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UNITE

UNIfication of accounts and marginal costs for Transport Efficiency

UNITE Case Studies 7F: Urban Congestion Costs

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UNITE Case Studies 7A to 7D - Inter-urban road user costs

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1. Introduction

The EU DG TREN UNITE project is aiming to quantify the full marginal social costs of transport in Europe in a variety of settings. This paper reports the outputs of one particular case study carried out during the project, which has used a Wardrop equilibrium assignment model (SATURN) to estimate the costs of congestion in three European urban road networks (Edinburgh, Helsinki and Salzburg).

The paper has five following sections. Section 2 details the underlying motivation for the study. Section 3 describes the SATURN model briefly, while Section 4 introduces the model applications for each of the three cities. Section 5 outlines the tests that have been carried out. Section 6 describes the results. Finally, Section 7 summarises the findings and presents conclusions and recommendations for further study in this area.

2. Motivation

Economists have recognised that congestion represents a significant external cost of road transport since the 1920s (Pigou, 1928). The continuous growth in traffic since has resulted in growing concerns about the (time and money) resources that are wasted due to transport inefficiency, particularly in urban areas and on major motorways. There is currently an increasing willingness among policy-makers to consider quite draconian action to tackle these concerns, such as the introduction of direct charges for road use. If such charges are to have a sound economic basis and, thus, are to attempt to levy fees that approximate the congestion costs that drivers impose on others when they travel, it is necessary for research to provide a sound understanding of the levels of external congestion costs that accrue in road networks and how they are distributed in time and space. Collecting and interpreting this information by direct observation would be a complex and costly process and has rarely, if ever, been attempted at the network level of detail. However, a useful insight into the problem may be provided by models of congested road networks that are based on concepts of economic generalised cost. In particular, real world applications of these models, incorporating local data about network topology, prevailing travel demand and the sensitivity of link travel times to traffic flows may represent our best opportunity to estimate the external costs of congestion at present.

3. The SATURN model

SATURN (Simulation and Assignment of Traffic to Urban Road Networks) is a steady-state Wardrop equilibrium assignment model which predicts route choices and resulting traffic flows on road networks, based on the generalised costs of travel (Van Vliet, 1982). It was developed by the Institute for Transport Studies at Leeds University and is used extensively by practitioners worldwide, enabling plentiful access to applications based on local data for research purposes. The key components of such applications are:

(i) a numerical description of the local road network, as nodes and links, with generalised travel costs calculated as a weighted combination of time and distance, using link-based speed-flow relationships to represent congestion; and

(ii) a numerical description of local travel demand patterns, in the form of a spatial matrix of origin to destination movements for a particular time period of the day.

Travel demand patterns are treated as aggregate flows of vehicles, expressed in passenger car units (PCUs), while travel costs on any given road link are assumed to be the average that is experienced across all vehicles for the prevailing volume of aggregate flow.

In its conventional form, the model assumes that road travel demand is fixed. However, the capability exists to introduce variable demand through an *elastic assignment* algorithm (Hall et al, 1992). This allows the representation of changes in demand which occur as a direct result of changes in the costs of travelling. Each origin to destination movement in the trip matrix is assumed to possess an additional connection to those available through the road network. Trips are transferred between this pseudo-link and the rest of the network on the basis of an own-price elasticity function which responds to cost changes between a base and a forecast situation. Changes to trip matrix cell values may be positive or negative, dependent on whether average travel costs for the particular origin to destination movement go up or down. Elasticity values are controlled by a single, global demand response function, of variable form, which attempts to include all the behavioural response alternatives to travelling through the road network. Therefore, detailed spatial variations in the availability of particular alternatives are not accounted for. There is also, currently, no explicit attempt to consider the transfer of trips to and from other locations and time periods.

SATURN has been used extensively in previous research to investigate the impacts of practical, second-best road pricing schemes (Ghali et al, ; May & Milne, 2000; May et al, 2001). The model has also been extended to allow representation of first-best pricing scenarios, under both fixed and elastic demand, through the application of a *system optimum assignment* approach (Williams et al,). Under traditional Wardrop assignment, a *user optimum* is achieved by each origin to destination movement attempting to minimise average travel cost (equivalent to *marginal personal cost* in a standard welfare economics analysis). Under *system optimum assignment*, the link-based speed-flow relationships in the network are raised from average cost to marginal cost levels. The resulting equilibrium minimises total generalised costs within the modelled system as a whole, as well as for individual users. In the elastic demand case, standard *rule of a half* assumptions are used to ensure consistency with economic welfare analysis.

4. The SATURN applications for Edinburgh, Helsinki and Salzburg

The SATURN applications for the three cities are discussed in turn.

4.1 Edinburgh

The SATURN application for Edinburgh was developed under the DG TREN AFFORD project, during modelling work that extended the findings of the previous OPTIMA and FATIMA projects. Its original purpose was to assist in the calculation of first-best prices, for comparison with outputs from a local strategic transport model. However, it has subsequently been used quite extensively in its own right to investigate pricing issues (Shepherd et al, 2001).

The Edinburgh network extends approximately 1,000 kilometres, covering all major routes within the city of Edinburgh and the surrounding Lothian region, including the road bridge across the Firth of Firth which is the main access point to and from areas to the north. Coverage of minor routes is limited. This simplifies the availability of alternatives within the route choice model somewhat compared with reality and means that coverage of congestion externalities across the study area is partial rather than complete. These constraints are common (albeit to variable degrees) within most network modelling applications, due to the logistical and resource implications of acquiring and using comprehensive data sets within such a spatially disaggregate modelling environment.

The Edinburgh demand pattern is subdivided into 25 spatial zones, a relatively coarse representation of real origin to destination movements. The work reported here focussed on morning peak hour conditions, when there are an estimated 55,000 PCU trips within the network.

4.2 Helsinki

The SATURN application for Helsinki has been developed during the UNITE project, based on data from an existing EMME 2 application that was used previously during the DG TREN AFFORD project. As the data requirement specifications of the SATURN and EMME 2 models are quite similar, conversion between the software platforms is relatively easy to achieve.

