OPTIMAL CHARGING STRATEGIES UNDER CONFLICTING OBJECTIVES FOR THE PROTECTION OF SENSITIVE AREAS: A CASE STUDY OF THE TRANS-PENNINE CORRIDOR

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ABSTRACT

Road user charging has been discussed in the literature to reduce local pollution in sensitive areas where general incentives to reduce fuel consumption or use cleaner vehicles cannot sufficiently reduce impacts (i.e. residential areas or National Parks). However, there has been little research on the implication of potentially conflicting objectives in the delivery of road user charging policies when several areas are affected. The key question for this paper is to investigate the interdependencies between the price setting strategies of neighbouring institutions and what the optimal strategy would be if environmental considerations are included. Such a situation can be encountered in the Trans-Pennine corridor where transport networks connecting major agglomerations cross areas of high natural value as well as densely populated conurbations. We selected two transport sensitive areas of different type: the Peak District National Park, as a sensitive ecosystem and area of high recreational value, and the Sheffield Air Quality Management Area (AQMA), as an area with very high population density.

Different combinations of user charging between both areas and the surrounding motorways have been analysed. For each combination, cordon charges respectively distance based motorway tolls have been determined that optimise the welfare gains under the objectives given in that scenario, measured by changes in user costs and costs to society, including environmental externalities. Under a global co-operative regulation scenario including all players the overall welfare of the region would be maximised. However, left to their own devices, the authorities might be tempted to play a Nash game amongst them and set the tolls at a level that results in a positive outcome for the local area but reduces the net welfare for the entire network compared to a co-ordinated introduction of charges. If motorways are not tolled, overall welfare can even be reduced due to wide diversion of traffic in the area. Regarding environmental impacts, substantial improvements within the sensitive areas and on the motorways for which charges have been applied can be achieved, although the reductions in environmental costs over the case study region are small. In conclusion, a charging instrument can be successful in reducing local environmental problems but implementation in isolation of surrounding areas needs to be avoided.

Keywords: Road user charging, environmental costs, sensitive areas, air pollution

1. INTRODUCTION

The economic justification for road user charging has a long established tradition. These recent years have seen a flurry of implementations of road user charging schemes within Europe, in particular in urban areas such as London (introduced in 2003), Stockholm (2007) and Valletta (2008). These schemes have as dominant objective the internalisation of the congestion externality of transport (CURACAO, 2009a) in the tradition following the seminal work of Walters (1961) with environmental benefits to the cities as additional justification.

The literature has tended to consider the impacts of road pricing and the determination of optimal charges in isolation from reactions from other nearby agglomerations or affected areas. Practical experiences of scheme implementations suggest that pricing is mainly used in capital cities which possess a strong economy and are not subject to competitive influences from neighbouring regions. We contribute by considering the added dimension of institutional competition when road pricing is used as a demand management tool simultaneously in both an urban and an environmentally sensitive rural setting, acting as a welfare maximising non-co-operative duopoly. Such a situation can be encountered in the Trans-Pennine corridor in the North of England where transport networks connecting major agglomerations cross areas of high natural value as well as densely populated conurbations. In one extreme, we have the urban agglomeration of Sheffield, a city of approximately half a million inhabitants. At the other end, we have the sparsely populated Peak District National Park protected on the basis of its natural value as well as a recreational and touristic site.

In addition we then consider the role of the National Government who have an interest in the welfare of all residents across the region. We do this by introducing a third player into the pricing scheme, here we assume that the Highways Agency acts for the Government and are able to apply a distance based toll on all motorways in the region. Thus we move from a two

player duopoly to a three player regime in which we consider co-operative and non-co-operative games.
The rest of this paper is organized as follows. In the subsequent section we summarise the literature on the two interrelated aspects investigated in this paper; namely that of road user charging in environmentally sensitive areas such as National Parks and the effects of competition between local authorities. We then introduce the case study region and the context of the primary environmental problems encountered by the local authorities in the Peak District National Park and in Sheffield. Section 4 presents our methodology and the different pricing strategies studied in this paper. Section 5 presents the summary of the results and the policy implications arising. We conclude in Section 6 and provide directions for further research.

2. RELATED RESEARCH

2.1. Pricing for Environmental Protection in Transport Sensitive Areas

The internalisation of externalities stemming both from congestion and environmental pollution through pricing measures has a long-standing tradition in general economic theory and its applications to road networks (e.g. Pigou, 1920, Baumol 1972, Johansson-Stenman, 1997, Yin and Lawphongpanich, 2006). There are also several real-world examples for road pricing schemes where environmental protection played a major part in their justification. E.g. Milan's introduction in 2007 of a variant of road user charging, via its *EcoPass* system, was primarily motivated by its desire to curb a plethora of environmental nuisances partly stemming from private vehicle usage (CURACAO, 2009b). Monitoring results after the first full year of operation have shown that it has been proven relatively successful in reducing the amount of pollutants within the charged area (Comune di Milano, 2009).

One aim of our research is to analyse pricing as an instrument for the protection of transport sensitive areas (TSAs) against environmental pressures. These have been defined in the ASSET project as areas "where the presence of a transport route deteriorates the quality of the area clearly more than the presence of the same transport route in another area because the local impacts caused are particularly high" (Lieb et al., 2008, p. 6). These can be areas which are particularly vulnerable or highly valuable due to environmental, cultural or social characteristics, such as very high population densities or the presence of sensitive ecosystems or cultural heritage sites. For our case study we selected two neighbouring areas of different type for the application of pricing, the Peak District National Park as a sensitive ecosystem and area of high recreational value and the Sheffield Air Quality Management Area (AQMA) as described in the following chapter.

Whilst there is much literature advocating road user charging in general as well as urban applications, few have focused on the implementation of road pricing in national parks. It is particularly important in this respect to make the distinction between through and visitor traffic. With regard to the latter itself, the tourism literature (e.g. Laarman and Gregersen, 1996) suggest the use of visitor fees to encourage sustainable management of national park resources but this tool is underutilised at the moment (Van Sickle and Eagles, 1998). Charging for the use of roads in national parks to manage both through and visitor traffic has also been separately studied. Steiner and Bristow (2000) investigated a hypothetical road pricing scheme in the Yorkshire Dales National Park and found that it was acceptable to half of all the respondents in the survey they carried out, who would switch to park and ride if it was an available option. Their finding of support for restrictive traffic management measures amongst visitors is similar to the conclusion reached by Holding and Kreutner (1998) in their study of Bayrischer Wald National Park in Germany, although it must be emphasised that these latter authors did not focus specifically on road user charging. Despite the apparent support amongst visitors, Downward and Lumsdon (2004) contend that very few national parks would move in this direction even though the legislative framework enables road user charging. Eckton (2003) studied pricing within the context of the Lake District National Park but found that road-user charging was impractical as inequity effects exceeded economic efficiency gains. This finding should not come as a surprise given the fear amongst residents that road user charging might damage the local visitor dependent economy of National Parks (Holding and Kreutner, 1998). Takama and Preston (2008), focusing on the Upper Derwent Valley in the Peak District National Park, employed an agent based simulation model to conclude that pricing will indeed reduce demand within the tolled area. For the Peak District National Park, pricing is not merely an academic option but has been recommended as part of the South Pennines Integrated Transport Strategy (Faber Maunsell, 2004).

