF) a number of times in a systematic way for different levels on the instruments. Each evaluation of OF requires a RETRO run, however, which iteratively uses EMME/2 for calculation of route choice and travel costs. This implies long run times.

Fowkes et al. (1998) developed an efficient method to find the unconstrained maximum of an objective function. The method evaluates the objective function at only a few points and uses polynomial interpolation through these points to obtain an approximate objective function. An optimisation algorithm is then applied to find the maximum of the interpolating function. A new interpolating function is found for the area around this maximum and so on iteratively until the maximum converges with good precision within a relatively short period of computation time.

The principle of polynomial interpolation can also be applied to develop a method for solving constrained optimisation problems: To do this we constructed 5×5 grids with selected values of toll charges and PT frequency. The OF and the indicators that define the constraints are evaluated at the grid points. Polynomials are then fitted to the grid values by smooth interpolation to generate approximate response surfaces for OF and the indicators with respect to varying levels on toll charges and PT frequency. Then the constrained maximum on the response surface of OF is found by using an implementation of the multiplier method (Luenberger, 1984) in the Mathematica software package by Culioli and Skudlarek (2001). The algorithm outputs optimised parameter vales and the shadow prices of staying within the constraint. Constraints are easily altered and new optimisations can quickly be run.

5. Results and discussion

Total fuel charges in Norway comprise about 70% of the fuel price. In this section, we present an optimal strategy for a situation where the authorities increase the total fuel tax by € 0.22 per litre to 90% of the fuel price by 2015. According to an estimate by Minken et al. (2001), this increase is required in order to comply with the general objective of reducing CO_2 emissions according to the Kyoto protocol. For comparison, we also derive an optimal strategy for a situation where the total fuel tax instrument is reduced by € 0.26–50% of the fuel price. We assume that the fuel tax increase leads to a fleet of smaller cars and a fuel consumption efficiency improvement of 15% towards 2015, and that fuel tax reduction inherits a 5% improved fuel efficiency by 2015.

5.1. Optimal strategy with increased fuel tax

The isolated effect of a fuel tax increase, comprise increased revenue and thus relieved constraint on PVF towards 2015. Overall welfare increase and accidents decrease. But increasing monetary car cost reduces the overall accessibility in zones distant from central areas where the PT services are scarce. The accessibility is relatively low in these zones in the base case, and increased fuel tax is generally to a greater disadvantage in these zones than in more central zones. Thus the differences increases and equity becomes worse relative to the base case situation (Table 1).

The constrained maximum of OF of € 1591 million is obtained by a +166% increase in toll charges, +27% increase in PT frequency, and an active land use instrument (Fig. 1). Elasticities at maximum implies that the OF is more sensitive to percentage changes in PT frequency than in toll charges (Table 1). Inactivation of the discrete land use instrument at the optimum reduces OF by 60%.

The optimal strategy improves equity relative to base case, and inspection of Fig. 1 reveal that increasing toll charges and PT frequency increases the distance to the equity constraint, which indicate that our measure of equity improves with increasing toll charge. It is in fact a greater reduction in accessibility in zones nearby the toll cordon than elsewhere. Since these zones have relatively high benefits in terms of accessibility in the base case, their disadvantage contributes to a more equitable situation. But the major reason why equity improves is that the active land use instrument relives the very high density in the city centre zone.

Only the accident constraint is active at the optimum. By removing the accident constraint, the optimum increases and the upper limit constraint on toll charges becomes active and PT

Table 1
Characteristics of the strategies, relative to the base case situation

Situation	Isolated effect of increased fuel tax	Isolated effect of reduced fuel tax	Optimal strategy with increased fuel tax	Optimal strategy with reduced fuel tax
Land use instrument	Inactive	Inactive	Active	Active
Toll ring charge	0%	0%	+166%	+200%
PT frequency	0%	0%	+27%	+46%
Accident costs	−2.2%	+2.36%	−5%	−5%
Shadow cost on 5% reduction of accidents[a]	–	–	609	1269
Shadow cost on upper limit on toll charge	–	–	–	105
Elasticity of W w.r.t. toll charge	–	–	+0.07%	+0.34%
Elasticity of W w.r.t. PT frequency	–	–	−1.0%	−2.4%
Kolm measure[b]	+2.95	−3.02	−6.9%	−15%
OF (€ million)	505	−1465	1591	764

