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Modelling social welfare effects of relocation and road pricing

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Modelling social welfare effects of relocation and road pricing[*]

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Abstract

Road pricing is a popular congestion reduction strategy. However, there may be wider impacts associated with a road toll. We consider a factor which is sometimes overlooked, namely that workers and firms may choose to change location in response to changes in the travel costs. A spatial equilibrium model is used to analyse suboptimalities in road pricing which may occur if relocations are ignored. We show that such suboptimalities can be substantial. The advantage of the model we use over many existing approaches is that it is easy to implement, and requires very little data.

Keywords: Relocation; Road pricing; Congestion; Spatial equilibrium modelling; LUTI modelling

JEL codes: R23; R41; R48

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1 Introduction

In recent decades, the amount of traffic on the roads has steadily increased, and is expected to increase further (IEA, 2009). One immediate solution to a problem of excess demand is to increase the capacity of roads to satisfy this demand. However, expanding road capacity can be costly and can generate induced demand. Therefore, policies to curtail demand have received considerable attention both from policy makers and academics. These policies may attempt to affect road users' mode choice, route choice or departure time choice. However, these same policies may have wider reaching effects, such as the choice of living or working location.

Road pricing is a well-known tool for reducing travel demand, as well as a providing a source of revenue for financing new roads. There are several studies in the literature which are devoted to investigating travellers' responses to road pricing. Many effects have been discussed, from short-term responses such as changes in route choice and departure time, to long-term effects like car ownership and changes of work or residential location.

Short-run effects of congestion pricing have been widely studied (Tsekeris and Voss, 2009). Considering only the short-term effects may lead to biased results and sub-optimal decisions (Tillema et al., 2010*b*). Despite the potential importance of long-run effects, these have received less attention in the literature (Arentze and Timmermans, 2007; Tillema et al., 2010*a*). In this paper, our primary focus will be on the long-run relocation effects.

Analysis of these location effects of road pricing is not new (e.g. Fujishima, 2011; Tillema et al., 2010*a*,*b*; Anas and Xu, 1999). Tillema et al. (2010*a*) show that road pricing can influence location decisions, and identified some of the most important factors determining the probability of relocating in response to road pricing. The effects were found to be strongest on people who had already decided to relocate in the next two years. This feature is more difficult to model (Tillema et al., 2010*a*).

Additional evidence comes from Arentze and Timmermans (2007), who found that 88.2 percent of respondents would not consider any change in location in response to road pricing, only 2 percent would change their job location and 11.1 percent would change their home location. Although they found limited evidence that a price increase might trigger relocation, they do mention the importance of congestion prices on a household's decision when they decide on their residential location.

Tillema et al. (2010*a*) emphasised that road pricing has a direct effect on relocation behaviour of commuters, although other types of marginal changes in travelling cost might not have the same effect. They speculate that the difference is due to the fact that road toll is more immediately linked to the travelling itself; therefore, commuters give more weight to congestion pricing than other travelling costs. Compared to Arentze and Timmermans (2007), Tillema et al. (2010*a*) showed a higher relocation probability for home relocation (4.1 percent) and slightly lower probability for job relocation (10.8 percent) in cordon-based pricing[1]. For kilometre-based pricing [2], they found a lower likelihood of relocation due to "spatial contrast" compared to cordon based pricing scheme. This conclusion corroborates the study done by MuConsult (2000) which reports relocation percentages due to kilometre-based road pricing would be between 3 to 5 percent.

There are many models which incorporate long-term effects of road pricing. These models are often referred to as land-use–transport interaction (LUTI) models or large-scale models. For a discussion of some LUTI models which have been developed, see for example Waddell (2011), Hunt (2005) or Wegener (2004). While many of these models capture several important effects, including relocation effects, they often impose certain costs on the user. One of the main costs associated with the implementation of these models is the data collection required. As noted by Waddell (2011, p. 215), " the data requirements are intimidating to even the most intrepid users". This can act as a barrier to using such models.

In this paper, we utilise the spatial equilibrium model presented in McArthur et al. (2014) to analyse the possible suboptimality in road pricing schemes which could arise if relocations are ignored. The main advantage of this modelling approach is that it can capture some of the important effects of the more comprehensive LUTI models while requiring only a modest amount of data. The data required by the model are typically easily available. The code used to implement the model is relatively compact which allows the model to be run on a standard desktop computer without encountering excessive run times.

The model can potentially be further simplified, moving it towards a purely analytical model, or its complexity can be increased to suit the needs of the user. In this paper, we present a simple version of the model which allows us to focus on the issues which are of interest to us. For instance, we do not account for worker/job heterogeneity, housing markets, land markets or modal choice. Despite these simplifications, it is still possible to extract interesting and important conclusions from the model about the partial effects of different variables.

We suggest that our approach could be useful for planners in situations where there simply are not enough resources to develop and implement a comprehensive LUTI model. This may be particularly relevant for semi-urban to rural geographies such as the case study of Bergen and its surrounding area in Norway presented in this paper. In the case study, we compare the results when assuming a fixed location pattern and when allowing for the relocation of both workplaces and workers. Such a comparison is relevant for situations where the alternative to using our low-cost model would be to use an even simpler model, such as a doubly-constrained gravity model or a multinomial logistic model.

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[1] In cordon-base pricing scheme, users have to pay a fee to enter a restricted area.

[2] In kilometre-based pricing scheme, users have to pay a variable fee based on the kilometre travelled.

The paper is structured as follows. In Section 2, the model and assumptions are explained. We apply the model on a sample network which is described in Section 3. Findings and observations are reported in Section 4, with some concluding remarks presented in Section 5.

2 Theory and models

Policies which attempt to influence people's transportation behaviour can be modelled as a game between road authorities and road users. In the literature, the game is assumed to be of different structure, such as social planner (system optimum), Stackelberg and Cournot games (Joksimovic et al., 2008). In our context, we assume that policy makers act first, and then road users respond to any change. Therefore, the structure of the Stackelberg game is more appropriate for modelling the situation. In Figure 1 we have illustrated the modelling framework formulated as a bi-level Stackelberg game.

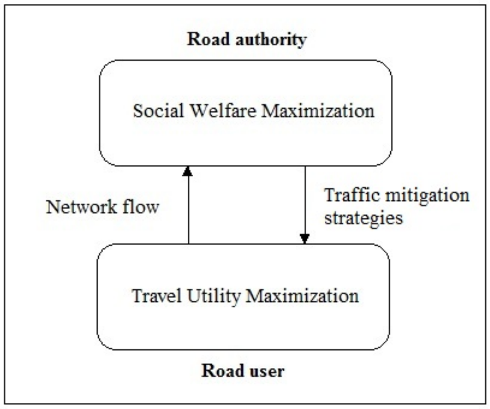

Figure 1: Model framework

The participants in the upper (authorities) and lower (travellers) levels of the problem have different objectives. To begin with, we specify how planners evaluate their decisions according to their objectives. In addition, we determine how travellers make decisions about their trips, including how they choose the route for their trips.

In spatial interaction models, there are four aspects which can be considered: 1) trip generation, 2) trip distribution, 3) mode choice and 4) route choice. In this paper we consider only trip distribution and route choice. However, in this paper only one mode of transport is assumed to exist. In the following sections, we briefly explain the aspects of the model used in this paper. Additional technical details are given in the appendix.

2.1 Trip distribution and route choice

We begin by considering the trip distribution. The trip distribution should have the property that longer commutes are chosen less frequently than short commutes. One model which fits this description is the doubly-constrained gravity model. The idea of a gravity model for spatial interaction is inspired by Newtonian physics, however variants of this model may also be derived from entropy maximisation (Wilson, 1967) or from random utility theory (Anas, 1983). The doubly-constrained gravity model can be shown to be identical to the multinomial logistic model (Anas, 1983).

In the gravity model, a measure of spatial separation is included. While it is common to include distance here, we choose to include a generalised cost measure. This allows the costs accruing from distance, time and tolls to be aggregated. It is important to account for these different elements of the cost, since this allows us to analyse the consequences of changing each of these components. McArthur et al. (2013) show how commuters may react differently to costs related to time and monetary expenses, and provide guidance on how such costs can be aggregated. We use this same measure of spatial separation throughout this paper.

