# The impact of monetary costs on commuting flows*

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**Abstract**

In western Norway, fjords cause disconnections in the road network, necessitating the use of ferries. In several cases, ferries have been replaced by roads, often part-financed by tolls. We use data on commuting from a region with a high number of ferries, tunnels and bridges. Using a doubly-constrained gravity-based model specification, we focus on how commuting responds to varying tolls and ferry prices. Focus is placed on the role played by tolls on infrastructure in inhibiting spatial interaction. We show there is considerable latent demand, and suggest that these tolls contradict the aim of greater territorial cohesion.

Keywords: Commuting; Gravity model; Toll charges; Investment financing; Road pricing

JEL Codes: R41, R48, R12

## 1 Introduction

The presence of topographical barriers such as mountains and fjords can cause the road network to become disjointed. In the coastal areas of western Norway, some large-scale investments have been made which aim to remove the effect of such barriers through the construction of bridges and tunnels. Further such investments are being planned which will connect areas which, at least from a Norwegian perspective, are relatively densely populated. Economic evaluations of such investments call for predictions regarding traffic flows and the willingness-to-pay for new road connections. This paper focuses on commuting flows, which represent one important component of travel demand.

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In most cases, a new tunnel or bridge is at least partly financed by toll charges. The main ambition in this paper is to study how monetary costs, represented by ferry prices and toll charges, inhibit commuting flows. The analysis is based on cross-section data from a region in western Norway with a high number of ferries and tunnels/bridges. The region is topographically heterogeneous, with fjords causing disconnections in the road transportation network. It is probably difficult to find other regions, anywhere, with a higher density of ferry connections. It is also fortunate for our purposes that the different connections vary considerably both with respect to travelling time and price. This region also has a high number of origin-destination combinations involving either a ferry, tunnel, bridge or toll road. This makes it a very appropriate study area for empirical analysis of how commuting flows are affected by monetary costs.

Gitlesen and Thorsen (2000) estimated some parameters which reflect the effects of reduced travelling time in this area of Norway. Possible changes in money expenses were not considered, and no attempts were made to transform such monetary costs into time units. In this paper, the estimated demand function for journeys-to-work is used to discuss how commuting flows depend on the pricing policy chosen for a new road connection. In addition, the analysis provides estimates of how commuting flows are affected by reductions in travelling time. The chosen model formulation also accounts for the effects of specific characteristics of the spatial structure.

The estimates and predictions which are presented in this paper are obtained from a modified version of the so-called competing destinations model (see Fotheringham, 1983*a*). In Thorsen and Gitlesen (1998) the relevant model formulation was empirically tested and compared to other specifications of gravity-based spatial interaction models. This evaluation was also based on Norwegian commuting flow data. This family of models is commonly applied to predicting traffic flow consequences of changes in the transportation network. However, such models are, in general, constructed to predict a trip distribution matrix at a given point in time; they are not constructed to account for possible long term effects on the spatial distribution of employment and population.

From a more long-run perspective, fundamental changes in the road transportation network might affect location decisions of firms and workers. These changes can be expected to influence the pattern of commuting flows and the traffic generated on the new road links. Hence, long-run predictions for generated traffic should ideally not be made within a static, doubly constrained modelling framework. Our predictions represent conditional statements, as they are based on the assumption that the location pattern remains unchanged. More comprehensive models than the one we use here are available where the assumption of fixed residential and working patterns is relaxed. Waddell (2002) offers a brief review of operational large-scale approaches for modelling land-use and transportation. In this paper, we consider a rural region. There are several parts of a large-scale urban land-use and transportation models that are not very relevant in such a context, for instance the traffic assignment module. Applications of large-scale models are very data- and time-consuming. At least as a first step, it provides useful insight to do the analysis within a more parsimonious and aggregate model formulation. One such example is the Lowry-type of model, see Thorsen (1998) for an application from the same parts of Western Norway considered in this paper.

In order to explore what the price effect estimated means in practice, two concrete examples are considered. One of these relates to the replacement of a number of ferry connections by a system of two bridges and one tunnel, financed in part by road tolls. The second case considers the construction of a tunnel through a mountain. This tunnel was also part-financed by a toll charge. We use our estimates of how commuting flows are affected by monetary costs to predict demand curves for the new road-links resulting from the aforementioned infrastructure investments. Based on the predicted demand curves we further find the toll charge which maximizes the revenue of the private operators of the new infrastructure, and the toll charge which leads to the maximum social welfare. If the demand curve is elastic, an increased toll charge will result in a great reduction in traffic volume, and there will be a limited potential for toll revenues. The optimal private and social toll charges are finally compared to the toll that is actually being charged.

The paper is structured as follows. The modelling framework is presented in Section 2. Section 3 presents the data and the region, focusing in particular on the two concrete examples which will be discussed later. Section 4 presents the estimation results and a discussion of the two examples chosen. Section 5 looks at the development of commuting flows over time. Section 6 considers the issue of what the optimal toll should be. Finally, some concluding remarks are offered in Section 7.

## 2 The modelling framework

The model used in this paper belongs to the gravity modelling tradition. For a general discussion of this tradition, see Erlander and Stewart (1990) or Sen and Smith (1995). In a gravity model, it is assumed that spatial interaction is explained by the distance between an origin and a destination, and by two aggregate measures: one to account for the generativity of origins and the other to address the attraction of destinations. In studies of journeys to work, we typically define the generativity of origins by the number of workers, while we usually measure the attraction of destinations by total employment.

In this paper, we will be using a doubly-constrained version of the gravity model. This means that we introduce a set of balancing constraints, ensuring that the column sums of the predicted commuting flow matrix equal the total number of jobs at the corresponding destinations, and that each row sum equals the number of workers residing in the corresponding zone. Hence, the model is based on the assumption of a given spatial distribution of jobs, and a given spatial residential pattern. It is well known that a constrained gravity model is equivalent to the multinomial logit model, see Anas (1983) for details. This means that the model can be derived from random utility theory.