2.2. Institutional Decision Making and Competition between Local Authorities

Whilst work on developing optimal transport strategies (e.g. May *et al*, 2000) indicated the importance of formulating integrated strategies utilising a combination of policy instruments, an implicit assumption is made that the institutional structures for the delivery of a given strategy are simply taken as given and is assumed to be benevolent and non-discriminatory between local and foreign users of the transport network. However some commentators recognised that the state of institutional governance of transport matters for the successful delivery of policy (Pemberton, 2000). Pemberton gave an example that when working out the package approach for funding of transport improvements, officials in Sunderland, North Tyneside, South Tyneside, as well as Gateshead perceived an *over dominance in terms of policy determination by Newcastle City Council* (Pemberton, 2000 pp. 300). Similarly, Marsden and May give an example that when implementing parking policy there is concern amongst local officials that it would lead to loss of business and reductions in trade to adjacent competing centres (Marsden and May, 2007).

The literature also suggests that authorities engage in tax exporting behaviour using tolls. Tax exporting behaviour is a concept from the public economics literature (e.g. Stiglitz, 2000). In the context of tolls as fiscal instruments, the argument is that local governments wish to score political points with their residents and do so by laying the burden of paying the toll onto "foreign" (i.e. non-resident) users in the local area. De Borger *et al* (2005) and Ubbels and Verhoef (2008) used highly stylised highway networks to show that governments, when intending to maximise the welfare of their residents, extract the maximum toll revenue from such non-resident users of its highway network. Similarly, Levinson (2000) demonstrated via an econometric model, that the more non-resident workers a state (in the United States) has, the greater the likelihood of tolling. Further, he shows that should other states toll, it is likely to retaliate by imposing a toll if most of its residents commute to work out of its jurisdiction when other neighbouring states impose a toll. De Borger and Proost (2004) recognise that a negative externality arises as a result of this desire to shift the burden of the toll onto non-local users. This tax exporting behaviour is not only of academic interest but practical experience has attested to its occurrence. For example, one institutional reason for the failure of the congestion charging proposal in Edinburgh is that authorities in the surrounding regions (e.g. Fife, West Lothian and Mid Lothian) opposed the proposed scheme because while there was an explicit exemption for Edinburgh residents, others had to pay. Thus the burden of the toll would fall (perhaps disproportionately) on non-Edinburgh residents (Saunders, 2005). This evidence suggests that in the absence of regulation by central government, local governments might be tempted to play a Nash game in their individual attempts to extract revenue from non-local users of the highway network. This would have policy implications not only on the local level as analysed in our case study but also for federal governments (as in the context of the United States) as well as supranational bodies such as the European Commission.

3. CASE STUDY

Our case study region is known as the Trans-Pennine Corridor and is characterised by high diversity in terms of terrain, natural capital, land use, economic activity, transport and population density (see Figure 1). There are extensive road and railway networks as well as three international airports (Manchester, Leeds, Sheffield / Doncaster) in the region. In total, these comprise 400 km motorways, 6,500 km interurban (primary and A roads), 10,350 km of B and minor roads, as well as 1,160 km railways. The corridor itself is the major east-west connection in the north of England, one of the most densely populated areas in Europe which covers the conurbations Liverpool, Manchester, Bradford, Halifax, and Leeds with a total of 13 million inhabitants. The region is an area of economic regeneration as part of the Northern Way initiative which aims at developing the regional economy in order to provide a balance to the London growth pole and narrow the income gap between the North and South of England. Within this initiative, the improvement of transport connections plays a vital part, in particular policies aiming at increasing the Trans-Pennine Corridor capacity and capability. This corridor crosses the low mountain range of the Pennines, an area of high natural and scenic value and a major tourist attraction. Thus, any extension of infrastructure and growth of traffic will potentially lead to high environmental pressures both on densely populated areas as well as sensitive natural areas. This brief overview serves to highlight the context of environmental issues and challenges faced by two authorities within the Trans-Pennine Corridor. The first is the Peak District National Park and the second is the city of Sheffield.

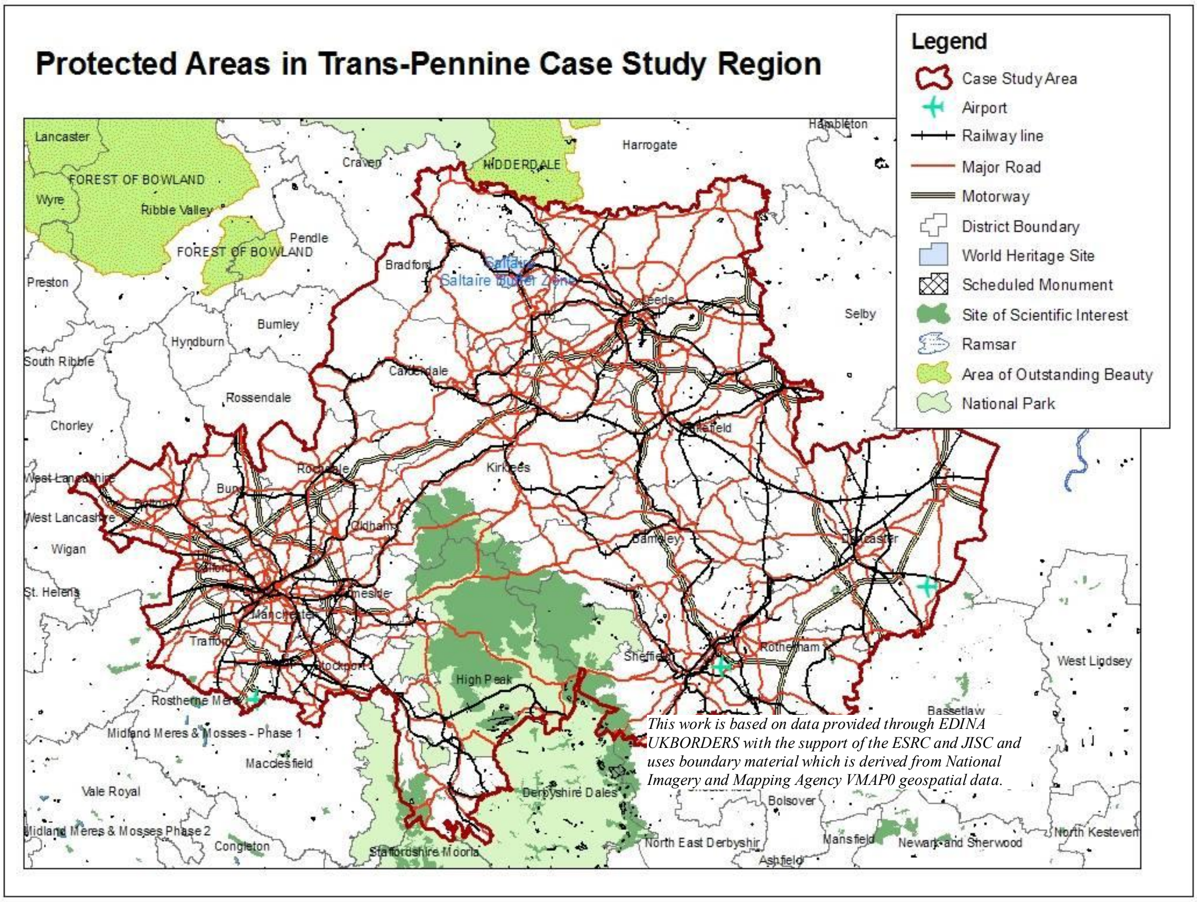

Figure 1: Protected Areas in the Trans-Pennine Corridor (Gühnemann et al., 2009)