The Helsinki network extends approximately 12,500 kilometres. It covers all significant routes across the Helsinki Metropolitan Area, including the two neighbouring cities of Espoo and Vantaa. It also includes a rather detailed representation of the road network in the city centre of Helsinki. Therefore, the size if the study area is somewhat larger than in the Edinburgh application and there is, perhaps, a little greater coverage of the available routes within.

The Helsinki demand pattern is subdivided into 145 spatial zones, providing a detailed representation of real origin to destination movements. Again, this work has focussed on the morning peak, during which more than 100,000 PCU trips take place within the modelled network.

4.3 Salzburg

The SATURN application for Helsinki was developed during the DGVII ICARO project, where it was used to assess the potential benefits from car pooling. Network and travel demand were derived from...

The Salzburg network extends approximately 8,500 kilometres, covering all significant routes within the city and all other major approach routes across the region (and some beyond). As in Helsinki, there is a more detailed representation of the road network in the city centre. Salzburg is noted for the fact that it has a rather constrained road network, as a result of both its local geography (including a limited number of river crossing points) and the historic nature of development in the centre.

The Salzburg demand pattern is subdivided into 369 zones, providing a very detailed representation of real origin to destination movements. The morning peak demand pattern includes approximately 21,000 PCU trips.

5. Test specification

SATURN system optimum assignment has been applied to all three model applications, assuming both fixed and elastic travel demand, for a range of input demand levels centred on prevailing morning peak situations. Outputs from the fixed demand case provide estimates of marginal external congestion costs within the networks under current conditions and show how these might be expected to change with the overall demand level. Outputs from the elastic demand case illustrate the potential impacts from imposing marginal cost pricing for road use within urban road networks.

Sensitivity to the input demand level has been addressed by testing five points, based on a global factor, across a range from 0.5 to 1.5 of the current demand level.

Elastic demand has been implemented based on data from a recent study, during which stated preference surveys were used to assess behavioural responses to road pricing in three UK cities (May et al, 2001). This found that a simple exponential function, in which elasticity varies related to absolute changes in generalised cost, provided the best fit to stated behavioural intentions. It also concluded that elasticities in a range from 0 to -1 were likely to result, except where changes in cost were unusually high.

6. Results

The SATURN model produces a large volume of output data, available at many different levels of detail. Typically, it is neither feasible nor desirable to analyse all of it and the most useful insights are provided by selective investigation and presentation of a limited number of measures in a customised form.

In this study, the following information has been extracted:

(i) global generalised cost data, from which network-wide measures of marginal external congestion cost can be calculated;

(i) spatial graphics regarding the incidence of marginal external congestion cost across the road network; and

(i) comparisons of costs, travel demand levels and resulting traffic flows between the fixed and variable demand situations, to illustrate the potential impacts of imposing marginal cost-based road prices.

These are addressed in turn.

6.1 Levels of marginal external congestion cost

Figures 1 to 3 show the marginal social cost (MSC, in red) and marginal personal cost (MPC, in blue) curves for the three cities, in the form of cost rates per unit of flow. As the SATURN model treats generalised costs in units of time, these have been expressed as PCU-minutes per PCU-kilometre.

While a sensible definition of the Y-axis that allows comparison between the cities is relatively easy to achieve, a similar definition for the X-axis is rather more challenging. Clearly, any absolute measure of flow is meaningless in comparison terms, as the scales of the three model applications are so different. The chosen measure of *flow density*, expressed as PCU-kilometres per kilometre of road network, provides a useful measure for comparison for traffic levels, but still fails to take account of natural variations in capacity between the networks. Therefore, the areas of the X-axes that are occupied by the MSC and MPC curves may themselves tell us something about the networks, and the ways in which they have been represented. For this reason, and the desire to show the cost curves clearly, the X-axis has not been fixed to common units.

Observing the X-axis scales, it may be possible to infer that the Salzburg network tends to have the lowest natural capacity, while the Edinburgh network has a capacity that is orders of magnitude higher than both the other networks. Certainly, it is true that road capacity in Salzburg is rather constrained and might reasonably be expected to be the lowest here. However, the scale of the axis for Edinburgh may be biassed by the lower level of detail of the model application and the consequent tendency to ignore lower capacity minor routes. Therefore, it may be dangerous to draw too many conclusions.

Figure 1:

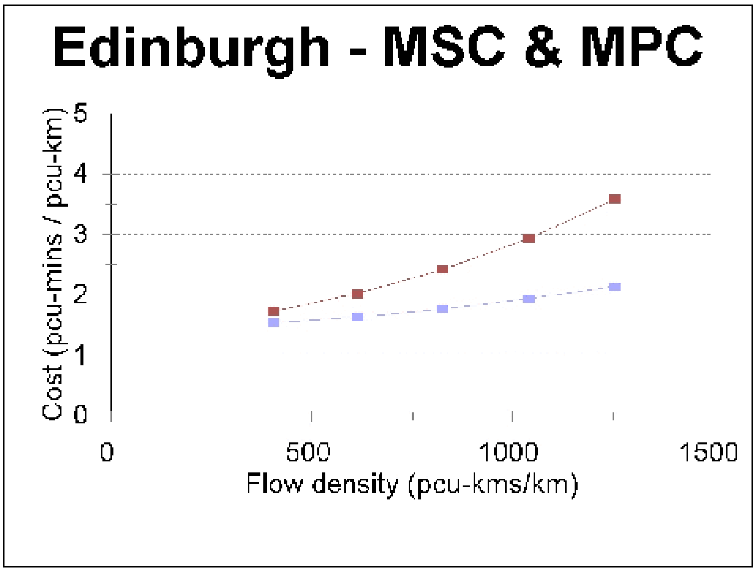


Figure 2:

