

**CALCULATING TRANSPORT CONGESTION AND
SCARCITY COSTS**

**FINAL REPORT OF THE EXPERT ADVISORS TO THE
HIGH LEVEL GROUP ON INFRASTRUCTURE CHARGING
(WORKING GROUP 2)**

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TABLE OF CONTENTS

SUMMARY AND RECOMMENDATIONS 4

INTRODUCTION..... 8

1. ROAD CONGESTION 10

RECOMMENDATIONS..... 15

2. CONGESTION AND SCARCITY COSTS OF RAIL 15

RECOMMENDATIONS..... 17

3. MONETARY VALUATION..... 17

RECOMMENDATIONS..... 20

4. CONCLUSIONS..... 21

REFERENCES..... 21

ANNEX A: EXAMPLES OF SPEED FLOW RELATIONS AND CONGESTION COSTS..... 24

ANNEX B: TYPICAL VALUES OF TIME (PETS D7) 29

SUMMARY AND RECOMMENDATIONS

Efficient pricing requires that prices reflect social marginal cost. To implement this, it is necessary that estimates be made of all the elements of social marginal cost. The current report aims to advise on the best approach to estimate external congestion and scarcity costs for road and rail infrastructure. This requires a method of forecasting the increase in journey time and unreliability for other traffic caused by an increase in traffic on the mode in question, and then placing appropriate money values on them. These values vary with vehicle type, road type and time of day, and thus fully reflecting them in prices requires price mechanisms which can themselves vary in these dimensions. Although it is outside our remit to consider the issue of implementation in detail, we consider that a combination of electronic road pricing in congested cities and on congested trunk roads, fuel tax and annual licence duty (and possibly electronic kilometre-based charges for certain vehicle categories) is capable of achieving a reasonable approximation to marginal social cost.

In the case of rail, as with other types of transport infrastructure where specific slots are allocated to particular users, the major issue is not so much congestion as the scarcity value of slots; when the infrastructure approaches capacity, other users are unable to obtain the slot they want. Whereas for road, keeping track of the use of the infrastructure by all individual users is a major problem, for rail the information is readily available to the infrastructure manager. It is therefore assumed that there is no great practical difficulty in implementing complex pricing structures for rail infrastructure - including two part tariffs or individually negotiated contracts - if this is desired.

It is not the task of this paper to review the arguments for and against marginal social cost pricing. However, we acknowledge that a number of issues other than economic efficiency, such as distributional effects, implementation costs and acceptability must be considered before such an approach is implemented. The degree of accuracy to which it is worth reflecting marginal social cost in price for roads must always be the subject of a cost-benefit analysis, given the relatively high implementation costs of electronic road pricing. Recent studies have shown net benefits from road pricing in London of £225m per annum after allowing for implementation costs (MVA, 1995), and of 2.5 billion francs per year before implementation costs in Paris (Prud'homme, 1999). Whilst these figures suggest that investments in these measures show very high benefit-cost ratios relative to other transport investments in large cities, they are an order of magnitude smaller than the often quoted but irrelevant figure of the total cost of congestion as 2% of GDP.

The environmental and safety implications of road congestion are not considered here as they are covered in the reports of other working groups.

The recommendations are grouped into three areas:

1. Forecasting road congestion and unreliability.

The requirement here is not simply to be able to estimate the impact on other road users of an additional vehicle at existing traffic levels. Rather it is necessary also to be able to forecast how road users would adapt to being charged for these costs, in order to find an

equilibrium combination of charges and traffic levels. Bearing this in mind, we make the following recommendations:

- 1.1 Wherever possible, external road congestion costs should be estimated from a model which simulates the interaction of demand and supply on the road network. The model can then be used to approximate the marginal external costs of congestion by rerunning it with small changes in traffic volumes, and examining the effects on journey time for existing traffic. This model would ideally incorporate a detailed network description, with both speed/flow relationships and junction delays, and allow for user behaviour in terms of rerouting, retiming, changing destination or mode or changing frequency of travel, in order to obtain a new set of flows and journey times following imposition of a charge. Data is therefore required on the base origin/destination matrix, base generalised costs and responses to changes in these values. The calculation of generalised cost requires knowledge of operating costs, values of time and vehicle occupancy rates. Only when the charge is equal to the marginal external cost in this new position has the optimal level of charge and traffic been found.
- 1.2 Where this is not possible, we recommend that calculations are undertaken for typical inter urban or rural roads at alternative traffic levels and mixes of vehicle types using link speed/flow relationships. Separate calculations will be needed according to the type of road (number of lanes; motorway or conventional road). Again, data on base traffic flows and generalised costs are needed, and traffic volumes should again be adjusted for the introduction of charges, if necessary by means of a simple price elasticity of demand, in order to obtain an equilibrium value.
- 1.3 For urban areas, the degree of interaction between roads means that such an approximation will be particularly crude. If a full network model is not available, the use of area speed/flow relationships relating to the entire network for central, inner and outer urban areas is likely to be preferable to link based speed/flow relationships.
- 1.4 Forecasting the impact of increased traffic on unreliability is more difficult, but given the importance of the issue it should be attempted wherever possible. A variety of approaches exists, including the use of micro-simulation models which model individual vehicles and can thus estimate the spread of journey times, and purely empirical approaches, which require data on unreliability and on traffic flows for a set of roads over time.
- 1.5 All the above relationships should relate to local conditions in the area concerned, and relate to conditions such as driving styles and typical speeds in that location. It would be counter-productive therefore to attempt to specify Europe-wide relationships, although results may with care be transferred from comparable situations elsewhere in Europe if local information is not available.

2. Forecasting rail delays and scarcity values

Fundamentally the approach we take to pricing on rail is consistent with our recommendations on road. That is we seek to reflect in the price all the social costs imposed by the operator on the rest of society by the use of a particular slot. However, in practice there are significant differences. Given the fact that specific slots are allocated to particular operators on rail infrastructure, the main effect of excess demand is not congestion as such, but the inability of particular operators to obtain the slots they want. The element of social cost to which this gives rise is the 'scarcity value' of the slot - i.e. its

value in the next best use. This cost is strictly only an externality however where it is borne by another operator; when the next best use is by the same operator the cost should be already internalised in that - provided they are efficient - they will already have assessed the alternative uses of the slot. There is no general way of calculating this 'scarcity value' from information about the volume of traffic and the characteristics of the route. This means that a rather different approach is needed to the estimation of the marginal social cost of rail infrastructure from that taken in the case of roads.

- 2.1 Estimation of the scarcity value of specific slots on rail infrastructure requires a way of revealing the value placed on the slots by alternative possible users, both in terms of commercial rail operators and in terms of government bodies wishing to provide social services. It may be possible in some cases to reveal these values by auctioning the slots, but given the complexities involved in terms of the alternative ways in which the infrastructure may be used, this is difficult. Some pre-packaging of slots is probably necessary, in order to offer attractive combinations to alternative bidders. In general, a process of negotiation appears the most practicable way forward. This might work in terms of train operators first registering their wishes, the infrastructure manager using these to produce packages of paths and charges and further negotiation then taking place to determine whether operators would be prepared to pay more to improve their package, or to surrender some of their paths in return for a reduced charge. Such negotiations would also naturally encompass investment in expanded or enhanced capacity and the sharing of the development costs.
- 2.2 Unscheduled delays imposed by one train operator on another may be measured ex post if adequate monitoring is undertaken to measure both the extent and the cause of delays. However, this will only measure the delays directly caused and not those where the presence of the additional train has worsened the consequences of other delays by absorbing part of the recovery margin. It is therefore more accurate to measure anticipated delays by simulation modelling and charge these as part of the tariff. Of course these additional delays will vary by route, type of train and time of day.

3. Monetary valuation

Changes in speed may lead to changes in operating costs in terms of fuel, tyres and brakes. This may be estimated from appropriate formulae, and converted to resource cost by deducting taxes. But the main effects of congestion and unreliability are in terms of the time of people, poorer utilisation of vehicles and delays to the goods they carry. In all cases, values for these must be converted to per-vehicle values (e.g. for passengers, by weighting by the occupancy of vehicles).