3.1. The Peak District National Park

The 1438 km^2 Peak District National Park is situated in the centre of the Trans-Pennine Corridor and serves as both a unique natural habitat and popular recreational site. It was the first National Park to be legislated as such in the UK in 1951. The Park receives approximately 22 million visitors yearly and is the second most visited National Park in the world (PDNPA, 2004). The majority are day visitors. Its defining features include moorland, conservation areas, designated sites, listed buildings and dry stone walls. In addition 35% of the Park is designated as Sites of Special Scientific Interest by Natural England[1] due to their importance for flora, fauna, geology and geomorphology. A variety of protected sites can be found within this area such as Special Protection Areas (sites classified in the EC Birds

[1] Quasi Non Governmental Organisation charged with the responsibility of providing advice to the British Government on the natural environment and safeguarding England's natural wealth.

Directive[2]), Special Areas of Conservation (sites classified in the EC Habitats Directive[3]) and other Areas of Outstanding Natural Beauty (AONB). Due to its location in the centre of dense urban agglomerations, traffic movement through the Park is a major cause for concern, with heavy traffic on cross park roads (in particular the A628, see Figure 2). The primary movement on these roads is traffic travelling between the conurbations of Sheffield and Manchester. Recent studies show that traffic levels on all cross park roads have increased over 100% since the 1980s (PDNPA, 2004). As a result, levels of Oxides of Nitrogen (NO_x) and Particulate Matter have often remained close to or exceeded national limits. Despite its sparsely distributed population (approximately 40000 residents, (PDNPA, 2004)), air pollution still has an adverse impact as it affects sensitive plants while exacerbating erosion of the peat.

3.2. Sheffield

In the UK, Air Quality Management Areas (AQMAs) are areas that have to be declared by local authorities when air quality targets are unlikely to be met and authorities have a statutory obligation (under Part IV of Great Britain's Environment Act, Chapter 25 of 1995) to draw up concrete action plans to improve the local air quality. With a population of just over half a million, the city of Sheffield is England's third largest metropolitan authority. Sheffield suffers from serious road traffic related air pollution and has declared the whole of the city excluding the areas which lie in the National Peak District National Park an AQMA for failing to meet annual national targets on reducing NO_x. Recently, the same area has been set up as an AQMA for fine particles. In addition, there is the M1 motorway which skirts the city (see Figure 2). Therefore, aside from local pollution sources, the close proximity of the town to this strategic motorway, carrying 100,000 vehicles per day in both directions between Junctions 33 to Junctions 34 (WSP, 2007), has also posed a significant challenge in dealing with the knock-on environmental effects of traffic. In its statutory action plan, the City Council has considered a range of measures which include improvements to public transport, infrastructure investment, encouraging cleaner vehicles, and softer demand management measures such as travel plans and financial support to car clubs (Sheffield City Council, 2006). A low emission zone for the city has been proposed but has thus far not been realised (Sheffield City Council, 2006).

[2] Council Directive 79/409/EEC "Conservation of Wild Birds"
[3] Council Directive 92/43/EEC "Conservation of natural habitats and of wild fauna and flora"

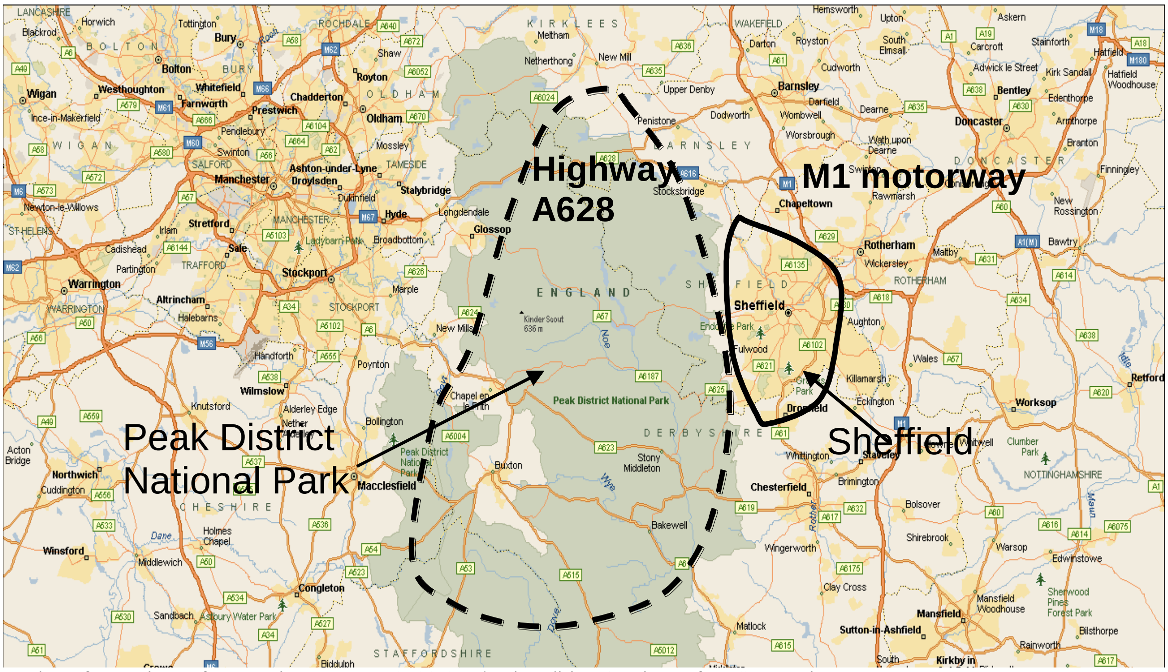

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Figure 2: Peak District National Park and Sheffield within the Trans-Pennine Corridor

4. PROBLEM DEFINITION

Our focus in this paper is to demonstrate the influence of different institutional arrangements which we refer to generically as the regulatory regime or scenario, in the choice of uniform toll levels around two predefined zones or cordons (shown in Figure 2) with dashed lines for the predefined zone around the Peak District and solid lines for the zone around Sheffield) to maximise social welfare. This situation can be described as a welfare maximising non-co-operative duopoly with the involved actors each solving the second-best problem for determining network tolls (see e.g. Rouwendal and Verhoef, 2006). We then extend the problem to include a third player – the Highways Agency who represent the national level government and are able to implement a distance based toll on all motorways in the region. This extends the problem by bringing in further two player games and finally to a triopoly in the most complex case where all players act as in a Nash game with each player maximising their own welfare function through setting toll levels in their respective areas.

