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CORDON TOLLS AND COMPETITION BETWEEN CITIES WITH SYMMETRIC AND ASYMMETRIC INTERACTIONS

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ABSTRACT

The aim of this paper is to model the impacts of competition between cities on both the optimal welfare generating tolls and upon longer-term decisions such as business and residential location choices. The research uses a dynamic land use transport interaction model of two neighbouring cities and analyses the impacts by setting up a game between the two cities to maximise the welfare of their own residents. The work builds on our earlier research which studied competition in a small network using a static equilibrium approach for private car traffic without accounting for the land use responses to the change in accessibility. This paper extends the earlier work by setting up a dynamic model which includes *active modes* of travel and the more usual *car* and *public transport* in a realistic twin city setting and assesses the longer term relocation responses. This paper firstly sets out the competition between two hypothetical identical cities i.e. the *symmetric case*; and then sets out the real world *asymmetric case* in which the cities are of different size representative of Leeds and Bradford in the UK but equally applicable elsewhere too. It was found that the level of interaction between the two cities is a key determinant to the optimal tolls and welfare gains. Our findings show that the *competition* between cities could lead to a *Nash Trap* at which *both cities are worse off* in terms of welfare gains. On the other hand, we found that cities, if regulated, would gain in terms of welfare and yet charge only half the toll compared with tolls under competition. We then show that the effect of competition increases with increased interaction between cities. In terms of residential location, cities with higher charges benefit from an increase in residents, though as with other studies, the relative change in population in response to cordon charging is small.

The policy implications are threefold – (i) while there is an incentive to cooperate at local authority level, this is not achieved due to competition; (ii) where cities compete they may fall into a Nash Trap where both cities will be worse off compared to the regulated solution; and (iii) regulation is recommended when there is a strong interaction between the cities but that the benefits of regulation decrease as interaction between cities decreases and the impact of competition is lessened.

Keywords: Competition between cities, land use transport interaction, strategic transport model, road user charging.

1. INTRODUCTION

Cities compete with each other. For more than fifty years, Public Choice Theory has explored the notion that cities compete to attract and retain residents and businesses (Tiebout, 1956; Basolo, 2000). Likewise, the Public Finance & Tax Competition literature identifies competition between cities on tax-and-spend policies (Wilson, 1999; Brueckner and Saavedea, 2001).

This paper forms part of a larger study which aimed to answer the following policy questions:

- In what ways do and could cities compete using fiscal demand management policies?
- How should cities design their policies to achieve individual and collective 'best' outcomes?
- Should cities consider sharing revenue streams – should they compete or co-operate?
- How significant are these policies to the redistribution of business and residents between cities?

Early work by Marsden and Mullen (2012) has looked at the motivations of decision-makers in local government in different towns and cities of four major city regions in England. It showed that towns and cities both compete and collaborate to maximise their own competitive position. The major cities are seen as the main powerhouses of growth, with other towns and cities trading on particular distinctive skills sets or tourist offers and spillover effects from the major cities. Working together they can act as a more powerful voice to argue for investment from central government.

Our interviews with local authorities confirmed that cities do consider competing, but they consider different cities as competitors for different aspects. For example when competing for investment from creative industries to locate jobs, cities from further afield will be considered as competitors, but when competing for regional funds from government they will team with neighbouring cities. However, when it comes to charges for using transport facilities such as parking then they will consider local neighbours as competitors and will consider the charges levied in other local towns. Finally, when it comes to road user charging (which is not common in cities within the UK except London), the cities suggest that there would be a hierarchy of charges to consider akin to the parking charges and so some form of strategic charging or competition may well evolve.

Whilst cities seem to compete at inter-city level for example through the use of parking charges or tolls, research in the transport literature has focused predominantly on intra-city issues. The strong focus in recent years has been on road user charging, economic theory suggesting benefits will accrue to a city from a combination of congestion relief and recycling of revenues within the city (Manville and King 2013, May et al 2010). Beyond the theoretical benchmark of full marginal cost pricing, the design of practical charging schemes, such as those adopted by local authorities in recent Transport Innovation Funds (TIF) bids in the UK, has generally focused on pricing cordons around single, mono-centric cities (Shepherd et al, 2008). It is possible in such cases to design the location and level of charges for a cordon so as to systematically maximise the potential welfare gain to the city (Shepherd and Sumalee, 2004; Sumalee et al, 2005), yet there is an implicit premise in here that the city acts in *isolation*.

Whilst we have found no empirical studies examining competing cities in the transport sphere, a handful of studies address aspects of competition. In the context of toll roads, several authors have studied the welfare implications of competition between a *public* and *private* operator (Verhoef et al, 1996; De Palma & Lindsey, 2000; Yang et al, 2009). The focus in these studies is on the impacts of alternative ownership regimes, and of public versus private control in the form of either monopoly pricing or competitive Nash Equilibria (*Nash Equilibrium* is reached when a player cannot improve their own welfare when the other players have decided their own strategies). De Borger et al (2007) and Ubbels & Verhoef (2008) studied a more closely related problem of competition between countries/regions setting tolls and capacities, investigating the implications of players adopting two-stage games or different strategies.

In parallel, several pertinent recent studies have appeared on the evolution of city structures and tolls under different assumptions. Levinson et al (2006) and Zhang et al (2007) used an agent-based approach to investigate how networks evolve over time. In this area of study, while Mun et al (2005) focused on the development of a non-monocentric, linear city, others have opted to develop two-dimensional continuum models involving finite element solution methods capable of representing multiple Central Business Districts (CBD) (Ho et al, 2005; Ho & Wong, 2007). From the field of Economic Geography, the recent contribution by Anas & Pines (2008) analyses the move away from monocentric to polycentric models. In spite of their relevance to the proposed study, none of the above approaches considers direct competition between cities, nor does the inter-play between parking charges and road user tolls (either within or between cities), for which Marsden (2009) found evidence.

When we move to a polycentric case, competition between cities may arise as described above. Issues of short-term destination changes and potentially longer term household and business relocation decisions thus need to be considered.

Mun et al (2005) studied optimal cordon pricing in a one dimensional *linear city* with more than one CBD. Their research revealed that cordon pricing is not always effective for congestion management in polycentric linear cities and it tends to be effective as the urban structure is more mono-centric. Our work differs significantly from that of Mun et al. in that we analyse the optimal toll between *two cities* competing with each other whereas Mun et al. consider *one city* with many CBDs.

The aim of this paper is to model the impacts of demand management strategies on optimal tolls and longer-term business and residential location choices in competing cities. This is a continuation of the work reported in Shepherd and Balijepalli (2012a, b) which had outlined the initial model set up and discussed the preliminary results. The research uses a dynamic land use transport interaction model of two neighbouring cities to analyse the impacts by setting up an optimisation game between the two cities which are assumed to maximise the welfare of their own residents. The work builds on the earlier work by Koh et al (2012) who studied competition in a small network using a static equilibrium approach for *private cars* who have a choice of route (when tolled) but *without* a *land use feedback* mechanism. It was found that when cities compete in terms of welfare, there was the possibility that the outcome of the game was a classic *Nash Trap* whereby both cities may end up worse off. That is to say that allowing competition between the two cities results in residents in both cities being worse off than under the co-operative or regulated case as well as worse off than in the no toll case. Our research extends this by setting up a dynamic model which includes slow modes, private car, public transport bus, rail and investigates the longer term location responses.

The model is used first to study an *isolated city* (representative of Leeds) and a standard welfare function is used to determine the optimal toll around the central area and its impacts on location decisions and other transport indicators. A *twin city* is then added to the model thus introducing traffic between the cities. This traffic may be charged to enter the central area along with own residents, however the revenue may be retained by the charging city - a form of tax exporting behaviour which would in theory increase the welfare of the city. Thus both cities will have an incentive to charge and a game may evolve.

With this simple model set up we study the impact on the optimal tolls set by the cities and how the game develops between cities, firstly of equal size and amenity (*the symmetric case*) and secondly with cities which differ in size and amenity (*the asymmetric case*). The impact on location decisions and other transport indicators will be investigated as will the implications for regulation and the development of cities within regional partnerships.

This paper is divided into four sections including the present one. Section 2 describes the development of a dynamic model and in particular introduces the *small model* approach to developing a land use transport interaction model for the cases of *symmetric* and *asymmetric* cities. Section 3 introduces the welfare measure used in the modelling and reports the numerical results on optimal tolls for various modelled scenarios including the regulated cases and competitive Nash Games. This section then reports the sensitivity of welfare gains to the level of interaction between the cities. Finally, Section 4 concludes the work and identifies the directions for further work.

