Foresight

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Intelligent Charging:
Smart Market Protocols for Road Transport (SMPRT)

Intelligent Infrastructure Systems Project: Final Report

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The work reported here is original research into novel methods of road charging. It was commissioned by the Office of Science and Innovation as part of its Foresight Project on Intelligent Infrastructure Systems. This independent study does not reflect government policy, nor does it reflect any intention by the Gateshead Metropolitan Borough Council (MBC), who kindly allowed their data to be used, to pursue any road charging policy in the foreseeable future.

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Executive Summary:

Our aim in the *Smart Market Protocols For Road Transport (**SMPRT**)* Project was to investigate how agent-based econometric and transport models might be combined to investigate complex issues related to the use of infrastructure.

The focus for our work was an investigation of how charging for infrastructure use might address congestion on a heavily used stretch of road. Employing the smart market simulation we investigated how the system responded to peak demand exceeding capacity and to other disruptive factors.

The three elements of our research were:

- An existing transport model of the road system around Gateshead, from which we established direct social and environmental measures related to the state of congestion

- The transport model outputs were fed into an agent-based smart-markets model, to explore how a virtual smart-market could be created, where people bid for a limited number of journey slots. Journey slots is a concept common in air travel, but has not been applied to roads.

- Demographic and other urban factors, and their effect on transport demand. To a limited extent we also investigated the co-evolution of infrastructure and demography in the North East.

The core of the research was a computational agent-based economics (ACE) methodology that we used to develop an optimal price for road use to incorporate the negative externalities of the subject road transport system.

The ACE model provides an integrated framework that we believe has application for most road network systems. The major stages were:

1. We first determine the optimal level of congestion defined in terms of the volume of traffic. This constitutes the optimal/ maximum biddable supply of travel slots, in a given time slot (peak hour), for a cordoned area of the road network identified as a congestion hotspot. This is based on the detailed micro-simulation model of the Gateshead road system made available to the project by Gateshead MBC.

2. The cap is set at the point at which the total distance travelled in a given time slot by all the vehicles in the system starts to fall, equating to maximum social benefit (the maximum distance travelled by people traversing the system in a given time). This is also the point at which vehicular emissions and pollution start to increase exponentially, as the pollution module linked to the microscopic traffic simulator has highlighted (see also Grosso et al (2002) for a description).

3. The core of SMPRT is the 'smart market' simulator, which uses a sealed bid uniform Dutch auction protocol to determine the winning bid. The market-clearing bid and all those who submitted bids above that will pay that cap price to travel. Those who bid below it are priced out of the market.

4. The road user bid submission process is modelled using individual agents that reflect the actual income, demographic and socio-economic classes of the commuters traversing the cordon area and re-creates the highly disaggregated form and heterogeneous demand characteristics of the congested system, based on available data.

Using the methods described above we found that the 16,740 passenger car units (PCUs) of the reference demand model would cause congestion of the road system and we calculated that a cap volume of 11,718 PCUs was required to maximise the social benefit of the slot system, a reduction of some 30% compared to the reference case. When the Dutch Auction ran using that reduced number of slots it corresponded to a clearing price of £2.87 per PCU.

The demographic information that we built into the SMPRT model suggested a differential impact upon socio-economic groups, strongly correlated to the ability to pay. So while managers and professionals were willing to bid higher to travel, much higher percentages of administrative and service staff bid below the clearing price and did not travel. There are policy implications and choices for infrastructure owners and operators. Demand for travel across Central Gateshead was to a considerable extent generated by commuters living over a wide area north and south of the Tyne. The study allowed us to examine what alternatives they might adopt in the short term. Also, to identify where greater public transport provision might be needed for those priced out of the car travel by road user charging. Consideration of the longer term also showed that the growth of the suburban/commuter lifestyle based on road travel was coming to an end and that regional development, housing and employment should begin to make plans with that in view.

We believe that the agent based SMPRT approach for congestion and environmental externalities has multiple applications, ranging from road networks that have a high proportion of habitual car users (example, peak time week day city centre traffic) and those where road users vary from one day to the next. The determination of the optimal cap for the road network system is fundamentally the same. The essential for the cap and bid system to work in practice is for demand to significantly exceed the cap and create the market. If that condition is met then the method values the externalities for that system.

Contents

1 Introduction

This report provides a summary of the work done by the three different groups involved. Considerable mathematical detail has been omitted in order to make it suitable for general readership. However, the full details are available by contacting any of the three groups. (p.m.allen@cranfield.ac.uk scher@essex.ac.uk P.T.Blythe@newcastle.ac.uk)

1.1 Objectives of project

The Intelligent Infrastructure Systems (IIS) project has largely focused on the transport domain, and includes consideration of how the operators of future transport infrastructure may harness the opportunities offered by ‘enhanced information and communication network technology (ICT) and intelligence’ to manage the competing claims on the transport infrastructure. A significant challenge is the management of road-space demand, particularly as ownership of private cars and the use of Heavy Goods Vehicles for the distribution of goods is continuing to grow.

Despite the implementation of a range of innovative traffic management and demand mitigation strategies, and the growth of the use of ICT in transport (known generically as Intelligent Transport Systems or ITS), there is a growing consensus that some form of road pricing is needed for effective demand management.

The UK is at the forefront of research and the deployment of road user charging is now in place with successful urban congestion charging schemes in the cities of London and Durham. This has grown from a legacy of almost no experience of charging for road use in the UK, except for a small number of tolled estuarial and river crossings and some innovative flirtations with congestion charging trials, such as the Cambridge congestion charging scheme in the mid-1990s. The Government is also now actively considering the feasibility of introducing a National road user charging system to fully or partially replace fixed car tax and fuel duty.

It is reasonable to consider that charging for road use could be implemented in some innovative way not yet considered by the transport community, particularly over the 50-year time horizon of the IIS project. This is what motivated the attempted fusion of expertise on smart markets, road pricing, transport modelling and complex systems that is described here.

Technological advances, such as speed of computer processing, the real time access to information and interactive communication in a parallel and distributed fashion, have altered the scope and design of markets. Smart market solutions can now use electronic information and communication network technology (ICT) to implement market protocols. They can produce price configurations that integrate dispersed information on demand and supply conditions providing either a a forward or spot market in the limited supply.

The cap and trade solution was investigated for SMPRT, as it is increasingly used as means of controlling and pricing negative externalities from economic activity. The core of the Smart market in road slots is a capacity to obtain bids from potential road users that represent their maximum willingness to pay for a limited or ‘capped’ supply of travel slots, in a given time slot through a cordon area of the congested road network. The parameters that determined the cap were derived from the VISSIM traffic micro-simulator developed by the logistics company PTV, which was used to probe traffic efficiency of the road system and identify an optimal level of congestion.