Ignore for a moment the marginal total constraints. The structural equation of a standard gravity model is represented by:

$$T_{ij} = A_i O_i B_j D_j \exp(-\beta d_{ij})$$

Here,

$T_{ij}$ is the estimated number of commuters from origin $i$ to destination $j$

$O_i$ is the observed number of commuting trips originating from zone $i$

$D_j$ is the observed number of commuting trips terminating in zone $j$

$d_{ij}$ is travelling time from origin $i$ to destination $j$

$\beta$ is a distance deterrence parameter related to travelling time

The model used in this paper extends this standard specification. First, we add an accessibility measure, to account for the possibility that the attraction of a destination depends on its position relative to competing destinations. Second, we account for the hypothesis that the standard gravity model does not adequately capture the tendency that workers prefer a job in the zone where they are living. Finally, we distinguish between travelling time and monetary costs in the distance deterrence function. Including the marginal total constraints, the analysis in this paper is based on the following model specification:

$$T_{ij} = A_i O_i B_j D_j S_{ij}^{\rho} \left( O_i^{\alpha_1} D_j^{\alpha_2} \right)^{\delta_{ij}} e^{(-\beta d_{ij} - \sigma c_{ij} + \mu \delta_{ij})} \tag{1}$$

$$A_i = \left[ \sum_j B_j D_j S_{ij}^{\rho} \left( O_i^{\alpha_1} D_j^{\alpha_2} \right)^{\delta_{ij}} e^{(-\beta d_{ij} - \sigma c_{ij} + \mu \delta_{ij})} \right]^{-1} \tag{2}$$

$$B_j = \left[ \sum_i A_i O_i S_{ij}^{\rho} \left( O_i^{\alpha_1} D_j^{\alpha_2} \right)^{\delta_{ij}} e^{(-\beta d_{ij} - \sigma c_{ij} + \mu \delta_{ij})} \right]^{-1} \tag{3}$$

Where:

$S_{ij}$ is the accessibility of destination $j$ relative to all other destinations, perceived from zone $i$

$c_{ij}$ is the toll charges and ferry prices incurred when travelling between origin $i$ and destination $j$

$\sigma$ represents the effect of the monetary costs on commuting flows

$\delta_{ij}$ is the Kronecker delta

$$\delta_{ij} = \begin{cases} 0 & \text{if } \; i \neq j \\ 1 & \text{if } \; i = j \end{cases}$$

while $\mu$ is a parameter which represents some kind of a benefit of residing and working in the same zone, or, analogously, a start up cost to be incurred if work and residence is not in the same zone. The parameters $\alpha_1$ and $\alpha_2$ are introduced to take into account the possible influence of local labour market characteristics on the diagonal elements of the trip distribution matrix. $A_i$ and $B_j$ are the balancing factors which ensure the fulfilment of the marginal total constraints; $\sum_j T_{ij} = O_i$ and $\sum_i T_{ij} = D_j$. Consequently, this doubly-constrained model specification is constructed for a pure trip distribution problem.

As mentioned above, the accessibility measure $S_{ij}$ is introduced to account for how the choice of a destination depends on its position relative to competing destinations. If a potential destination is located in a cluster of alternative destinations, accessibility is high, while a more peripherally located potential destination has a lower value of accessibility. This is achieved by the following measure of accessibility:

$$S_{ij} = \sum_{\substack{k=1 \\ k \neq i, k \neq j}}^{w} D_k e^{(-\beta d_{ij} - \sigma c_{ij} + \mu \delta_{ij})} \tag{4}$$

Here, $w$ is the number of potential destinations. If $n$ denotes the number of destinations for which there is observed interaction from origin $i$, then $w \geq n$. The standard reference for this kind of accessibility measure is Hansen (1959), and it can be interpreted as a job opportunity density measure (Gitlesen and Thorsen, 2000). Notice that the impact of distance and price upon the perception of accessibility is not distinguished from the direct impact of distance and price upon commuting choices. In other words the parameters $\beta$, $\sigma$ and $\mu$ in the ordinary distance deterrence function are not distinguished from the corresponding parameters in the definition of $S_{ij}$.

Due to the introduction of the accessibility term, the model is termed a competing destinations model. Sheppard (1979) introduced the idea that the probability of choosing a destination depends on how this destination is located relative to alternative opportunities. The competing destinations model was introduced by Fotheringham (1983*a*) to improve the ability of this modelling tradition to capture spatial structure effects. It is well known in the literature that a traditional gravity model represents a misspecification of spatial interaction if, for example, agglomeration or competition effects are present. If such effects are present, the distribution of trips will be affected by the clustering system of destinations in addition to distance, see for example Fotheringham (1983*a*,*b*, 1984). When agglomeration forces are dominant, the sign of the parameter $\rho$ in Equation (1) will be positive, while the parameter takes a negative value if competition forces are dominant. For a more detailed discussion of these effects, see Lo (1991). References for empirical evaluations of this model specification are available in Pellegrini and Fotheringham (1999). The competing destinations model can also be explained with a hierarchical processing search strategy rather than with a simultaneous evaluation of all alternatives. Both Fotheringham (1988) and Pellegrini and Fotheringham (1999) focus on this interpretation of the competing destinations model as a framework for explaining and predicting spatial choices.

Thorsen and Gitlesen (1998) tested a hypothesis that special care should be taken regarding the potential benefits of residing and working in the same zone, represented by the additive constant $\exp(\mu\delta_{ij})$ to the diagonal elements of the trip distribution model specification. This approach was found to contribute significantly to the explanatory power of the model, suggesting that the option of residing and working in the same zone should be specifically accounted for in a model explaining commuting flows. In some respects, the additive constant attached to the diagonal elements is analogous to specifying the so called Champernowne distance deterrence function, which incorporates an additive constant start-up cost in addition to distance, see for example Sen and Smith (1995). This additive constant attached to the diagonal elements can also be motivated by the possible existence of measurement errors, see Thorsen and Gitlesen (1998).

Thorsen and Gitlesen (1998) also proposed an approach where the diagonal elements of the trip distribution matrix are influenced by local labour market characteristics. Labour market characteristics are reflected by the demand for labour originating from the firms in a specific zone, relative to the supply of labour originating from the zone. The results presented in Thorsen and Gitlesen (1998) supported a hypothesis which states that the relative frequency of within-zone journeys-to-work is high in a zone where employment is low relative to the labour force. This hypothesis corresponds to a situation with parameter values $\alpha_1 > 0$ and $\alpha_2 < 0$.

## 3 The region and the data

The study area is comprised of the southern parts of Hordaland county, in western Norway. As is clear from the map in Figure 1, there are 8 municipalities in the region. The road transportation network in the area is highly disjointed, mainly due to the presence of numerous fjords, splitting the study area into separate subareas. These subareas are isolated, as interaction with other areas is restricted by the topographical barriers.