2. DYNAMIC LAND USE TRANSPORT INTERACTION MODEL

Metropolitan Activity Relocation and Simulation (MARS) is a strategic dynamic Integrated Land Use and Transport model. The basic underlying hypothesis of MARS is that settlements and activities within them are self-organising systems. MARS is based on the principles of systems dynamics (Sterman 2000) and synergetics (Haken 1983) and can model the complex interactions between the land use and transport systems. The present version of MARS is implemented in Vensim®, a System Dynamics programming, simulation environment. MARS is capable of analysing policy combinations at the city/regional level and assessing their impacts over a 30 year planning period. Figure 1 shows an overview of the MARS model. There are *three sub-models* within MARS, viz., transport, residential location and workplace location sub-models. The transport sub-model determines the demand for travel between zones for a given land use pattern and estimates the number of trips by a given mode of transport such as *car, bus, train, walking and cycling* for peak and off-peak periods. The output of the transport sub-model includes an accessibility measure which influences the residential and workplace location choices. Rents, land prices and land availability also influence where land is developed and the location choice of residents. These sub-models then interact over *time* and the system responds to exogenous inputs for growth in residents, jobs and car ownership and to any policy instruments simulated. Thus the system modelled here is a non-equilibrium one as it keeps evolving continuously over time.

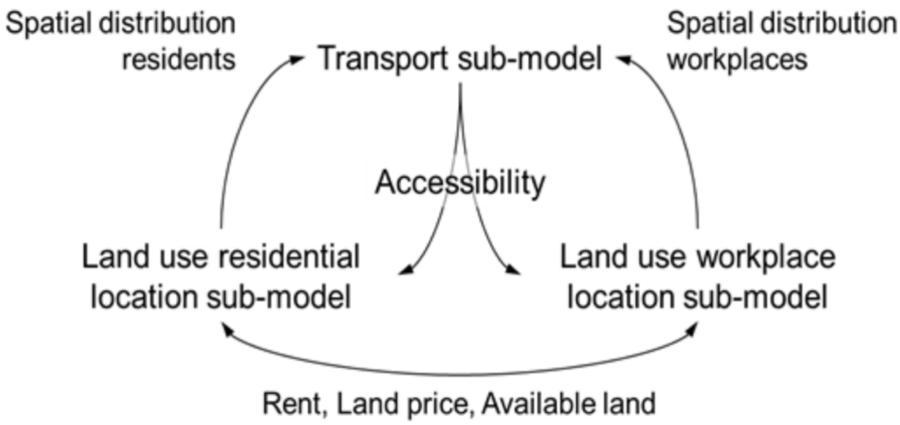

Figure 1 Overview of the MARS model

Figures 2 and 3 show examples of the Causal Loop Diagrams (CLD) for the main responses included within MARS for commute trips by car and for development and relocation of residences respectively.

Figure 2 shows the CLD for the factors which affect the number of commute trips taken by car from one zone to another. Starting with the balancing feedback loop B1, commute trips by car increase as the attractiveness by car increases which in turn increases the search time for a parking space which then decreases the attractiveness of car use – hence the balancing nature of the loop. Loop B2 represents the effect of congestion – as trips by car increase speeds decrease, times increase and so attractiveness is decreased. Loop B3 show the impact on fuel costs, in our urban case as speeds increase fuel consumption is decreased – again we have a balancing feedback.

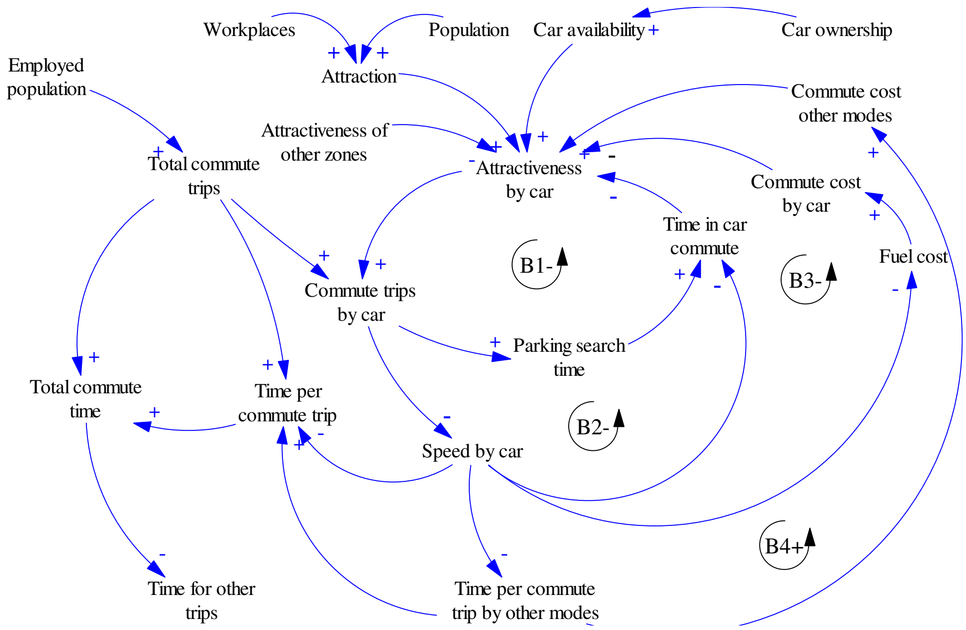

Figure 2 CLD for the transport model – commute trips by car in MARS

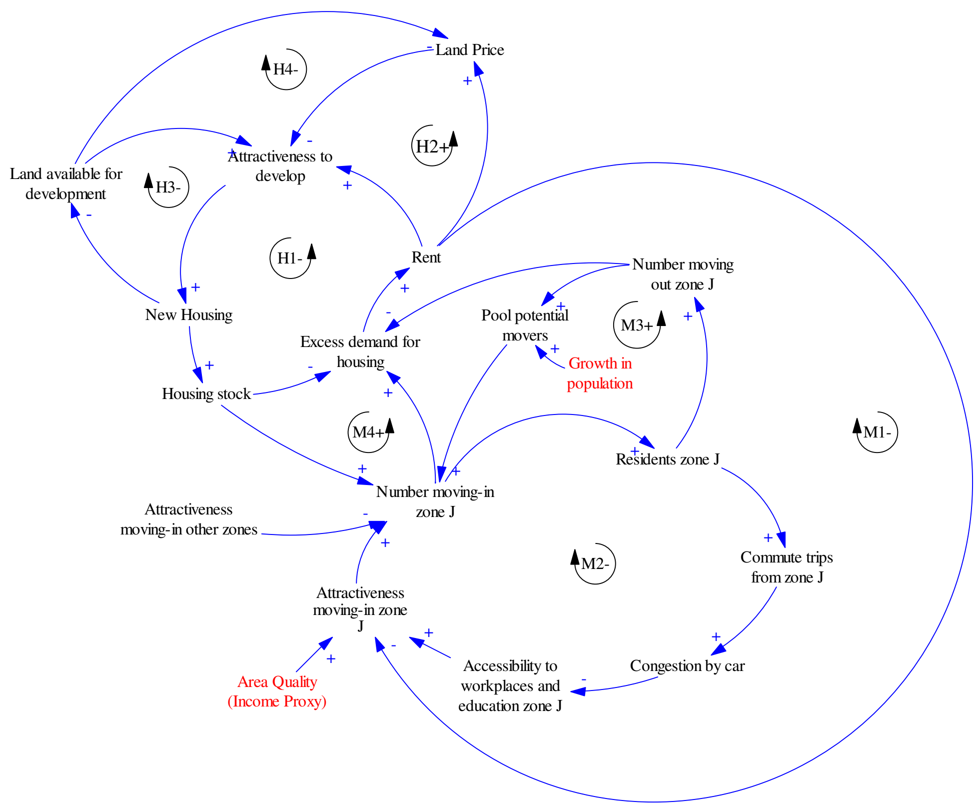

Figure 3 CLD for development of housing in MARS

Figure 3 shows the CLD for the development of housing and the interaction with location choice of residents in MARS. Starting with the development of housing, loop H1 is a balancing feedback loop which shows that the attractiveness to the developer to develop in a given zone is determined by the rent which can be achieved. The level of the rent is driven by the excess demand for housing which in turn is related to the housing stock and new housing developments. As new houses are developed the stock is increased which reduces the excess demand which then reduces the rent achievable which reduces the attractiveness to develop – resulting in a balancing loop. Loop H2 is a reinforcing loop as new housing reduces the excess demand which reduces rent and hence land price which in turn makes development more attractive all other things being equal. Loop H3 represents the restriction of land available for development; as land available is reduced then the attractiveness to develop is reduced. Loop H4 extends H3 to represent the effect of land availability on land price.

The housing development loops are linked to the residents' location choice. Firstly the main elements considered to influence the choice of location are rent, accessibility and area quality. As area quality is difficult to measure it is normal to take some kind of proxy for quality, in this case average income. The main loops in the residential choice are M1 which is a balancing feedback loop – as more people move in excess demand increases which increases rent which then reduces attractiveness to move in. M2 is also a balancing loop which shows that as the number of residents increases in a zone then congestion out of that zone increases which reduces accessibility to workplaces and so reduces attractiveness to move in.