In summary we consider below how SMPRT based solutions can be used to address the two main negative externalities associated with road transport: congestion and pollution. Our study was focused on people's movements rather than freight and our objectives were:

(i) To outline the scope and design challenges of SMPRT;
(ii) To demonstrate the viability of the agent based SMPRT model to create a virtual Smart Market;
(iii) To import the outputs from a transport micro-simulator (VISSIM) of the Gateshead road system into SMPRT, determining a possible optimal level of early morning congestion;
(iv) To calibrate SMPRT against the size and patterns of flow of people, goods and services around Gateshead in that part of the north-east of England

1.2 Control and pricing of negative externalities to road use

The traditional view has been that economic development with its ever increasing demand for road transport and the consumption of non-renewable energy sources in this mode of transport, with their respective consequences of congestion and pollution, are but necessary evils that must be collectively borne. A program of economic development that fully prices and internalizes the externality costs that the private cost- benefit calculus cannot incorporate is increasingly being seen as essential to prevent the overuse and degradation of resources. The latter is powerfully brought out in Garett Hardin's paper on the Tragedy of the Commons, Hardin (1968), where a decline in social welfare and total output occurs as there is no institution to signal and correct for the negative societal impact of private behaviour.

Congestion, pollution and other environmental negative externalities from road transport arise when the volume of traffic exceeds the free flow capacity on the road network and when any additional vehicle entering the systems causes increased delays to other vehicles, with a knock on effect of higher environmental costs to society as a whole.

Optimal road pricing can be viewed as the application of a corrective or Pigouvian tax (Pigou,1920, Vickrey,1955, 1969, Walters, 1961) that seeks to internalise the costs of the negative externality via a marginal social cost principle. However, marginal social cost pricing of road use externalities has been considered by many to be impractical to determine and implement, and when it manifests as a spot price applying in a person-place-time specific form it has been criticized on the grounds that road users need to know what to pay before the journey, Nash and Sansom (2001). The ADEPT (Automatic Debiting and Electronic Payment for Transport) project, which conducted a field study in Cambridge over a period of three years from October 1992, is such an example of spot pricing (Blythe, 1993, and Blythe and Hills, 1994).

Further, political constraints are cited for why the use of road pricing has failed to materialize except in a limited number of cities despite the growth of traffic congestion. Nevertheless, the continued and predicted growth in the ownership of cars and the use of HGVs for the distribution of goods, along with environmental concerns of expanding road capacity has led to innovative traffic management and demand mitigation strategies being actively sought by governments of many countries and especially in the UK.

1.3 London congestion charging

The London Congestion Charging Scheme which was introduced on 17 February 2003 involved a single charge of £5 on vehicles to drive or park in the central London zone from 7am –6.30 pm. It is a major example of a successful social experiment, in addition to the examples of Singapore and Durham, where the public has complied with a congestion charge. The London congestion charge was recently increased to £8.

It is far from clear that the determination of the London congestion charge price, the increase in it and the analysis of the economic implications of the charge along a number of relevant dimensions, has been based on a set of modelling tools that can be tested out or reproduced in a coherent and integrated way. Shaffer and Santos (2003) claim the estimated fall in the volume of vehicles in the Central London zone after the introduction of the charge was around 15% and resulted in a 21 % increase in speed, which implies that the congestion charge of about £5 was about right according to a 'generalized' marginal congestion cost calculation done *ex post*. Apart from noting that there have been improvements in congestion in London, there is no means of assessing to what extent congestion abatement is to be pursued. While some estimates of price elasticity of aggregate demand are made, there is little scope to gauge the price elasticities of demand for the different socio-economic and income groups of road users and hence of the impact of the charge on the less well off. Finally there has been no discussion of the allocation rules governing the revenues raised, with the concerns that the authority can exploit its monopoly status by raising the congestion charge by a large margin in the face of inelastic demand.

1.4 Rationale behind cap and trade in SMPRT

The cap and trade approach by assigning property rights to the 'bads' of economic activity is increasingly being used as a means of controlling negative externalities. A landmark is the 1990 Clean Air Act Amendments imposed by the US Environmental Protection Agency, aimed at reducing sulphur dioxide ($S0_2$) emissions from coal and oil fired electricity generating plants (see Schmalensee *et. al.* , 1998, Jaskow *et. al.* 1998).

Unlike traditional command and control methods where a plethora of prescriptive engineering and performance standards on the abatement technology is imposed at the level of the individual polluter, the cap and trade approach shifts focus to the total acceptable amount of the negative factor from the economic activity at a collective level. The choice of abatement technology is then decentralized with the traded prices for permits reflecting the lowest industry wide marginal cost of abatement.

Despite early doubts about the practicability of the EPA proposed cap and trade market for SO_2, the market arrangements have been judged a success. In recent years there has been a move toward market-oriented solutions based on an appropriate auction platform in many industries to overcome the drawbacks of committee or command and control allocation of scarce resources or capacity.

In the case of the pollution control scheme on utilities there is an auction system for fully tradable permits. For the negative externalities of road transport pricing, we only envisage a submission of bids to travel given a fixed supply of slots, with the market-clearing price determined as in an electronic, uniform price, sealed bid Dutch auction. This is a possible format for a smart market for passenger road transport (SMPRT) congestion and its environmental externalities. The bids are assumed to arrive up to a final deadline at the electronic market place to determine a forward price for the time and location specific SMPRT permits. Given the fixed supply of travel slots, the market clearing price in the uniform Dutch auction is the price at which those who bid at and above this level is equal to the chosen cap on slots available.

The smart market concept with the use of a bid submission process that signals willingness to pay for immediacy or priority of service in the context of Internet congestion was first suggested by Mackie-Mason and Varian (1995). The crucial difference between a fully tradable system of permits for negative externalities abatement and one in which only bids can be made is that all participants are given an incentive to seek out cheaper transport modalities but also to use revenues received from sales to make necessary abatement investments. In the bid only system, the revenues are collected solely by the owning or operating authority and they alone have access to funds to make the technological improvements for abatement of the externality.

1.5 **Artificial simulation and implementation: Agent based approaches to policy design**

There is a growing recognition of the value of cap and trade of permits for all manner of negative externalities or for the allocation of scarce resources such as airline takeoff and landing slots and broadcasting licences. However, the design of the market platforms and auctions is critical to the efficiency and success of the process.

Economic agent modelling is increasingly being used for 'wind tunnel' testing of market protocols and their variants in *advance of* implementation. see Markose and Sunder (2006), Ledyard and Moore (2004), Smith (1967). It is useful to know if proposed protocols would achieve intended outcomes or bring about unintended consequences that are socially undesirable. The latter can occur directly through poor design of protocols or indirectly through strategic behaviour permitted or even encouraged (inadvertently) by the protocols. As well as the studies mentioned above for the design of pollution markets, a number of such experimental and agent based models have been created, such as in the case of reforming the UK electricity markets, see Bower and Bunn (2001), Bunn and Oliveira (2001), Koesrindartoto and Testfasion (2004).