When the aggregated cost of travelling is fixed, the solution to the gravity model is well known; see for example Sen and Smith (1995). However, in our model, the cost of traversing on a road (c_a) varies by the level of traffic on the road (F_a). This feature increases the complexity of computing the trip distribution matrix.

The cost of travelling along a stretch of road, a, can be split into three components: 1) a fixed cost per km, 2) any costs imposed by congestion and 3) any road tolls levied. Therefore, the time taken to travel on a given link a needs to be defined. In this paper, the travel time is defined as a function of the length of the link, d_a, the flow of traffic on the road, F_a, and the capacity of the road, ω_a. For this purpose, we use a simple speed-density relationship such as that given by Noland (1997). See Castillo and Benitez (1995) for a history of the speed-density relationship and a discussion of functional form.

When faced with more than one route between, we assume the agents choose the route which will have the minimum cost associated with it. This implies that the decisions of a particular road user will depend on the decisions of other road users. See Section B.B for details of how this is implemented in the model.

2.2 The relocation of workers and jobs

We begin our discussion with the determinants of worker relocations. The aim is to construct a matrix of migration probabilities of the type outlined in Nævdal et al. (1996). In this paper, we follow the spatial equilibrium model presented in McArthur et al. (2014), which incorporates the principles of the Nævdal et al. (1996) approach. For technical details about how the ideas presented in this non-technical description are implemented, see Section B.D. We conceptualise the migration decision as being taken in two parts. Firstly, a person will consider whether they wish to remain in their current zone. This gives the diagonal elements of the migration matrix. If the person chooses to move, the second part of their decision will be selecting a destination.

Several important features are incorporated into the diagonal elements of the migration matrix. Firstly, every person has a certain probability of moving for reasons which are unrelated to the characteristics of the geography. These probabilities may be a function of individual characteristics. In this paper, we assume a fixed probability for every worker. This means that in a given period everyone has a certain baseline probability of moving. For the people within a zone, their migration decisions may not be independent. One such interdependency which can occur is that if the population of a zone drops below a critical threshold, the zone becomes an unattractive place to live. When a zone undergoes a loss of population, it may result in the loss of amenities such as schools, medical facilities and retail facilities. We therefore increase the baseline probability of out-migration the further a zone's population drops below a critical threshold, as shown in Equation 16.

In addition to the exogenous probability of moving, there are certain features of a zone which will influence the probability of moving. We begin by accounting for the balance between the supply and demand of labour within a zone's internal labour market. Zones which have more workers than jobs will be more likely to experience out-migration. This naive approach fails to account for the fact that an excess supply of labour in a zone will have very different implications depending on the size and location of a zone. For instance, a suburb may well have an excess supply of labour in its internal labour market without triggering increased out-migration. It is easy to commute from such a zone to a workplace. If the zone is rural and isolated, an excess labour supply may lead to increased out-migration. On a related note, people are less likely to migrate out of large zones since these zones offer some important amenities such as a more diversified labour market, better matching between jobs and workers and better opportunities for dual-earner households. Although we do not explicitly account for such amenities, we capture the logic by allowing the effect of an excess supply of labour to be modified by the zone's accessibility (where is zone's accessibility depends, in part, on its size). For the implementation of this idea, see Equations 15 and 17.

Haven taken care of the first stage in the migration decision process, we now turn our attention to the destination choice. The first law of migration is that migrants tend to move only short distances (Ravenstein, 1885). This feature is incorporated into the model, where the greater the distance from the origin to a destination, the less likely that destination is to be selected. In addition we account for an absorption effect. A potential destination is less likely to be selected the greater the number of intervening zones between the origin and that destination. Details of the implementation of these mechanisms are given in Equations 13 and 14.

Having now discussed the movement of workers, we turn our attention to the relocation of workplaces. We distinguish between two types of employment based on economic base theory: basic-sector jobs and local-sector jobs. We assume that the distribution of basic-sector jobs is exogenously given. These jobs are defined to be in industries which primarily sell their goods and service outside of the region in question. They are therefore not sensitive to changes in the local economy.

Local-sector jobs are jobs in industries which primarily cater for local demand. The retail sector would be one such example. The more people live in a region, the higher the employment in the retail industry in that region. One approach would be to assume that the size of the local-sector is proportional to the region's population. While this may be appropriate for an interregional analysis, it is less appropriate for our intraregional analysis. Instead we base our approach on Gjestland et al. (2006). In this approach, the density of the local-sector (the number of jobs as a percentage of the population) is a function of the distance from the region's centre[3].

Based on Norwegian data, Gjestland et al. (2006) find that the local sector density is highest in the centre of a region, at it's lowest in the areas immediately surrounding the centre and then approaching the regional average as the distance from the centre increases. If we take the example of retail, we can explain how this pattern is generated. The density is highest in the centre due to the agglomeration benefits shops can enjoy by co-locating in the centre. These benefits allow these businesses to offer a wider range of goods and services and often at a lower cost. This makes the centre an attractive location for shoppers. The effect of this is that people in the suburbs will tend to direct a fairly large portion of shopping trips towards the centre. This has the effect of depressing local-sector demand within their own zone. The zones immediately surrounding the city centre will therefore tend to have a lower local-sector density than should be expected given their population size. As the distance to the centre increases, an increasing portion of shopping trips will tend to be intrazonal trips. This results in an increasing density of local-sector businesses.

We have now outlined the mechanisms which underlie the relocation behaviour within our model. One feature which is worth commenting on, is that our specifications of relocation mechanisms create an economic base multiplier. Assume for instance that a zone benefits from an improvement in transportation infrastructure. The improved accessibility increases the attractiveness of the zone. This may cause people to move to that zone. An increase in population in turn increases the demand in the local-sector, thus leading to the creation of new jobs in the sector. The expand in the demand for labour further increases the attractiveness of the zone, which in turn attracts additional migrants. This mechanism can lead to interesting, non-linear

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[3] In this paper, we assume a monocentric region. This approach can be extended to include more than one centre, as demonstrated in Gjestland et al. (2006).

effects such as virtuous and vicious circles. For an example of how negative shocks can lead to a vicious circle and depopulation, see McArthur et al. (2014).

One point which is important to remember when interpreting the results from this model is that the mechanisms here are based on an equilibrium concept. When a change is made to a parameter of the model, the model gives the expected long-run equilibrium which will result from that change. The long-run effects of a change may be considerably larger than what we would expect to see in the short run. Given that the migration of people and firms can be a slow process, the long-run in our model may be on the scale of decades. This of course depends, among other things, on the magnitude and nature of any changes made.

2.3 The social welfare function

We assume that the policy maker will aim to maximise social welfare. The social welfare change is computed as the sum of consumer surplus changes and revenue from the road toll, as is suggested in Verhoef (2002). The function for social welfare is shown in Equation (1).

$$\max_{s \in S} \sum_{i,j} \int_0^{f_{ij}^s} D_{ij}(x_{ij}) \mathrm{d}x_{ij} - \sum_a (c_a^s - \delta_a^s R_a^s) F_a^s \tag{1}$$

S is the set of alternative policies which must be compared and the optimal policy is the one that creates the highest social welfare change. R_a^s is the level of toll on road a under strategy s and δ_a^s shows if road a is priced under the chosen strategy. F_a^s and c_a^s are flow and cost of travelling on road a which are imposed as a result of strategy s.

In Equation (1), $D_{ij}(x)$ is the inverse demand function. The expression therefore equates to subtracting the total cost from the total benefit. For a discussion of Equation (1), see Verhoef (2002)[4].

We calculate changes in social welfare by summing the change in consumer surplus and any change in revenue brought about by road pricing. To calculate the change in consumer surplus, we have used linear approach for which we need to have the generalised travelling cost for each origin destination under every pricing scheme. Then, the consumer surplus change can be computed as:

$$CS_{a,b} = \sum_{i,j} \frac{1}{2} \left(f_{ij}^b + f_{ij}^a \right) \left(C_{ij}^b - C_{ij}^a \right) \tag{2}$$

where $CS_{a,b}$ is the consumer surplus change between pricing scheme a and pricing scheme b. f_{ij}^a and C_{ij}^a are traffic flow and generalised travelling cost from zone i to zone j under pricing scheme a. Likewise, f_{ij}^b and C_{ij}^b are traffic flow and generalised travelling cost from zone i to zone j under pricing scheme b. More

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[4] Although the second expression in the objective function looks different from Verhoef's model, it is only due to the difference in definition of c_a. In this paper, c_a includes the road toll but in Verhoef's model it does not.

explanations over different evaluation measures are available in Tillema et al. (2011).