[a] Shadow costs corresponds to the marginal change in OF while altering the strictness of constraints. Only non-zero shadow costs (implying active constraints) are listed in this table.

[b] Reduced Kolm measure implies improved equity.

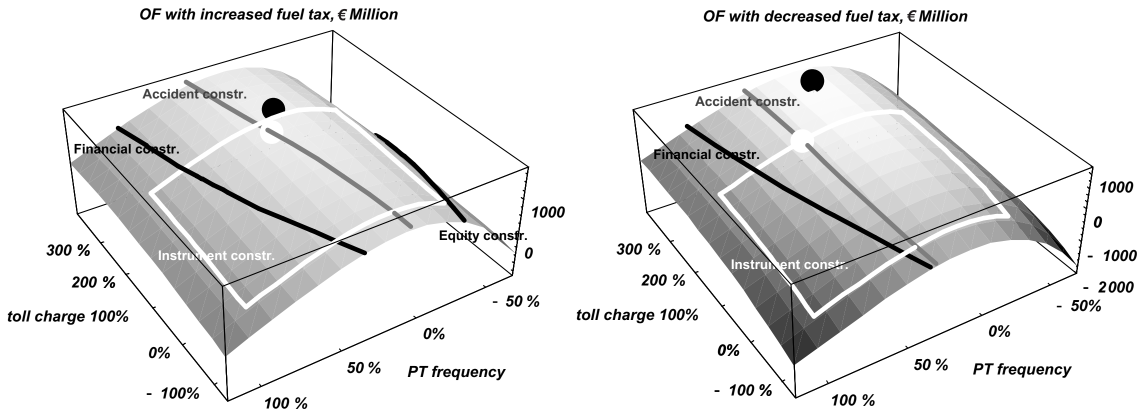

Fig. 1. Constrained and unconstrained maxima, represented by white and black bullets, respectively and constraints represented by solid curves for: the upper and lower levels on acceptable toll and PT frequency (white), lower level on equity (black), upper level on accidents (grey) and lower level on PVF (black) for the situations with increased and decreased fuel taxes.

frequency reduces to +14% relative to the base case situation. By removing the upper limit constraint as well, we obtain the unconstrained optimum at € 1630 million with toll charges of +222%, PT frequency staying at +14% and accident costs of −3.15% relative to the base case situation. To check the sensitivity of the constraints we maximise OF constrained by an accident cost reduction of −6.85% relative to base case (i.e., in order to assess OF values at ±1.85% relative to 5% accident reductions). The OF declines to € 1456 million, and toll charge and PT frequency respectively becomes +44%[3] and +38%. Hence, the concavity of the OF increases the marginal cost of accident reductions with increasing strictness on accident reductions. The concavity also explains why the difference between the constrained and unconstrained OF value is less than we expect according to the shadow costs at the constrained optima (Table 1).

5.2. Optimal strategy with decreased fuel tax

Decreased fuel tax impacts negatively on OF, accidents costs and PVF, relative to the base case situation (Table 1). But equity improves, which is expected since the equity became worse with increasing fuel taxes. The distant zones with initially bad accessibility improves their accessibility relatively much and a more equitable situation is obtained.