Loop M3 is a positive feedback loop which simply shows that as the number of residents increases in a zone then the potential for moving out also increases (set as 10% of residents per year in the simplest case). This increases the pool of potential movers, which also includes growth in population (which could come from natural growth or in-migration and is taken from an exogenous forecast per annum). Loop M4 is a positive feedback loop which extends H1 – as more people move in this increases excess demand which increases rent and so increases attractiveness to develop which in turn increases the housing stock. Here it should be noted that housing stock available can limit the number of people allowed to move in to a zone as any excess demand is reallocated to other zones. This process reflects reality where excess demand must be taken up elsewhere if the capacity for residential occupation is reached in any one time period. Following the principles described above, a MARS model was developed for the *Leeds Metropolitan Area* with *33-zones* representing the electoral wards. The population, employment, land available for development were based on official data from the Council and national census data. The transport data was taken from publicly available data and from an aggregation of the Leeds SATURN model. Growth in population and workplaces were based on DfT's TEMPRO forecasts (DfT 2010). The outcomes of the model were calibrated to match the official forecasts available, for more detail see Pfaffenbichler et al (2010).

The performance of the MARS Leeds model has also been assessed by evaluating *outturn elasticities*, viz., fare and fuel elasticities. The out-turn fare elasticities were compared with standard values as reported in *The Demand for Public Transport: a Practical Guide*, (Balcombe et al, 2004). Similarly, the fuel elasticities were compared with the values published by Goodwin et al (2004). The fuel price elasticity was seen to be -0.1 which agrees well with the commuter value of Litman (2013) and also with the mean value of Goodwin et al (2004), while the fare elasticity was seen to be -0.16 which is low but within in the range for urban areas as per TRL Report 593.

2.1 Developing an aggregate model

Following the discussion in Ghaffarzadegan et al (2011) who highlight the benefits of using small system dynamics models in addressing public policy issues, we chose to aggregate the model from *33 zones* to only *2 zones* to simplify the presentation of the results which would otherwise become difficult to follow when moving to a twin city model with many zones. However while recognising the benefits of simplification for presentation of results, we first of all describe the aggregation process and compare results of the 2-zone model with the previous 33-zone model. Demographic and land use parameters such as population, number of jobs, land available for development have been summed for zones 1-13 of the large model to form zone 1 (inner zone) of the small model; the remaining zones in the large model viz., 14-33 are then summed to form the outer zone 2 of the small model. During the aggregation process we compared the results with the model outcomes of the 33-zone model to ensure that the small model responds in a similar manner to that of the large model in two different scenarios viz., do-nothing and then with a 5€ cordon charge. Table 1 compares the population in the base year 2001 and forecast year 2030 between the 33-zone model and the 2-zone model. The aggregate model of Leeds was calibrated to reproduce a similar distribution of residents across the zones in year 2030. Table 2 shows that the total growth in jobs in the 2-zone model is consistent with that in the 33-zone model, however, their distribution between the zones is less so. Akin to the large model the aggregate model also predicts a higher growth in zone 2 than in zone 1 though to a lesser extent. Whilst this is not as consistent as the residential response, it is the relative change between tolled and un-tolled scenarios which informs our analysis.

Table 1: Distribution of population in Leeds

	33-zone model			2-zone model		
Area	Year 2001	Year 2030	Growth (%)	Year 2001	Year 2030	Growth (%)
Zone1 (1-13)	262560	343384	30.8%	262560	342879	30.6%
Zone2 (14-33)	453042	621801	37.3%	453042	621780	37.3%
Total	715602	965185	34.9%	715602	964659	34.8%

Table 2: Distribution of jobs in Leeds

	33-zone model			2-zone model		
Area	Year 2001	Year 2030	Growth (%)	Year 2001	Year 2030	Growth (%)
Zone1 (1-13)	218700	246634	12.8%	218700	262746	20.1%
Zone2 (14-33)	133400	188303	41.2%	133400	171615	28.7%
Total	352100	434936	23.5%	352100	434361	23.4%

Table 3 compares the modal share in year 2001 and year 2030 between the 33-zone model and the 2-zone model. It is noted that the 2-zone model reproduces the modal shares of the large model well with the exception of rail which is slightly under-predicted in the aggregate model.

Table 3: Modal share of commuting tours

	33-zone model		2-zone model	
Mode	Year 2001	Year 2030	Year 2001	Year 2030
Car	49.7%	51.1%	50.1%	51.1%
Rail	2.9%	2.7%	1.3%	1.2%
Bus	28.0%	27.1%	28.5%	28.3%
Slow	19.5%	19.2%	20.1%	19.4%

In order to verify further whether the 2-zone model would respond to policy inputs in a similar manner to that of the 33-zone model, a 5€ cordon charge to enter the inner zone in both the models (zone 1 in the small model and zones 1-13 in the large model) was implemented. It was noted that the relative change in population and jobs with a 5€ charge over the do nothing scenario are small (results for the twin city cases will be discussed in detail later). These results are similar to those noted by others e.g. Jenson (1999), Anas & Xu (1999) and Anas and Hiramatsu (2013). Table 4 shows the main impact which is the change in modal share of commuting tours with a 5€ charge. In particular, it shows that car mode loses about 3% of its share and most of it would be absorbed by the bus. As a result of the shift in modal use, the travel times in MARS would improve for all road users which are accounted for in the welfare function as described later. It is noted that under the charging regime both models show a very similar reduction in car share in the peak, the small model shows a slightly higher increase in share for bus but this is still a good representation of the more detailed model and suitable for the purpose of this study.

Table 4: Change in modal share (peak) in year 2030 with 5€ charge

	33-zone model		2-zone model	
Mode	Do-nothing	5€ charge	Do-nothing	5€ charge
Car	51.1%	48.5%	51.1%	48.1%
Rail	2.7%	2.8%	1.2%	1.2%
Bus	27.1%	28.9%	28.3%	30.9%
Slow	19.2%	19.8%	19.4%	19.8%

2.2 Symmetric case

In order to investigate the impacts of competition between cities on optimal tolls and other indicators, our first step was to develop a simple hypothetical case study involving two identical cities. Thus we took the 2-zone model of Leeds as described in the previous section and copied it to form a *twin city model* with 4 zones based on the idea of two identical cities within reach of one another (see Figure 4). In the single city model the population of Leeds is split between the inner zone 1 and the outer zone 2 with more growth predicted in the outer zones by 2030. We call this *City A* and the additional hypothetical neighbouring city we will call *City B*. The model naturally deals with interaction between cities in terms of commute choices and also allows for relocation between the cities. In what follows, each city may decide to charge car users to travel to the central area (zones 1 or 3) within the peak period. A charge will be applied to their own residents as well as those from the other city.

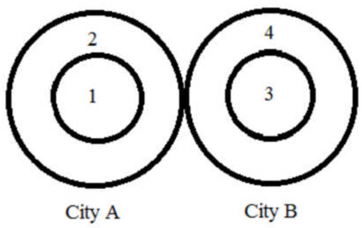

Figure 4: The twin-city zones

2.3 Asymmetric case

After developing the symmetric case and in order to make the case more realistic, we then extended the model of *symmetric cities* to *asymmetric cities* by revising the characteristics of

City B. City A continues to be based on the population of Leeds which is split between the inner zone 1 and the outer zone 2 as described earlier, but the neighbouring City B is now reduced in size and is based loosely on Bradford which is located 18km (11.2 miles) away from Leeds. Thus we now have the case of two neighbouring cities with differing populations and workplaces and thus with different workplace-population ratios based on a realistic setting.

Table 5 shows the distribution of base year population, work places and workplace/population ratio in the zones in City A and City B in the census year 2001. Note that the population and work places have been calibrated to match the estimates for Leeds and Bradford as given by TEMPRO. Notice that the workplace population ratios for zones 1 and 2 (City A) are slightly higher than the corresponding values in zones 3 and 4 (City B) so we should expect a higher proportion of trips to travel from City B to City A than in the reverse from A to B.

Table 5 Distribution of base year population and workplaces in the two cities

Region	Base year population	Base year work places	Workplace/ population ratio
City A: Zone 1	262,560	218,700	0.833
City A: Zone 2	453,042	133,400	0.294
City B: Zone 3	168,038	134,369	0.800
City B: Zone 4	289,947	81,961	0.283

The asymmetric case has been calibrated to the level of interaction between the two cities represented by the observed number of trips between Leeds and Bradford (See Table 6). This is achieved by introducing city specific factors which weigh up the attraction between inter-city origin-destination pairs. This can be thought of as a proxy for some unobserved preference to work in a city over the other such as a skills mis-match or other household decisions which impact on travel choice such as child care. In other words there are barriers to travel across city boundaries other than those which can be explained by the transport costs. The resulting trips after the calibration exercise are shown in Table 6. The proportions of trips from Leeds to Bradford and from Bradford to Leeds are comparable to the proportions given in a study by Simmonds and Skinner (2006). As expected the proportion from Bradford to Leeds is much higher due to the higher jobs to population ratio in Leeds which will give the larger city greater tax exporting opportunities.