3 The example network

In this paper, we use an example network in order to test our argument. The network is illustrated in Figure 2. This road network is based on the city of Bergen, Norway, and its surrounding area. The geography of the west coast of Norway provides an interesting case study. The presence of fjords and islands necessitates the use of bridges and ferries, as well as involving significant deviations from the Euclidean distance. This creates bottlenecks in the network which may result in congestion.

The city of Bergen itself is the second largest in Norway, and has a population of around 270 000. The city has suffered from traffic problems for many years (Ieromonachou et al., 2006; Odeck and Bråthen, 2002). This has led to queuing in the city, as well as contributing to rather serious air quality problems (McArthur and Osland, 2013).

A total of 25 zones were defined in Hordaland county, based on post code areas. Out of the 25 zones identified, 16 zones are considered inside Bergen city and the rest are smaller towns in the county. The zones vary in size, both with respect to geographical area and population. They range from the densely populated central business district (CBD) of Bergen, to the suburbs and to settlements in the periphery. The number of people living in each zone, and the number working in each zone are taken from Statistics Norway, and are given in detail in Table 1 in the Appendix.

Not all of the zones are directly connected to one another. This results in journeys between certain pairs of zones passing through other zones on the way. In total, there are 34 main roads in the simplified network which we consider. Each road has different speed limit; therefore, we have calculated distance between all pair of zones both in kilometres and in minutes. Distances for directly connected zones are summarized in Table 3 and Table 4 in Section C.

In the network, we distinguish between roads which are congested, and those which are not. The majority of the roads in the network are uncongested, as the capacity exceeds the demand by a considerable margin. In order to create congestion on a road we have assumed the capacity of the road to be marginally less than the traffic in the unconstrained case.

In this network, zone 1 is the city centre which experience congestion, and therefore, the roads which go to and from this zone will be the focus of this paper. There are four congested roads connecting zone 1 to other zones. These roads will be priced in order to reduce their congestion. We will consider cordon-based pricing scheme in this paper by setting fixed price on all roads going from the central area of the network. The focus will be on the difference between a situation where relocation behaviour is modelled and one where

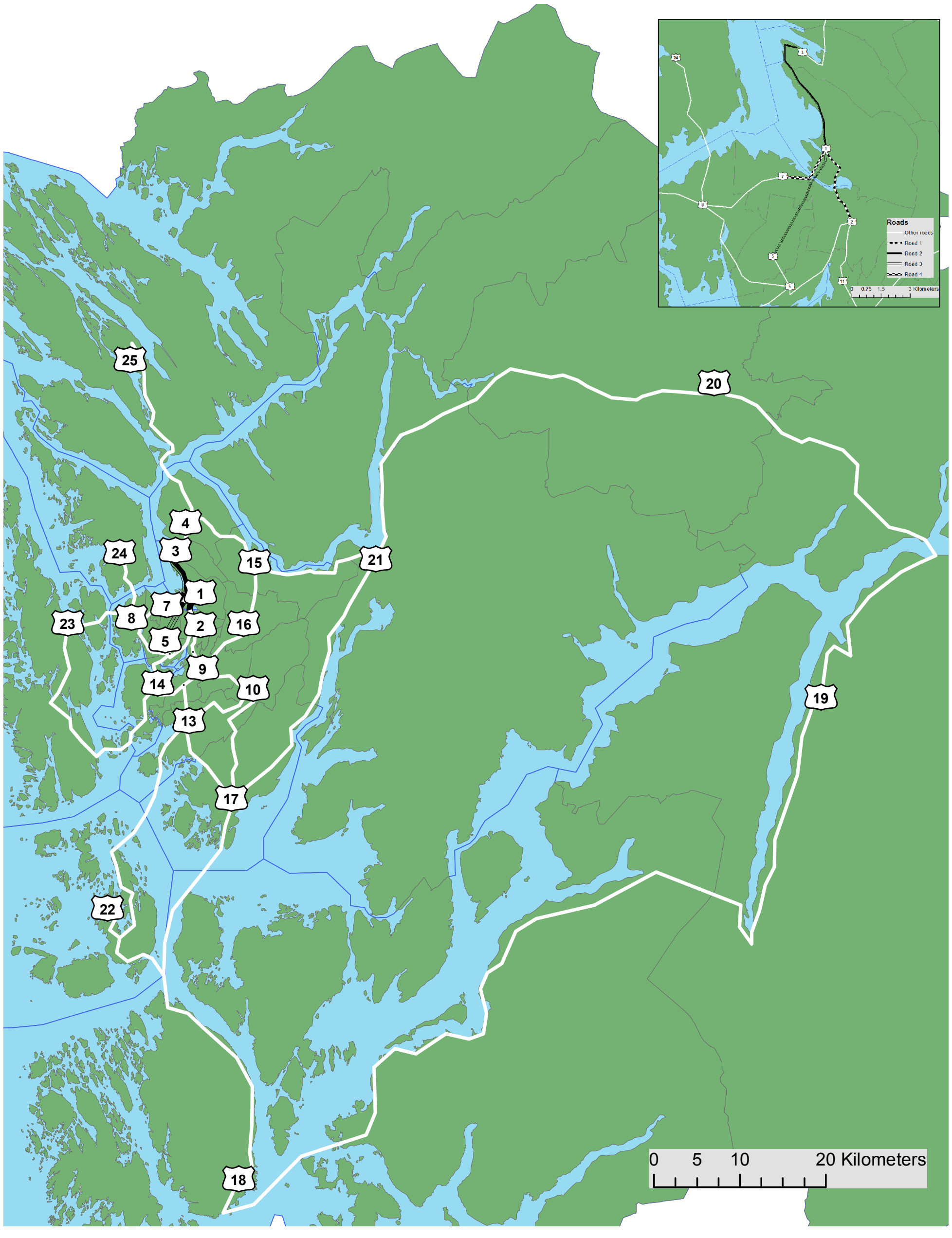

Figure 2: A map of Bergen with the transportation network we consider. Zone numbers are displayed. The inset map shows the centre of Bergen, along with the four roads which are assumed to be congested and where prices will be applied.

it is not.

It is worth noting that in this network, the roads are neither perfect substitutes nor perfect complements. Due to the complexity of the network, a commuter travelling from a given origin to a given destination may have several alternative routes. Whether a road is a substitute for or a complement to another road will depend on the start and end points of the commuters journey.

4 The effect of relocation on the optimal policy choice

There are many different managerial strategies which can be employed to manage congestion. We will analyse two possible interventions. Firstly, we will consider how road pricing may be used to improve social welfare. Secondly, we will consider the effects of moving workplaces out of the city centre to surrounding areas.

4.1 Road pricing

In this paper we consider a cordon pricing scheme. The model can be extended to account for different prices on different roads. All prices refer to a single trip. However, we begin by calculating what we will refer to as a naive optimum. By this, we mean an optimisation which maximises social welfare on the assumption that the location pattern of jobs and workers will remain fixed. We limited our investigation to price levels which are practically possible, i.e. we examined integer values between 0 NOK and 50 NOK[5]. We selected the charge which maximised welfare under the assumption of no relocation. This resulted in a price of 14 NOK. This is the charge which the authorities would implement if they wished to optimise social welfare and had ignored the possibility of relocations.

Now consider a relaxation of the no-relocations assumption. Maximising social welfare while accounting for the relocation of jobs and workers yields a charge of 20 NOK, some 6 NOK above the naive optimum. To understand the consequences of this difference on social welfare, it is useful to examine plots of the social welfare functions. Such a plot is presented in Figure 3, along with the suboptimality associated with each possible congestion charge. The changes in social welfare, and the suboptimality, are measured in Norwegian Kroner. The values represent the change for all commuters for a one-way trip. This can be aggregated, although we leave it in its current form, since it is primarily the difference between the different scenarios we consider which are of interest.

Figure 3 takes a situation without any charge as a base. A no-charge situation results in a suboptimality of 62 561 NOK, i.e. social welfare could be improved by that amount by imposing the optimal charge of 20 NOK. The most interesting feature of the figure is the difference between the ‘relocation’ and ‘no

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[5] At the time of writing, 10 NOK is worth around £0.96, €1.20 or $ 1.63.