No strategy satisfies all constraints simultaneously in the situation with decreased fuel taxes. To circumvent this problem we assume that external funds are made available such that PVF is always similar to PVF in the situation with increased fuel taxes, but we do not add these external funds to the OF. The constrained maximum of OF of € 764 million is obtained with a +200%

[3] Reduced toll charges, alone, lead to less soft travellers, which explain why optimal toll charges are reduced with stricter accident constraints.

increase in toll charges, a +46% increase in PT frequency, and an active discrete land use instrument. Inactivation of the discrete land use instrument would reduce OF from € 764 to −€ 254 million. Equity is considerably improved for the same reasons as with the optimal strategy in the situation with increased fuel taxes.

Both the accident constraint and the upper constraint on toll charges are active (Fig. 1), and it is noticed that the shadow costs on accident reductions at the optimum are greater than with increased fuel tax. By removing the accident constraint, OF increases to € 961 million, PT frequency is reduced to +11% and the upper limit constraint on toll charges stays active. By removing the upper limit constraint as well, we obtain the unconstrained optimum where the OF function increases to € 1002 million, toll charges increases to +334% and PT frequency reduces to +11%. Accident costs increase by +0.24%, relative to the base case situation.

5.3. Land use and transport changes

The rest of this article focuses on consequences of optimal strategies for year 2015 as specified in Table 1 (i.e., with the 5% accident reduction constraint).

As expected, the *increasing fuel tax* alone has a centralisation effect on residents and workplaces, whereas the optimal strategy adds the effect that people and workplaces tend to move away from the toll ring—both towards the city centre and to the more distant districts. As a general picture, the population increases in four areas: central, southwest, northeast, and south, i.e., a decentralised centralisation. There is a workplace increase in the densely populated south-western areas and in the central areas where accessibility is good due to the central train station and other PT transport services. People tend to choose residential location, workplace and other activities in places where they need less toll ring crossings. Hence relocation reduces toll ring crossings, but increasing PT frequency contributes to this as well by inducing a greater share of PT trips and less car trips (Table 2). There is a drop off in the number of cars and car trips. Average travel speed and distance for car trips declines as well (Table 2), which are both direct effects of increasing fuel taxes and optimal strategies and indirect effects of household relocation. A greater share of PT trips on train, which is not affected by higher toll ring charges, and less on the slower subways within the city, explains increasing average PT distance and speed increases, resulting in reduced average PT time.

The situation with *reduced fuel taxes* and optimal strategy lead to relocation of residents and workplaces to less central and more sparsely populated districts outside of Oslo. But a few city districts have a net positive inflow. This is explained by the benefits of easy access to railways and bus terminal in these zones, giving fast access to workplaces and other activities that are moved out of the city. The almost 50% increase of PT frequency contributes herein. Reduced fuel taxes alone lead to more car use, congestion and thereby reduced car speed. The optimal strategy indirectly compensated for this through relocation and directly trough less car trips and shorter average trip distance by car (Table 2). Overall the strategy with reduced fuel taxes leads to car speed increase, as well, and thereby trip time decrease, relative to base case situation. The number of PT travellers increases even though the fuel tax is reduced below the base case level. This is primarily due to increased PT frequency which attract travellers that otherwise would use the walk/bicycle mode. The increase of toll charges in the peak period attracts some travellers from the car mode as well.

Table 2
Average levels of transport indicators in peak periods (4.34 h per day) in Greater Oslo in base case 1998 and 2015, and percentage changes relative to the base case in 2015 imposed by land use and transport strategies