Estimation results in this paper are based on a subdivision of the region into 58 postal delivery zones. This is the most spatially disaggregated level for which data on jobs and workers is available. The information on the spatial distribution of jobs is based on Statistics Norway's

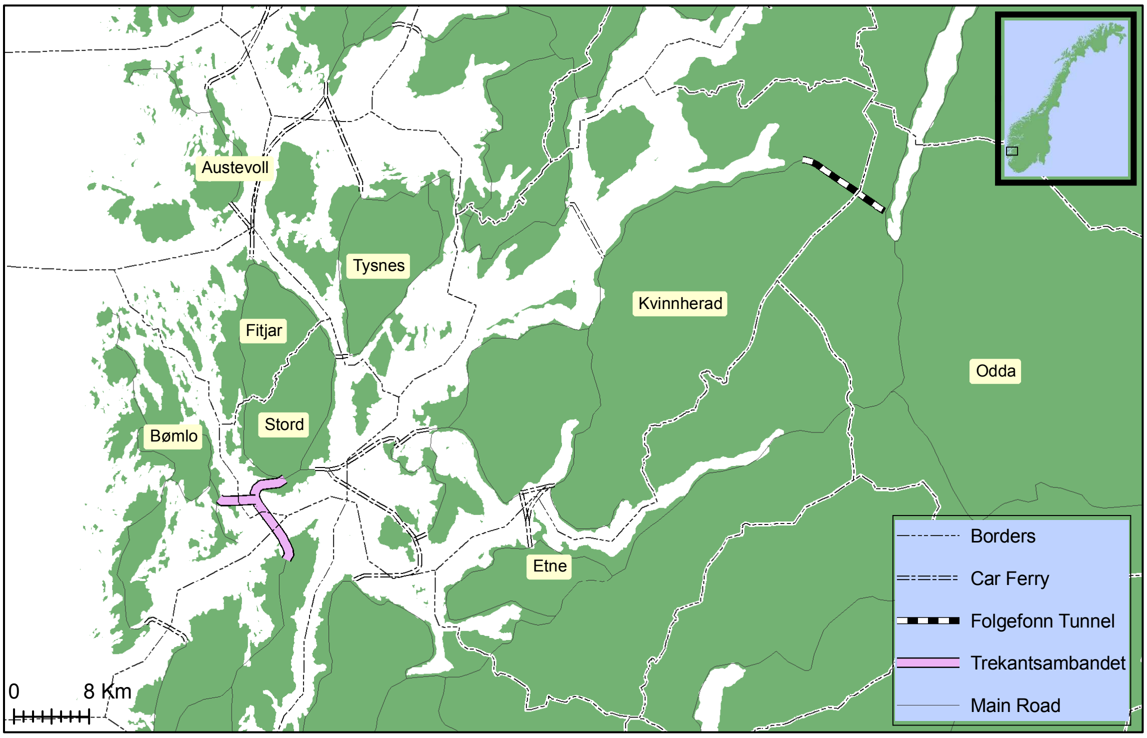



Figure 1: The municipalities in the study area and the main transportation network in 2006.

Employer-Employee register. The register includes only employees and not the self-employed. Data refer to the autumn of 2006. The ferry companies in this region operate a degree of price discrimination. This means that for a particular ferry, there is not one single price. A discount is available if trips are bought in advance. For journeys-to-work, it seems reasonable to apply the cheapest alternative. This means that the price per trip is calculated based on workers purchasing 40 pre-pay journeys.

The matrices of travelling times were prepared by the Norwegian Mapping Authority[1] using information on the road network and the distribution of the population. Roads are classified according to distances and speed limits, with account being taken for the fact that the actual speed achieved will vary by road category. Information on speed limits and road categories was converted into travelling times by the Norwegian Mapping Authority using rules developed by the Institute of Transport Economics. The centroid of each postal zone is population-weighted. Finally, the matrix of travelling times was generated using a shortest route algorithm.

The spatial pattern of population and employment in this region is appropriate for our

[1]www.statkart.no

problem. Population and employment tend to be concentrated in the zonal centres rather than being more evenly dispersed, and the division of zones corresponds to a natural kind of clustering, where the interzonal distances are in general considerably longer than intrazonal distances.

As indicated in the introduction, a particular argument in favour of choosing this region for studying the price responsiveness of commuting flows is that there are a high number of ferry connections, and that many origin-destination combinations involve toll charges resulting from new bridges/tunnels. In 2006, there were 17 combinations of zones directly linked by ferries, while 4 combinations of zones have relatively recently been linked by new roads, financed by toll charges. Three of those links connect the most densely populated parts of this sparsely populated region. This contributes to the fact that a relatively high number of potential origin-destination combinations involve monetary costs, even if only combinations corresponding to a reasonable commuting time are considered. This dataset further gives sufficient variation in prices to estimate the price response in commuting. Such variation in prices could also be found in an urban system, for instance as a result of varying link-specific toll charges or varying parking costs in different areas. Such fixed costs related to specific zones could definitely influence the mode choice (see for instance Washbrook et al. (2006)), but potentially also the job location. In the rural region we consider, parking costs can be ignored. Private cars, including car ferries, are the (totally) dominant mode for interzonal commuting. Hence, we find no need to add the extra complexity of modal choice into our model.

The total population in our study area was 59,355 on January the 1st 2010. The largest municipality was Stord, with 17,565 inhabitants. Kvinnherad had a population of 13,187, Bømlo 11,275, Odda 7,047, Fitjar 2,931, while Tysnes had 2,779 inhabitants. In the period from 1990 to 2000 the population increased by approximately 3.9% in the study area, while it increased by 2.7% from 2000 to 2010. The population increase has primarily been concentrated on the islands of Bømlo and Stord, with inner areas typically lagging. Stord has experienced a population growth of approximately 21.3% in the period from 1990 to 2010, while the population in Odda has declined by approximately 15% during the same period. Concerning employment, this is one of the regions in Norway that makes the largest contributions to the total value creation in manufacturing industries. The dominating industry in the study area is related to the production of installations for the Norwegian oil and gas industry, and the region also hosts some shipping companies, mainly operating a fleet of vessels supporting oil and gas activities. Though the region is not the fastest growing and most prosperous region in the south-west of Norway, wages are slightly above the national average. The regional disparities in wages are modest, however, and the national average annual income in manufacturing industries gives an adequate impression of the income level in our study area. This average was NOK 425,600 (€51,154 or $48,090) in 2009 (see Statistics Norway[2]). Unemployment in the region has been persistently low the last couple of decades, only very occasionally exceeding 4% of the workforce for a municipality. Most of the municipalities have experienced unemployment rates below 2% for long periods.

To enhance the interpretation and understanding of the key variables used in this paper, it may be useful to provide some summary statistics. 2,263 workers live in the most densely populated zone, while only 39 workers live in the smallest zone. The average number of workers per zone is 428, which is of course equal to the average number of jobs per zone. Jobs tend to be more concentrated, however. The zonal distribution of jobs has a standard deviation of 681, while the corresponding number is 451 for the spatial residential pattern of workers. The zone with the highest employment has 3,485 jobs, while there are only 7 jobs in the zone with the lowest employment. The largest number of workers commuting between two separate zones is 505, while about 77% of the entries in the commuting flow matrix have zero commuters. The study area has an average number of 32 commuters per entry in the matrix. The highest level of monetary costs on a specific link is 81 NOK (€9.74 or $9.15), while the lowest nonzero level is 20 NOK (€2.40 or $2.26).