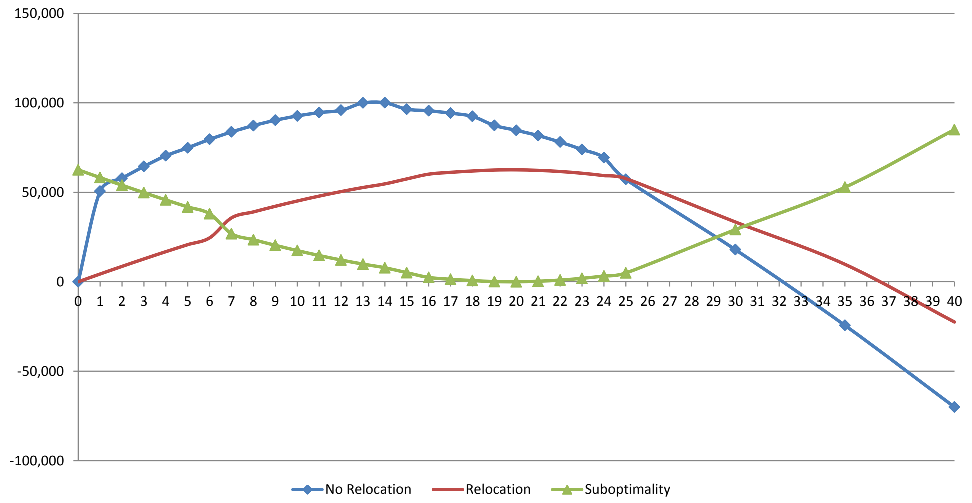


Figure 3: The social welfare associated with different prices for situations where relocations are accounted for and when they are not. In addition, the suboptimality associated with each price is shown.

relocation' curves. In a situation where the authorities do not account for relocations, they will believe they are operating on the 'no relocation' curve. This curve rises very sharply as the charge increases from zero, reaching a maximum of 100 033 NOK at a charge of 14 NOK. However, if the authorities try to reach this point, they will in fact move along the 'relocation' curve and obtain a change in social welfare of 54 716 NOK. This leaves a suboptimality of 7 845 NOK. The reason for the disparity is that people and jobs relocate in response to the introduction of a charge. This results in a much shallower social welfare curve.

It is worth noting that the cases we present could also be considered as a short- and long-run situation. At first when prices are introduced, there may be very little relocation behaviour. However, in the long-run we would expect to see some adjustments. This may take several rounds of a time-consuming base multiplier process.

The difference between the two curves in Figure 3 is caused by relocations. It is therefore interesting to examine the population changes associated with the introduction of a congestion charge. Figure 4 shows the percentage change in population in the central zones associated with a charge of 20 NOK compared to an unpriced situation. Whilst we focus on population here, the pattern of changes is similar for workplaces, since employment in the local sector is a function of the population in a zone.

Figure 4 shows some fairly complex relocation patterns in response to the introduction of a 20 NOK charge. The CBD (zone 1) experiences a drop in population. All roads out of this zone are tolled, which will make inter-zonal commuting more expensive for people living in this zone. The effect seems to have been to encourage people to move to adjacent zones. Zones 2 and 3 appear to have been particularly population choices, and to a lesser extent zones 5 and 7. Being adjacent to the CBD, these zones have a relatively high

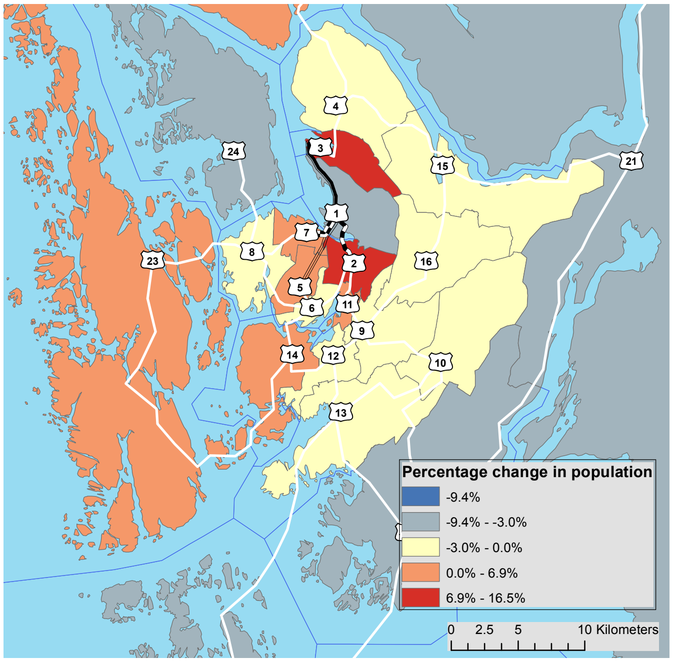


Figure 4: Percentage change in population in the central zones associated with a charge of 20 NOK compared to an unpriced situation.

number of jobs, and offer toll-free access to several zones while still offering access to the CBD. In addition, the extra cost associated with travelling to the CBD will have acted to expand employment in the local sector in these zones. For instance, more people may chose to shop within their residential zone rather than travelling into the CBD.

The zones to the north, east and south of the city centre experience a mild decline in population. Even though some of these zones appear adjacent to the CBD, the centre of Bergen is surrounded by mountains and water, which prevent direct road connections in some cases. The attractiveness of these outer zones will have declined since the cost of reaching the CBD and the jobs located there has increased. The increased population in the zones immediately surrounding the CBD and the enhanced local sector employment there may have increased the attractiveness of these zones to the original residents in the arc of zones to the east of the CBD. The overall effect of the toll has therefore been to increase population and employment in the zones lying just outside of the toll ring.

These findings support the results from Eliasson and Mattsson (2001). They found that while a congestion charge will generally increase the density of a city, there are some important nuances. In their model, as in ours, the primary increase in density was in the innermost ring of suburbs. The outer suburbs tended to lose population and employment. Shops (local sector employment in our model) also followed this pattern. They make the important point that this effect will depend on the extent of the area inside the toll ring.

For small toll rings such as the Bergen example, the area outside of the ring may be more attractive. If the ring were larger, then people may choose to locate within the ring. Similar findings are presented in a study of Chicago by Anas (2013).

The most interesting changes take place close to the city centre where the toll ring was introduced. There is also a ripple effect across the entire study region. These far reaching effects of the toll ring explain why the naive optimum toll is in fact suboptimal.

4.2 Relocating basic sector jobs out of the CBD

The second congestion-easing strategy which we consider is relocating basic sector jobs out of the city centre. The decentralisation of employment has been tried at the national level by countries such as Norway and the UK, where government departments have been relocated out of the capital in an attempt to distribute activity more evenly throughout the country. In this paper, we consider intraregional moves. Such policies could be relevant for Bergen. The city has a municipal government as well as hosting the headquarters of Hordaland county government. It is conceivable that some of these sorts of jobs could be relocated by the authorities in an attempt to manage congestion and other agglomeration diseconomies of scale. Anas and Xu (1999) find that dispersing jobs can be an effective way of reducing congestion. In that example, it is suggested that the relocation of jobs should be facilitated by relieving zoning restrictions rather than have the policy makers move the jobs directly.

As an example, we choose to relocate a block of 1 000 basic sector jobs out of the city centre, zone 1. This represents just over two percent of total employment in the cbd. We assume that these jobs must all be relocated to the same destination i.e that the jobs form one department which must be kept together. The relevant questions then become should the jobs be moved and if so, where should they be moved to. Once again, our aim is to maximise social welfare. Of interest is the effect of accounting for the relocations of jobs and workers in response to the initial redistribution of employment. We consider the expected effect of the job moving strategy under the naive assumption that nobody else relocates after our initial intervention, and then again when allowing for relocations. The change in social welfare associated with moving 1 000 jobs from the city centre to each of the other zones is shown in Figure 5.