	1998	2015	Isolated effect of increased fuel tax (%)	Isolated effect of reduced fuel tax (%)	Optimal strategy with increased fuel tax (%)	Optimal strategy with reduced fuel tax (%)
Total number of trips	819,497	954,865	+0.03	−0.07	+0.03	−0.06
Car trips	447,159	619,255	−2.2	+2.7	−4.3	+0.1
Public transport trips	265,620	238,724	+4.2	−5.1	+9.4	+1.6
Walk/bicycle trips	107,716	96,886	+4.2	−5.3	+4.5	−4.9
Avg. distance by car (km)	20.2	17.6	−1.8	+3.3	−2.5	+0.8
Avg. PT distance along road (km)	17.3	17.8	−2.1	+2.8	+1.0	+3.3
Avg. trip time by car (min)	23.8	24.7	−4.4	+7.9	−8.8	−2.0
Avg. PT time along road (min)	51.0	51.4	−1.0	+1.3	−3.0	−3.9
Avg. car speed (km/h)	50.9	42.7	+2.7	−4.3	+6.9	+2.8
Avg. PT speed along road (km/h)	20.3	20.8	−1.1	+1.5	+4.2	+7.5
Toll ring car crossings (%)	20.9	18.2	−0.4	+2.8	−15.5	−15.0
Total number of cars	384,385	525,115	−1.9	+2.1	−1.9	+2.1

5.4. Financial benefits

Increasing fuel tax reduces the number of cars. Fewer cars imply less annual car taxes paid by the travellers and less revenue to the government (Table 3). Though, the total revenue from both fuel taxes and toll charges increases, and car drivers get an overall monetary loss. One could imagine, however, that some of the revenue from fuel taxes is redistributed as reduced income taxes (i.e., towards green taxation). *Reduced fuel tax* stimulates car sale and the revenue from annual car taxes increases correspondingly (Table 4). But the total revenue from fuel taxes decreases, and car drivers get an overall monetary gain in spite of higher toll charges.

Both strategies incur increased PT frequency which imposes extra investment costs on PT operators, but yield an income increases due to more PT travellers. PT fares are unchanged, however, giving no monetary savings for PT travellers in either strategy. Higher toll charges give extra income to the toll ring operator despite less toll ring crossing. It is noticed that the toll ring operator benefits are greater for the situation with reduced fuel taxes since this strategy incurs greater toll charges and since there is less reduction in toll ring crossings. Parking operators gain a small benefit in the situation with increasing fuel taxes since relocation gives increased transport activity in some central districts where parking charges are high.

Table 3
Net cost and benefits (€ million) in year 2015 with increased fuel tax and optimal strategy

Benefit or cost cat.	Travellers		Operators			Gov./H.prov and external	Row sum
	Peak	Off peak	PT	Parking	Toll		
Financial benefits							
Invest./annual car tax	10.47		−97.83	0.00	−0.00	−14.66	−102.03
Money savings, road	−147.74	−144.26		−0.01	50.89	177.12	−63.99
Money savings, PT	0.00	0.00	29.82			0.00	29.82
Housing rent[a]	10.52					52.15	62.67
Housing lower sh.cost[b]	6.18					−5.76	0.42
Housing upper sh.cost	−68.28					110.26	41.97
Time and location benefits							
Time savings, road	52.39	24.15					76.54
Time savings, PT	37.57	42.29					79.86
Time savings, w/b	0.00	0.00					0.00
Attraction utility	0.63	0.20					0.83
Residential disutility	39.03						39.03
External costs							
Accidents cost savings						0.36	0.36
Pollution cost savings						5.04	5.04
Noise cost savings						9.20	9.20
Dust cost savings						1.31	1.31
CO2 cost savings						57.44	57.44
Column sum	−136.84		−68.01	−0.01	50.89	392.46	
Welfare *W*							238.49

[a] Based on the hedonic price function $q(h)$.
[b] The shadow added or subtracted from the housing rent to keep the number of residents within the upper and lower limits on the number of residents in the zones.