Table 6 Modelled commuting tours between City A and City B

	Number of commuting tours (2001) per day#	Modelled commuting tours per day in MARS	Proportion of trips to other city
Leeds to Bradford	15260	15266	4.7%
Bradford to Leeds	21261	21267	10.9%

Source: # City of Bradford Metropolitan Council, Big Plan II, Transport Intelligence Briefing, 2010

3. NUMERICAL STUDIES

This section describes the application of the MARS model under various charging regimes for the symmetric and asymmetric cases as described above. Before explaining the scenarios considered, we first explain the welfare measure used.

3.1 Welfare measures

For each city, the local authority is assumed to maximise the welfare of their citizens. The traditional form of welfare measure within the transport field is the Marshallian measure which sums the *consumer* and *producer* surpluses. For tolling, the welfare measure includes the assumption that all revenues collected are *recycled within the system* i.e. shared back between the residents of the charging city, typically by investing in improving/maintaining the roads/public transport. In our case study, we assume that the revenue collected from non-residents is retained by the charging city and is recycled within the charging city i.e. tax exporting behaviour is assumed. The welfare measure may be estimated by the so called “rule of a half” (Williams, (1977)) and is based on official UK Department for Transport advice (DfT, 2011). We simplify the welfare measure within our study by considering the impact on private traffic in the peak hours only. Whilst this is a simplification of the full appraisal, it does account for the main impacts of a peak charging scheme, i.e. private traffic time savings due to a change of mode and the monetary impacts of a peak charge where revenue is assumed to be ear-marked for the city.

For the isolated city, the local authority objective to maximise welfare coincides with the objective of a higher level regulator e.g. the national government or some appointed regulator. But in the two city case, we now have two authorities whose aim is to optimise the welfare of their residents – including their journeys to/from the other city region. The welfare measure for each city is similar in principle to that of an isolated city, but now we need to consider transfers of revenue from City A to City B and vice versa, and the particular welfare measures for each of City A and City B are written as below:

$$W_A = \sum_{i=1}^{2}\sum_{j=1}^{4}\left\{-\frac{1}{2}\left[\propto\left(t_{ij}^1 - t_{ij}^0\right)\left(T_{ij}^1 + T_{ij}^0\right)\right] - \frac{1}{2}\left[\tau_A\left(T_{21}^1 + T_{21}^0\right)\right] - \frac{1}{2}\left[\tau_B\left(T_{i3}^1 + T_{i3}^0\right)\right]\right\} + T_{21}^1\tau_A + \sum_{i=3}^{4} T_{i1}^1\tau_A - \sum_{i=1}^{2} T_{i3}^1\tau_B \quad (1)$$

$$W_B = \sum_{i=3}^{4}\sum_{j=1}^{4}\left\{-\frac{1}{2}\left[\propto\left(t_{ij}^1 - t_{ij}^0\right)\left(T_{ij}^1 + T_{ij}^0\right)\right] - \frac{1}{2}\left[\tau_B\left(T_{43}^1 + T_{43}^0\right)\right] - \frac{1}{2}\left[\tau_A\left(T_{i1}^1 + T_{i1}^0\right)\right]\right\} + T_{43}^1\tau_B + \sum_{i=1}^{2} T_{i3}^1\tau_B - \sum_{i=3}^{4} T_{i1}^1\tau_A \quad (2)$$

where,

t_{ij}^1 = travel time between each Origin destination (OD) pair *ij* with road charge (superscript 1)

t_{ij}^0 = travel time between each OD pair *ij* without road charge (superscript 0)

T_{ij}^1 = trips between each OD pair with road charge

T_{ij}^0 = trips between each OD pair without road charge

τ_A , τ_B = toll charge to enter the central zone in City A or City B

α = Value of travel Time[1] (VoT)

Equation (1) sums the rule of half *time benefits* and the rule of half *money benefits* (*consumer surplus*) with the *net* revenue to residents of City A (*producer surplus*). The time

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[1] Based on UK Department for Transport guidance – webtag unit 3.5.6 see www.dft.gov.uk/webtag

and money benefits include the savings accrued to all trips originating from City A, i.e. i = 1,2, destined to any of the zones in City A or City B i.e. j = 1,2,3,4. This means time savings to residents of City A are accounted for in both the cities i.e. whether they occur on the network in City A or City B. The *net* revenue collected by City A is equal to the sum of the toll revenue collected in A from City A's residents and that from City B's residents together with the transfer of money from City A to City B to account for the toll paid in City B by the residents of City A. These revenue terms which transfer funds between the two cities are important and form the basis of the tax exporting mechanism. An identical logic has been used to derive the welfare sum for City B as shown in equation (2).

The welfare measure adopted in this research is a simplified version of the full scale of welfare. It is further simplified by considering the impact on private traffic in the peak hours only. However, we affirm that this is not too simplistic as it does account for the main impacts of a peak charging scheme, i.e. private car traffic time savings and the monetary impacts of a peak charge whose revenue is assumed to be ear-marked for the city. Moreover the time savings to private traffic take into account the secondary effect of modal shift towards public transport as well as the re-distribution of trips. However, a full scale welfare function would include the benefits accrued to public transport passengers and those using slow modes. As we are interested in peak road user charging only in our study the monetary and time benefits accruing to the private car users would tend to dominate the full welfare function and so the welfare functions described in (1) and (2) are taken to be sufficiently robust to offer interesting insights into the dynamics of competition between the cities when considering only road tolls of this nature. Equally, we ignore any impacts due to changes in land use as is acceptable when changes are relatively small, see for example the advice in the PROSPECTS methodological guidebook (Minken et al, 2003).

For a global regulator the welfare is simply equal to the sum of the welfare of City A and City B which is written as:

$W \quad = W_A + W_B$ (3)

Note that in equation (3) when the welfares of City A and City B are summed together the non-resident toll revenue transfers between City A and City B cancel out with each other i.e. there is no benefit or consideration of tax exporting behaviour in the regulated case. In all cases below, the benefit streams generated over the 30 year study period will be discounted to form a Net Present Value of benefits discounted at 3.5% (DfT 2012).

Before presenting the results of various scenarios, it is useful to demonstrate how the welfare measures evolve over time and how the individual and collective benefits may vary when a toll is imposed. Figure 5 shows, in the *symmetric cities* case, how the welfare varies over time for City A, City B and in total as City A charges a toll of 5€ from year 5 onwards.

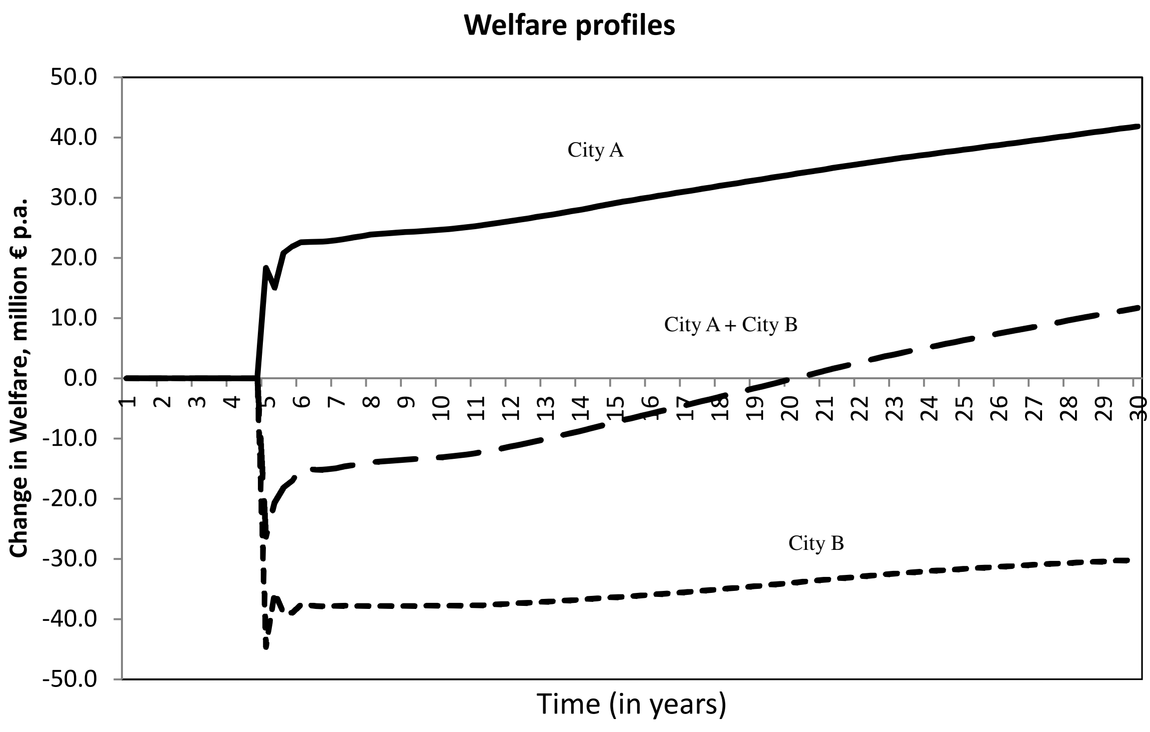


Figure 5 Variation in welfare over time when City A charges €5

From the figure we can see that when the charge is applied there are immediate positive benefits to City A which increase steadily over time as the demand from exogenous growth in population provides more potential for time savings and revenue from additional users willing to pay the charge compared to the do-nothing case. The benefits are made up from a combination of time and money benefits and also include the revenues collected from both residents (City A) and non-residents (City B). City B's residents whilst benefitting from some time savings, lose all the toll revenues paid to City A and so the welfare change in City B is negative. The total welfare for City A and City B put together becomes positive after year 20 when the time savings outweigh the money losses in the system. Note that in the first year of implementation the benefits *oscillate* for a few months as the feedback loops in the model take time to respond to the charges imposed. Whilst City A gains significantly from a charge of 5€, City B clearly loses out and given the symmetry in this case we would expect them to react with a charge of their own (there is obviously an incentive to begin charging for both cities from the above figure).