Traditional modelling for policy design uses econometric or analytical methods. Econometric methods run into what is referred to as the Lucas Critique that arises from the lack of structural invariance as agents game the system. In other words, the estimated parameters of behavioural equations are no longer valid after the change of policy rules. Further, analytical methods use simplifying assumptions for tractability and cannot give 'ball park' figures for the actual responsiveness of the system.

2 Bid Based Smart Market For Congestion Pricing

The SMPRT model allows the calculation of the behaviour of commuters taking into account their individual views concerning the value of their time, of the journey in question and considering the vehicle that they use. Commuters who traverse the cordon area and are categorised by socio-economic groups ('types') with corresponding income distributions. As the bulk of peak week day demand for road use is related to people's jobs, then it is reasonable to suppose that their budget for commuting and their value of time is related to their income.

Thus, different user types are distinguished by the size of their budgets for commuting and their time valuation. This means that we can value the journey time of different commuters and consider this in conjunction with the delays caused by different levels of congestion. The detailed vehicle flow model (see next section) allows us to know the relationship between traffic congestion, travel times, pollution levels and traffic volume. From this we can choose a cap which would reduce traffic volume, and the economic model of this section allows us to know the price that will dissuade a sufficient number of drivers from commuting by car.

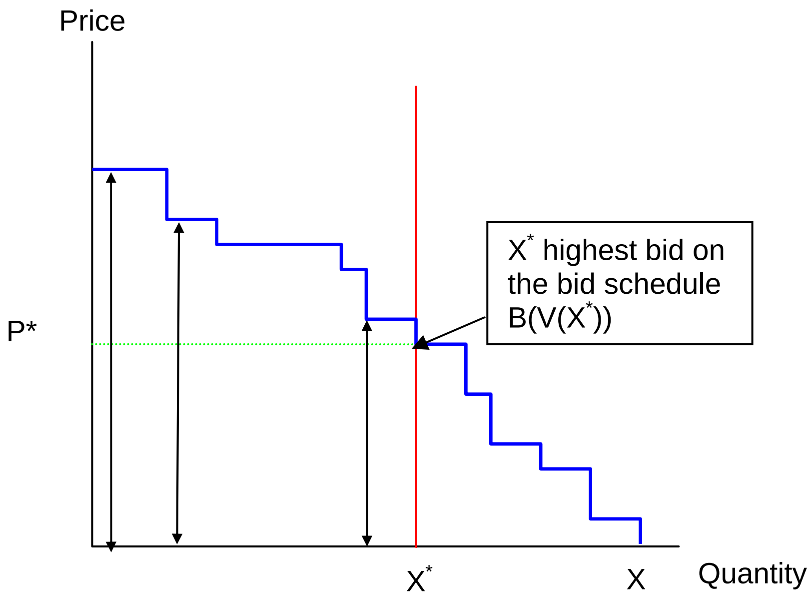

Figure 1: Price Determination in uniform Dutch auction with a fixed supply of X^* travel slots

Figure (1) shows how the demand from road users will fall with a rising price and also the bid required to reduce traffic flows to the cap traffic volume that has been chosen.

2.1 Overview of results

To control and price negative externalities in passenger road transport, we developed an innovative computational agent based economics (ACE) methodology to simulate a market oriented cap and trade system. The ACE model provides an integrated framework (see Figure 2) with the following components that can be used for most road network systems.

The computational assessment of a digitized road network model of the real world congestion hotspot determines the traffic volume cap at the point where traffic efficiency deteriorates and environmental externalities take off exponentially.

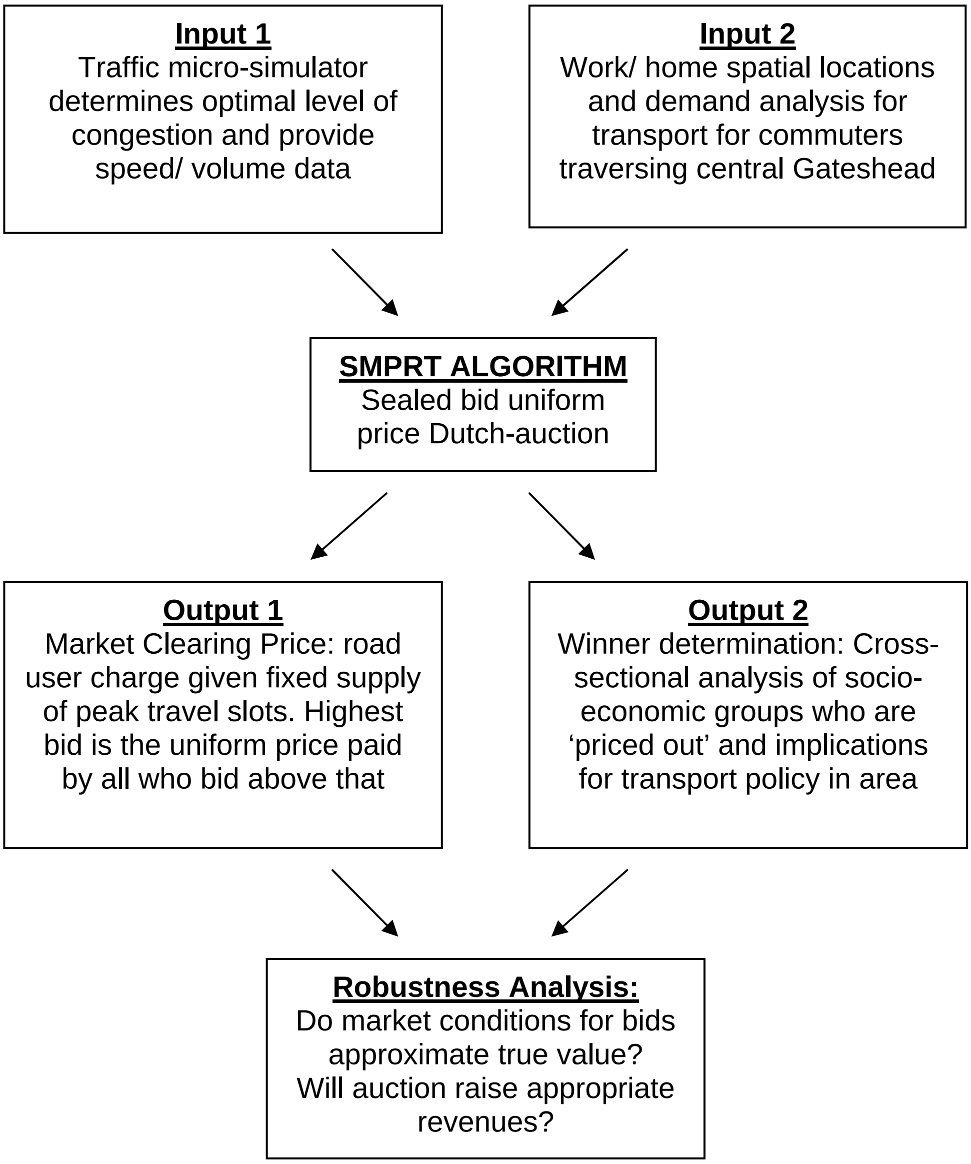

Figure 2: Integrated framework of a cap and trade based smart market to price negative externalities from road use

Road users submit bids to travel through the cordon area. Based on these bids and the fixed supply of travel slots, the uniform price sealed bid Dutch auction conducted electronically determines the market clearing price.