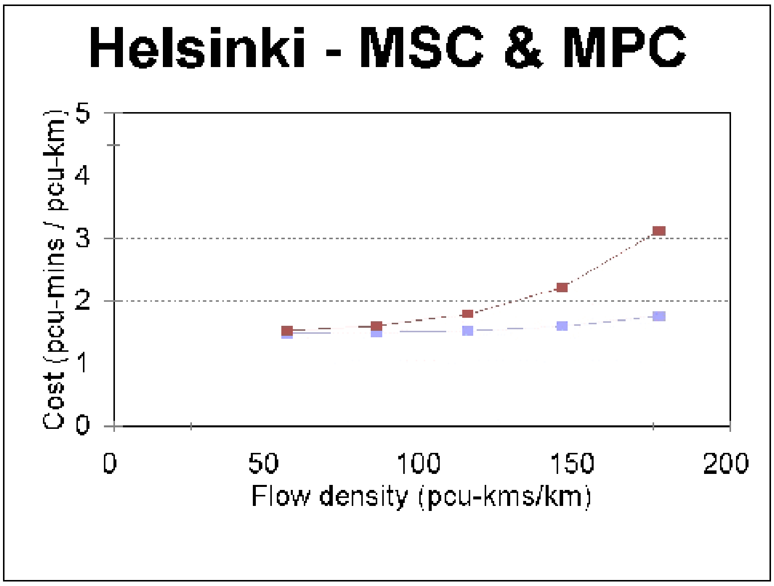
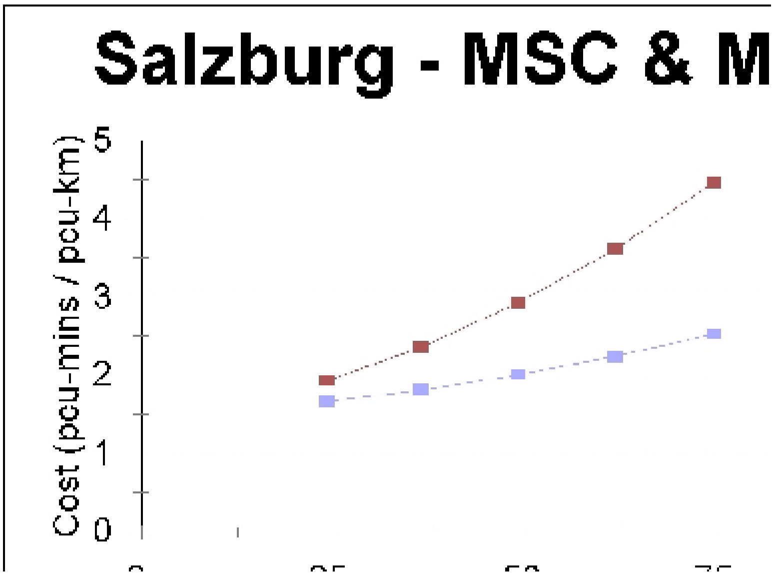


Figure 3:



The MPC curves show that the prevailing levels of generalised travel cost experienced by drivers in the three cities (given by the middle point on each curve) fall within a relatively small range of 1.5 to 2 PCU-minutes per PCU-kilometre. The highest cost is in Salzburg and the lowest is in Helsinki. This is reasonably consistent with expectations. Furthermore, it may be possible to infer from the three MPC curves that a cost of 1.5 PCU-minutes per PCU-kilometre is consistent with uncongested conditions in a variety of networks.

In contrast, the MSC curves show that prevailing levels of social cost vary across a more significant range of 1.75 to 3 PCU-minutes per PCU-kilometre. Again, the highest cost relates to Salzburg and the lowest to Helsinki.

Marginal external congestion cost is given by the difference between the MPC and MSC curves. This shows that congestion externalities in Salzburg are currently as high as 50% of the generalised travel costs experienced by motorists, while those in Helsinki may be just 15%. The general trends in congestion externality against flow are similar in the three cities, with all showing significant increases in inefficiency related to rising demand across the range tested. It may be possible to interpret the plots as suggesting that the prevailing conditions in Edinburgh and Salzburg represent positions higher up the MPC and MSC curves compared to Helsinki. In all three cities, increases in travelling beyond current levels are predicted to result in considerable increases in congestion cost, with a 50% increase in demand resulting in at least a doubling of marginal external congestion cost.

6.2 Spatial incidence of marginal congestion cost

Figure 4 illustrates the relative levels of marginal external congestion cost per PCU across the Edinburgh network, under prevailing demand levels. This shows that the highest levels of cost are incurred by traffic crossing the Forth Bridge, to the north-west of the city, and on major radial routes approaching the centre (especially to the west). This pattern suggests that it might be possible to approximate externalities quite well in the Edinburgh region through second-best charging based on a bridge crossing toll and a single cordon on the urban radials.

Figure 5 qualifies the above findings by showing relative levels of marginal external congestion cost as totals incurred by all traffic on each link. The general picture is the same, but those links with higher flows now tend to predominate. This confirms the significance of the Forth Bridge as the key link in the network and of two major radials to the west of the centre. However, it also emphasises, for the first time, the significance of orbital links of the outer ring road to the south of the city.

The general impression from these plots is that the spatial incidence of congestion externalities in Edinburgh is largely consistent with intuitive expectations. However, an important caveat must be that the relative coarseness of the network representation may oversimplify the reality and that anyone wishing to use this information as the basis for designing second-best charging approaches may find it more difficult.