Household rent is subdivided in costs represented by the hedonic price function $q_i(h_i)$, and upper limit scarcity costs and lower limit price reduction. With *increasing fuel tax*, overall household density increases in all zones with in-migration, except in the city centre where the new areas for residential purposes outweigh centralisation. Housing rents $q_i(h_i)$ are overall reduced due to worse accessibility caused by increasing fuel—and toll charges. Residents experience a net positive consumer surplus by locating in zones where prices drop off. At the same time, housing providers increase their income (see corresponding row in "Gov./H.prov and external" column, Tables 3 and 4) since more land for residential purpose increases the number of residents in expensive areas, which compensate for the reduced housing rent payment per household. The city centre zone is an exception, where reduced density gives an overall increase in housing rents. Overall depopulation or scarcity of houses, as represented by lower and upper shadow costs, adds to the housing rents $q_i(h_i)$ in a few zones where the 15% upper limit population increase is reached. Most of the scarcity cost is in the city centre zone, where prices become very high due to the density decrease and due to the constraint that there can be only a 15% increase in the share of household in this zone despite increases in areas for residential purposes. With optimal strategy in the situation with *reduced fuel tax*, overall housing rents increases due to improved accessibility and

Table 4
Net cost and benefits (€ million) in year 2015 with reduced fuel tax and optimal strategy

Benefit or cost cat.	Travellers		Operators			Gov./H.prov and external	Row sum
	Peak	Off peak	PT	Parking	Toll		
Financial benefits							
Invest./annual car tax	−11.57		−163.71	0.00	0.00	16.20	−159.08
Money savings, road	24.33	188.95		0.32	69.43	−267.28	15.76
Money savings, PT	0.00	0.00	20.57			0.00	20.57
Housing rent[a]	−102.87					161.41	58.54
Housing lower sh.cost[b]	9.89					−9.36	0.54
Housing upper sh.cost	−88.61					131.14	42.52
Time and location benefits							
Time savings, road	15.25	−34.30					−19.05
Time savings, PT	54.87	63.31					118.18
Time savings, w/b	0.00	0.00					0.00
Attraction utility	0.44	0.19					0.62
Residential disutility	43.06						43.06
External costs							
Accidents cost savings						0.37	0.37
Pollution cost savings						−0.99	−0.99
Noise cost savings						−7.82	−7.82
Dust cost savings						−1.11	−1.11
CO2 cost savings						2.40	2.40
Column sum	162.93		−143.15	0.32	69.43	24.96	
Welfare W							114.51

[a] Based on the hedonic price function $q(h)$.
[b] The shadow added or subtracted from the housing rent to keep the number of residents within the upper and lower limits on the number of residents in the zones.

scarcity costs are even higher than in the situation with increased fuel taxes. Most of the scarcity costs are due to population increase in the city centre zone here as well but other scarcity costs outside of Oslo where people tend to relocate are also significant.

5.5. Time and location benefits

The optimal strategy in the situation with *increased fuel tax* leads to shorter car trips and higher car speed. Thus car travellers experience time savings. With *reduced fuel tax*, the length of peak car trips increases but car speed increases as well, giving time savings in peak periods of this strategy as well! This means that the isolated time cost increase due to reduced fuel taxes is outweighed by the optimal strategy. Hence, car drivers earn both monetary and time benefits in the peak period with reduced fuel taxes. Off peak car travellers experience a time loss since toll charges are low in the off peak period. PT travellers experience overall time savings in *both strategies*. This is despite the longer PT distances with reduced fuel taxes, which is outweighed by higher PT frequency and thereby shorter trip time—and greater passenger volumes on fast commuting trains and buses.

The very small positive attraction utility change in *both strategies* is due to a more or less evenly distribution of residences and work places in the zones. Both strategies yield decreasing density in most zones within Oslo city. With increasing fuel tax there is a density decrease as well in some Akershus municipalities. But density increases in almost all Akershus municipalities when fuel prices decrease. Overall the density changes are beneficial and thus reduce the overall disutility.

5.6. External costs

CO_2 cost savings constitute the greatest environmental cost saving in the situation with *increased fuel tax*. Altered costs of accidents, pollution, noise and dust are relatively small, where pollution costs go down even though increasing PT frequency increases emissions from buses. With *decreased fuel tax*, the costs of pollution, noise and dust increase, whereas CO_2 costs are slightly reduced in spite of the reduced fuel costs. The reason is due to the assumed improved fuel efficiency and that CO_2 emissions are less sensitive to speed changes than the pollution constituents NO_X, VOC and PM_{10}. However CO_2 cost savings are much greater with increased fuel tax.