A fixed cap supply of travel slots is determined for a given peak hour time slot by a sealed bid uniform price Dutch auction conducted electronically. Road users submit bids to travel through this cordon area. The demand data on car users who traverse the cordon area is used to model and calibrate the heterogeneous bid submission behaviour over the different socio-economic classes, to understand the consequences of road user charging in terms of price elasticities of demand.

Finally, we provide an appropriate test to see if revenues from the model where agents are assumed to bid truthfully can be achieved given agents behave strategically in the real world.

3 Traffic Micro Simulation and Optimal Congestion

3.1 Central Gateshead congestion hotspot and Gateshead MBC VISSIM model

We chose to model Gateshead MBC as a network with the necessary data for both the agent-based smart market and complex people-goods lifestyle modelling. We considered that the location offered a wide range of different land uses and boundary conditions that would be important to the modelling task.

Gateshead has a physical boundary with Newcastle (the River Tyne), a congested section of the A1 (Western by-pass), significant out of town sites (Team Valley industrial/retail park) and the Metro Centre (largest out of town shopping and retail centre in Europe). It has a good rural, urban and peri-urban mix with areas of affluence and significant areas of social deprivation.

We were allowed to use Gateshead MBC's VISSIM ('GCV') model, covering a cordon area in Central Gateshead prone to serious congestion during peak hours. This model was provided to us for research purposes only. We used the model to generate the data on traffic related variables required for the SMPRT simulator. The GCV model is based on a detailed network topology and data inputs where (signalised/unsignalised) junctions and speed limits are explicitly coded. This is essential to understand how congestion and other road use externalities build up. The GCV model has been calibrated/ validated for traffic conditions of the morning peak period by Faber Maunsell. More details on the car following model behind VISSIM and its calibration/validation can be found in Wiedemann (1974) and Fellendorf and Vortisch (2001). We then adapted it to the requirements of the project by increasing the size of the entry links in order to accommodate all vehicles wanting to enter the network.

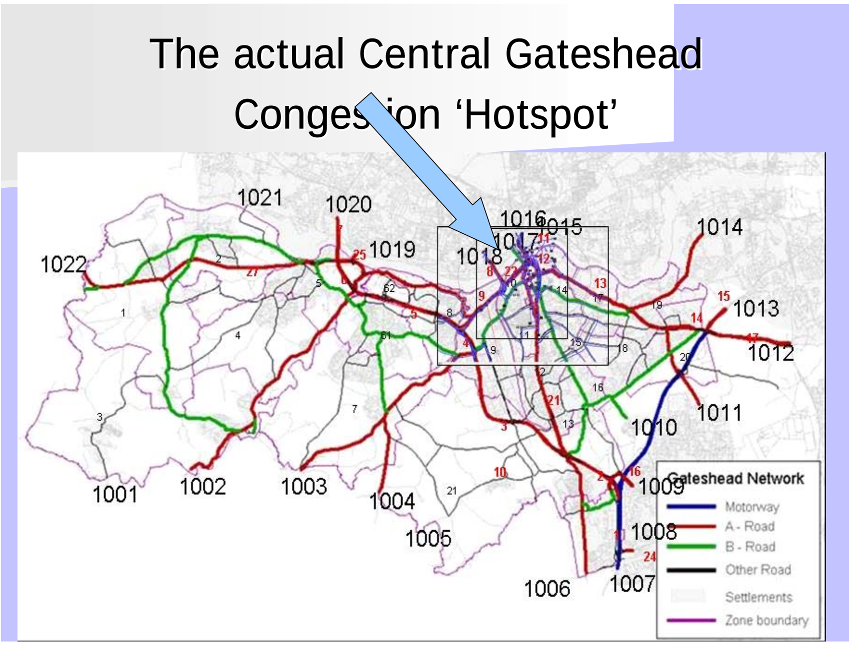

Figure 3: Central Gateshead congestion hotspot and surrounding road system

The location of the GCV model for Central Gateshead within the greater Gateshead area is given in Figure 3. Figure 4 shows the road network and the zones used in the determination of the origin-destination matrices of trips traversing the cordon area. The GCV model contains 2,942 links and approximately 83,876 miles of traffic lanes. The model is broken down into 57 *zones*, yielding therefore a total of 3,192 Origin and Destination (OD) pair relationships (= 56 x 57, if we exclude movements from one zone to itself). However, only 816 OD flows are actually different from 0, meaning that not all origin-destination relationships are serviced by traffic.

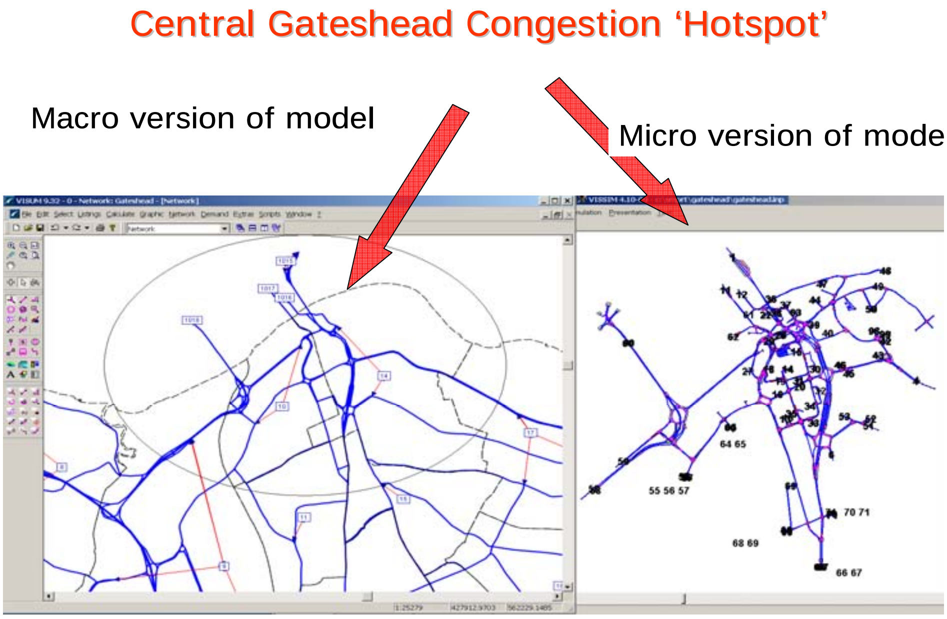

Figure 4: Representations of macro and micro versions of Gateshead model

The traffic demand in the GCV model for the peak hour and traffic composition with conversion to PCUs is given in Table 1 in Appendix 1.