The discussion to follow focuses on two road infrastructure investments. One of the projects, Trekantsambandet, connects the islands Bømlo and Stord to each other and to the mainland. Stord was connected to the mainland at the end of 2000, while Bømlo was connected to Stord and the mainland in the spring 2001. The new road connections consist of a combination of two bridges and a subsea tunnel (260 meters below sea level), and it substituted 4 ferry connections. The total investment costs were around 1.85 billion NOK in 2001 prices (€222m or $209m), with the project being primarily financed by toll charges. The traffic increase and the incomes from toll charges have been higher than predicted; on average more than 4,000 vehicles used the new road links per day in 2006. In addition to serving local traffic between the municipalities of the region, some of the new links are a part of the main road connecting the major population

[2] www.ssb.no

centres in western Norway.

We focus our attention on the link between Stord and Bømlo and not the tunnel connecting them to the mainland. To provide some information on travel time differences before and after the opening of Trekantsambandet, consider the connection between two largest central places on Stord and Bømlo (Leirvik and Bremnes, respectively). Prior to the opening of the new links the estimated travelling time between the two centres was 55 minutes. After the opening of the new road link, the travelling time was 32 minutes.

Another investment project which was finished in 2001 was the Folgefonn tunnel, connecting the municipalities of Odda and Kvinnherad. The 11 km long tunnel has reduced travelling time between the two municipalities substantially. It is still, however, a relatively long distance between Odda and the most populated parts of Kvinnherad. According to our estimates, travelling through the tunnel between Odda and the closest subcenter in Kvinnherad (Rosendal) takes 49 minutes. Prior to the infrastructure investment the travelling time was 2 hours and 15 minutes, effectively prohibiting daily commuting.

As mentioned in the introduction, the analysis to follow assumes a given number of jobs and workers in all the zones of the region. We do not enter into a discussion of the possibility that infrastructure improvements may generate a process of regional economic growth. For the case of Trekantsambandet, recent developments indicate considerable investments in an industrial area and a shopping centre at the Stord side of the new bridges/tunnel. This may lead to a new agglomeration of economic activities. As stated in the introduction, such an analysis calls for a more general economic model, however, and is considered to be beyond the scope of this paper.

# 4 Results

The parameters are estimated simultaneously by the method of maximum likelihood. Maximum likelihood was found through an irregular simplex iteration sequence (Nelder and Mead, 1965). Standard errors were estimated by numerical derivation. The parameter estimates are reported in Section 4.1. Section 4.2 presents demand curves for commuting between two pairs of nodes in the network. In both of these examples, new infrastructure has recently been introduced and a toll charge is levied.

### 4.1 Parameter estimates

In this paper we are primarily focusing on the parameters $\beta$ and $\sigma$, reflecting the response to changes in travelling time and monetary costs on commuting flows. It follows from the parameter estimates and their respective standard errors in Table 1 that increased travelling time and/or increased monetary costs deter commuting.

Information on the goodness-of-fit is useful for an evaluation of the model. The Relative Number of Wrong Predictions (RNWP $= \frac{\sum_{i,j}(|\hat{T}_{ij} - T_{ij}|)}{\sum_{i,j} T_{ij}}$) was found to be 0.189, while the Standardized Root Mean Square Error (SRMSE) is 0.721. The maximum log likelihood value ($L$) for the model is $-126486.24$. For a comparison, consider next a model that is defined by Equations (1)-(4), except from the fact that monetary costs, $c_{ij}$, are not accounted for. This reduced version resulted in considerably less satisfactory values of the goodness-of-fit measures; RNWP$=0.235$, SRMSE$=0.978$, and $L = -126956.30$. The estimate of the distance deterrence parameter was $\hat{\beta} = 0.0787$ in this case.

Table 1: Parameter estimates based on the model which is specified by Equation (1).

| | Parameter value | Standard error |
|---|---|---|
| $\hat{\beta}$ | 0.065 | 0.001 |
| $\hat{\sigma}$ | 0.024 | 0.001 |
| $\hat{\mu}$ | 4.080 | 0.170 |
| $\hat{\alpha_1}$ | 0.083 | 0.045 |
| $\hat{\alpha_2}$ | -0.585 | 0.033 |
| $\hat{\rho}$ | -0.078 | 0.038 |

According to our estimates of $\beta$ and $\sigma$, the factor $\frac{0.064495}{0.024402}$ transforms changes in travelling times into monetary values. This means that a one minute reduction in travelling time corresponds to a reduction of approximately 2.64 NOK in monetary costs (€0.32 or \$0.30). In other words, the value of an hour spent on a journey-to-work is evaluated to be approximately NOK 159 (€19 or \$18), in 2006-prices.

One complicating factor when such estimates are interpreted is that commuting expenses for many commuters can be deducted when taxable income is calculated. In Norway, this applies to workers with a commuting distance exceeding 20 km. Those workers may deduct commuting expenses exceeding a lower limit, according to specific rates per km, and the income tax is then reduced by 28% of those expenses. If commuting expenses resulted in a proportional reduction in income tax the value of an hour spent on a journey to work would be $(159 \cdot 0.72 \approx)$ 114 NOK (€14 or \$13). This estimate ignores a lot of technical details in the rules of taxation, and implicitly assumes that all expenses related to ferries and tolls are deductible. As a benchmark for the estimates of the value of time we add some information on the wage level. Since spatial wage disparities are relatively modest in Norway, information on the average national wage level provides a rough estimate of the wage level also in the region we study. According to information from Statistics Norway, the average yearly earnings for full-time employees were around NOK 380,000 (€45,673 or \$42,938) in 2006. This corresponds to an average hourly wage of around 215 NOK (€26 or \$24).

Compared to the values officially recommended for cost benefit studies in Norway, our estimate of the value of time is very high. In Statens Vegvesen (2006), the value per hour for light vehicles is recommended to be NOK 198 (€24 or \$22) for time savings of work related trips, while trips to and from work should be evaluated by 57 NOK (€6.85 or \$6.44) per hour per person, in 2005 prices. Statens Vegvesen (2006) further recommends that this estimate should also be used for commuting trips involving ferries. The officially recommended values of time savings are based both on national and international empirical studies. Based on data from the Trondheim toll ring, Tretvik (1995) finds that the value of time on average was 52 NOK/hour (€6.25 or \$5.88) for commuters, and this result is in line both with Ramjerdi et al. (1997), and with results from international empirical studies, see Small (1992) for a survey.