Figure 6(a) shows how the NPV of welfare for City A (and, due to symmetry, City B) varies with combinations of tolls from City A and City B in the range 0-8€ while Figure 6(b) shows the NPV of total welfare surface. The surfaces are smooth and convex in nature which indicates that we do not expect multiple local Nash Equilibria as was found in Koh et al (2012). Looking at the City A surface, it can be seen that when City B does not charge, we should expect a maximum change in welfare for City A to occur for a toll of around 5 €. However as City B would have the same welfare surface with tolls transposed (due to symmetry) they would also be incentivised to toll. The Nash Equilibrium in this case will be at a point where the *derivative of own city welfare with respect to own toll is zero* for both cities. Due to the symmetry in this case, we can plot the point of intersection between the line where the gradient = 0 and the equal toll line and so the Nash Equilibrium should be found for a toll of around 6€ as shown by point N.

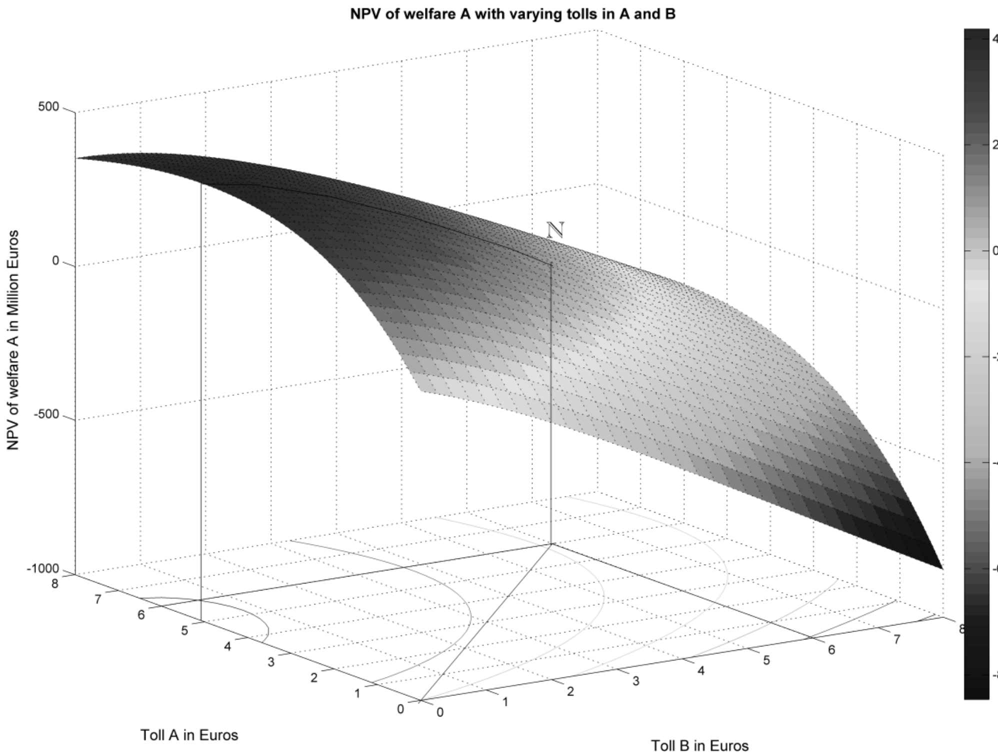


Figure 6(a) NPV of welfare in City A

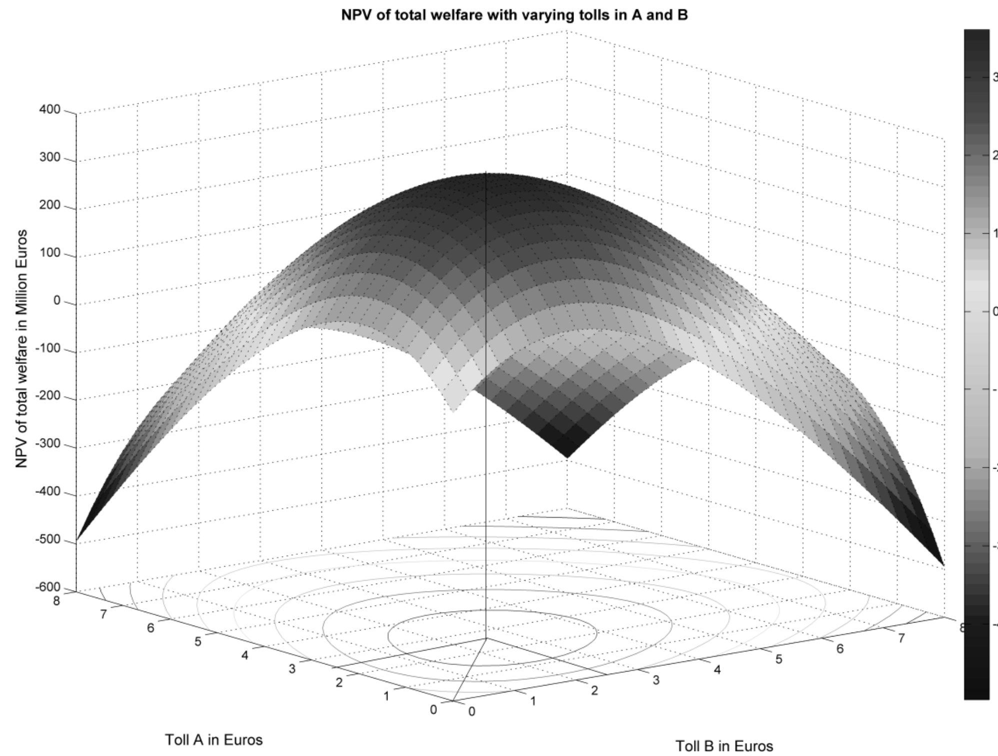


Figure 6(b) NPV of total welfare

Figure 6(b) shows the total welfare surface as tolls are varied. By inspection we may expect that a regulated solution (i.e. when a higher authority e.g. National Government or City-Region Combined Authority aims to maximise the total welfare as specified by equation (3) earlier) would be for both cities to set tolls of around 2.5€. In this case the tax exporting behaviour or incentive is removed by regulation and all toll revenues are recycled within the whole system.

3.2 Modelled scenarios

This section sets out the optimal tolls and welfare implications for a number of different scenarios, namely :-

- Isolated city – City A tolls (2-zone model)
- City A *or* B tolls alone within the two city set up (4-zone model)
- City A *or* B regulated (4-zone model)
- City A *and* City B – regulated (4-zone model)
- City A *and* City B Nash Game (4-zone model)

In the first scenario, City A is considered in *isolation* and the local authority solution is to maximise the welfare of all residents. In this case there is no tax exporting behaviour as there is only one city to investigate. The next two scenarios consider City A or City B tolling within the *two-city* set up so some tax exporting behaviour is now possible. The addition of the 'City A or B regulated' test allows us to compare the solutions when a higher level regulator controls the toll in one of the cities to maximise the welfare of residents from both cities. The final two scenarios consider tolling in both cities of which the first one is a *regulated scenario*[2] where tolls are set to maximise the *total welfare* of all residents, and the second is a *Nash Game* where cities compete *against each other* aiming to maximise their own residents' welfare in a non-co-operative manner. In this final scenario, tax exporting behaviour is assumed and revenues are not recycled between the cities. Note that all four of

[2] Regulation is a form of cooperation but when two cities play a cooperative game whether they reach the global optimal solution is a completely different point. We have dealt with that question in a separate paper. See Shepherd and Balijepalli (2015) for further details.

the two-city scenarios from the above consider both *symmetric* and *asymmetric* cases except the City A or B scenario for the symmetric case where presenting the results for one city would sufficient due to the symmetry.

Next, it should be noted that as the model predicts the impacts over a 30 year period we could in theory allow the tolls to vary over time. We would expect as the population is set to increase, the congestion would increase so we may expect the tolls to increase over time as potential time benefits increase. However to simplify the discussion and presentation of results we instead only consider constant or flat tolls over time fixed in absolute terms.