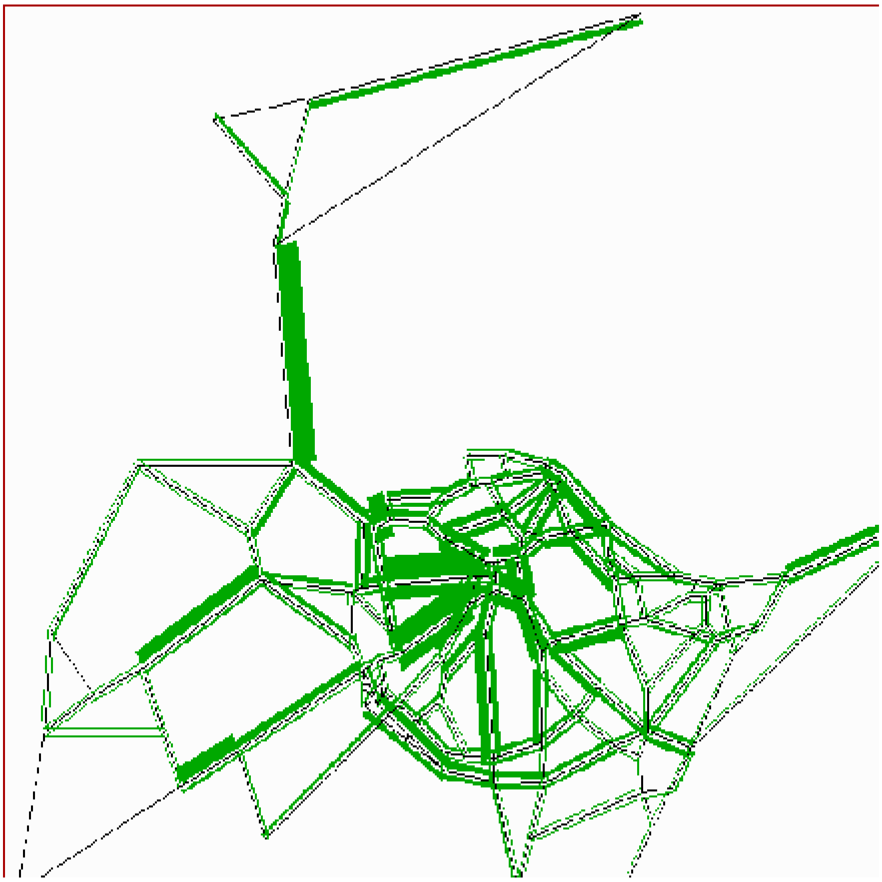
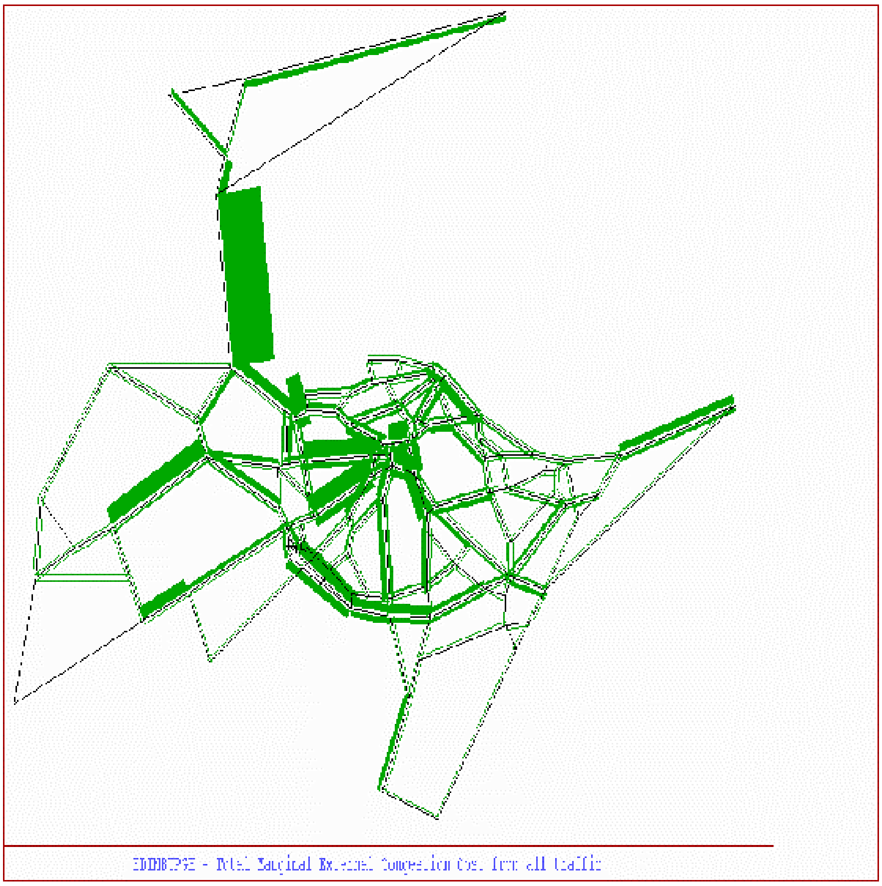


Figure 4:
Figure 5:



Figures 6 and 7 show the relative prevailing levels of marginal external congestion cost per

PCU for the Helsinki and Salzburg networks, respectively. In both cases, the general impression is rather different to that from the Edinburgh model application.

In Helsinki, few individual links are easily identified as contributing disproportionately to congestion externalities. Rather, externalities are spread quite evenly across the city centre and along the main radial routes throughout the region. The one exception to this is a small pocket of congestion to the north of the city centre, in the Vantaa area. This general pattern is intuitively sensible and is undoubtedly primarily a result of the relatively low levels of externality overall. It suggests that any attempts to approximate congestion externalities through second-best pricing may be best focussed on continuous charging approaches, such as payments based on distance travelled.

In Salzburg, by contrast, a small number of links is easily identified as contributing disproportionately to congestion externalities, located primarily on approaches to the city, around the perimeter of the modelled network. The city centre itself is relatively congestion free. Without a detailed consideration of the local geography, this pattern is, intuitively, the most difficult to rationalise. However, it suggests a network where the performance is dominated by a small number of bottlenecks, such as river crossings, and that second-best pricing based on charges at these points could yield considerable benefits.

Plots of marginal external congestion cost as totals incurred by all traffic were found to provide little in the way of additional insights for the Helsinki and Salzburg networks and have, thus, been omitted.

Figure 6:

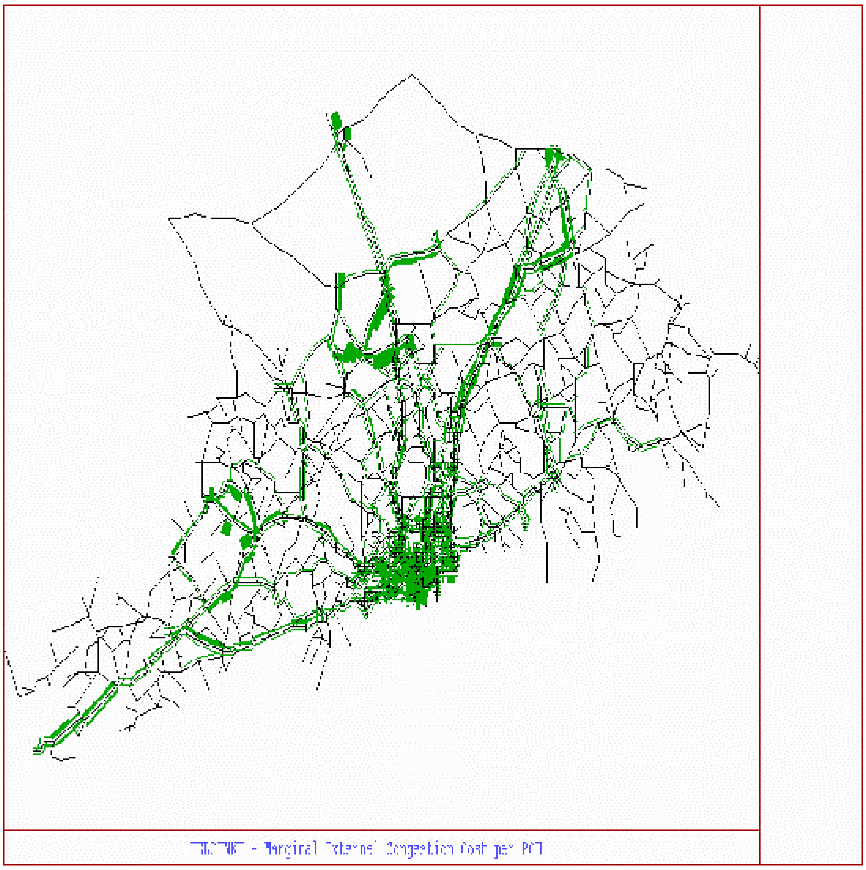
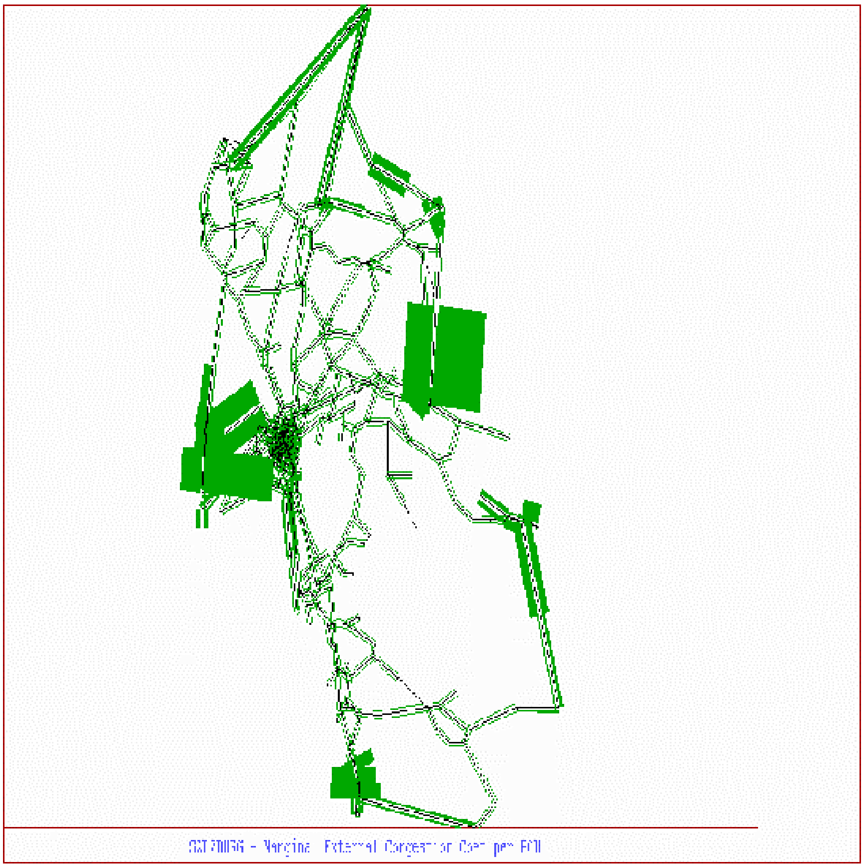


Figure 7:



6.3 Comparison of fixed and variable demand patterns

Table 1 provides data to allow comparison of the current situation with what might be expected if marginal cost prices were imposed on the networks, resulting in behavioural responses affecting both travel demand levels and route choice.

	Edinburgh	**Helsinki**	**Salzburg**
% travel time congested 2002	33	12	37
% trip reduction from MCP	13	4	6
% travel time congested under MCP	24	4	24
% change congestion cost under MCP	-35	-43	-46
% change traffic flow (PCU-km) under MCP	+8	-3	-11

Table 1: Comparison of the current situation with marginal cost pricing (MCP) under variable demand

The percentage of travel time which is congested (where congestion is defined by all delays in excess of free-flow travel time) is an extremely useful measure of network conditions. It shows that around one third of total travel time is congested in both the Edinburgh and Salzburg SATURN applications, which is typical for urban peak hour conditions. In contrast, the percentage of congested travel time in Helsinki is only of the order of 12%.

The application of marginal cost prices is predicted to result in a rather variable impact on numbers of trips in the three cities. Not surprisingly, trip reduction in Helsinki is estimated to be very low, at around one third of that estimated in Edinburgh. What is, perhaps, less expected, at least initially, is the small scale of the trip reduction estimated in Salzburg. The explanation here lies in Figure 7, which shows that externalities are concentrated on a small number of links towards the perimeter of the network. The clear implication of the elastic demand result is that a relatively small proportion of trips is responsible for generating externalities compared to the other networks.