It is well known in the literature that there may be spatial variation in the estimates of the value of time. The deviation between our estimates and the officially recommended estimates is, however, substantially larger than suggested by the literature. The officially recommended estimates are typically based on data collected before and after changes in toll levels at specific links in the transportation network, see for instance Tretvik (1995). Our estimates are based on cross section data from 2006. This means that the observed commuting flows reflect a situation where the transportation network had been more or less unchanged for a period of 5 years, after the opening of Trekantsambandet and the Folgefonn tunnel. Neither travelling times nor relative monetary costs of different alternatives have changed notably in this period. Our estimates result from a pure cross section approach, they are not estimated from the effects of the changes in terms of travelling times and monetary costs. Still, our estimates may have been different if we used cross section data from the first year after the substantial changes in the transportation network. To some degree our estimates represent a more long-term effect, reflecting a situation where workers have been given considerable time to adjust their combinations of job and residential location. Our scenario also differs from observations made in more urban areas, in that the modal choice and the traffic assignment perspectives are not relevant.

It is not unreasonable that the estimated value of time savings depends both on the time perspective and on spatial structure and transportation network characteristics of the region considered. At least, the estimates in Table 1 give rise to the hypothesis that the officially recommended value of time spent on journeys to work represents an underestimate in a long-run, rural, setting. There is also empirical support in the literature in favour of the hypothesis that revealed preference approaches like ours, typically result in higher value of time estimates than approaches based on stated preferences, see for instance Shires and de Jong (2009) and Brownstone and Small (2005). Hensher (2004) also offers an example where a stated choice design results in relatively low estimates of the willingness to pay for travel time savings.

Like most other studies of commuting flows, we have ignored the commuters' valuation of travel time variability. Based on stated preference data from Barcelona, Asensio and Matas (2008) find that travel time variability is valued on average 2.4 times more than travel time savings. Travel time variability is of course less relevant in the rural region we consider than for a metropolitan area. Still, the substitution of a ferry connection with a new road may lead to a substantial reduction in travel time variability. This is not accounted for in our analysis.

Concerning the time perspective, it is important to make clear that our observed commuting flow matrix does not represent a final, long run, effect of the investments in the local transportation network. Our estimates are based on the assumption that the spatial distribution of jobs and residents remains constant, according to what was observed in 2006. Both people and jobs can be expected to move between the municipalities, however. As mentioned in Section 3 there is a tendency that people in this region move towards the coastal areas; the population on Stord and Bømlo is increasing considerably. This further attracts local sector jobs to the area, and it can be expected to result in an increased number of commuters using Trekantsambandet. The situation is the reverse for the Folgefonn tunnel, located in an area experiencing a declining population. It is not obvious if, and how, such changes in the marginal totals of the commuting flow matrix will affect our parameter estimates. It is, however, obvious that our model is not appropriate for making long-run predictions on the number of commuters using the new links.

The parameter estimates may prove to be relatively autonomous to changes in spatial structure. McArthur et al. (2011) study the issue of the spatial transferability of gravity model parameters in this area of Norway. They find that in some cases, parameters estimated in an area with a different spatial structure can give reasonable predictions of commuting flows in this region. This suggests that the parameters estimated here are robust to at least some changes in the spatial structure. Clearly however, predictions of the changes in the spatial distribution of jobs and households call for a more general model specification. As mentioned in the introduction, UrbanSim (Waddell, 2002) is an example of an operational large-scale model constructed for studying problems related to transportation and land use. It is of course possible to construct a modified version of such a model for the rural kind of region that we consider, but as mentioned in the introduction, this is beyond the scope of this paper.

This paper is not primarily focused on the parameter estimates that relate to the tendency of within-zone journeys to work, nor the parameters which are specific to the accessibility measure $S_{ij}$. The relevant parameter estimates are worth some comments, however. They are not qualitatively different from the corresponding estimates in Thorsen and Gitlesen (1998), where the estimation is based on data from a different study area, adjacent to the area that is mapped in Figure 1. Our results leave no doubt that special care should be taken to within-zone journeys to work ($\mu > 0$), and the relative frequency of within-zone journeys to work is found to be high in zones where employment is low relative to the labour force, and vice versa ($\alpha_1 > 0$ and $\alpha_2 < 0$). The estimate of $\alpha_1$ and $\rho$ are substantially lower than the corresponding estimates in Thorsen and Gitlesen (1998), but the signs are the same. The estimates in Thorsen and Gitlesen (1998) were based on 1989-data from a region located south of the one considered in this paper. For a more detailed discussion of the interpretation of the parameters, see Thorsen and Gitlesen (1998).

### 4.2 Demand curves

The model, represented by Equations (1)-(4), can be used to predict commuting flows for specific origin-destination combinations. Assume that we have all the information we need on distances

($d_{ij}$) and the spatial distribution of workers ($O_i$) and jobs ($D_j$) at a specific point in time. Assume next that the monetary costs $c_{ij}$ are varied systematically. Our estimated set of parameter values can then be used to predict commuting flows for different values of the monetary costs, and this procedure may be used to predict a demand curve for any link in the transportation network.

As a first experiment we have predicted a demand curve for commuting between the municipalities Stord/Fitjar (which occupy the island of Stord) and Bømlo. This commuting represents the major part of the commuting flows across the combination of subsea tunnels and bridges that is called Trekantsambandet in Figure 1. We have used the model to predict commuting flows between the 8 postal delivery zones on Stord, and the 8 zones on Bømlo, and then aggregated to get predictions of the flows between the two islands.

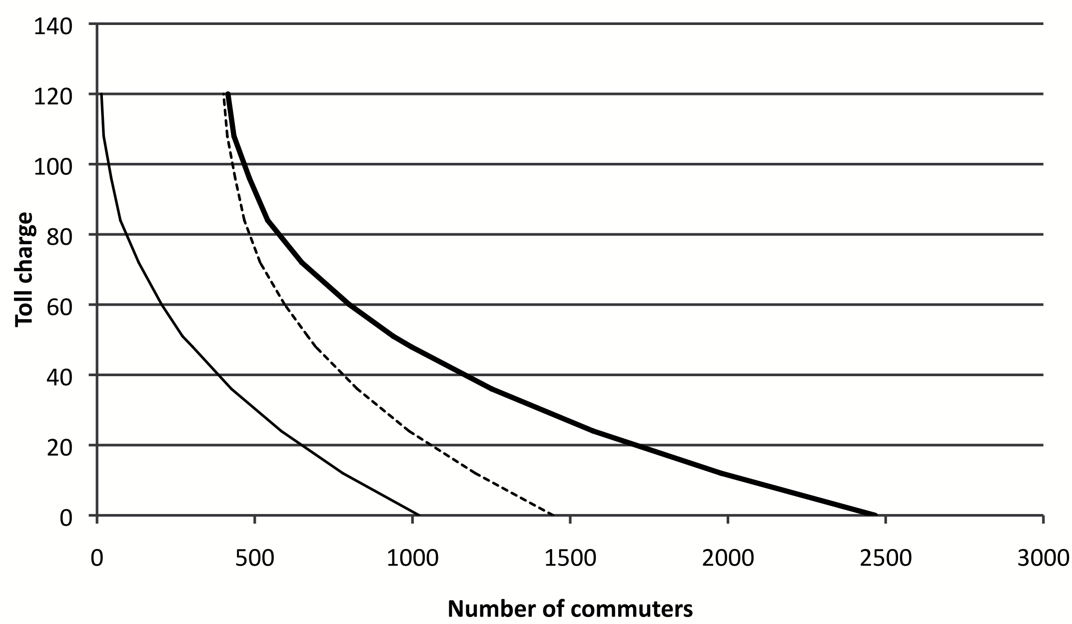



Figure 2: Predicted demand curves for commuting between the municipalities Stord/Fitjar and Bømlo. The toll charge is the price of a one way trip for commuters with a 40 trip price coupon. The dashed line represents predicted commuting from Bømlo to Stord/Fitjar , while the thin solid line predicts commuting in the opposite direction. The thick solid line represents total, aggregated, commuting between the municipalities.