In order to find the optimal toll levels, the VENSIM optimisation tool was used to maximise the appropriate welfare measure by varying the values of the relevant tolls. Note that to calculate the Nash Equilibrium solution, a *diagonalisation approach* was used whereby City A maximises their own welfare first with tolls for City B held constant, then City B optimises their welfare with tolls for City A held at the previous iteration value. This was repeated until convergence which was usually found to be within three to four rounds of each optimisation game.

3.3 Optimal tolls: symmetric cities

Table 7 shows the optimal tolls and Net Present Value (NPV) of welfare change for each city plus the total welfare change for both cities for the symmetric cases.

Table 7: Optimal tolls and NPV of welfare in year 30 for the symmetric cases

Scenario	Optimal Tolls €	Welfare A Million €	Welfare B Million €	Total Welfare Million €
City A 2-zone only	2.63	71.7	N/A	71.7
Single City A	5.00	419.1	-502.0	-82.9
Regulated Single City	1.86	287.1	-155.1	132.0
Regulated 2-city	2.53	179.3	179.3	358.6
Nash Game	6.08	-27.9	-27.9	-55.8

First of all the optimal tolls found by the VENSIM optimisation facility for the single city (in the twin-city setting), the Nash Game and the regulated 2-city scenario are in line with the grid search results shown in Figures 6(a)-(b). Next, if a city is assumed to be an isolated city then the optimal tolls are lower than when the same city has a neighbour and is able to extract toll revenue from a neighbouring city. The welfare for City A is also significantly higher when A tolls alone and toll exporting behaviour is allowed. This increase in the welfare of City A is at the expense of those living in City B, but the total welfare change over both cities shows that together they are worse off as the total welfare change is negative. Regulation of a single City A, in the twin city setting, results in lower tolls for the regulated city, with lower welfare for City A, and a corresponding lower reduction in welfare for City B and the two cities together are better off in terms of the overall welfare. This is due to the fact that the regulation considers residents of two cities together and thus mitigates the issues associated with tax exporting behaviour. However residents from City B are still worse off compared to the no toll situation and the regulator should consider some re-distribution of the revenues from City A to City B to compensate for the negative welfare in City B.

Due to symmetry, the tolls under the twin city regulated case are equal and are between the single city toll levels and those resulting from the Nash Game, they are also higher than the single city regulated case. The regulated two city case returns the highest total welfare as would be expected, but the welfare to each city is much lower than could be achieved in regulated and un-regulated single city case. The most interesting case is the Nash Game where both cities engage in a competitive game against each other and results in the highest tolls. As a result, both cities are worse off than in the no toll case with a reduction in welfare. This is the classic Nash Trap outcome which appeared in the work of Koh et al (2012) as described earlier. Note that whilst we have found a classic *lose-lose* outcome similar to that in the earlier work, we have shown that in the present case there are no Local Nash Equilibria (LNE) as observed in Koh et al (2012). The LNE reported in Koh et al arose due to network specific route choices where the path-set varied with the toll. The fact that we have only one Nash Equilibrium simplifies the discussion around policy implications as there are no local solutions which lie close to the regulated solution as was the case in the earlier work.

3.4 Optimal tolls: asymmetric cities

Table 8 shows the optimal tolls and NPV of welfare for the asymmetric cities. In this case the level of interaction has been calibrated as described earlier to be representative of the interaction between Leeds and Bradford. The results show that the optimal charge for City A alone is higher than for City B alone and the welfare gain is also higher. This is due to the larger size of City A together with a proportion of non-residents entering the cordon and paying the fee in City A (recall City A has a higher workplace/population ratio and so draws in a higher proportion of commuters from City B, than City B does from City A). Comparing these results shows that City A has more of an incentive to begin charging than does City B. When a regulator controls City A alone then the tolls are lower than for the un-regulated City A scenario with greater total welfare gain together with lower gains for City A, and a lower reduction in welfare for City B as in the symmetric case. Similar changes are seen for the regulation of City B. From the whole system point of view there is more to be gained from tolling in City A than in City B due to the greater population and associated *time savings*. Regulation of both cities results in higher charges in both cities compared to single regulated cases, though the tolls are still lower than the cities would charge in the single city cases. The total welfare is the highest for the 2-city regulated case, though the individual city welfare gains are lower than all previous single city cases. This would suggest that a city may prefer the single city regulated case over the 2-city regulated case, though a regulator would prefer both cities to be under its control. The Nash Game again results in the highest charges for both cities, as cities react to the tolls set by the other city. The welfare changes are however both *positive* in the asymmetric case, though still lower than the regulated case and with higher optimal tolls applied to both cities. So while this is a Nash Trap, it does not result in a negative outcome for either city as was the case in the symmetric scenario. This is thought to be due to the *lower level of interaction* between the cities than that observed in the Leeds-Bradford case presented here and therefore lower opportunity for tax exporting behaviour. The sensitivity of results to the level of interaction will thus be interesting which is discussed further in Section 3.6 later.

Table 8: Optimal tolls and NPV of welfare in year 30 for the asymmetric cases

Scenario	Tolls €	Welfare A Million €	Welfare B Million €	Total welfare Million €
Single City A	2.47	128.08	-57.58	70.50
Single City B	2.17	-50.75	61.76	11.01
Regulated City A	1.76	119.72	-39.96	79.76
Regulated City B	1.16	-26.63	50.54	23.92
Regulated 2-city:	A:1.93 B:1.48	97.68	19.67	117.34
Nash Game:	A:2.63 B:2.41	87.48	12.64	100.12

3.5 Long term land use response to tolls

The land use response is measured in terms of change in residents and change in the number of workplaces over the do-nothing case at the end of the study period i.e. year 30. A negative value indicates residents/jobs moving out of the zone and a positive number indicates residents/jobs moving into the zone.

Table 9 shows the change in residents for the *symmetric case*. First of all we can see that with a 2-zone model, residents are attracted to the charged zone. This is because of the reduction in accessibility for residents in zone 2 due to the change which increases the relative attractiveness of residing within zone 1. Note that there is also a small increase in accessibility for those already living in zone 1 as there is less congestion within the charged area. Note that the change in residents is less than 1% of the total residents residing in zone 2 in the do-nothing case and that small changes noted due to road pricing are consistent with other studies (e.g. Jenson (1999), Anas & Xu (1999) and Anas & Hiramatsu

(2013) for large cordons). Moving onto the four zone model scenarios, with the single City A charging alone Table 9 indicates that residents are attracted from zones 2, 4 towards the charged zone 1. Residential location choice is based on housing costs, relative accessibilities and income to represent the attractiveness of an area. Whilst the absolute accessibility of zones 2, 3 and 4 is reduced by the toll around zone 1, the relative attractiveness of zones 1, 3 improves so residents relocate from zones 2 and 4 towards the central zones with more going towards the charged zone 1. The net effect on City B is a loss of over 3000 residents to City A (still only a small percentage of the total residents in City B). When a regulator controls a single city or both cities, the impacts are dampened due to the lower tolls. Finally, when the cities compete against each other we have the highest tolls and greatest movements from outer to inner zones (still only around 1.25%). However as this is a symmetrical case, when both cities charge the same toll there is no net movement of residents between cities.

Table 10 shows the change in residents for the *asymmetric cases* in response to optimal tolls described earlier. The location choice again depends on changes in relative accessibility and we can see that when City A charges alone, residents move into the charged area and City B loses over 900 residents to City A after allowing for the gain in zone 3. When City B charges alone in the asymmetric case, whilst zone 3 attracts over 2000 residents, an even larger number of residents (over 3100) move from zone 4 City B to City A and zone 3 of City B. This is because of the larger number of job opportunities in City A and so despite absolute reductions in accessibility from zones 1 and 2 due to the charge to travel to zone 3, the relative accessibilities of zones 1 and 2 improve compared to zone 4 which has the largest absolute reduction in accessibility. Regulated single city cases show similar patterns to the unregulated cases but responses are smaller due to lower charges. The regulated two-city case and the Nash Game scenario display similar trends in that residents are attracted to the inner zones. However, City B loses residents to City A in both cases and more so in the Nash Game where the tolls are higher. These results suggest that City B loses residents in all scenarios and could be seen as the weaker city. However the losses are only in the order of 1-2% in the worst case. Whilst this movement was only in the order of one percent of all residents, it still could be a cause for concern where cities are perceived to be in decline.