We begin by examining the expected changes when the location of jobs and workers is assumed fixed (excluding the jobs which we explicitly move). With the exception of zone 7, it appears that moving the jobs to any zone other than the centre improves social welfare. There is surprisingly little variation in the expected change in social welfare between the different zones. Zones 1, 3, 7 and 25 appear to be less good locations, but otherwise the benefit is fairly equal across zones. The optimum zone to relocate the jobs to is

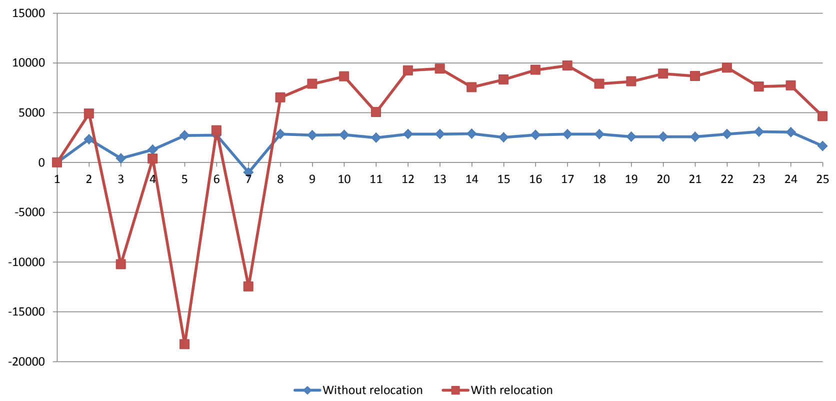


Figure 5: Social welfare change when we move 1000 basic jobs from city centre to other zones. The change in total social welfare which would result from moving the jobs to each of the zones is shown on the vertical axis. The zones are displayed on the horizontal axis.

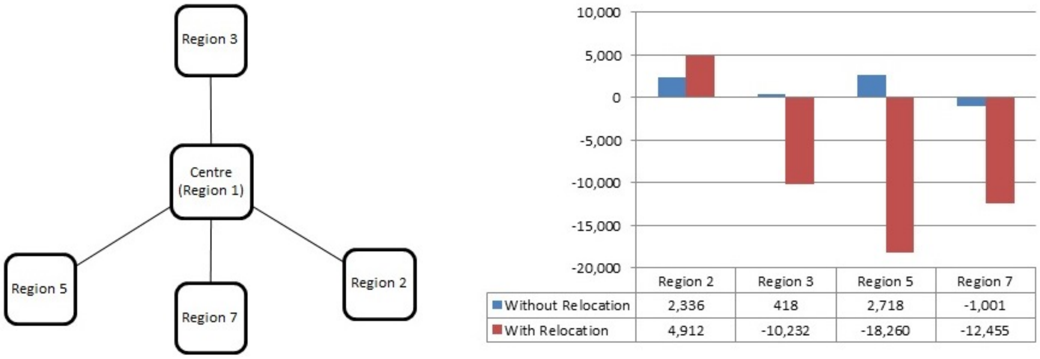
zone 23.

The picture is rather different when account is taken of the possibility that workers and jobs will relocate in response to the initial job relocation. Perhaps one of the most striking features is that there are now several options which would substantially reduce social welfare. This loss appears to be associated with the zones closest to the city centre. Among the zones further away from the city centre, the outcomes are more evenly distributed. The social welfare change associated with these zones is greater than in the case where relocation was not accounted for. This shows that the relocation can act to amplify the benefit available from the initial policy intervention. In this case, the optimal choice is zone 17.

The model has shown that without relocations, the optimal choice of zone was 23 whereas when the relocation behaviour was accounted for it was 17. Choosing the naive optimum of 23 when the true optimum is 17 is associated with a suboptimality of 6 642 NOK. In fact, the scope for suboptimality is even greater than this.

Consider a policy where the only feasible zones for the initial relocation are zones 2, 3, 5 and 7, all of which are close to the city centre. In such a case, the optimum without allowing jobs and workers to relocate in response to the intervention would be zone 5, which would yield an improvement of 2 718 NOK in social welfare. However, when relocation is accounted for, the true optimum is zone 2 with a social welfare change of 4 912 NOK. Choosing zone 5 would result in a welfare change of -18 260 NOK, and a suboptimality of 23 172 NOK. This is illustrated in Figure 6.

To further explore the suboptimality which results from locating jobs in zone 5 rather than zone 2, we display the resulting population changes on a map in Figure 7. The job relocation has result in a significant degree of centralisation. The population in zone 5 increases by 14%. The adjacent zone 2 experiences a population increase of 2.5%. All of the other zones experience population declines. The intervention of



	Region 2	Region 3	Region 5	Region 7
🟦 Without Relocation	2,336	418	2,718	-1,001
🟥 With Relocation	4,912	-10,232	-18,260	-12,455

Figure 6: Social welfare change when we move 1 000 basic jobs from city centre to the zones adjacent to the cbd. The bars represent the change in social welfare for each zone resulting from moving the jobs to each of the zones, where the zones are displayed on the horizontal axis.

moving jobs therefore acted to increase centralisation rather than decrease it.

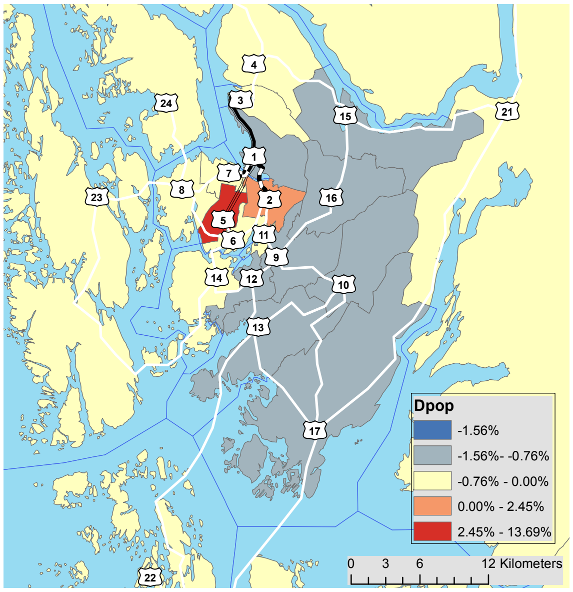


Figure 7: Percentage change in population in the central zones associated with a relocation of 1 000 basic sector jobs to zone 5.

5 Concluding remarks

In this paper, we focused on modelling some of the effects of ignoring job and worker relocations on the suboptimality of congestion reduction policies. Our findings show that ignoring relocation effects can result in substantial losses in social welfare, either potential or realised. Two congestion reduction strategies were considered: road pricing and decentralising basic-sector jobs.

According to the model, the naive optimal road price (i.e. one assuming fixed locations) led to a suboptimality of 14%. This was caused by the relocation of jobs and workers in response to the new pricing regime. Similar results were obtained when we examined a strategy or relocation a block of 1 000 jobs out of the cbd. In this example, social welfare was to be optimised by relocating the jobs to one of the other zones in the region. The naive choice of optimum zone resulted in a suboptimality of 214%. We also showed that under some constrained optimisation problems, the intervention may even result in a deterioration in social welfare from the do-nothing scenario.

We suggest that the model applied in this paper may be useful for planners who are unwilling or unable to develop a more comprehensive and costly LUTI model. The model makes a large number of simplifying assumptions. The benefit of this is that the model requires only a modest amount of easily available data and can be run relatively quickly on a standard desktop computer. Despite the simplifications, we argue that our model can provide important and valuable insights compared to a model assuming fixed locations. We would therefore recommend implementing a model such as ours over a more simplistic approach such as a doubly-constrained gravity model, given that our model requires almost the same level of effort and offers more flexibility.

It is worth mentioning explicitly some of the limitations of our model. We have considered only one mode of transport, namely private cars. In the rural areas surrounding Bergen this is likely to be a reasonable assumption, since there are few alternatives to private cars. In the city of Bergen, other modes of transport are available. However, private cars are still used extensively for commuting in the city centre area. We consider only a static model, which does not allow commuters to vary departure times. An additional assumption is that wages and house prices are exogenous, all workers and jobs are homogeneous, and that there is full employment. These assumptions can of course be relaxed, and indeed are relaxed in other models in the literature, however this increases the cost of implementation.