- 3.1 For staff working in the transport industry, the usual approach of estimating the marginal cost of their time as their wage rate plus an allowance for the overhead costs of employing labour is generally appropriate. Similarly, the costs of poorer vehicle utilisation may be estimated by calculating the impact on fleet size of the delay, and the additional interest and depreciation costs of a larger fleet.
- 3.2 For other staff who travel in the course of their work, a more sophisticated approach, which takes account of factors such as their ability to work on route, the fact that part of their journey time may be at the expense of leisure time and the fact that the length of

their journey time may affect their productivity later in the day, is needed. Appropriate formulae exist, and a number of studies have made estimates of the elements involved.

- 3.3 Values of commuting and leisure time should be based on empirical evidence, and segmented by variables such as journey purpose, length, mode and income of travellers, whenever evidence of significant variation by this variable exists. A large number of studies, using revealed and stated preference methods, exists, and both methods appear capable of producing reliable results when used with care.
- 3.4 The evidence that travelling in congested conditions produces higher values of time than in uncongested conditions requires particularly careful examination because of its importance in the current context.
- 3.5 Empirical estimates also exist, and should be used, for valuing time spent waiting for public transport, late arrivals and the difference between desired departure time and the time at which the service actually departs. All may be affected by congestion or scarcity of slots.
- 3.6 As a first approximation, values of time for passengers may reasonably be assumed to increase over time in proportion with income. The value of marginal external cost of congestion will also need to be updated for changes in traffic volumes, infrastructure capacity, technology and operating cost.
- 3.7 Valuations of time for freight consignments for which transit time is increased, or made more unreliable, are an important component of social costs, and should be based on empirical estimation (using revealed and/or stated preference methods) rather than the alternative approach which is in use, which is to make estimates of the interest cost of stock in transit.

INTRODUCTION

The background to this report is the conclusion of the Commission in its White Paper on infrastructure pricing, and following the deliberations of the High Level Group on infrastructure pricing, that social marginal cost pricing of infrastructure is the most efficient policy to follow. However, in order to implement this conclusion, practical methods of estimating social marginal costs are needed. The scope of this report is to consider alternative ways of estimating the costs of congestion and scarcity that are relevant for the pricing of existing transport infrastructure.

Detailed consideration of the resulting price structure, and of the implications of this for equity, or of considerations such as administrative costs of pricing systems and of the implications of second best theory, are outside the scope of this report. However, it should be noted that for road charging, because the value of marginal social cost varies with vehicle type, road type and time of day, full implementation of marginal social cost pricing requires a pricing system that can also vary in these dimensions. We consider that a combination of electronic road pricing in congested cities and on congested trunk roads, fuel tax and annual licence duty (and possibly electronic kilometre-based charges for certain vehicle categories) is capable of achieving a reasonable approximation to marginal social cost.

In the case of rail, as with other types of transport infrastructure where specific slots are allocated to particular users, the major issue is not so much congestion as the scarcity value of slots; when the infrastructure approaches capacity, other users are unable to obtain the slot they want. Whereas for road, keeping track of the use of the infrastructure by all individual users is a major problem, for rail the information is readily available to the infrastructure manager. It is therefore assumed that there is no great practical difficulty in implementing complex pricing structures for rail infrastructure - including two part tariffs or individually negotiated contracts - if this is desired.

It is not the task of this paper to review the arguments for and against marginal social cost pricing. However, we acknowledge that a number of issues other than economic efficiency, such as distributional effects, implementation costs and acceptability must be considered before such an approach is implemented. The degree of accuracy to which it is worth reflecting marginal social cost in price for roads must always be the subject of a cost-benefit analysis, given the relatively high implementation costs of electronic road pricing. Recent studies have shown net benefits from road pricing in London of £225m per annum after allowing for implementation costs (MVA, 1995), and of 2.5 billion francs per year before implementation costs in Paris (Prud'homme, 1999). Whilst these figures suggest that investments in these measures show very high benefit-cost ratios relative to other transport investments in large cities, they are an order of magnitude smaller than the often quoted but irrelevant figure of the total cost of congestion as 2% of GDP.