Notice first from Figure 2 that some workers are predicted to commute from Stord to Bømlo even when the toll charge is very high; the demand curve becomes completely inelastic. This is a result of the additivity constraints, rather than travelling behaviour.

In 2006 the toll charge for a one way trip was 51 NOK (€6.13 or $5.76) for commuters who had pre-paid 40 journeys. For this level of $c_{ij}$ our model predicts 668 commuters from Bømlo to Stord, and 271 commuters in the opposite direction. According to our data from the autumn 2006, the corresponding observed numbers of commuters were 519 and 130, respectively. Hence, our model overestimates the commuting flows across the new road connection between the municipalities.

The demand curves in Figure 3 represents the number of commuters between the municipalities Odda and Kvinnherad, using the Folgefonn tunnel. Those demand curves are less smooth than the demand curves for commuting flows between Stord/Fitjar and Bømlo. This reflects the fact that our model predicts a small number of commuters between Odda and Kvinnherad. The 50% discounted price for a one way trip is 30 NOK (€3.61 or $3.39). For this price our model predicts 68 commuters from Kvinnherad to Odda, and 82 commuters in the opposite direction. Once again, however, our model overpredicts the commuting flows. The observed number of commuters from Kvinnherad to Odda was 19 in 2006, while 42 workers commuted in the opposite direction through the Folgefonn tunnel.

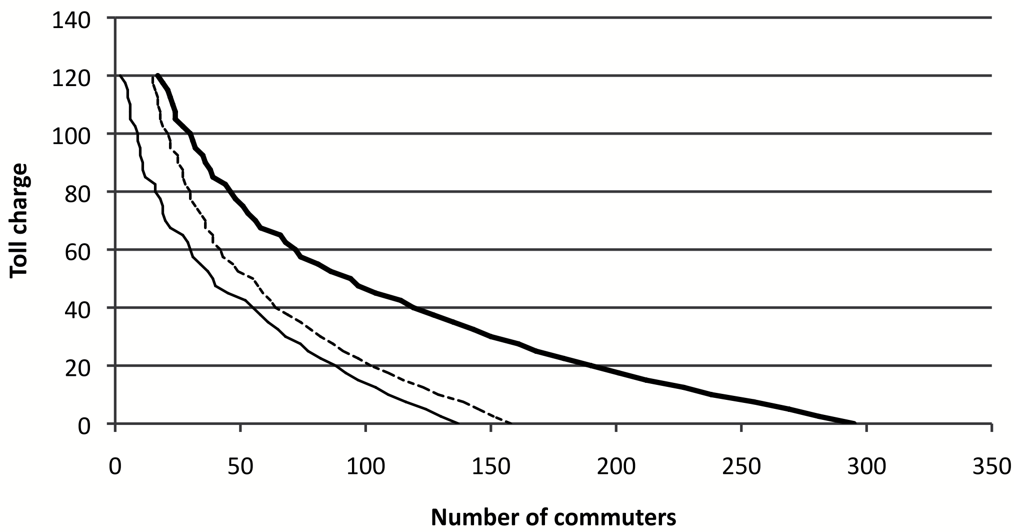



Figure 3: Predicted demand curves for commuting between the municipalities Kvinnherad and Odda. The toll charge is the price of a one way trip, rebated by 50% for regular commuters. The dashed line represents predicted commuting from Odda to Kvinnherad, while the thin solid line predicts commuting in the opposite direction. The thick solid line represents total, aggregated, commuting between the municipalities.

Kvinnherad and Odda are neighbouring municipalities, with 13,071 and 7,247 inhabitants in 2006, respectively. Stord/Fitjar had 19,583 inhabitants in 2006, while the neighbouring municipality Bømlo had a population of 10,808. All 5 municipalities are located a relatively long distance from municipalities other than their neighbouring municipalities connected by the relevant road infrastructure investments. Hence, the location relative to alternative labour market areas is similar, and the population sizes are reasonably equal in the two areas where the large-scale changes in road infrastructure have been introduced. Why then are there such a large difference in both the predicted and the observed commuting flows between the two pairs of municipalities that have been connected by the new road links? The main reason is that the central places at Stord/Fitjar and Bømlo are located relatively close to the new road connection, while this is not the case for the Folgefonn tunnel. Odda has a relatively concentrated population close to the tunnel, but the dominating central places in Kvinnherad are located a long distance from the tunnel. This prevents the labour market in the area getting substantially better integrated as a result of the investments. The population distribution is shown in Figure 4.

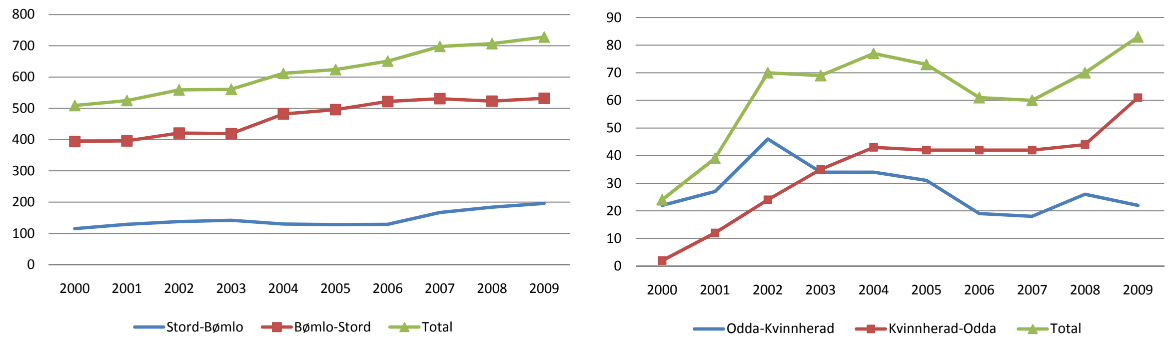
In our model, commuting flows are deterred by toll charges and travelling time. Bridges and/or tunnels and the presence of toll charges may represent a psychological barrier for some workers, causing an additional deterrence effect. This is one possible reason why our model overestimates commuting flows across new road connections. Another possible reason is related to dynamic aspects. It may take quite a long time for the system to adjust to fundamental changes in the road infrastructure network. For both workers and employers, the adjustments to new labour market options may be sluggish, causing a lengthy divergence of commuting flows from the pattern elsewhere in the geography.