Table 9 Change in residents in year 30: symmetric cases

Scenario	Zone 1	Zone 2	Zone 3	Zone 4
City A 2-zone only	2230 (0.66%)	-2230 (-0.35%)	NA	NA
Single City A	7277 (2.16%)	-4165 (-0.66%)	219 (0.07%)	-3331 (-0.53%)
Regulator City A	3491 (1.04%)	-2076 (-0.33%)	229 (0.07%)	-1644 (-0.26%)
Regulator 2-city	4622 (1.37%)	-4622 (-0.73%)	4622 (1.37%)	-4622 (-0.73%)
Nash Game	7851 (2.34%)	-7851 (-1.25%)	7851 (2.34%)	-7851 (-1.25%)

Table 10 Change in residents in year 30: asymmetric cases

Scenario	Zone 1	Zone 2	Zone 3	Zone 4
Single City A	2672 (0.76%)	-1765 (-0.27%)	515 (0.26%)	-1427 (-0.37%)
Single City B	2557 (0.73%)	649 (0.10%)	2137 (1.07%)	-5343 (-1.37%)
Regulator City A	2210 (0.63%)	-1407 (-0.22%)	362 (0.18%)	-1165 (-0.30%)
Regulator City B	1523 (0.44%)	427 (0.07%)	1240 (0.62%)	-3190 (-0.82%)
Regulator 2-city	3673 (1.05%)	-786 (-0.12%)	2075 (1.04%)	-4962 (-1.27%)
Nash Game	4360 (1.25%)	-595 (-0.09%)	3113 (1.56%)	-6878 (-1.77%)

In terms of changes in workplace locations, jobs were seen to move out from the charged areas and the results were found consistent with the modelling work carried out by Jenson (1999) based on a road user toll ring in Oslo, Norway. They reported a slight employment decentralisation and residential centralisation in Oslo. In our case study, the relative change in employment was even smaller than for residents and is not discussed here.

3.6 Sensitivity of optimal tolls and welfare to level of interaction between cities

As mentioned earlier, the *level of interaction* between cities in the symmetric case was *higher* than that seen in reality between the cities of Leeds and Bradford. It was noticeable that the Nash Game tolls were only slightly higher than the regulated tolls in this case and that the resulting welfare was positive for both cities rather than negative as in the symmetric case. In order to understand the relationship between the *level of interaction* and *optimal tolls* a set of sensitivity tests were conducted for both the symmetric and asymmetric cases. The tests involved factoring the level of interaction up/down between the cities by a common value in both directions. This is achieved by multiplying the ‘attraction’ in the distribution part of the model for trips between the cities. We then calculated the new optimal tolls and the associated welfare changes for the two city regulated and Nash Game scenarios. The level of interaction was varied from *no interaction* (factor = 0) through the current value with a factor of 1, to a doubling of the level of interaction (factor = 2). Figure 7 shows how the optimal tolls vary with the factor on level of interaction for the symmetric cases. The Nash Game tolls are higher than the regulator tolls and the gap between regulated and Nash Game tolls widens as the level of interaction increases. The optimal tolls converge when there is no interaction between the cities i.e. when there are no trips between them. In this case, the two cities are acting *independently* from each other, competition does not have an adverse effect on the system and there is no need for regulation.

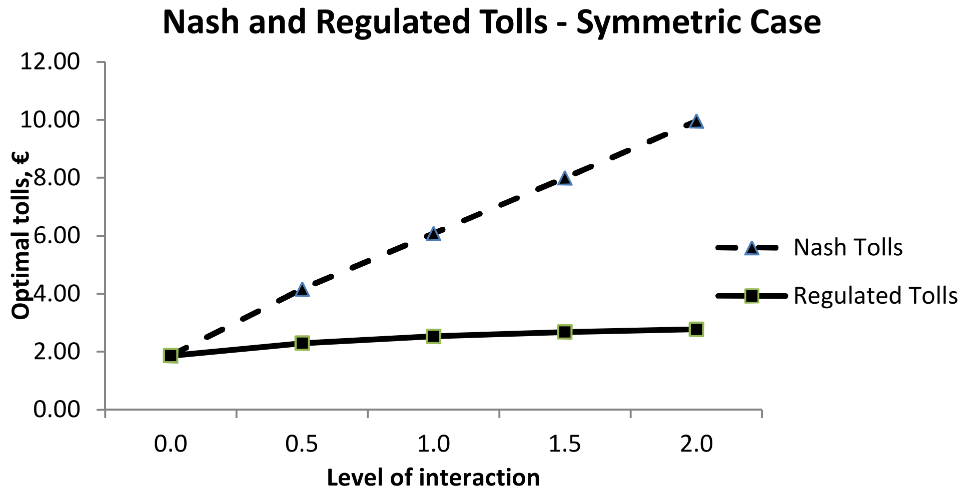


Figure 7 Optimal Nash Game/Regulator tolls: symmetric cases

Figure 8 shows the NPV of total welfare for the Nash Game and Regulator cases as the level of interaction is varied. (Note that for this symmetric case we do not need to present city level welfare changes as they are equal and half the total welfare). As may be expected, the Nash Game welfare is always lower than the regulator welfare and that the gap in welfare increases with an increase in the level of interaction. This means as the level of interaction increases the ability of each city to extract revenue from non-residents also increases. This results in higher tolls being charged, which are sub-optimal from the congestion or total welfare point of view. As explained earlier the best response surface for each authority results in a potential Nash Trap and where interactions are higher the total welfare turns out to be negative. On the other hand, as the level of interaction decreases, the welfare outcome for the Nash Game scenario is positive which is consistent with the earlier comments. Thus when cities strongly interact with each other regulation should be considered to avoid the negative impacts of competition.

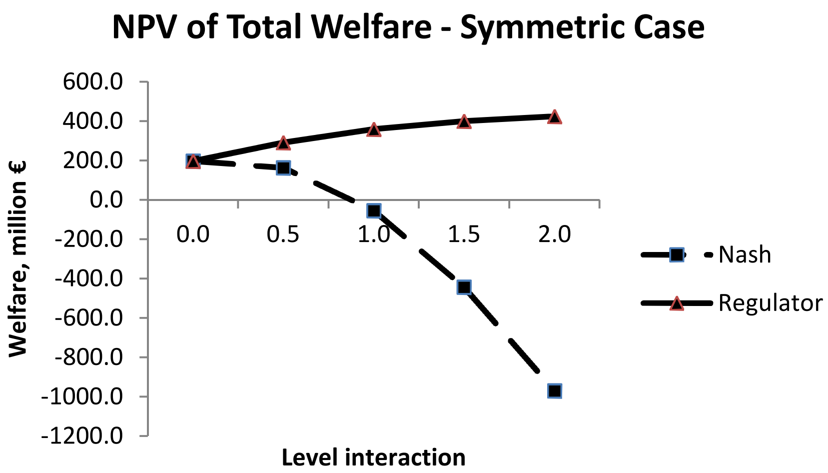


Figure 8 Optimal total welfare: symmetric cases

Figure 9 shows the Nash Game and Regulator tolls for the asymmetric case. For a factor of 1.0, the figure shows the optimal tolls for the calibrated case of Leeds-Bradford. In general, the asymmetric cases follow the same trend as that of the symmetric cases, with an increasing gap between the Nash Game tolls and the regulated tolls as the level of interaction is increased. As explained previously the initial level of interaction between the cities is low which reduces the role of tax exporting behaviour. Due to this the welfare for the asymmetric case is closer to the regulated case and so the optimal tolls under Nash Game are also low. As the interaction increases the toll by City B exceeds that of City A under the Nash Game. This is due to the greater proportion of trips coming from City A relative to the trips within City B which results in a greater impact from the tax exporting element of the optimal toll in City B compared to City A. Clearly the optimal toll is dependent on the relative size of the city and number of non-resident drivers making a trip to the charged area. The increase of toll in City B relative to City A also dampens the net migration from City B to City A though the effects as discussed previously are relatively small.

When there is no interaction in terms of trips between the cities, the tolls tend to converge exactly as in the symmetric case. The slight deviation in Nash and Regulator tolls in City B can be explained by the location response of the residents. While there is no interaction in terms of trips between the cities, the residents are still able to relocate between the cities and as explained in the above it is the relative accessibilities which affect the location decision. Thus there are some relatively small differences in the location of residents which arise between the Nash Game and the Regulated Scenario which in turn affects the optimal tolls. The cities are competing albeit indirectly for residents to increase their own welfare. This did not arise in the symmetric case as the location responses are symmetric and cancel each other out as shown earlier where both cities respond with the same tolls.