The environmental and safety implications of road congestion are not considered here as they are covered in the reports of other working groups..

In contrast to the case of environmental externalities, congestion and scarcity costs are internal to the transport sector as a whole. They are of concern in the current context not because they are unpriced, but because existing ways of pricing for the use of transport infrastructure are inadequate. The result is that additional users of transport infrastructure may well impose externalities on other transport users, as well as experiencing congestion themselves.

It is very important to distinguish between this external element of the cost of congestion or scarcity and total or average congestion cost. It is sometimes argued that the total cost of congestion is borne by the sum of users themselves. The point, however, is that, in a situation of congestion, each additional user inflicts costs on other users as well as suffering costs himself or herself. It is this external element – that inflicted by one user on other users – that is relevant for pricing purposes.

A further reason why estimates of total congestion costs are not helpful for pricing purposes is that congestion costs vary enormously in time and space. It is thus necessary to prepare estimates of the marginal external cost of congestion for various circumstances. For roads, we might think in terms of a three way categorisation e.g.

- location: inner city, outer city, other urban area, inter urban, rural
- type of road: motorway, dual carriageway, single carriageway
- time of day: peak, inter peak, off peak

How many categories to adopt depends on a trade off between the accuracy with which costs are reflected in prices and the cost and complexity of the pricing instruments.

For railway lines, and other infrastructure on which specific slots are prebooked, no such simple categorisation is likely to be helpful, as discussed in section 2 below.

A key distinction must be made between infrastructure where access is open to anyone without prebooked slots, as is the case with roads, and infrastructure where pre-booking of specific slots is required, such as railways, airports and ports. For roads, increased demand materialises as more traffic coming on to the road. Beyond a certain level, the result is reduced speeds and queuing at junctions and other bottlenecks; in other words congestion. In congested conditions, there is a clear externality involved, as additional road users delay others.

For systems where access takes the form of allocation of specific slots, the situation is very different. It may still be the case that additional users impose costs on existing users by causing delays, and indeed delays do become more common the closer the system is to capacity. But the key point on a scheduled system is that as it approaches capacity some users are unable to get the slots or run to the schedules they want. As a result, slots acquire scarcity value. Strictly, this is only an externality where the competition for slots is between different train operating companies; otherwise it is already internalised. However, with separation of infrastructure from operations now a part of European Rail Policy, this situation is becoming more common, and pricing of rail infrastructure therefore needs to take it into account. Of course, congestion may also take place on trains themselves, leading to a case for taking this into account in prices to final users, but that is outside the scope of this note.

For both road and rail systems one obvious reaction to shortages of capacity is to invest in new capacity. One approach to marginal cost pricing would be to try to estimate the costs of capacity expansion caused by additional traffic. However, this is inclined to vary enormously with the precise circumstances and the extent of the capacity expansion required. Charging this amount will also lead to misallocation of the existing infrastructure capacity during the (often long) time period before the capacity is adjusted.

The approach adopted by the Commission, correctly in our view, is to examine the costs of adding additional traffic to the existing infrastructure. This is consistent with the short run marginal cost approach taken by Working Group 1, on infrastructure costs, which does not include the capital costs of infrastructure expansion. It should be stressed however that an optimal outcome requires that such capacity expansion takes place whenever the benefits of doing so exceed the costs. The result is that charges will adjust according to the level of capacity; as investment takes place on a congested road other things being equal, optimal charges will fall, whereas traffic growth on currently uncongested roads may cause the optimal charge to rise.

This note considers first road congestion, then rail congestion and scarcity values and finally the crucial issue of value of time. Ports and airports are not considered further, although many of the same issues arise, and indeed there is a much greater literature on slot allocation at airports than exists for rail systems.