## 5 Development of commuting flows over time

As mentioned above, labour market adjustments to a substantially changed transportation network may be sluggish. Figure 5 offers information on the annual changes in the number of commuters after the opening of the two connections described in Section 3. Notice first that there was commuting from Kvinnherad to Odda prior to the opening of the Folgefonn tunnel. In that situation the travelling time between the two municipalities would normally prohibit any


Figure 4: Population per square meter by basic statistical unit (grunnkrets; the most disaggregated measure for spatial data in Norway). Darker shading represents a denser population. As can be seen, while the population in Odda is concentrated at the entrance to the Folgefonn tunnel, this is not the case in Kvinnherad. Regarding Stord/Fitjar and Bømlo, most of the population is located close to Trekandsambandet.

daily commuting. The observed commuting reflects noise in the data, and may for instance be due to weekly commuting, or to part-time working for a limited period.




(a) Commuting between Stord/Fitjar and Bømlo (b) Commuting between Odda and Kvinnherad

Figure 5: Observed commuting flows after the opening of Trekantsambandet and the Folgefonn tunnel. Both were opened in 2001.

According to Figure 5(b) there was a one-off increase in the number of commuters between Odda and Kvinnherad immediately after the opening of the Folgefonn tunnel in 2001. After the immediate response, the commuting flows do not indicate a further development towards a better integrated labour market. For the new road connections between Stord/Fitjar and Bømlo, the situation is the reverse. At best, a very minor immediate increase is observed after the opening of the new road links in 2001, but there seems to be a tendency that the labour market in the area gets better integrated over time. The adjustments are, however, apparently very sluggish. The most likely explanation for this sluggish adjustment lies in the price. Prior to the opening of Trekantsambandet, it was possible to commute using a ferry connection. As mentioned in Section 3, the opening of the new infrastructure has led to substantial reductions in journey times. This should have led to an increase in commuting flows. However, with a toll of 51 NOK each way, commuting between these two areas has remained expensive and as a result there has been only a minor increase in commuting. This raises the obvious question of what an optimal toll might be.

## 6 Optimal and current toll charges in the case of Trekantsambandet

The optimal toll charge for the infrastructure depends on who is asking the question. The infrastructure was part-financed, and now operated, by a privately owned enterprise who has the exclusive right to charge a toll. This firm has a monopoly and can be expected to act as a profit maximiser. Since most of the costs involved in the operation of the infrastructure are fixed, profit maximisation will approximate revenue maximisation. Evaluating the optimal charge from society's perspective is more complicated.

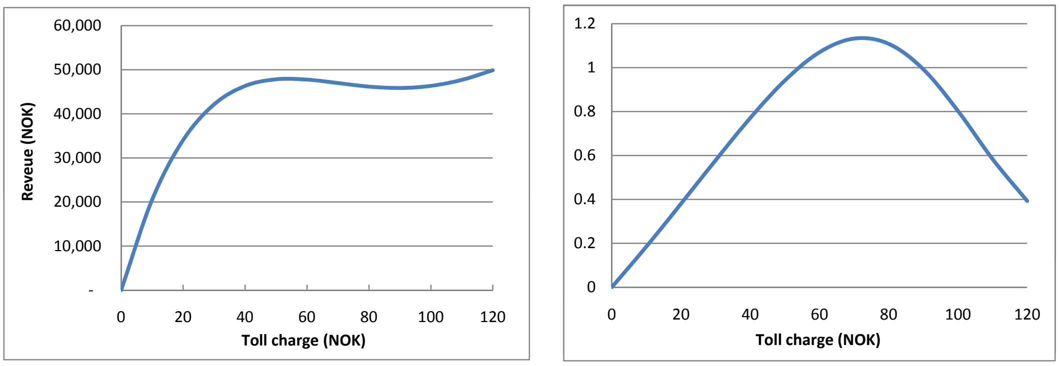
The sort of road pricing which has received most attention from economists has been pricing which is introduced to ration scarce capacity. This is the case when the marginal social cost of commuting exceeds the marginal private cost. However, there is no congestion on Trekantsambandet or the Folgefonn tunnel. In part this reflects the nature of the infrastructure. During the planning phase, consideration must be given to the potential long-term demand. Because it is not easy to increase capacity after construction, it makes sense that the infrastructure is constructed with a capacity higher than current demand (assuming rising demand over time). This means that capacity in the early years of the project is not a scarce resource. Unfortunately, this is precisely the time when charges designed to finance the infrastructure are levied.

Small and Verhoef (2007, pp. 163-190) present a discussion of rules for optimal investment and address the issue of financing through tolls. They show that under given assumptions, revenue from optimal congestion pricing can result in self-financing capacity expansion. They also show that this result breaks down when we consider discrete capacity. The example used by them is a small country road where the minimum feasible capacity exceeds any conceivable level of demand for it. This mirrors the situation with both Trekantsambandet and the Folgefonn tunnel. Here, the revenue from the optimal charge is zero, so the possibility of the improvement being self-financed is ruled out.

Aside from congestion, there may be other reasons why a non-zero charge on the infrastructure can be optimal for society. An important point to consider is how an optimal congestion charge (of zero in our case) interacts with other externalities connected to transport. Parry and Bento (2001) provide a review of studies looking at such issues. These issues include a consideration of congestion on unpriced routes (Liu and McDonald, 1998; Verhoef et al., 1996), accident rates (Newbery, 1988), pollution externalities (Small and Kazimi, 1995) and public transport subsidies (Glaister and Lewis, 1978).

The recommendations from the literature would seem to be that the optimal charge should be close to zero when capacity exceeds demand. The charge may be slightly above zero to cover variable maintenance costs and to reflect distortions in other markets. Even after such adjustments, it seems unlikely that the charge should be as high as 51 NOK for a one-way journey. Raux and Souche (2004) note that externalities such as noise and pollution will be lower if the population exposed to them is low, as is often the case in rural areas. This would apply to our case studies. It is important to note that the charge is only levied until a fixed amount of money has been collected. After this, it is abolished. This is an implicit acknowledgement that the socially optimal charge is zero. One question which has not yet been addressed is what the optimal charge is from the perspective of the private operators of the infrastructure.

As stated, the operators of the infrastructure have a monopoly. This gives them considerable price setting power. The demand curve for Trekantsambandet shown in Figure 2 can be used to determine the revenue maximising price and the price elasticities. It turns out that this demand curve can be very closely approximated with a cubic function ($R^2 \approx 1$). This allows the optimal price to be found analytically. The revenue function and price elasticities are presented in Figure 6.