In general, social welfare is measured as the sum of user benefits, revenues from tolls and the monetised benefits of reduced pollution with tolls in place. In each scenario, however, the definition of the precise scope of user benefits as well as savings in pollution reduction differs due to the viewpoint assumed for each player and under each regulatory scenario or regime, as summarised in Table 1 and Table 2.

Table 1 : Definition of welfare measure for each player

Player	Definition of Objective Function
Peak	Difference in consumer surplus for travellers originating in the Peak District, destining in the Peak District or with both origin and destination in the Peak District plus Revenue from Peak cordon tolls plus a share[4] of the motorway toll revenue Environmental benefits in the Peak District
Sheffield	Difference in consumer surplus for travellers originating in Sheffield, destining in Sheffield or with both origin and destination in Sheffield plus Revenue from Sheffield cordon tolls plus a share of the motorway revenue Environmental benefits in Sheffield
Highways Agency	Difference in consumer surplus for all travellers (regardless of Origin and Destination) plus Revenue from cordon tolls from Sheffield and Peak District plus revenue from motorway pricing plus Environmental Benefits from the entire network (including benefits from Sheffield and Peak)

The scenarios in Table 2 show all possible combinations of players and assumptions regarding the actions of each player. Under the global regulation scenarios we assume the players are acting co-operatively to maximise the welfare for all residents in the study area. Under the local regulation scenarios we assume that each player maximises their own objective function only and where more than one player is involved then a Nash game will be the result.

Table 2 : Definition of scenarios by regulatory regime

	Regulatory scheme	
Players involved	Global regulation	Local regulation (Nash game)
HA	G1(HA)	L1(HA)
Peak	G1(P)	L1(P)
Sheffield	G1(S)	L1(S)
HA+Peak	G2(HA+P)	L2(HA+P)
HA+Sheffield	G2(HA+S)	L2(HA+S)
Peak+Sheffield	G2(P+S)	L2(P+S)
HA+Peak+Sheffield	G3(ALL)	L3(All)

[4] The share of revenue recycled to Peak and Sheffield are based on the proportion of trips considered in the welfare measure without tolls compared to the total trip matrix. This is a proxy for per capita recycling and the shares were 0.42% and 17.4% for Peak and Sheffield respectively.

4.1. Welfare Measurements

For each policy package, cordon charges and/or motorway tolls have been determined that optimise the welfare gains in terms of user benefits, revenues and benefits from pollution reduction under the objectives given in that scenario.

The user benefits capture the difference in generalised cost between the Business as usual (no toll) vis-à-vis the Tolling scenarios. The user benefits are approximated in all scenarios by applying the Rule of a Half to changes in generalised costs (Williams, 1977) between the Business as Usual (BAU) (i.e. no charge) vis-à-vis the user charging scenarios. These include vehicle operating costs, time costs and charges using the UK national appraisal software COBA (Department for Transport, 2006).

The monetary valuation of the environmental impacts followed the guidelines for a harmonized European approach developed in the HEATCO project (Bickel et al., 2006), amended by national values where necessary. The air pollutant emissions have been calculated applying emission per vehicle km as used for the UK (Collier *et al.*, 2005) to which the HEATCO values were applied. The key pollutants considered were Non Methane Volatile Organic Compounds (NMVOC), Oxides of Nitrogen (NO_X), and Particulate Matter of 10 microns in diameter (PM_{10}). According to HEATCO, only four pollutants have to be considered, namely oxides of nitrogen (NO_x), non methane volatile organic compounds (NMVOC), sulphates (SO_2) and fine particles ($PM_{2.5}$). The costs related to $PM_{2.5}$ are divided into two groups reflecting the relative damage of this pollutant in urban and extra-urban locations. Specific pollutant cost values for the UK are given in 2002 PPP prices.

Table 3 : Estimated values for pollutants in 2002 PPP € prices

	NO_x	NMVOC	SO_2	Primary $PM_{2.5}$ Urban	Primary $PM_{2.5}$ Outside built-up areas
UK value	8,068	1,098	12,593	519,118	81,033

(Bickel et al., 2006)

The estimation programmes currently used in UK do not account for SO_2 emissions and thus we could not estimate the volume of this pollutant generated by traffic flows. However, this shortcoming could be seen as minor one. Modern generation of automotive fuels has an extremely low content of sulphurous matters and thus sulphates are generally considered of decreasing importance for pollution from road transport. For the valuation of particulate matters, we were able to derive the volume of $PM_{2.5}$ emissions from the initial estimation of PM_{10}. The conversion factors were taken from NEEDS (2005), where different dose–response functions were discussed. In order to take into account the uncertainty about the proportion of primary and secondary PM's and their relative toxicity, we decided to adopt the conservative conversion factor, namely 1 PM_{10} = 0.6 $PM_{2.5}$.

4.2. Modelling Assumptions

The impacts of these pricing scenarios have been assessed using a simple elastic assignment model using a standard software packet (SATURN (Van Vliet, 1982)) which can take into account the response to increases in congestion and travel costs through changes of routes or trip suppression. For the purposes of carrying out the simulations, we used the calibrated highway network from Faber Maunsell (2006) with the coverage as shown in Figure 3. The links shown in red are motorway links and are the control of the Highways Agency (mainly the M6, M62, M60, M606, M621, M1, A1(M)). The links shown in magenta denote the tolled links of the Sheffield cordon (black cordon lines) and links in blue are the tolled links of the Peak District (green cordon). The model comprises a total of 773 zones and 4 user classes (cars, light goods vehicles, rigid and articulated heavy goods vehicles). The 2005 base year matrices of the model and growth factors according to current UK guidelines have been used to forecast the 2020 trip demand matrices for the business as usual (BAU) scenario. These comprise in total about 280,000 trips by car, 30,000 by light goods vehicles and 12,500 by heavy goods vehicles. The expected transport growth between 2005 and 2020 in the Trans-Pennine corridor is +27%, with the Peak District National Park expecting an overall higher growth of +37%. This leads to a significant increase of links close to or above capacity and increase in air pollution despite assumed improvements in vehicle technology.

4.3. Optimisation Procedure for Finding Optimal Tolls

With this network we carried out the tests described below for the morning peak period between 0800-0900 hrs. We assumed the toll schemes would be operational in 2020. A range of tests were carried out with tolls applied in 50 pence intervals in the range of £0 to £8 for Sheffield, £0 to £5 for the Peak District, and 0 to10 pence/km (stepping in 2 pence intervals) for the motorway charges. This created a grid of results for changes in welfare for each player and globally. In addition, the specific assumptions made in each scenario are discussed below.