6. Concluding remarks

Application of the framework envisages strategies with both direct and indirect effects on travel behaviour, i.e., car use changes directly through changed transport prices and indirectly through land use changes. The decrease in fuel taxes in one situation and the increase in the other implies that many effects are opposite in the two situations. However, the optimal strategies in both situations incur higher toll charges and PT frequency, which pushes some effects in the same direction (e.g., both strategies lead to shorter trip times by car, more travellers by PT, and overall reduction in location disutility). Here, the increasing toll charges alone do not reduce accidents significantly. The reason is that increasing toll ring charges, alone, lead to more soft travellers that are more vulnerable. If PT frequency increases, however, car traffic is reduced and soft travellers start to use PT, which reduces the number of accidents. Though, sensitivity analysis demonstrated increasing marginal costs of stricter accident reductions.

The optimal strategies with reduced fuel taxes lead to urban sprawl, increasing demand for transport and more emissions. Increased fuel tax leads to a more compact city, generally shorter travel distances, a greater share of the population gets access to the more developed parts of the PT services, and total emissions decline. This gives great potential for reducing CO_2 emissions. The benefit of a compact city hinges on the instruments applied, however, since it is crucial that the instruments also reduce or is accompanied by measures that reduce private car traffic. Otherwise, there is the danger of more congestion and increasing local pollution in the central zones.

The travellers loose in the situation with increasing fuel taxes, but get a net positive surplus in the situation with reduced fuel taxes (see column sums Tables 3 and 4). But the decision maker's logic choice would be to choose the strategy with increased fuel tax since this strategy is acceptable and give the greatest value of the objective function OF. There is still a trade off, however, since equity is better in the situation with reduced fuel taxes.

Acknowledgments

This work was part of the PROSPECTS project financed by the European Commission, the Norwegian road administration and the Norwegian Ministry of Transport and was part of the 5th Framework program. I am indebted to Harald Minken, Tony May, Simon Shepherd and other participants at the PROSPECTS project and to anonymous referees for their constructive criticism and advice.

References

Anderstig, C., Mattsson, L.-G., 1991. An integrated model of residential and employment location in a metropolitan region. Papers in Regional Science 70, 167–184.

Bang, J., Flugsrud, K., Holtskog, S., Haakonsen, G., Larssen, S., Maldum, K.O., Rypdal, K., Skedsmo, A., 1999. Utslipp fra vegtrafikk i Norge—Dokumentasjon av beregningsmetode, data og resultater. Norwegian Pollution Control Authority (in Norwegian).

Ben-Akiva, M., Lerman, S.R., 1985. Discrete Choice Analysis, Theory and Application to Travel Demand. The MIT Press, Cambridge, MA.

Bhattacharyya, G.K., Johnson, R.A., 1977. Statistical Concepts and Methods. Wiley, New York.

Brotchie, J.F., 1987. A generalized design approach to solution of the non-convex quadratic programming problem. Applied Mathematical Modelling 11, 291–295.

Culioli, J.C., Skudlarek, J.P., 2001. Multiplier Method—A general purpose algorithm for nonlinear programming. http://library.wolfram.com/infocenter/MathSource/795. Mathematica Information Centre, Wolfram Research.

Dagum, C., 1987. Gini ratio. In: Eatwell, J., Milgate, M., Newman, P. (Eds.), The New Palgrave: a Dictionary of Economics, Vol. 2. The Macmillan Press Ltd., London, pp. 529–532.

De la Barra, T., 1989. Integrated Land Use and Transport Modelling, Decision Chains and Hierarchies. Cambridge University Press, Cambridge.

DSC, 2001. Appraisal in Land-Use/Transport interaction: Design. David Simmonds Consultancy, Cambridge.