The results of a benchmarking process show that in the peak hour period of 8-9am some 16700 PCUs enter the congestion hotspot in Gateshead and traffic slows to about 4 km/h. The average trip length in the cordon area is 1.8 km.

3.2 Determining the cap of the road network system

Commonly the free flow at legal speeds is often used as a benchmark to measure the state of congestion, but it is well known that it is not the optimal level of congestion. To date there has not been a consensus on how to gauge the optimal level of congestion in the road network system. For the cap and trade approach to control negative externalities, the cap of travel slots should entitle commuters to travel at a defined minimum average kilometres per hour at a given time slot.

We can determine the cap by identifying an optimal level of congestion in the relevant cordon area. The VISSIM traffic simulator derives the production function of traffic, which is based on the virtual or digitized physical environment of the cordon area of road network system, including all relevant features such as traffic lights, topography and extant speed rules. The total distance travelled by cars entering the cordon is taken to be the main positive ‘output’ of the system and this is recorded against incremental growth in PCUs.

The cap for the road network system is identified as the point at which the total output of the system measured in total distance travelled, which initially increases as

PCU demand increases, starts to fall with further increased demand. We scaled demand given by the extant GCV model OD matrix for the peak time (8am-9am) road users in the cordon area relative to the benchmark (16740 PCU). Traffic demand in the time slot was scaled up and down in portions of background (or unrestricted) demand, and the traffic model used to derive speed, volume and emissions outputs for the cordon area. This method of scaling or 'factoring' probes the production function as increasing vehicle demand is combined with a fixed supply.

Our analysis shows that free flow of traffic is not optimal and a situation of free flow for all vehicles for all times and all roads corresponds to a costly over provision of road space. The decline in total output in terms of total distance travelled happens to be *after* the precipitous decline of the average speed (see Figure 5) and well after speeds associated with free flow. Thus, it is it is only at about 0.7 of background demand, corresponding to a volume of 11,718 PCU's, that the total output of the traffic system given in terms of total distance travelled by all vehicles starts to decline. At this point social benefits from using the cordon area fall as no individual can benefit by his/her travel without making everybody else worse off.

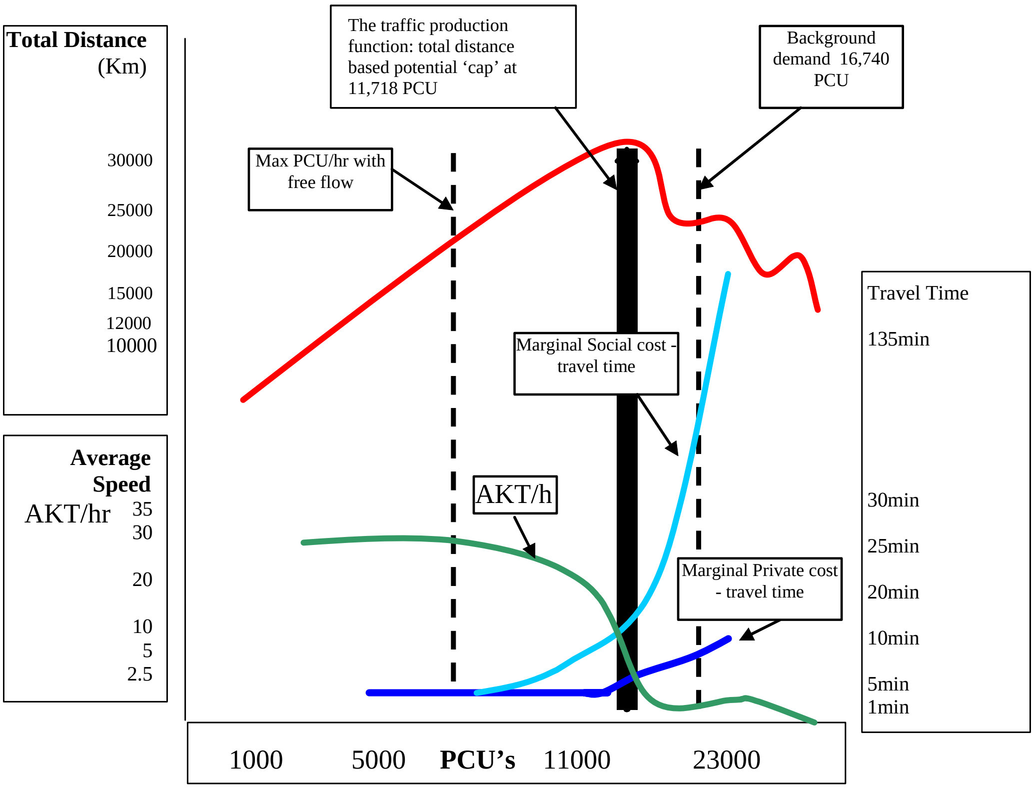

Figure 5: The production function for traffic (total distance traveled) based on GCV model. Identifies potential 'cap' and illustrates the 'Tragedy of the commons' problem.

Other negative externalities of road use, such as vehicular emissions altered from a linear to an exponential rate of growth at this point. We concluded therefore that the road system of the GCV cordon area for Central Gateshead should be capped at 11,718 PCUs, equivalent to a 30% reduction in background demand.

4 Factors determining trip demand generation

From the work of Allen (1997), it is understood that demand for road transport depends on a complex and coevolving set of factors. These simultaneously involve and determine, at different time scales, patterns of travel, residence and employment and the state of transport modes and ICT in a region. If we ask why people travel at all, we find that it is because of the spatial distribution of diverse activities and opportunities:

- Dispersed distribution of affordable/desirable housing
- Concentrated distributions of employment
- Concentrated distributions of retail opportunities
- Dispersed distributions of leisure and cultural facilities

The demand for transport is generated by these interacting spatial distributions and the transport congestions and patterns of access then themselves affect the locations of the different spatial distributions, which in turn feedback on the demand for transport. For example, the current spatially dependent rises in house prices is shaping longer commuting patterns for large numbers of people, possibly even threatening the successful functioning of cities, as lower paid workers find it increasingly difficult to find homes within reasonable distances. Clearly, it is important to understand how the impact of pricing for efficient road use on the different socio-economic groups will contribute to such trends and, for example, whether this will enhance further ICT developments in favour of tele-working.

4.1 Patterns of demand for road use affecting central Gateshead using spatial model of work-home loci

The spatial analysis of socio-economic and income distribution characteristics of commuters who traverse the cordon area of Gateshead was done because:

(i) The SMPRT is directly based on the demand for road user travel through the cordon area during morning peak hour with their willingness to pay related to their *pro rata* daily and hourly income.

(ii) Short term and longer term trip demand factors relating to regional growth rate for incomes, car ownership etc to see to what extent excess demand for road use is likely to increase

(iii) The consequences of growing and ‘untreated’ city centre road congestion compared with those that follow from efficient road use with pricing as pointed out above may help maintain the economic viability of urban centres by appropriate public transport provision and other measures.