Global regulation Scenarios

The global regulatory Scenarios are instances of mathematical programs with equilibrium constraints (Luo *et al* ,1996) where the regulator sets the tolls and the highway users follow by choosing their routes obeying Wardrop's Equilibrium Condition where equilibrium is reached when unilateral changes to route choices yield no benefits for the travellers (Wardrop, 1952). For these cases we simply used the grid search described earlier to identify the optimal tolls for each cordon so as to maximise the single welfare objective in each case.

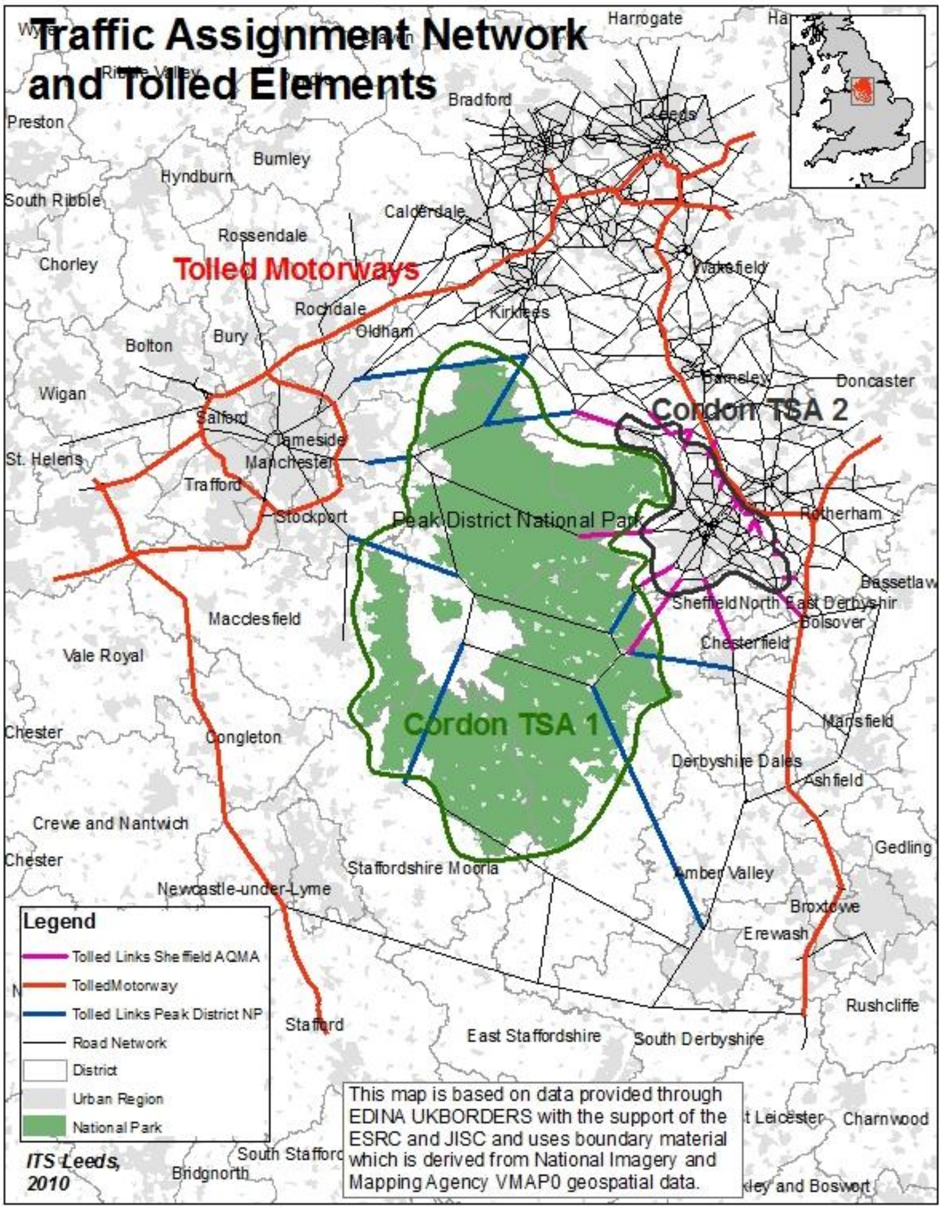

Figure 3: Coverage of the Traffic Assignment Model and Charged Elements

Local regulation Scenarios

Where there are two local regulators or more is an instance of an Equilibrium Problem with Equilibrium Constraints (EPEC) (Mordukhovich, 2005). Unlike the first two scenarios, here each local regulator sets the tolls independently and the highway users choose their routes obeying the Wardropian rule, but in addition, the local authorities and/or highways agency play a Nash game. In other words, each player is assumed to maximise its own individual objective given what their counterpart competitor is doing (in terms of toll setting) and the Nash equilibrium (Nash, 1950) of this game is reached when no player can benefit by unilaterally deviating from the final toll strategy. The study of this genre of EPEC problems involving networks is still in its infancy and solution methods are not widely available. Instead a simple search method was used to solve this problem. This iterative process entails fixing the toll level for the first player and performing a simple grid search for the toll level (between the bounds specified) that maximises the objective for the second player. Then with this toll fixed for player 2 the toll level for the first player is varied (by simple grid search) to maximise the objective for that player. This iterative process is repeated until convergence is achieved and it can be easily extended to the three player case.

5. RESULTS AND POLICY IMPLICATIONS

5.1. Comparing Across Alternative Scenarios

Based on the assumptions and modelling approach described above, the resulting optimal toll levels for each scenario along with welfare implications are presented in Table 4. The following paragraphs discuss the results at this high level for all scenarios. The next section then goes into more details on the environmental consequences for the global three player scenario and the local three player scenario.

Table 4 : Optimal Tolls, welfare changes and rankings for the various scenarios (sorted by Global Welfare level)

Regulation Scenario	**Peak**		**Sheffield**		**Highways Agency**		**Rank**		
Global G Or Local L (players)	Toll £ per crossing	Benefits (£)	Toll £ per crossing	Benefits (£)	pence per km	Benefit (£) (= Global Objective)	HA	S	P
G3(All)	1	2,011	2	10,638	6	18,143	**1**	**3**	6
G2(HA+S)	N/A	-714	2	11,755	6	17,407	**2**	**2**	11
L2(HA+S)	N/A	-783	2.5	12,061	6	16,898	**3**	**1**	12
G2(HA+P)	1.5	3,508	N/A	3,597	6	15,848	4	8	5
L3(All)	4	5,118	2.5	8,112	8	15,110	5	4	**3**
G1(HA)=L1(HA)	N/A	-367	N/A	4,923	6	14,337	6	7	10
L2(HA+P)	4	5,865	N/A	1,282	6	13,610	7	10	**1**
G1(S)=L1(S)	N/A	-240	2	5,723	N/A	1,577	8	5	8
G2(P+S)	0	-240	2	5,722	N/A	1,571	9	6	9
G1(P)	0.5	1,459	N/A	-569	N/A	235	10	11	7
L1(P)	4	5,394	N/A	-4,047	N/A	-2,767	11	12	**2**
L2(P+S)	4	4,318	5.5	1,433	N/A	-4,467	12	9	4

Single player results

Considering the single player scenarios (G1x and L1x) first we can see that the highways agency through motorway tolling of 6 pence/km would have a significant positive impact on global welfare an order of magnitude above the impacts of cordon charging around the Peak or Sheffield – being sixth in the overall rankings. Sheffield would actually benefit from this scenario through their share of the revenues and potentially reduced congestion and pollution. This is slightly surprising as stronger negative impacts from traffic diversion as for example analysed by Bonsall & Maher (2009) could have been expected.