The impact of marginal cost prices on congested travel time is, as might reasonably be hoped, to produce a significant reduction. However, these results suggest that congestion would still be some way from being eliminated altogether. Indeed, the prediction that a quarter of travel time would remain congested in Edinburgh and Salzburg after the introduction of marginal cost pricing suggests that network conditions would still be recognisable as equivalent to the current peak in a smaller urban environment. Similarly, marginal external congestion cost is predicted to be reduced by between a third and a half, again demonstrating that a significant element of congestion externality would remain.
Perhaps the most interesting measure is that for total traffic flows, which shows very different trends in all three cities. In Helsinki, change in total traffic flow is small, which is to be expected given the similarly small change in the total volume of trips. In Salzburg, the change in flow is in the same direction, but larger, than the change in total trips. This too is easily explained. Given that the links generating the greatest congestion externalities are outside the city and that a rather small reduction in trips produces a considerable reduction

in congestion, it follows that those trips are also of longer distance than the mean for the study area. By contrast, in the Edinburgh case, the largest reduction in total trips is combined with a significant increase in total traffic flow. At first sight, this may appear counter-intuitive. However, it is wholly consistent with previous work and relates to the (typically, unconsidered) impact of traffic redistribution in a spatial network through route choice responses (May and Milne, 2000). In simple terms, pricing approaches which focus on congestion will tend to encourage trips to choose longer, more circuitous routes to avoid particularly 'costly' parts of the network. The precise impact of this will vary by location, dependent on the prevailing travel demand pattern and the availability of alternative routes, but experience suggests that in many cases it will result in a strategic transfer of traffic from radial to orbital routes. This may have the effect of increasing traffic flows on as many roads it is decreased and, as in this case, may even outweigh the effect of decreasing trip volume when considered as total PCU-kilometres travelled. As this measure is, potentially, the most reliable for representing perceptions of traffic at the roadside, it is interesting to speculate whether any pricing approach which caused it to increase would be considered successful in practice, even if it also produced significant reductions in congestion.

7 Summary, conclusions and recommendations

This paper has presented findings from the application of the SATURN model to three European cities, to investigate the levels and incidences of marginal external congestion costs. It has found that prevailing travel demands imply congestion costs ranging from 0.26 PCU-pence per PCU-kilometre in Helsinki, through 0.65 PCU-pence per PCU-kilometre in Edinburgh, to 0.92 PCU-pence per PCU-kilometre in Salzburg. These values may be converted to money units, using a standard value of time of..., to give...

Investigation of the spatial incidence of congestion costs has shown significantly different patterns in the three cities, related to prevailing demand levels and local geography. This has suggested that practitioners looking for second-best pricing approximations may need to consider different approaches by location.

Finally, estimates of the impacts of imposing marginal cost prices on the three networks has suggested that reductions in marginal external congestion costs of the order of a third to a half could be achieved. However, estimates for the total volumes of trips and traffic flows has suggested that impacts may be very case sensitive and that, in some situations, perceived traffic levels may rise when pricing is introduced.

Although inevitably limited by resources, this case study has (hopefully) provided a useful insight into the nature of congestion costs in urban road networks. Its key strength has been in the use of multiple networks, which has afforded a degree of robustness to some of the most basic findings, while highlighting some important respects in which the model results are clearly case specific. In order to gain a fuller picture of the issues regarding marginal external congestion costs in urban road environments, it would be desirable to conduct similar work for a wider selection of locations and, potentially, using different modelling approaches (eg to include explicit junction modelling, micro-simulation etc) and software packages.

References

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Ghali, M.O. et al () PTRC book

Hall et al (1992)

May et al (2001) TEC paper on Historic Cities

May & Milne (2000)

Shepherd et al (2001) paper with Agachai’s Edin results in

Van Vliet (1982)

Williams et al ()

Appendix: Differentiation of Results

In order to provide better understanding of the network-wide marginal external congestion cost (MECC) estimates from the Edinburgh, Helsinki and Salzburg model applications, outputs have been disaggregated and analysed in more detail.

For each city, estimates of MECC per unit distance (as minutes per kilometre) for the prevailing traffic conditions have been produced for three separate areas. These are:

(i) the city centre;
(ii) the main approach routes through the developed urban area; and
(iii) the more strategic routes beyond.

This information shows how MECC varies spatially over the study area, identifying the areas that suffer from the greatest congestion and, potentially, allowing greater comparability with other studies. Absolute totals for MECC and distance travelled are also presented, to show how the scale of particular areas contributes to the network-wide estimates.

In addition, the individual links with the highest estimates of MECC per unit distance have been identified and presented, to show the extremes of congestion.

This information is provided for each city in turn.

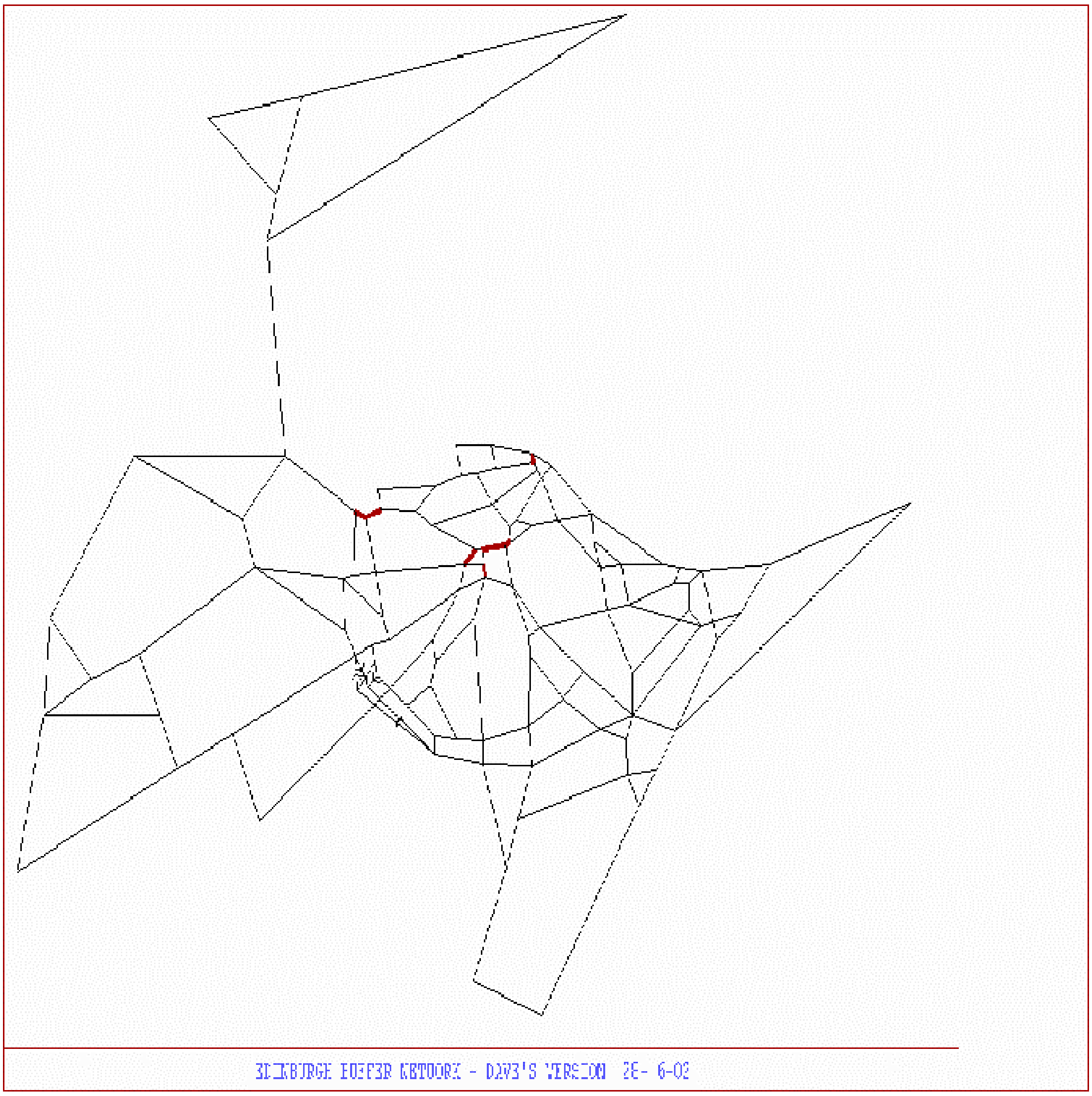
EDINBURGH:

The table below shows the breakdown of MECC by area for Edinburgh.

	Total Distance (PCU-km)	Total MECC (minutes)	MECC/Distance (mins/PCU-km)
Strategic Routes	582160	211653	0.364
Main Approaches	267838	286786	1.071
City Centre	33929	77126	2.273
TOTAL	**883927**	**575565**	**0.651**

It can be seen that significant variation exists in the estimates between areas. The general trend is one of increasing congestion towards the city centre. The distance travelled on strategic routes makes up around 66% of total travelling, meaning that the lower level of congestion found here tends to push down the network-wide estimate.

Looking at the estimates for individual links, eight have MECC per unit distance values greater than or equal to 3 minutes / PCU-kilometre, the highest value being 5.78 minutes / PCU-kilometre. The locations of the most congested links are shown below. They are concentrated in the city centre and on a small number of critical access points to the urban area.



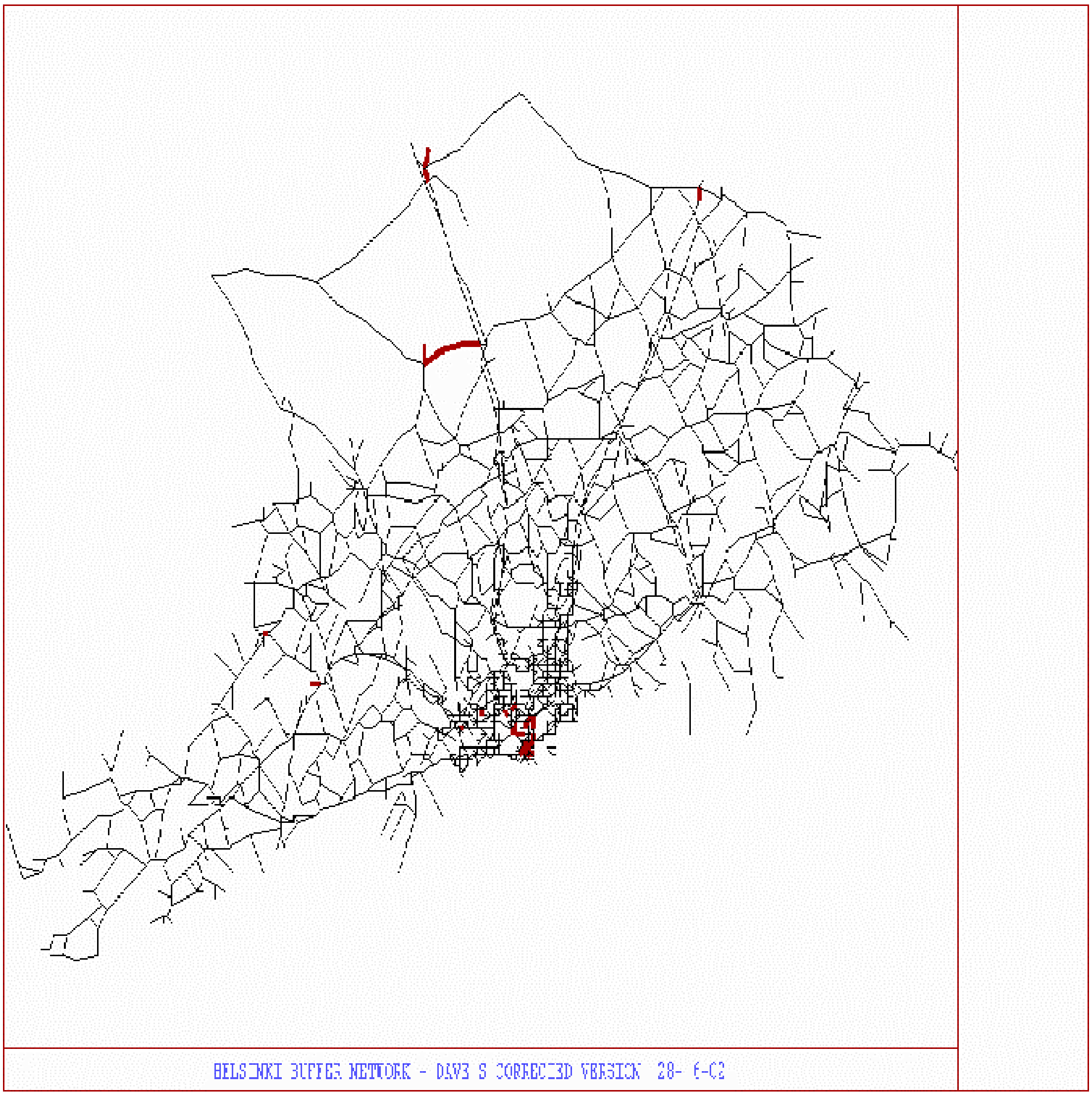
HELSINKI:

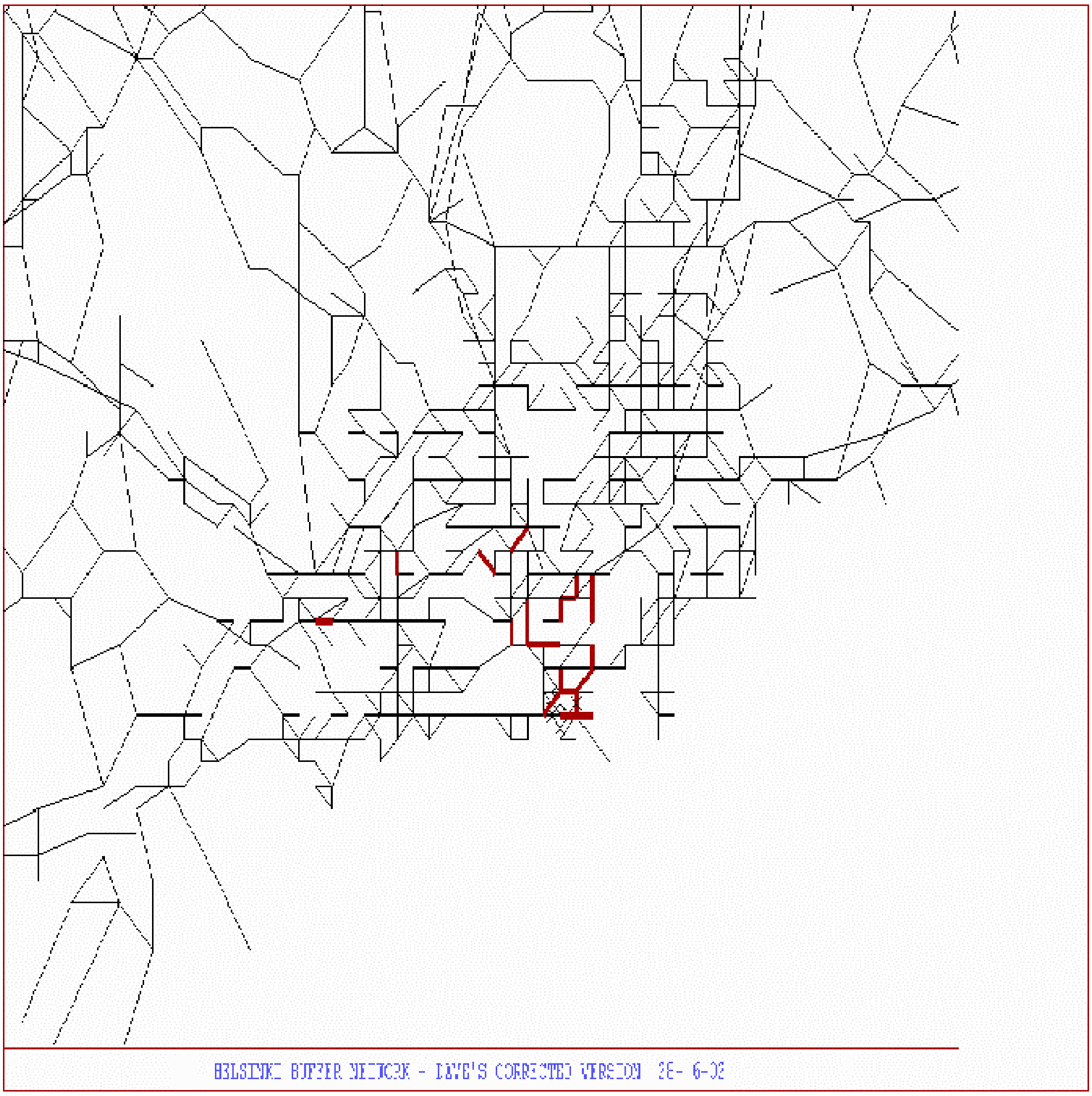
The table below shows the breakdown of MECC by area for Helsinki.

	Total Distance (PCU-km)	Total MECC (minutes)	MECC/Distance (mins/PCU-km)
Strategic Routes	446381	280599	0.629
Main Approaches	256524	18848	0.073
City Centre	752208	85625	0.114
TOTAL	**1455110**	**385071**	**0.265**

This shows that, again, there is significant (relative) variation in congestion by area. However, the absolute levels for all three areas are low, in what is known to be largely an uncongested network. The greatest external cost levels are found on the strategic routes, which cater for traffic across the Helsinki region. On the other hand, congestion is close to non-existant on the main approaches to the centre.

Estimates for individual links show that 93 have MECC per unit distance values greater than or equal to 1 minute / PCU-kilometre, across what is a considerable region-wide network. The highest value is 4.77 minutes / PCU-kilometre. The locations of the most congested links are shown in the two plots below. The first plot, for the full region, shows congestion affecting a significant stretch of a key strategic orbital route. The second shows that the majority of the most congested links are to be found in the city centre.





SALZBURG:

The table below shows the breakdown of MECC by area for Salzburg.

	Total Distance (PCU-km)	Total MECC (minutes)	MECC/Distance (mins/PCU-km)
Strategic Routes	292525	352085	1.204
Main Approaches	74396	10076	1.354
City Centre	61164	28719	0.470
TOTAL	**428085**	**390880**	**0.913**

The main feature of the breakdown is that the congestion estimate for the historic city centre is significantly lower than for the other two areas.

Estimates for individual links show that 13 have MECC per unit distance values greater than or equal to 10 minutes / PCU-kilometre, the highest value being 34.5 minutes / PCU-kilometre. These figures demonstrate the main feature of congestion in the Salzburg model application: that it tends to relate to a small number of very serious bottlenecks on strategic routes and approaches to the city that are primarily a result of local geography. Nevertheless, the plot below, focussing on the city centre, shows that a number of the most congested links are also located there.