1. ROAD CONGESTION

External congestion costs occur when the presence of one vehicle increases the journey time of another. This phenomenon may happen for two distinct reasons as traffic builds up. Firstly, increased traffic density obliges drivers to drive more slowly simply because the gap between vehicles is reduced. Secondly, queuing may occur at junctions or other bottlenecks. The standard way of estimating levels of congestion for inter-urban roads is via the use of speed-flow curves. Estimated speed/flow curves differ with the characteristics of the road (number of lanes, lane width, urban or rural etc). Frequently – as in the COBA manual (UK DOT, 1996) used for cost-benefit analysis of road schemes in Britain - they are estimated as a series of linear segments according to the traffic level on the road as well. The COBA manual suggests speed-flow curves which consist of two linear segments, with a steeper slope of the segment at higher flow levels indicating that at higher densities additional vehicles have a greater impact on reducing speeds. Some difficulties with this relationship are that:

- the relationship breaks down near capacity (e.g. for COBA it is undefined below 40 kph);
- this is the most important segment for charging purposes – it is where charges rise steeply and the role of charging is most important and effective¹.

Thus, a more appropriate speed-flow relationship will be non-linear, or have a large number of linear segments to enable the approximation of non-linear relationships.

Most countries will have estimated speed-flow relationships to suit their own situation in terms of road characteristics, topography and driving styles, and we do not consider that it would be sensible to try to adopt a single set of speed flow curves throughout Europe (see Annex A).

Particularly in urban areas, however, heavily congested roads are almost always the result of bottlenecks. These bottlenecks are frequently due to junctions but also sections with steep

¹ For more complex non-linear functions, external congestion pricing will become relevant at around 90% of capacity; for simpler non-linear functions at around 75% of capacity. Thus, the choice of speed-flow function which is appropriate to the observed road characteristics is a fundamental issue, particularly in the region where an equilibrium congestion charge is likely to lie. As an example, HGV speeds begin to be affected only in the highest peaks.

gradients, reduced carriageway width, reduced number of lanes or roadworks or accidents. (The costs of congestion caused by roadworks or accidents should of course be attributed to the vehicles that create that condition.)

Bottlenecks require an alternative form of model based on queuing (Small, 1992). Basically whenever demand exceeds the capacity of the bottleneck, queues build up, and these will only dissipate when demand falls below capacity. The result is that in a queuing model, vehicles that arrive when the queue first starts to form impose delays on all subsequent vehicles for the duration of the queue; the external cost of congestion in this situation declines steadily through the duration of the queue. The implied pattern of charges is very different from those implied by the standard speed/flow relationship.

In practice, in a road network, delays occur for a mixture of reasons, and traffic between different origin/destination pairs interacts at junctions, where the capacity in one direction depends also on the flows on the other arms of the junction. In addition, traffic may reassign itself to different routes, so that the delay occurs because of a longer journey distance rather than a reduced speed. Ideally, the additional congestion created by extra traffic is best measured by running a detailed traffic simulation model, which assigns traffic to specific roads. An example of such a model is SATURN, which has been used to estimate the costs of congestion in Cambridge (Newbery, 1998).

Another approach is to approximate the speed-flow relationship for a discrete area of the road network. The aggregate relationship derived is known as an area speed/flow curve. This estimates a relationship between the time per kilometre and the overall volume of traffic in an area of the road network, allowing for the re-routing possibilities in an urban network, and for the crucial issue of delays at junctions. Such a relationship may be estimated by repeated running of a traffic simulation model (May et al, 1998); it will of course need modification if the characteristics of the network change. It is the approach taken to the urban studies in the TRENEN project.

For the development of a practical charging system for an urban area it may be appropriate to estimate a number of area speed-flow relationships, for example, working out from the central core, inner city area and suburban area.

The two main components of delay costs for road users (leaving aside accident and environmental costs, which may also vary with the level of congestion²), are time costs, and vehicle operating costs represented in terms of fuel, tyres, etc. The derivation of the external element of time costs from a speed-flow relationship is given below, following Newbery (1990). External operating costs may be derived in a similar fashion. Formulae are available showing how vehicle operating costs for various types of vehicles vary with speed (see for example the COBA manual in the UK). It should be noted that if elements of vehicle operating cost, such as fuel, are subject to tax in excess of the standard level of Value Added Tax, this should be deducted from any additional costs, as it does not constitute a true resource cost; rather it is a transfer between vehicle users and the government concerned. Since they are typically very small compared with time costs, changes in vehicle operating costs are not considered in detail here. For public transport and freight vehicles, the time costs should be expanded to consider

² These are not the focus of this paper, although they are highly relevant for pricing purposes and should be considered in conjunction with the environmental and accident papers.

vehicle utilisation, and the resulting increase in interest and depreciation costs if the fleet needs to be expanded. Increases in journey time and reliability for the consignments themselves may also have a value. Other elements of increased operating cost are again small.