For Sheffield the global regulation scenario is equivalent to the local regulation scenario when only Sheffield is charging. This is probably due to the assumption made regarding the welfare function where we assume that Sheffield also considers the consumer surplus of those ending their trips in Sheffield (as we assume Sheffield wants to provide a high level of service to those visiting Sheffield for work or leisure as well as for its own residents). The ability to export taxes to "through traffic" is also limited by the location of the M1 motorway which takes the majority of the through traffic around Sheffield which leads to environmental impacts on Sheffield's residents.

For the Peak district there is a marked difference between the global and local regulation results with much higher charges (£4) under local regulation than under global regulation (£0.50). This is due to the ability to charge the through traffic and so export taxes. In fact this local regulation scenario with only the Peak district charging users ranks second for the Peak district (marginally beaten by the local regulation involving HA+Peak). This makes the Peak district the most likely "first mover" when it comes to charging. As this leads to a negative overall welfare results a reaction from the other players can be expected.

Two player results

Firstly, it should be noted that for all two player results the global regulation scenario provides greater global benefits than does the local regulation scenario as is to be expected. Secondly, involving the highways agency will bring in greater benefits as was the case in the single player game.

The two player game involving Sheffield and the Peak District under local regulation (or Nash game) is the lowest ranking scenario from a global welfare perspective which suggests that this situation should not be allowed to develop. The reason for this is that traffic has to either divert a long distance or pay the tolls. In this scenario, the highest toll levels for the sensitive areas are encountered. However, once the Highways Agency decide to charge something then both Sheffield and Peak would prefer to have a two player game under local regulation with the highways agency as the opposing player – L2(HA+S) and L2(HA+P) are ranked number one by Sheffield and Peak respectively. From the Peak District perspective, any scenario that does not involve charging this cordon leads to a negative welfare impact. Under a two player global regulation scenario with the Peak and Sheffield, no charge is applied to the Peak District. This is partially due to the fact that HEATCO (2006) values the impacts on human mortality rather than on the destruction of flora and fauna as a result of pollution leading to lower monetized value for pollution in non-built up areas. Thus, any re-routing out of the Peak District by introducing a charge may increase the costs of pollution per km travelled as the traffic now travels through the Sheffield sensitive area which attracts the higher value on emissions.

Three player results

As expected the global regulation of three players delivers the greatest increase in global welfare. Moving to the local regulation of three players reduces the global welfare by around £3k per peak hour with increases in charges for all users. Notice that the charges for the Peak rise from £1 to £4 when local regulation is allowed, again showing the tax exporting strength of the Peak District local authority.

In terms of preferences from the national government (HA) perspective the results indicate that it would be preferable to have a two player set up involving the highways agency and global regulation with the Peak or global and local regulation with Sheffield over the three player local regulation scenario. From the perspective of Sheffield, any charge applied in the Peak District reduces the expected welfare for its residents.

As noted above the preferences of Sheffield and the Peak are first to have a two player game with local regulation involving the HA as the other player. Second/third preference of Sheffield is more in line with that of the global regulator or HA with global regulation of the two player set up involving the HA and Sheffield coming above the global regulation of the three player game. The second and third preference for the Peak is to have a local charge only L1(P) followed by the local regulation of all three players. The Peak District is the strongest player in terms of ability to export tax to through traffic and so any scheme should be well regulated.

In terms of what is likely to happen we can only suggest possible storylines as follows:-

1. Peak move first. Being the only player to charge actually ranks second for the Peak District which makes them a likely first mover. However, this would induce significant dis-benefits for Sheffield and so they are likely to begin charging. As the Nash game between Sheffield and Peak is the worst result possible in terms of global welfare the HA are likely to respond and we end up with the three player Nash game with local regulation.

2. HA move first. It makes sense from a global perspective to begin with motorway charges in the order of 6 pence per km. This would benefit Sheffield (see G1(HA)) but cause disbenefits to the Peak residents and so provoke a response. This would naturally move from G1(HA) to L2(HA+P) which would then bring in Sheffield in response to depleted benefits. The likely result without regulation is a Nash game with three players L3(All) which is only fifth in terms of global welfare. A similar story evolves if Sheffield moves first.

3. Global regulation. One possibility to avoid the three player local regulation scenario is for the government to implement a global regulator or to encourage a co-operative solution. Whether this is possible will perhaps depend on other aspects such as arguing the case of acceptability as this scenario has lower charges than others.

4. Banning one of the players. The results also suggest that it would be beneficial for the Government to effectively ban one of the local authorities from charging to enter their sensitive area rather than accept the three player Nash game. The results suggest that the Peak should be banned rather than Sheffield – as Sheffield are more in line with the global regulation than are the Peak District. This would have severe implications for the Peak District as both HA+S scenarios result in negative benefits for Peak.

The above storylines suggest the real choice is between global regulation and local regulation of the three player scenario – assuming someone takes the first step that is! Hence, we chose these two scenarios for a more detailed comparison of the environmental impacts on the different areas in the case study region.

5.2. Comparing Environmental Impacts Across Alternative Scenarios

Table 5 shows the annualised peak hour emissions and emission reductions for NMVOC, PM_{10}, NO_x and CO_2 differentiated for the networks in the Peak District and Sheffield cordon area as well as for the motorways and un-tolled rest of the network for the global and local three player scenarios. Although CO_2 has not been part of the welfare maximisation function it is reported here to reflect changes in global environmental impacts.

In both scenarios moderate reductions of emissions over the whole network can be achieved. These are larger in the local regulatory scenario than in the global, mainly due to higher reduction on the motorway network. The reason for this scenario performing better in environmental than in welfare terms is that due to the overall higher tolls in this scenarios, a larger proportion of trips will be suppressed leading to a reduction of consumer surplus. Both scenarios also perform positive in terms of reductions of CO_2 emissions. Although these reduction seem moderate at about 2% to 3% (see Figure 4) compared to BAU, they correspond to annual savings of 1.1 million Euros for G3 and 1.7 million Euros for L3, if a social cost value of 26 € / ton CO_2 is applied in accordance with HEATCO values.