We needed to answer the questions:

- Who are the commuters that cross Central Gateshead at peak hour?
- Where do they come from and what alternative routes exist?
- What is the income distribution of these commuters?

Our study told us that many people live south of the Tyne, but work in Newcastle and provide a major part of the congestion that occurs in Central Gateshead (Figure 6). This demonstrates that the origin of the problem in Gateshead lies in the spatial distribution of residences relative to the spatial distribution of employment. This in turn is linked to choices of lifestyle, quality of environment, and the relative ease of commuting. If we ask how these spatial distributions of residences and employment are set to evolve in the future. the Multi-Modal study of Tyne and Wear suggests traffic flows and congestion in the region is set to grow. Factors cited in (ii) above are also found to be on the increase.

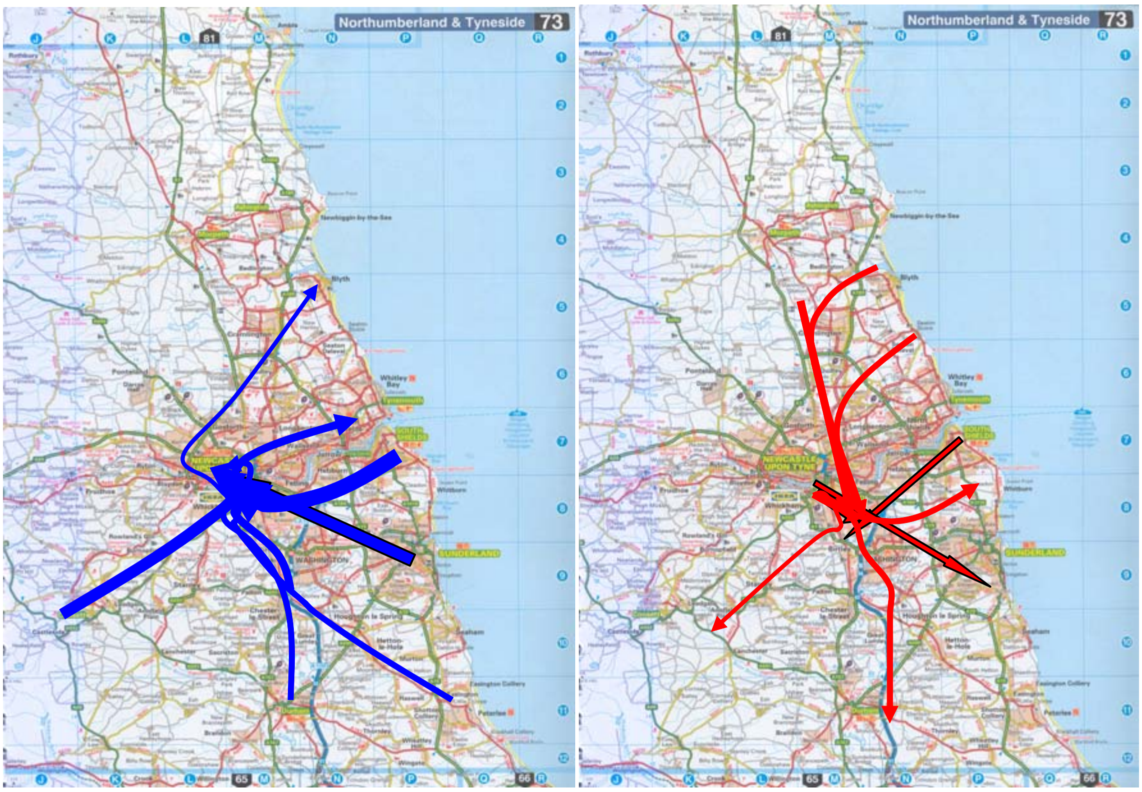

Figure 6: Maps illustrating the spatial distribution of commuters traversing the Gateshead road system from North and from South and West of the region

4.2 Socio-economic characteristics and income distribution of commuters

By using the figures for the differences between the commuters entering and leaving each local authority, we were able to correlate the peak time road users that traverse the cordon area given by the OD matrix with their socio-economic classes, and the result is shown in Table 4.

Table 4: Distribution (%) of different occupations within commuter group

Managers	16%
Professionals	11%
Semi-routine	31%
Administrative	14%
Personal Service	3%
Sales	14%
Routine	11%

Using regional statistics it was then possible to obtain the data for the income distributions of these different socio-economic groups and this provided the information concerning the income distribution of commuters crossing Central Gateshead at peak hour.

Group	Jobs 000's	Percentiles									
		10	20	30	40	50	60	70	80	90	100
Managers	87	**12,093**	**17,033**	**19,890**	**23,492**	**26,711**	**29,931**	**34,092**	**40,000**	**47,719**	**53,021**
Profession	101	9,223	**13,759**	**17,251**	**19,567**	**21,930**	**24,294**	**26,686**	**28,477**	**33,978**	**37,753**
Semi-routine	70	**10,142**	**12,310**	**14,210**	**16,152**	**17,922**	**19,692**	**21,664**	**25,021**	**30,704**	**34,115**
Admin.	121	6,216	8,570	**10,833**	**12,268**	**13,461**	**14,655**	**16,114**	**18,125**	**23,557**	**26,174**
Personal Service	69	4,194	6,117	7,618	8,870	10,263	**11,657**	**13,048**	**14,345**	**17,256**	**19,173**
Sales	71	3,754	4,980	5,860	7,003	8,595	10,187	**11,989**	**13,597**	**16,629**	**18,476**
Routine	100	2,022	3,246	4,831	6,860	8,999	**11,138**	**12,980**	**15,505**	**19,381**	**21,534**

Table 5: Income range of each socio-economic group in the North of England

We found that 78% of commuters through Gateshead are car drivers, and that the distribution of drivers is skewed towards the high earners. An income threshold of £10,500 for car ownership was assumed and this gives us the figure of 78% car driving commuters. Assuming also that the total population of car users is 16,740 the income distribution can be estimated as in Figure 7**.**

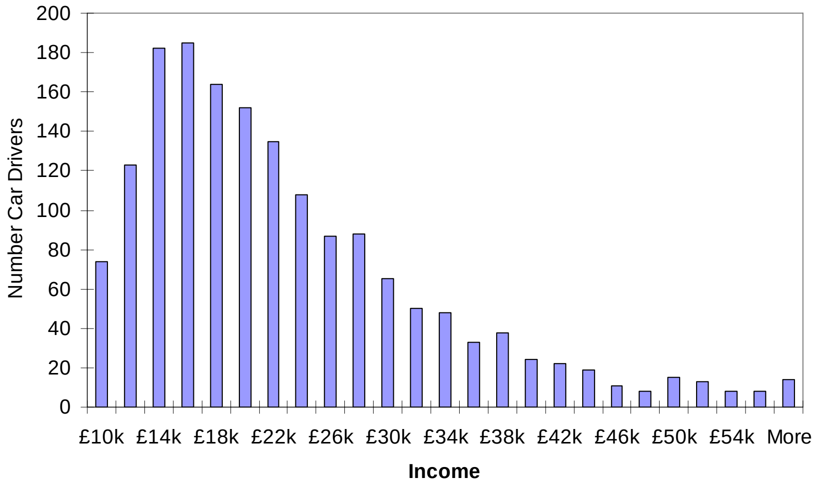

Figure 7: Income distribution of car drivers. NB mean annual income is £21,990

Using the income data for the 16,740 road users and standardized Vehicle Operating Costs (VOC) of 47.5 pence for the cordon average trip length of 1.8 km, the pattern of bids was generated. Information coming from the GCV model was used to relate average speeds to traffic volume.