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Appendices

A Notation

N	Set of zones/nodes in the network
A	Set of roads/links in the network
F_a	flow on a particular road link a
c_a	Generalised cost of traversing a particular road link a
d_a	Length of a particular road link a in km
ω_a	Capacity of a particular link a
f_{ij}	flow between origin i and destination j
O_i	Number of trips originating from node i
D_j	Number of trips terminating in node destination j
β	the distance decay factor in gravity model
A , B	Balancing factors in gravity model
C_{ij}	The lowest generalised cost of travelling between origin i and destination j
γ	Fixed travelling cost per km
α	Value of time
T_a	Time to travel on road a in the presence of congestion
δ_a	Dummy variable which is equal to 1 if a toll can be charged on road link a, and 0 otherwise
R_a	Toll on road link a if applicable
T_a^0	Time to travel 1 km on road link a in the absence of congestion
T_a^1 , ε	Parameters associated with congestion sensitivity of travel time on road a
λ_{ij}^a	is the binary decision variable which is equal to 1 if commuters between zone k and l include road a in their route from k to l, and 0 otherwise
$D_{ij}(.)$	Inverse demand function for commuting from origin i to destination j

B Technical description of the model

In this section, the technical details of the model are given. The model is coded in Mathematica due to its convenience. Although there are other more efficient alternatives for coding, Mathematica code was efficient enough for our purpose[6].

B.A Trip distribution

As mentioned in section 2, we represent demand for travelling between origin i and destination j with f_{ij}:

$$f_{ij} = A_i B_j \mathrm{e}^{-\beta C_{ij}} \tag{3}$$

$$A_i = \frac{O_i}{\sum_j B_j D_j \mathrm{e}^{-\beta C_{ij}}} \tag{4}$$

$$B_j = \frac{D_j}{\sum_i A_i O_i \mathrm{e}^{-\beta C_{ij}}} \tag{5}$$

In this model, A_i ensures that the rows of the trip distribution matrix sum to O_i while B_j ensures the columns sum to D_j.

B.B Travelling cost formulation

A user commuting from an origin to a destination compares the travelling cost for any possible alternative route and chooses the one that incurs the minimum cost. Route choice by commuters creates the traffic pattern on road networks. In other words, route choice by commuters and traffic flow are inter-dependent. If authorities intervene in this loop and change the cost of travelling in some routes, then commuters' travelling behaviour might be affected, and consequently, traffic flow on roads might change.

There are different routes between every origin-destination pair that a commuter can choose among. The road users objective might be to minimise travel time, travel cost or maximise individual travel utility (Joksimovic et al., 2008, p. 156). In this paper, we consider the travel cost as the metric which road users try to minimise. In short, road users will choose the least costly route among all possible routes between every origin-destination pair. Length of a route and congestion on the roads in the route determine the cost attributed to each route. For any road user travelling from k to l, this may be formulated as:

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[6] The Mathematica code will be made available by the authors on request.

$$\min_{\lambda_{kl}^{1},\ldots,\lambda_{kl}^{m}} \sum_{a\in A} c_a \lambda_{kl}^{a} \tag{6}$$

Subject to

$$\begin{aligned}
&F_a = \textstyle\sum_{i,j\in N} \lambda_{ij}^{a} f_{ij} && a \in A \\
&f_{ij} = A_i B_j \mathrm{e}^{-\beta C_{ij}} && i \in N, j \in N \\
&C_{ij} = \textstyle\sum_{a\in A} \lambda_{ij}^{a} c_a && i \in N, j \in N \\
&c_a = \gamma d_a + \alpha T_a + \delta_a R_a && a \in A \\
&T_a = d_a T_a^0 \left[1 + 0.15 \left(\tfrac{F_a}{\omega_a}\right)^4\right] && a \in A \\
&\lambda_{kl}^{a} = \begin{cases} 1 & \text{if road a is in the least costly path from k to l} \\ 0 & \text{otherwise} \end{cases} && a \in A
\end{aligned} \tag{7}$$

Here, A is the set of roads and N is the set of zones in the network. F_a if the flow on road a, f_{ij} is the flow between origin i and destination j which is estimated by a doubly constrained gravity model. C_{ij} is the lowest generalised cost of travelling between origin i and destination j and c_a is the traversing cost on road a. d_a, T_a and R_a are travelling distance, travelling time and toll on road a respectively.

λ_{kl}^{a} is the binary decision variable which is equal to 1 if commuters between zone k and l include road a in their route from k to l, and 0 otherwise. The objective function implies that the commuters select a set of roads which incurs the least cost among all possible routes connecting zones k to zone l.

The first constraint specifies the traffic flow on each road. It is defined as the sum of all commuting flows between all origin-destinations which include road a in their minimum cost route. The second constraint represent flow between all origin-destinations. The flow depends on the minimum possible cost between the origin-destination pair, C_{ij}. The cost is formulated in the third constraint. This constraint explains why the route choice can be considered as a game between all commuters. In other words, the optimal decision for a particular commuter (λ_{kl}^{a}) depends on the decisions of other commuters (λ_{ij}^{a}). This problem can therefore be considered as a game between commuters.

The fourth constraint characterises travelling cost on each single road which is assumed to be the linear function of length of a road and the time needed to travel from one end to the other. The length of a road is fixed and therefore it is straightforward to calculate. However, the travelling time is a function of traffic flow on the road. The function is given in the fifth constraint. If a road is priced, the road toll is also considered in the travelling cost and the attributed binary variable δ_a is set equal to 1. This implies that road users' decisions also depend on the authorities' pricing decision which is made in the first stage of the game.

Cost of commuting along road a can be expressed as:

$$c_a = \gamma d_a + \alpha T_a + \delta_a R_a \tag{8}$$

if two zones like i and j are not directly connected by road a, the cost of a journey from origin i to destination j can be obtained by summing over all of the roads which link i and j.

The travel time is defined as a function of the length of the link, d_a, the flow of traffic on the road, F_a, and the capacity of the road, ω_a i.e. $T_a = f(d_a, F_a, \omega_a)$. We would like a smooth function which is twice differentiable, and which has the properties that $\frac{\partial T_a}{\partial F_a} > 0$ and $\frac{\partial^2 T_a}{\partial F_a^2} > 0$. The speed-density relationship given by Noland (1997) is used in this paper.

$$T_a = d_a \left[T_a^0 + T_a^1 \left(\frac{F_a}{\omega_a} \right)^{\varepsilon} \right] \tag{9}$$

The quantity T_a^0 represents the time taken to travel 1 km in the absence of congestion. The values T_a^1 and ε control how quickly journey times rise as the ratio of use to capacity changes. A value of 0.15 is usually used for T^1 and a value of 4 for ε in Noland (1997). We allow the values of T_a^0 and T_a^1 to vary by road, to account for differences in speed limits. We set $T_a^1 = 0.15 T_a^0$, which implies that congestion affects travelling time more on roads with lower speed limits (Liu and McDonald, 1998). This results in the travel time function given below.

$$T_a = d_a T_a^0 \left[1 + 0.15 \left(\frac{F_a}{\omega_a} \right)^4 \right] \tag{10}$$

In Equation (10), d_a, T_a^0 and ω_a are constants. The flows on road a, F_a are calculated based on the flows calculated in Equations (3)-(5).

When the traffic flows are known, it is relatively straightforward to calculate the traffic on any individual link in the road network, as shown in Equation (11).

$$F_a = \sum_{i,j} \lambda_{ij}^a f_{ij} \tag{11}$$

B.C Basic- and local-sector jobs

Similar to many spatial general equilibrium models, we distinguish between two types of jobs: (1) basic sector jobs which are treated as exogenous and (2) non-basic/local sector jobs which are estimated endogenously.

The number of basic jobs in each zone depends on the competitiveness of the zone while the number of local sector jobs represent the residential pattern and shopping behaviour of households. One approach is to assume the number of local jobs proportionate to the number of residents in each zone; however, we apply another approach which is more appropriate which results from the trade-off between travelling costs and price savings (Gjestland et al., 2006). Due to such a trade-off, the distribution for number of local sector jobs is as follows: (1) In centre, the density of local sector jobs is very high due to the low prices (2) In suburbs, the density of local sector jobs is relatively low because a high share of shopping will be pulled towards the centre since the travelling cost to centre is low and (3) In zones which are located in a long distance from the centre, the number of local sector jobs is proportional to the number of residents in the zones.

Therefore, the distribution of local jobs is affected by the residential location pattern. On the other hand, the residential location pattern in a zone is dependent on the job opportunities in that specific zone. It means that the number of residents and number of jobs in one zone are interdependent.

In this paper, the initial number of basic jobs and local jobs in each zone is calculated based on economic base analysis techniques. Two different techniques are applied: (1) “Assumption Technique” and (2) “Location Quotient Technique” (see for example McCann (2013)). First, we “assume” that all jobs in Mining, Agriculture and fishing are considered basic jobs and jobs in retail industry, teaching and health services are all non-basic jobs or local jobs. However, for other sectors such as Electricity, Transportation, Business activities, etc. we calculated location quotient of each zone and identified the share of basic and non-basic jobs in different zones.