Table 5 : Pollutant Emissions in BAU, G3 and L3 scenarios

	NMVOC [kg /a during peak]			PM_{10} [kg /a during peak]		
Total	BAU	G3	L3	BAU	G3	L3
Motorways	418,093	372,137	361,364	51,097	49,280	48,979
Peak	46,788	49,329	43,049	4,572	4,779	4,192
Sheffield	40,988	39,749	39,505	3,845	3,704	3,686
Untolled	390,130	410,933	418,256	39,254	40,844	41,361
Network	***895,999***	***872,148***	***862,173***	***98,768***	***98,606***	***98,219***
Change	G3-BAU	L3-BAU	L3-G3	G3-BAU	L3-BAU	L3-G3
Motorways	-45,956	-56,730	-10,774	-1,817	-2,118	-301
Peak	2,541	-3,739	-6,280	207	-380	-587
Sheffield	-1,239	-1,483	-244	-141	-158	-17
Untolled	20,803	28,126	7,323	1,590	2,107	518
Network	***-23,851***	***-33,826***	***-9,975***	***-161***	***-549***	***-388***

	NO_x [kg /a during peak]			CO_2 [1000 ton /a during peak]		
Total	BAU	G3	L3	BAU	G3	L3
Motorways	2,551,097	2,371,212	2,327,570	1,206	1,126	1,107
Peak	225,915	234,295	203,649	108	112	98
Sheffield	136,656	127,722	126,046	77	74	74
Untolled	1,528,070	1,606,293	1,625,002	807	845	855
Network	***4,441,738***	***4,339,522***	***4,282,266***	***2,199***	***2,157***	***2,134***
Change	**G3-BAU**	**L3-BAU**	**L3-G3**	**G3-BAU**	**L3-BAU**	**L3-G3**
Motorways	-179,885	-223,527	-43,643	-80.4	-99.4	-19.0
Peak	8,379	-22,266	-30,646	4.5	-9.6	-14.1
Sheffield	-8,934	-10,610	-1,676	-3.1	-3.7	-0.6
Untolled	78,223	96,932	18,709	37.8	48.0	10.2
Network	***-102,216***	***-159,472***	***-57,256***	***-41.2***	***-64.7***	***-23.5***

As can be expected, emissions on the un-tolled links have increased in both scenarios. This increase is bigger in the local than in the global regulation scenario because the higher toll levels in this scenario will lead to stronger rerouting effects.

The largest overall decrease of emissions is experienced on the motorway network due to its size and the traffic volumes involved. However, even though of smaller magnitude the cordon charges can make a substantial difference in the overall burden from pollutants from the perspective of the sensitive areas. This becomes obvious when looking at the relative changes as shown in Figure 4.

For the Sheffield AQMA, emissions of NO_x and fine particles are of primary concern. These can be reduced by 6.5% (G3) / 7.8% (L3) for NO_x and 3.7% (G3) / 4.1% (L3) for PM_{10}. The local regulation scenario achieves slightly better results for the AQMA due to higher tolls.

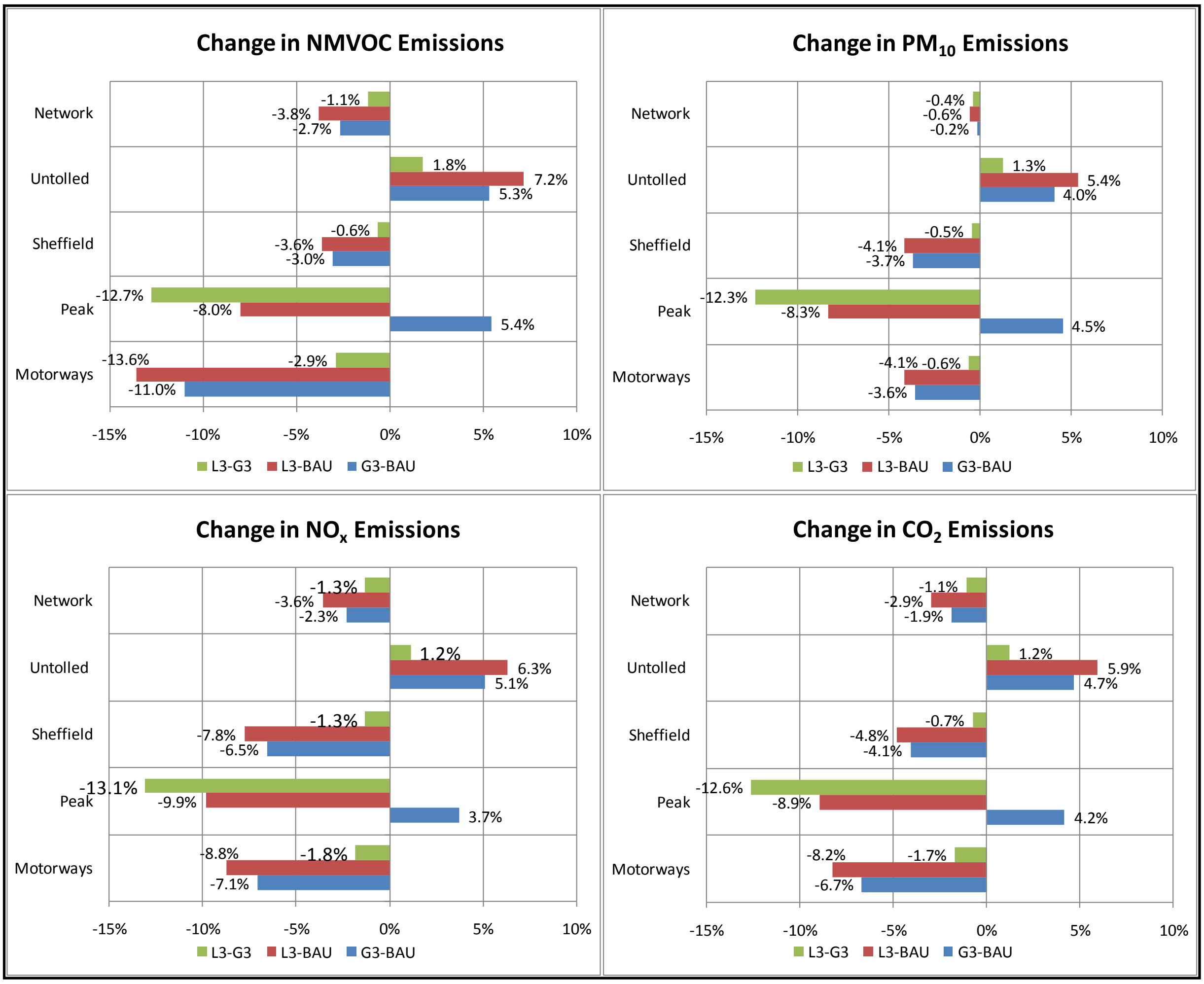

Figure 4: Relative Change in Emissions between Scenarios

In the Peak District, a local regulatory solution can decrease pollutant emissions up to 10% in comparison to the BAU scenario. However, the Peak is actually experiencing increases in pollution in the global regulation scenario. This is caused by traffic diverted from the tolled motorway through the Peak District, in particular in the Northern Part onto the A628.

This effect becomes more apparent when looking at the local changes of emissions on the links in the network as displayed in the maps in Figure 5. Some links where tolls apply experience considerable reductions of emissions of more than 20%. The biggest losers in terms of increases of emissions are in particular links at the fringes of the sensitive areas and those running parallel to the motorway network. For these links, complementary measures would need to be taken to avoid the additional burden from the diversion of traffic. They could either be included in a charging scheme, banned for certain types of vehicles or traffic calming measures to reduce their attractiveness for 'rat-running' could be taken. However, as our network does not contain all roads down to the lowest level, simulation runs with a more refined model would be necessary to estimate the exact extent of diversion effects.