The bid schedules are plotted in Figure 8 with a colour code for each group. With Average speed on the vertical axis and £ value of bids on the horizontal axis, the representative agent from the higher income group has a bid schedule further to the left (viz. higher £ value) than those in lower income groups. Of course, in traffic conditions of close to free flow speeds, the size of bids are primarily determined by the size of commuter's daily travel budget as the time cost of congestion is small.

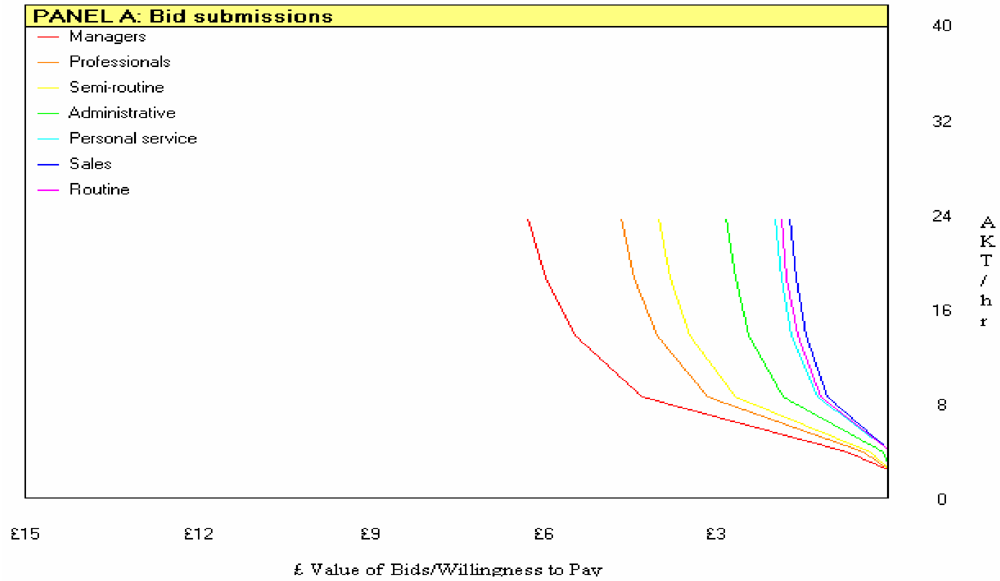

Figure 8: Bid schedule of representative agent from each socio-economic class

For the higher income group (Managers) with greater opportunity cost of time, the willingness to pay at higher speeds is relatively greater than at lower speeds. For example, the range of bids for the managerial group goes from close to £6 to as little as 35 pence. In contrast, those whose value of time is low (lower income groups) the bids remain more constant (viz. vertical in Figure 8) starting at relatively low values of about £1.56 for those in Personal Service, for example. This because their VOC with *pro rata* hourly wage being relatively small, they are less responsive to increasing time costs of congestion.

If we consider all 16,740 individual bids then the pattern generated is as in Figure (9)

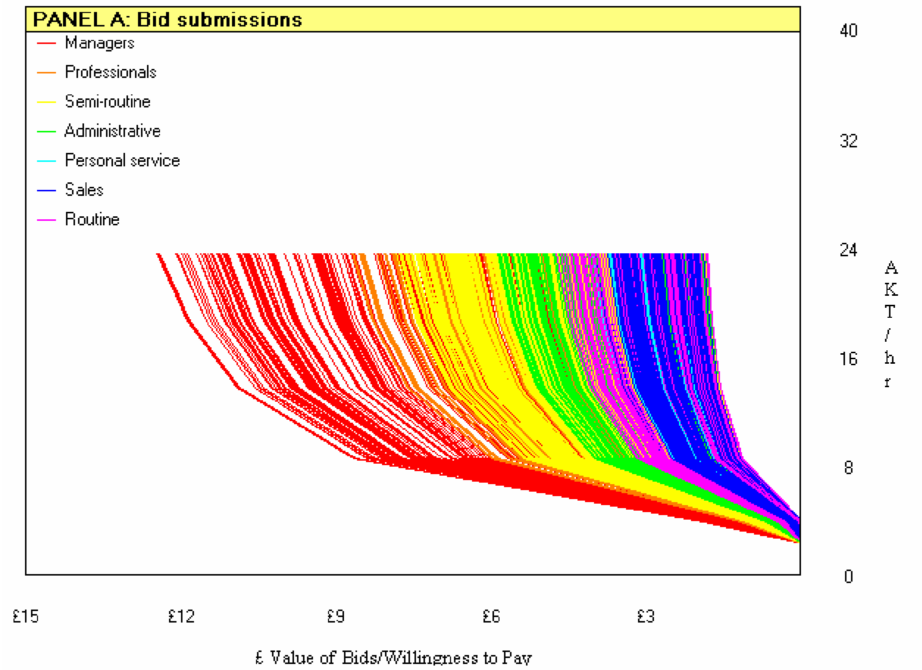

Figure (9). Pattern of bids of 16,740 individuals, by socio-economic group.

4.3 **SMPRT simulation outputs**

The market model of the Dutch auction process allows us to calculate how many people of each type will be dissuaded from commuting across Central Gateshead for a given cap price. The groups with more auction losers are the ones from lower income groups, while higher income groups such as managers and professionals have higher percentage of winning agents. The columns in Figure 10 below indicate background demand and actual demand at different cap volumes.