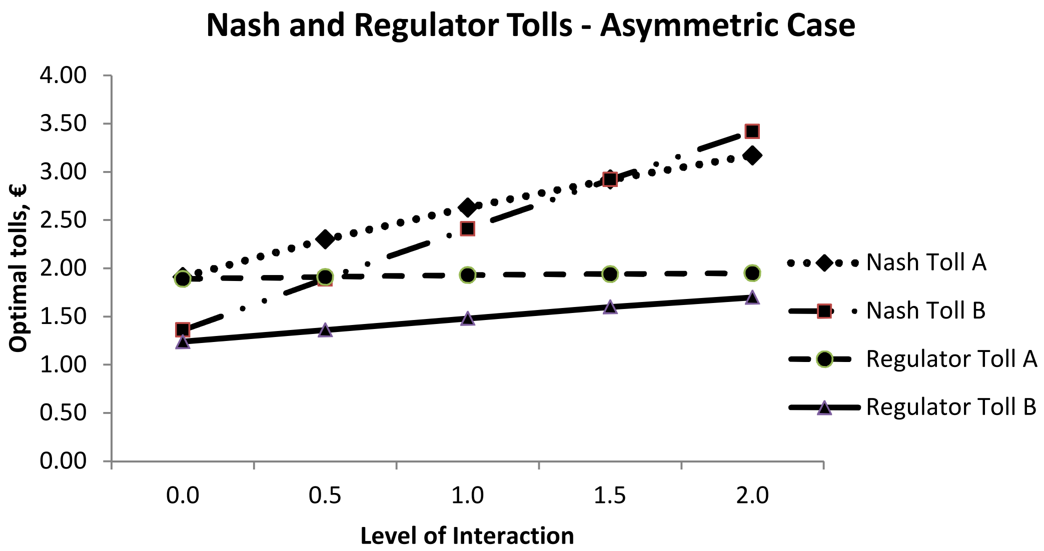
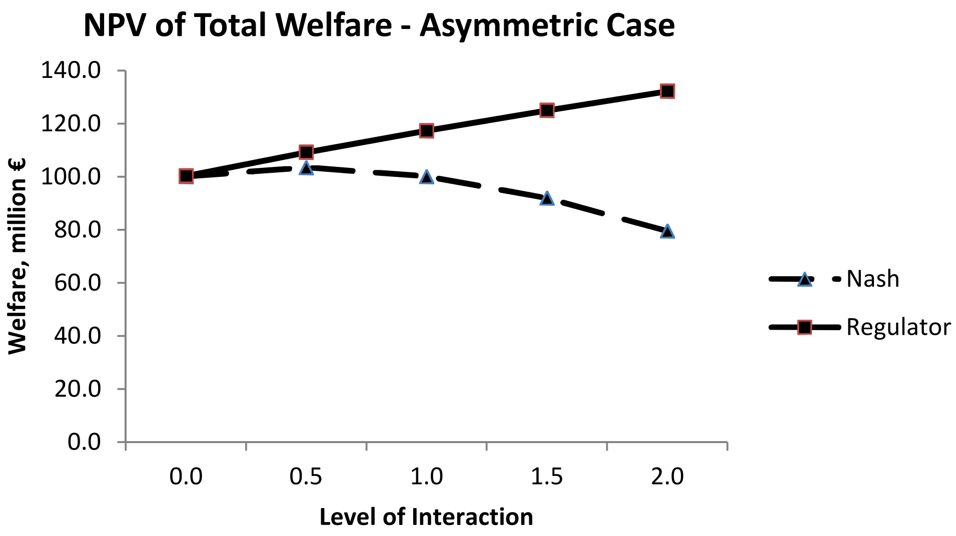
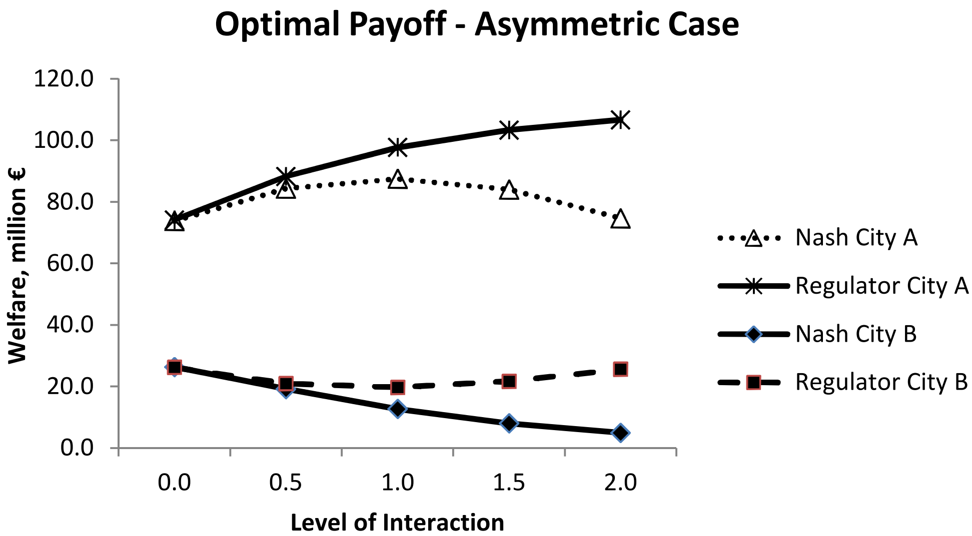


Figure 9 Optimal Nash Game/Regulator tolls: asymmetric case



(a) Optimal total welfare



(b) Optimal Welfare by City

Figure 10 Optimal welfare: asymmetric case

Figure 10a shows the total welfare for the Nash Game and regulated scenarios with varying level of interaction. Figure 10b shows the welfare changes for City A and City B individually. As the level of interaction is increased the welfare gap between the Nash Game and regulated scenarios increases and as expected the Nash Game total welfare is always less than or equal to the regulated case. The variation in welfare for each player does not follow the same trend however. As the level of interaction increases, the Nash Game welfare decreases for both cities though not as much as in the symmetric case. Thus as the level of interaction increases there is a greater incentive for cities to accept regulation as the potential gain in welfare is higher for both cities.

4. CONCLUSIONS

This paper addresses the general problem of how cities may compete when cordon tolls are applied using a strategic land use transport interaction model. This allowed us to consider all modes of transport together with the longer term re-location response to any tolls imposed.

Firstly the response surface and grid search approach shows that there exists only one Nash Equilibrium with our model for the cases considered. As the MARS model does not include route choice, this would suggest that the multiple local Nash Equilibria found by Koh et al are a result of changes in the path set. Whether or not multiple equilibria exist in more realistic networks still requires further research, but at least for our model, we found that only one equilibrium was possible which meant that we could rely on the VENSIM optimisation results and use the diagonalisation approach to solve the Nash Game scenario.

We then investigated various tolling regimes for a single city and two cities under regulation and competition. Firstly, we found that if a city planner adds a neighbouring city into the planning process, then this allows tax exporting behaviour where the city may toll users from the other city and retain revenues for its own residents. This results in higher tolls and increased welfare at the expense of the other city.

Regulation of tolls reduces the tolls imposed while increasing the total welfare, though individual city welfare is lower than can be achieved if tolling alone. This incentive to tolling alone means that the Nash Game scenario resulted in the highest tolls and the cities fell into a Nash Trap where both become worse off compared to the no toll case for the symmetric interaction between the cities.

The asymmetric case study is based on the population and workplace distribution of Leeds and Bradford and the level of interaction between the two cities was calibrated to observed data. In general the differences in tolls between the regimes followed the same pattern as the symmetric case. However, while the tolls are still the highest in the Nash Game scenario, the outcome is positive in terms of welfare change for both cities. This raised the question about the sensitivity of tolls and welfare to the level of interaction under competition.

The sensitivity tests show that as the level of interaction is increases, the potential for tax exporting behaviour also increases and so the tolls under competition increase. The gap between welfare outcomes for the cities under competition and for the cities under regulation also increases with an increase in the level of interaction. As the level of interaction tends to zero, the tolls under competition converge to the regulated tolls. This suggests, intuitively, that regulation should be considered where there is significant movement between cities and that the cities should be encouraged to collaborate for the greater good. Where there are no significant flows between cities then competition has little adverse impact and cities will not be competing for revenue from their neighbours but for something on a different level such as investment from government or the private sector in terms of jobs. In all the sensitivity tests, both cities would be incentivised to accept regulation though the larger city always takes a larger share of the welfare changes.

Finally, the long term response to tolls is that the residents move into the charged areas and the jobs move out of the charged cordons. While the case of symmetric cities showed identical pattern when both cities charge, the case of asymmetric cities is more interesting in that the smaller city loses some residents but gains a small number of jobs from the larger city.

The question of which is the strongest city in terms of cordon charges depends upon how we view the problem – if we define strength based on toll level, then the larger City A appears to be strongest, but the smaller City B seems to be implicitly stronger as it can charge a higher proportion of non-residents and so has a greater tax exporting 'strength'. However if as one would expect cities are more concerned about losing residents and jobs to other cities, then the larger city is the stronger one in this case. Whilst these relative changes were small, they could be of concern to cities which are thought to be in decline and the regulator would be under pressure to provide equal benefits per capita via some kind of re-distribution of revenues between cities. This would reduce the incentive for the larger city to accept regulation.

The policy implications are threefold – (i) while there is an incentive to cooperate at local authority level, this is not achieved due to competition; (ii) where cities compete they may fall into a Nash Trap where both cities will be worse off compared to the regulated solution; and (iii) regulation is recommended when there is a strong interaction between the cities but that the benefits of regulation decrease as interaction between cities decreases and the impact of competition is lessened.

Future research should consider extending the model to include more than two cities and to include other objectives such as a reduction in CO_2 which would be greater here under the competitive regime than under the regulated case due to the higher charges imposed.

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