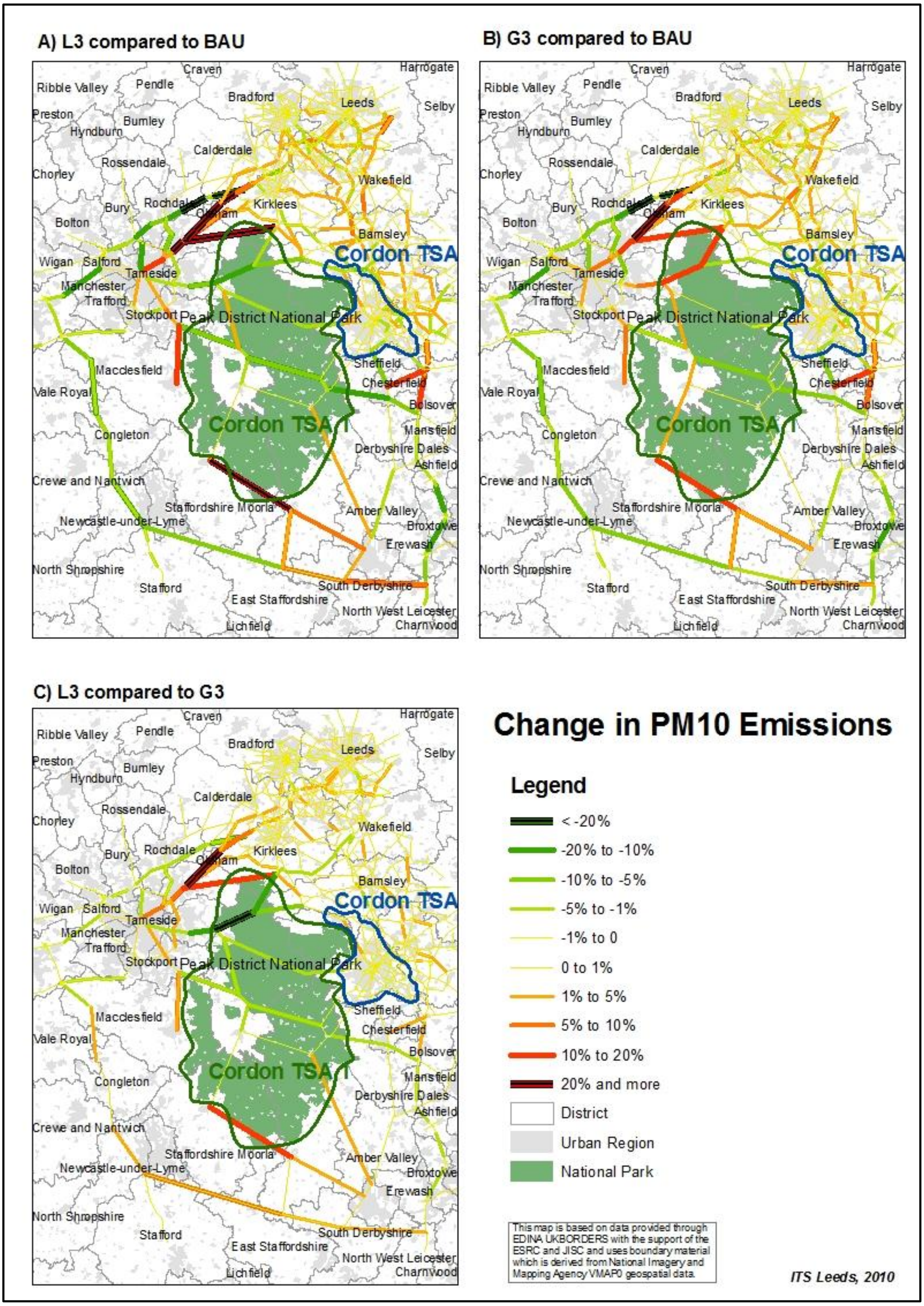

Figure 5: Localised Changes in PM 10 Emissions between Scenarios

6. CONCLUSIONS

In this paper we have considered the impacts of tolling strategies which could be employed by two neighbouring local authorities and the Highways Agency within the Trans-Pennine corridor working under different regulatory regimes. Our results suggest that a global co-ordinated regulation scenario delivers the overall greatest benefits in terms of welfare improvements. Generally, including motorway charging into the scenarios brings significant benefits. Due to its location in the middle of the corridor the Peak District plays an important role for the welfare results, in particular for residents of Sheffield. In a non co-operative local regulation scenario, the Peak District has the strongest incentive to exercise tax-exporting behaviour. This makes it the most likely first mover from a theoretical point of view. However, in reality the administrative and legislative powers of the Peak District National Park Authority make it unlikely to introduce charging as it relies on seven Highways Agencies and at least six Local Authorities in its region.

Yet, irrespective of which local authority moves first, the three player local regulation scenario is the most likely outcome despite lower welfare than a global regulation scenario including all players. The seemingly obvious policy implication is that structures for pricing should be regulated at a global level rather than adopting a myopic or local approach. In particular the local approach is the manifestation of a "beggar my neighbour" policy that is harmful to the overall welfare level. If in a two player scenario as it could be encountered between nations, regulation at the global level is not feasible then the next best option would be to put in place some regional regulator who accounts for both sensitive areas.

Whilst pollution can be reduced significantly within the charged areas, at the same time traffic is re-routed and it is this diversion of traffic that serves to transfer the environmental problem elsewhere so that the total reduction over the whole network is small. However, it must be noted that the results are biased towards areas with dense population. The pollutants emitted within the Peak District national park are valued, according to HEATCO (Bickel et al., 2006), at a lower level than in densely populated areas. This results in a bias towards highly populated areas and we suggest is one reason behind low toll level around the park in the global regulation scenarios. It is only when the Nash game is played out that the Peak District benefits significantly, hence from the view point of the Peak District national park local regulation is the preferred option.

In our scenarios we assumed that revenues are fully recycled to the residents of the charging authority. Part of these revenues could, however, be lost in order to pay for the implementation and running costs of the pricing schemes which would need to be included in a full assessment of the scenarios. For a full picture, also further environmental impacts, in particular noise and loss of tranquillity would need to be included in the considerations. Current appraisal and valuation methods cover noise impacts on humans in urban areas but generally ignore impacts on recreational activities. Hence, further research would be needed to include these into the consideration.

The problem of relocation of traffic underlines that accompanying measures to reduce undesired impacts of pricing are crucial. These could be the extension of capacities in public transport, traffic bans, low emission zones or traffic management measures. We also only included a charge at the morning peak hour. One can assume that in such a case, part of the trips that cannot be made by another mode would be rescheduled in order to avoid the charge. This would avoid the long-distance rerouting and shifting of pollution to other areas, but might reduce the overall pollution benefits in the affected TSAs.

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