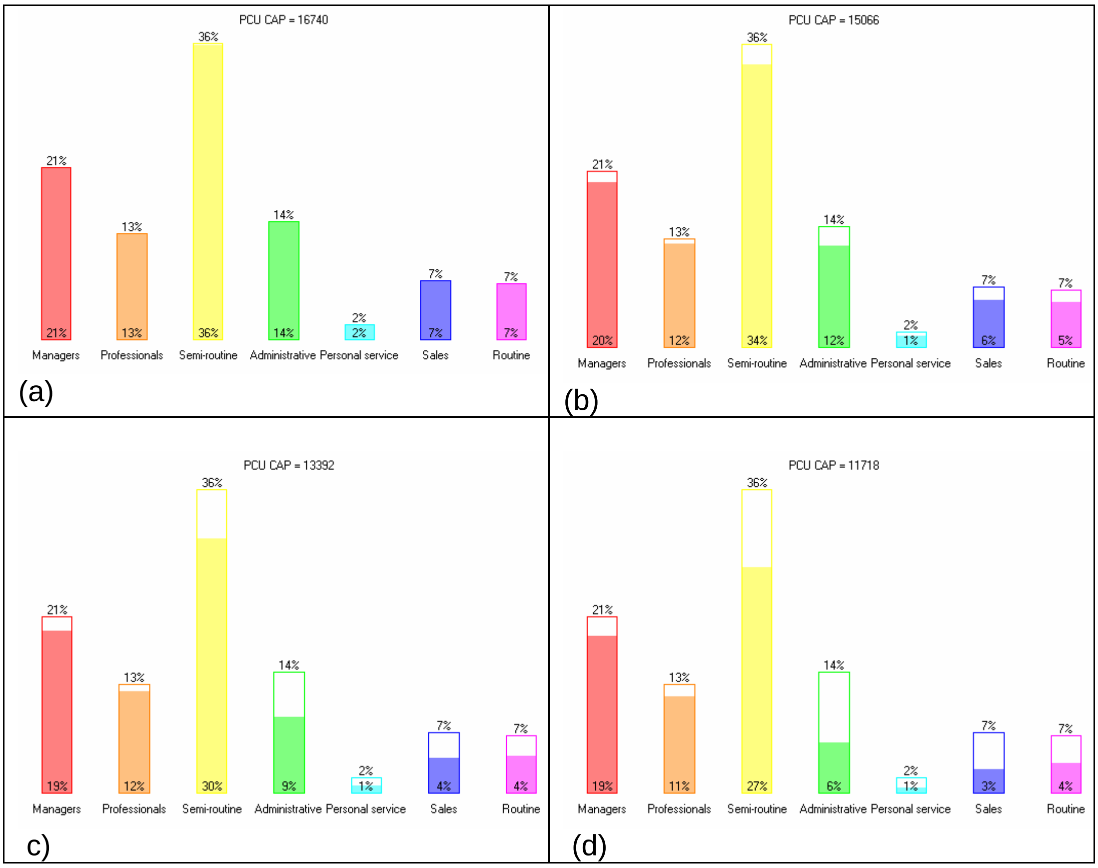

Figure 10: Socio-economic group restrictions for different CAP values.

The method we have developed provides a wide range of information about the differential socio-economic impacts of a possible charging regime, based on the ability to programme underlying characteristics for the groups into the model. This is a useful tool for policy makers seeking to understand the impacts of a policy decision, such as the setting of a cap.

5 Concluding Remarks and Future Work

Through the SMPRT we have successfully delivered an integrated agent based methodology based on the cap and trade approach for the pricing of negative externalities. This has application to the determination of peak time congestion charging in a cordon area of a road network system. The principles that we have demonstrated and the steps in its implementation can be followed in any road transport congestion pricing problem, where congestion hotspots have been identified.

The methodology for determining the cap in a cordon area of the road network, though computationally intensive, and based on a micro simulative transport model of fine granularity, is within the scope of state of the art transport micro simulators.

The cap is the point at which the so called total output function of road travel, which is total distance travelled in the cordon area for the fixed time slot, falls with incremental increases in volumes of traffic. This is a point at which the total social welfare gains from travel begin to diminish rapidly.

The electronic Dutch Auction heterogeneous bid submission process based on the actual distribution of income and socio-economic characteristics of road users who traverse the cordon area has obvious advantages over extant generalized cost function methods for estimating congestion charging. Details on how the bid functions were calibrated can be found in Markose et. al. (2007). The SMPRT simulator is capable of probing the system for demand elasticities, especially for the different socio-economic classes. Further, our approach clearly indicates that an arbitrary increase in road user charging beyond the 'cap' price cannot be justified in terms of welfare gains to society.

The bid-only format of the SMPRT model has two drawbacks when compared to the double-sided market of a fully tradeable system of road user permits. First, there are no clear economic incentives to deploy the money collected by the owner or operator for abatement technology, with the risk of bureaucratic and political interference. Second, our method cannot distinguish between those who can and cannot pay the charges, as is the case with existing congestion charging, and risks pricing out those who will not or cannot pay the charge.

In a double-sided auction with fully tradable permits, those who sell the permits receive the incomes and hence, avoidance of road use is not only less regressive but also provides direct economic incentives to road users and to others indirectly to economize on road use and use the money to provide other transport modalities. The design of a system of fully tradeable road user permits, however, is more complex in term of its property rights allocations and the full study of its socio-economic consequences are beyond the scope of this study.

5.1 Acknowledgments

The Consortium wishes to express their gratitude to the Gateshead MBC for their continuous support to research and development activities and the provision of data and models which are at the core of the work described.

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Appendix 1

Table 1: Traffic demand in original GCV model by time interval and traffic composition

Time interval		Traffic composition	Traffic demand	
[from]	[to]	[Name]	[vehicle trips]	[PCU]
07:30	08:00	Dynamic Light	6,500	6,660
08:00	08:15	Dynamic Light	3,225	3,304
08:15	08:30	Dynamic Light	3,300	3,381
08:30	08:45	Dynamic Light	2,975	3,048
08:45	09:00	Dynamic Light	3,075	3,151
08:00	***09:00***	***Dynamic Light (SUM)***	***12,575***	***12,884***
07:30	08:00	Fixed Light	1,550	1,594
08:00	08:15	Fixed Light	769	790
08:15	08:30	Fixed Light	788	810
08:30	08:45	Fixed Light	713	733
08:45	09:00	Fixed Light	731	752
08:00	***09:00***	***Fixed Light (SUM)***	***3000***	***3084***
07:30	08:00	Dynamic Heavy	165	360
08:00	08:15	Dynamic Heavy	85	185
08:15	08:30	Dynamic Heavy	85	185
08:30	08:45	Dynamic Heavy	75	163
08:45	09:00	Dynamic Heavy	80	174
08:00	***09:00***	***Dynamic Heavy (SUM)***	***325***	***707***
08:00	***09:00***	***Buses (SUM)***	***300***	***600***
08:00	***09:00***	***Total (SUM)***	***16,200***	***17,275***

Table 2 gives the vehicle conversion factors to PCU units that were used

Vehicle type	**Traffic composition**		**Vehicle Characteristics**	**Conversion**
	[Name]	[%]	[Length in m]	[PCU]
Car	Dynamic Lights	86.6	3.99 to 5.00	1
Motorbike		0.36	1.8	0.6
LGV		13.04	5.11 to 6.31	1.2
Car	Fixed Lights	86	3.99 to 5.00	1
LGV		14	5.11 to 6.31	1.2
OGV1	Heavys	35.6	6.31 to 10.21	1.6
OGV2		64.4	9.54 to 18.36	2.5
Bus	n/a (PT)		10.92 to 11.54	2