(a) Total revenue (NOK) (b) Price elasticity

Figure 6: Total revenue collected from the toll charge between Stord/Fitjar and Bømlo and the price elasticity of demand.

Figure 6(a) shows the revenue generated by commuting flows between Stord/Fitjar and Bømlo for different prices. Solving for the revenue maximising price gives a local maximum at a price of 54 NOK (€6.49 or \$6.10). Increasing the price beyond this level does eventually increase revenue. However, as mentioned in the previous section, the inelastic demand in this region of the demand curve is caused by the additivity constraints of the gravity model rather than actual behaviour. For this reason, 54 NOK for a one-way trip can be thought of as the unique revenue maximising price. Interestingly, the optimal price calculated here is almost identical to the 51

NOK which was being charged in 2006. This suggests that the pricing of the infrastructure reflects the interests of the infrastructure operator rather than society as a whole.

Figure 6(b) shows the point price elasticity of demand for commuting. Demand is inelastic for prices below the optimal toll of 54 NOK. Still, our results mean that demand is inelastic for reasonable values of the toll charge. This is in accordance with other empirical studies of travel demand, see for instance Hirschman et al. (1995) or Burris (2003) for a review. For prices higher than the optimal toll level, further increases in price has a negative effect on revenue due the disproportionately large fall in demand. Once again, the apparent return to inelastic demand for prices above 89 NOK (€10.70 or $10.06) reflects the additivity constraints placed on the gravity model rather than actual behaviour.

We have noted that the opening of the new infrastructure had only a modest effect on interregional commuting and that this appears to be due to a high toll charge. Given the lack of congestion and unpriced environmental externalities, the most efficient toll is much closer to zero. It follows from Figure 2 that commuting flows are predicted to increase considerably if the toll charge is abolished. The current toll is much closer to the revenue maximising toll and is therefore more closely aligned with the interests of the private sector operator than with society as a whole.

In order to judge the success of the investment, it is useful to consider what the aims were at the start of the project. According to the operator of Trekantsambandet[3]:

> "*A permanent road connection between the islands is very important for businesses in the region, to meet increasing demands for mobility in the labour market, and as a general stimulus for the economy and businesses. In addition, the connection will give increased social contact and choice with regard to education and leisure.*"[4]

Our analysis allows us to draw some conclusions with respect to whether these objectives have been achieved. There are, however, some important limitations. Firstly, we consider only commuting flows. Secondly, we are considering only flows between the two islands and not to the mainland. However, a consideration of commuting allows something to be said about labour market mobility between the islands of Stord and Bømlo.

[3] www.trekantsambandet.no
[4] Translation from the original Norwegian.

The lack of an increase in commuters after the opening of the Trekantsambandet in 2001 suggests that the aim of a better integrated labour market has not been met, or at least not to the degree it could have been. This could simply reflect a lack of demand. However, our gravity model suggests that around 2,500 commuters will utilise the link between Stord/Fitjar and Bømlo when the charge is abolished. This increased interaction between the labour market areas would improve the matching efficiency, and would achieve the objective of a more integrated labour market. At least within a relatively short term time perspective, ignoring possible effects on location decisions, the abolition of the toll charge in the case of the Folgefonn tunnel does not lead to a substantially improved labour market integration between the areas involved. According to Figure 3 the number of commuters between Odda and Kvinnherad will not exceed 300, even in a case with no toll charge. The difference between the two infrastructure projects considered in this paper reflects the importance of accounting for specific characteristics of the spatial structure in predicting commuting flows and the willingness to pay for new road links.

## 7 Concluding remarks

Like most empirical research within the social sciences, our approach is based on a set of practically motivated simplifying assumptions concerning the definition and measurement of independent variables. We have for instance ignored some potentially relevant aspects concerning the calculation of income tax. Our data neither allows for taking into account the possibility that colleagues and/or neighbours might coordinate their journey to work, with several commuters per vehicle. Similarly, our data do not allow us to account for the fact that some commuting might be on a weekly rather than daily basis, and we do not consider modes of transportation other than ferries and cars. Hence, this study is of course subject to problems of missing variables and measurement errors as a result of data restrictions and standard aggregation problems. Still, we think that our definitions of travelling time and price represent adequate proxy variables of the relevant attributes, and we think that our parameter estimates adequately represent the average response to changes in monetary costs and travelling time.

The paper was successful in its primary aim of estimating the effect of monetary travel costs on commuting flows. This is not a straightforward matter since it requires a number of charges to be present on the network and significant variation in price. These requirements seem to have been met in our data. The ability to forecast how commuting flows will respond to changes in tolls and ferry prices is useful for policy makers as well as the private enterprises operating the ferries and tunnels.

As an example, demand curves were estimated for two links where tolls are charged. These tolls are temporary and designed to finance the investment rather than to correct for congestion or environmental externalities. An analysis of the development of commuting flows since the opening of the infrastructure showed that there was only a modest increase in interregional commuting. Our gravity model suggests that this modest increase was not the result of a lack of demand, but the toll being prohibitively high. This had two main negative effects. The first is that the toll has substantially degraded the ability of the projects to meet their objectives of increased spatial interaction. The second is that the charge has resulted in a large amount of spare capacity being wasted. This is a particularly important issue since part of the infrastructure is financed with public funds.

We suggest that it would be more effective to fully finance such infrastructure out of general taxation. This way, the local economy could benefit from the increased connectivity as soon as the project is complete, rather than having to wait until the toll is abolished. This benefit could then be captured through general taxation in order to pay for the infrastructure. Local government could also contribute funding, as it currently does, if they felt that their region would benefit from new infrastructure. Over time, it is possible that the demand curve we estimate will shift outwards, as workers and jobs relocate to benefit from the new infrastructure. If this resulted in congestion, marginal cost pricing could be introduced since capacity would have become scarce. This could also contribute to financing the infrastructure.

A number of interesting and important questions are raised in this paper. Unfortunately, it is beyond this paper's scope to fully explore all of these. For instance, it is natural to wonder whether replacing the ferries with the bridge was in society's best interest. There are also questions relating to whether the authorities should have granted the tunnel and bridge operator a monopoly on the route. Answering these questions would require a consideration of the value of the infrastructure for non-work related journeys, as well as the strategic role played by the infrastructure as a key link in one of Norway's main transport corridors. This lies beyond the scope of this paper, although the results from this current study would provide a useful input into such a discussion.

Another point to note is that the tolls on these projects will be removed once a pre-determined level of revenue has been collected. Future research should focus on the response of commuting flows and the local economy to this development. This information would indicate what benefits might have been achieved when the infrastructure opened 2001 if a toll had not been levied. An estimate of the cost of delaying these benefits could then be made.

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