B.D Relocation matrix

A core component of the modelling in this paper is to construct a migration probability matrix. The factors included in the matrix must be compatible with what is already known in the literature about the main factor affecting the probability of relocating from one zone to the other. The matrix representing Markov chain is constructed based on the concept introduced by Nævdal et al. (1996).

For constructing the relocation matrix, we start with the connectivity matrix which is defined as follows:

$$con_{ij} = \begin{cases} 1 & \text{if } i \text{ and } j \text{ are connected by a direct road} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

Then, the level of neighbouring must be determined for every origin i and destination j. Now, the symmetric matrix Q_{ij} can be calculated as:

$$Q_{ij} = \begin{cases} s^{m_{ij}} C_{ij}^{-\beta_{dd}} & \text{if } i \neq j \text{ and } m_{ij} \leq n \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

s is absorption parameter, n is the maximum transition length, C_{ij} is the generalized travelling cost from

i to j, and β_{ij} is a distance deterrence parameter. Having calculated Q_{ij}, the Markov transition matrix is:

$$M_{ij} = \begin{cases} 1 - \alpha_i & \text{if } i = j \\ \frac{Q_{ij}}{\sum_{k,k \neq j} Q_{ij}} \alpha_i & \text{otherwise} \end{cases} \tag{14}$$

α_i denotes the probability that a person in zone i will move out within a given time frame. This probability is calculated based on the residential and job location patterns. For this purpose a number of functions are utilised in order to express the probability of staying in zone i, α_i, as a function of E_i , number of working population in zone i and L_i, the number of residents in zone i. The functions are as follows:

$$\alpha_i = \alpha_i(L_i) + G(C_i)\text{max}\{\rho \left(\frac{L_i - E_i}{L_i} \right), 0\} \tag{15}$$

the first part of the expression, $\alpha_i(L_i)$, represents the attractiveness of zone i as a function of its population. In other words, if zone i is bigger and it has higher population, the zone is more attractive for job seekers. Therefore, the probability of moving out from the zone is smaller since the probability of finding a job is higher. In this paper, we have used a simple function for $\alpha_i(L_i)$.

$$\alpha_i(L_i) = \begin{cases} \alpha^{minimum} & \text{if } L \geq L^{critical} \\ 1 + \frac{\alpha^{minimum} - 1}{L^{critical}} L & \text{if } L \leq L^{critical} \end{cases} \tag{16}$$

If the population of a zone is over a threshold, the probability of moving out is constant. While for smaller zones, out-migration increases linearly with falling population. In this paper, $L^{critical}$ is assumed to be 1000.

The second expression in α_i is incorporating the accessibility of zone i from all other zones. It accounts for the fact that the zones with cheaper accessibility connections are more popular to live in. This is formulated by defining a generalized cost deterrence function $G(x)$ which is decreasing if the average generalised cost for a zone is higher.

$$G(x) = \frac{1}{1 + e^{-k(x - x_0)}}, x_0 = \frac{1}{2}(C_0 + C_\infty), k = \frac{2\text{log}(\frac{1}{\mu} - 1)}{C_\infty - C_0} \tag{17}$$

Parameters C_0, C_∞ and μ captures the sensitivity to the generalised cost in the model. The average generalised cost for zone i is defined as:

$$C_i = \sum_{i \neq j} \frac{W_j}{\sum_{k \neq i} W_k} C_{ij} \tag{18}$$

It is observed that the average generalised cost of zone i is weighted average of all generalised costs attributed to zone i. The weights, W_j, represent the size of alternative job destinations. In other words, the definition of average generalised cost for zone i accounts for two factors: the generalised travelling cost from zone i to other zones and competition for jobs in alternative locations. Therefore, the weights, W_j, in the average generalised cost formulation is defined as:

$$W_j = E_j(1 - G(C_{ij}))\frac{E_j}{L_j} \tag{19}$$

The equilibrium is reached if applying the transition matrix does not considerably change the distribution of jobs and residents in the network.

It is worth mentioning that we ignore the job diversity, house prices and wage differences in the model.

C Network detail

Table 1: Initial residential and working population in each zone

	Residential population	Labour population
Zone 1	20 387	46 989
Zone 2	19 799	24 039
Zone 3	2 340	1 687
Zone 4	16 801	12 409
Zone 5	8 938	8 095
Zone 6	5 011	2 021
Zone 7	6 061	5 344
Zone 8	12 321	6 821
Zone 9	8 475	7 549
Zone 10	713	192
Zone 11	2 614	1 801
Zone 12	7 341	4 437
Zone 13	2 517	1 220
Zone 14	8 247	17 539
Zone 15	4 691	3 288
Zone 16	1 339	721
Zone 17	8 633	5 703
Zone 18	24 671	24 048
Zone 19	6 773	6 474
Zone 20	6 747	6 586
Zone 21	12 301	10 208
Zone 22	2 452	2 548
Zone 23	15 733	13 202
Zone 24	12 490	6 950
Zone 25	14 919	12 443

Table 2: Distribution of type of jobs in Hordaland county, used for initial estimation of number of basic and local sector jobs

	Bergen	Stord [7]	Voss	Eidfjord [8]	Vaksdal [9]	Os	Austevoll	Fjell [10]	Askøy	Meland [11]
Agriculture and fishing	423	1496	405	345	769	157	477	277	100	400
Mining and quarrying	6007	33	6	4	16	5	1	315	30	64
Industry	10018	5008	334	1011	1953	727	496	2303	487	2597
Electricity, water and sanitation	1822	444	91	182	178	6	34	138	63	262
Construction	11348	2164	729	772	917	617	111	1255	868	1049
Wholesale and retail trade, repair of motor vehicles	21358	2860	1085	689	974	824	196	1839	1060	1339
Transportation and storage	8714	1195	383	316	634	316	383	1149	339	983
Accommodation and food service activities	5589	584	396	352	205	225	38	215	54	182
Information and Communication	5869	279	69	65	31	33	52	177	35	120
Finance and Insurance	5216	182	73	51	65	30	11	92	26	67
Technical services, property	11692	914	247	291	210	203	159	913	179	467
Business activities	10391	771	104	142	214	105	30	506	246	343
Public administration., Defense, social insurance	8414	991	291	293	545	257	71	746	600	518
Teaching	13720	2238	653	508	1079	592	188	1153	691	1281
Health and Social Services	31316	5667	1695	1518	2302	1542	403	2311	2178	2842
Personal services	6317	604	225	177	211	189	31	376	174	339
Unknown	566	91	23	35	55	35	15	56	28	54
	(-14628)	(-1473)	(-223)	(-277)	(-150)	(-160)	(-148)	(-619)	(-208)	(-464)
TOTAL	144152	24048	6586	6474	10208	5703	2548	13202	6950	12443

Table 3: Travel distance measured in kilometres

	Zones																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Zone 1	-	6	6	-	8	-	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 2	6	-	-	-	-	7	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 3	6	-	-	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 4	-	-	8	-	-	-	-	-	-	-	-	-	-	-	15	-	-	-	-	-	-	-	-	-	29
Zone 5	8	-	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 6	-	7	-	-	4	-	-	12	-	-	-	-	-	-8	-	-	-	-	-	-	-	-	-	-	-
Zone 7	7	-	-	-	-	-	-	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 8	-	-	-	-	-	12	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18	14	-
Zone 9	-	-	-	-	-	-	-	-	-	10	5	5	-	-	-	11	-	-	-	-	-	-	-	-	-
Zone 10	-	-	-	-	-	-	-	-	10	-	-	-	10	-	-	-	21	-	-	-	-	-	-	-	-
Zone 11	-	3	-	-	-	-	-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 12	-	-	-	-	-	-	-	-	5	-	-	-	6	6	-	-	-	-	-	-	-	-	-	-	-
Zone 13	-	-	-	-	-	-	-	-	-	10	-	6	-	-	-	-	20	-	-	-	-	40	-	-	-
Zone 14	-	-	-	-	-	8	-	-	-	-	-	6	-	-	-	-	-	-	-	-	-	-	37	-	-
Zone 15	-	-	-	15	-	-	-	-	-	-	-	-	-	-	-	7	-	-	-	-	21	-	-	-	-
Zone 16	-	-	-	-	-	-	-	-	11	-	-	-	-	-	7	-	-	-	-	-	-	-	-	-	-
Zone 17	-	-	-	-	-	-	-	-	-	21	-	-	20	-	-	-	-	56	-	-	45	-	-	-	-
Zone 18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	56	-	140	-	-	48	-	-	-
Zone 19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	140	-	62	-	-	-	-	-
Zone 20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	62	-	60	-	-	-	-
Zone 21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	21	-	45	-	-	60	-	-	-	-	-
Zone 22	-	-	-	-	-	-	-	-	-	-	-	-	40	-	-	-	-	48	-	-	-	-	-	-	-
Zone 23	-	-	-	-	-	-	-	18	-	-	-	-	-	37	-	-	-	-	-	-	-	-	-	-	-
Zone 24	-	-	-	-	-	-	-	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 25	-	-	-	29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4: Travel time measured in minutes when there is no congestion