Echenique, M.H., Flowerdew, D.J., Hunt, J.D., Mayo, T.R., Skidmore, I.J., Simmonds, D.C., 1990. The MEPLAN model of Bilbao, Leeds and Dortmund. Transport Reviews 10, 309–322.

Elvik, R., 1994. The external costs of traffic injury: definition, estimation, and possibilities for internalisation. Accident Analysis and Prevention 26 (6), 719–732.

Elvik, R., 1998. Opplegg for konsekvensanalyser av tiltak for gående og syklende, Forprosjekt. TØI-notat 1103/1998. Institute of Transport Economics, Oslo (in Norwegian).

Elvik, R., Mysen, A.B., Vaa, T., 1997. Trafikksikkerhetshåndboken. Institute of Transport Economics, Oslo (in Norwegian, English edition forthcoming).

Eriksen, K.S., Markussen, T.E., Putz, K., 1999. Marginale kostnader ved transportvirksomhet. TØI-rapport 464/1999. Institute of Transport Economics, Oslo (in Norwegian).

Fowkes, A.S., Bristow, A.L., Bonsall, P.W., May, A.D., 1998. A short-cut method for strategy optimisation using strategic transport models. Transportation Research 32A, 149–157.

Fridstrøm, L., 1999. Econometric models of Road use, Accidents, and Road Investments Decisions, vol. II. TØI-report 457/1999. Institute of Transport Economics, Oslo.

INRO, 1999. EMME/2 On-line Documentation Release 9.2. Montréal, Qubéc.

Jansson, J.O., 1994. Accident externality charges. Journal of Transport Economics and Policy (January), 31–43.

Kolm, S.-C., 1976. Unequal inequalities I. Journal of Economic Theory 13, 82–111.

Luenberger, D.G., 1984. Linear and Non-linear Programming, second ed. Addison-Wesley, Reading, MA.

MEET, 1999. Methodology for Calculating Transport Emissions and Energy Consumption. European Commission, Belgium.

Minken, H., Shepherd, S., Jonsson, D., Järvi, T., May, T., Page, M., Pearman, A., Pfaffenbicler, P., Timms, P., Vold, A., 2001. Developing Sustainable Land Use and Transport Strategies, A Methodological Guidebook, Deliverable 14 of PROSPECTS. European Commission, Belgium.

NOU, 1997. Nytte-kostnadsanalyser—Prinsipper for lønnsomhetsvurderinger i offentlig sektor. NOU 27/1997, Oslo (in Norwegian).

Powell, W.B., Sheffi, Y., 1982. The convergence of equilibrium algorithms with predetermined step sizes. Transportation Science 16, 45–56.

Ramjerdi, F., Rand, L., 1992. The National Model System for Private Travel, Report on phase II of model development. TØI-report 150/1992. Institute of Transport Economics, Oslo.

Rosendahl, K.E., 2000. Helseeffekter og samfunnsøkonomiske kostnader av luftforurensning (Health effects and social costs of air pollution). SFT-rapport 1718/2000. Norwegian Pollution Control Authority (in Norwegian).

Simmonds, D., Still, B., 1998. DELTA/START: Adding Land Use Analysis to Integrated Transport Models, Paper no. 688. David Simmonds Consultancy, Cambridge.

Sweet, R.J., 1997. An aggregate measure of travel utility. Transportation Research 31B, 403–416.

Vold, A., 1999. Regional transport model for the greater Oslo area (RETRO) Version 1.0. TØI-report 460/1999. Institute of Transport Economics, Oslo.

Vold, A., Minken, H., Fridstrøm, L., 2001. Efficiency and equity of marginal cost pricing in road networks. Paper presented at the 9th World Conference on Transport Research (WCTR), Seoul (CD-ROM).

Wadell, P., 2000. A behavioural simulation model for metropolitan policy analysis and planning: residential location and housing market components of UrbanSim. Environment and Planning B: Planning and Design 27, 247–263.