	Zones																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Zone 1	-	12	10	-	16	-	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 2	12	-	-	-	-	13	-	-	-	-	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 3	10	-	-	11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 4	-	-	11	-	-	-	-	-	-	-	-	-	-	-	18	-	-	-	-	-	-	-	-	-	36
Zone 5	16	-	-	-	-	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 6	-	13	-	-	8	-	-	19	-	-	-	-	-	12	-	-	-	-	-	-	-	-	-	-	-
Zone 7	15	-	-	-	-	-	-	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 8	-	-	-	-	-	19	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	25	21	-
Zone 9	-	-	-	-	-	-	-	-	-	14	10	10	-	-	-	15	-	-	-	-	-	-	-	-	-
Zone 10	-	-	-	-	-	-	-	-	14	-	-	-	14	-	-	-	25	-	-	-	-	-	-	-	-
Zone 11	-	8	-	-	-	-	-	-	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 12	-	-	-	-	-	-	-	-	10	-	-	-	9	11	-	-	-	-	-	-	-	-	-	-	-
Zone 13	-	-	-	-	-	-	-	-	-	14	-	9	-	-	-	-	25	-	-	-	-	90	-	-	-
Zone 14	-	-	-	-	-	12	-	-	-	-	-	11	-	-	-	-	-	-	-	-	-	-	109	-	-
Zone 15	-	-	-	18	-	-	-	-	-	-	-	-	-	-	-	14	-	-	-	-	17	-	-	-	-
Zone 16	-	-	-	-	-	-	-	-	15	-	-	-	-	-	14	-	-	-	-	-	-	-	-	-	-
Zone 17	-	-	-	-	-	-	-	-	-	25	-	-	25	-	-	-	-	50	-	-	50	-	-	-	-
Zone 18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	50	-	192	-	-	76	-	-	-
Zone 19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	192	-	55	-	-	-	-	-
Zone 20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	55	-	45	-	-	-	-
Zone 21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	17	-	50	-	-	45	-	-	-	-	-
Zone 22	-	-	-	-	-	-	-	-	-	-	-	-	90	-	-	-	-	76	-	-	-	-	-	-	-
Zone 23	-	-	-	-	-	-	-	25	-	-	-	-	-	109	-	-	-	-	-	-	-	-	-	-	-
Zone 24	-	-	-	-	-	-	-	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Zone 25	-	-	-	36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

C.A Parameters estimation

The parameter β in gravity model is calculated to be 0.016 based on least square method comparing the flow generated by the gravity model and actual flow on roads. Travelling cost is calculated based on the average fuel consumption for urban area speed. From urban driving cycle, the average fuel consumption is assumed to be 12.5 litre per 100 kilometre. With the average fuel cost of 14 NOK per litre and depreciation cost of 0.75 NOK per kilometre, we estimated the travel cost per kilometre to be 2.5 NOK. In addition, the average net wage per hour is assumed as 200 NOK.

D Results detail

Table 5: Change in residential population of each zone resulting from road pricing in comparison with unpriced scheme

		Price Level			
Zone No.	Zone name	0	10	14	20
1	Bergenhus (Sentrum)	—	-2.5 %	-3.5 %	-4.7 %
2	Årstad	—	8.8 %	11.8 %	15.5 %
3	Eidsvåg	—	9.2 %	12.5 %	16.5 %
4	Åsane	—	0.1 %	0.0 %	-0.2 %
5	Fyllingsdalen	—	3.3 %	4.1 %	5.0 %
6	Bønes	—	-0.3 %	-0.4 %	-0.6 %
7	Laksevåg	—	4.4 %	5.7 %	6.9 %
8	Loddefjord	—	-1.1 %	-1.4 %	-1.8 %
9	Nesttun	—	-1.0 %	-1.3 %	-1.6 %
10	Kalandseidet	—	-1.4 %	-1.9 %	-2.5 %
11	Paradis	—	1.9 %	2.3 %	2.7 %
12	Rådal	—	-1.2 %	-1.6 %	-2.1 %
13	Fana	—	-1.5 %	-2.0 %	-2.6 %
14	Ytrebygda	—	1.2 %	1.6 %	2.2 %
15	Arna	—	-1.6 %	-2.1 %	-2.6 %
16	Epseland	—	-1.4 %	-1.8 %	-2.4 %
17	Os	—	-2.1 %	-2.8 %	-3.6 %
18	Stord	—	1.1 %	1.5 %	2.1 %
19	Eidfjord	—	-6.0 %	-7.7 %	-9.4 %
20	Voss	—	-2.3 %	-3.0 %	-3.6 %
21	Vaksdal	—	-2.2 %	-2.9 %	-3.7 %
22	Austevoll	—	-3.0 %	-4.0 %	-5.1 %
23	Fjell	—	1.2 %	1.6 %	2.2 %
24	Askøy	—	-1.8 %	-2.4 %	-3.0 %
25	Meland	—	1.2 %	1.6 %	2.2 %

Table 6: Change in residential population of each zone resulting from moving basic jobs out of the CBD

		Moving 1000 jobs from zone 1) to:			
Zone No.	Zone name	Årstad (Zone 2)	Eidsvag (Zone 3)	Fyllingsdalen (Zone 5)	Laksevåg (Zone 7)
1	Bergenhus (Sentrum)	-0.5%	-0.6 %	-0.9 %	-0.6 %
2	Årstad	8.5%	-0.5 %	2.5 %	-0.5 %
3	Eidsvåg	-0.8%	16.9 %	-0.2 %	-0.6 %
4	Åsane	-0.4%	-0.3 %	-0.6 %	-0.5 %
5	Fyllingsdalen	-0.6%	-0.4 %	13.7 %	-0.5 %
6	Bønes	-0.5%	-0.6 %	-0.5 %	-0.6 %
7	Laksevåg	-0.7%	-0.6 %	-0.6 %	19.5 %
8	Loddefjord	-0.5%	-0.6 %	-0.7 %	-0.6 %
9	Nesttun	-0.4%	-0.5 %	-0.8 %	-0.6 %
10	Kalandseidet	-0.4%	-0.5 %	-1.1 %	-0.7 %
11	Paradis	-0.5%	-0.6 %	-0.5 %	-0.7 %
12	Rådal	-0.4%	-0.5 %	-0.9 %	-0.6 %
13	Fana	-0.4%	-0.5 %	-1.0 %	-0.6 %
14	Ytrebygda	-0.5%	-0.5 %	-0.4 %	-0.5 %
15	Arna	-0.5%	-0.5 %	-0.8 %	-0.6 %
16	Epseland	-0.4%	-0.5 %	-1.0 %	-0.7 %
17	Os	-0.3%	-0.4 %	-0.9 %	-0.5 %
18	Stord	-0.5%	-0.5 %	-0.4 %	-0.5 %
19	Eidfjord	0.1%	0.0 %	-1.6 %	-0.2 %
20	Voss	-0.3%	-0.3 %	0.0 %	-0.4 %
21	Vaksdal	-0.2%	-0.3 %	-0.5 %	-0.4 %
22	Austevoll	-0.2%	-0.2 %	-0.5 %	-0.4 %
23	Fjell	-0.5%	-0.5 %	-0.4 %	-0.5 %
24	Askøy	-0.3%	-0.3 %	-0.6 %	-0.4 %
25	Meland	-0.5%	-0.5 %	-0.5 %	-0.5 %