The time cost per km of an average vehicle is simply the time per kilometre times the appropriate value of time. Since the time per kilometre is simply the reciprocal of the speed, this may be written:

Equation 1
$$t = \frac{b}{v}$$

where v is speed in km/h and b is the value of time for the average vehicle (i.e. it takes into account factors such as the value of time for the driver and occupants).

The total time costs per kilometre of a flow level q , measured in passenger car units (PCU) per hour is simply the time cost per kilometre times the flow: $T = t * q$.

Note that, because traffic flow in this equation is always measured in PCU values, the varying composition of traffic is automatically allowed for. Similarly, the differing effect of adding different type of vehicle to the traffic flow is given by multiplying the value of the marginal external cost of congestion as derived below by the PCU value of the vehicle in question. For example, the speed/size characteristics of a goods vehicle may mean that it has a PCU factor of 2, i.e. to convert to charges per vehicle the per PCU charge is doubled. Of course, this requires knowledge of the relevant set of PCU values to use, and substantial empirical work has derived factors for use in road traffic modelling.

The marginal cost of an additional vehicle is obtained by differentiating this expression by q ,

Equation 2
$$\frac{dT}{dq} = t + q * \frac{dt}{dq}$$

In words, the marginal time cost of an extra vehicle is the cost it incurs itself (t), plus the increase in the average time cost, multiplied by the number of vehicles incurring that increase.

Differentiating equation 1 gives that the increase in time cost per vehicle is equal to the proportionate change in speed multiplied by the time ($1/v$) multiplied by the value of time:

Equation 3
$$\frac{dt}{dq} = -\frac{b}{v^2} \frac{dv}{dq}$$

and substituting equation 3 into equation 2 gives:

Equation 4
$$\frac{dT}{dq} = t - q \frac{b}{v^2} \frac{dv}{dq}$$

Clearly the first element in this equation, t , is the time cost (including congestion) borne by each user, including the marginal user, themselves (this is what we defined it as in equation 1). Therefore the second part of Equation 4 represents costs over and above those borne by the individual (i.e. by other road users), so the marginal external congestion cost (MCT), in terms of the value of time of other drivers and occupants is:

Equation 5

$$MCT = -q \frac{b}{v^2} \frac{dv}{dq}$$

It is clear that the marginal external cost of congestion will vary with:-

- $\frac{dv}{dq}$ - the slope of the speed/flow relationship, which varies with the type of road and volume of traffic
- q - the volume of traffic (in PCUs)
- v - the resulting speed, which varies with the type of road and volume of traffic
- b - the value of time, which varies with the mix of journey purpose and income of the users

It is therefore necessary to think in terms of varying charges whenever these characteristics of the road or its traffic vary. DIW et al (1998) survey speed/flow relationships and congestion costs throughout Europe, and produce estimates of marginal congestion costs for some countries including the UK (Annex A).

Clearly, weather conditions have a direct impact on the speed-flow characteristics of roads. The practical implications of this impact raise the possibility of varying charges to take account of weather conditions; indeed, this currently occurs in San Diego, California, where dynamic tolls based on traffic levels may be doubled during adverse weather conditions.

Apart from congestion due to the volume of traffic, other causes of congestion can include road maintenance, vehicle breakdowns and accidents. The delays due to such factors may be calculated by means of a simple traffic model which takes account of road capacity and (essentially random) events such as vehicle breakdowns and accidents. In the UK, the QUADRO model is used to calculate time delays due to road works and incidents in road works leading to delays. This model is also used to calculate charges to road maintenance companies, “lane rental charges”, to build in incentives for timely completion of maintenance. A similar model could be used in order to calculate appropriate ex-ante vehicle charges.

It is important to note that the optimal congestion charge will be at the point where the marginal social cost equals the marginal social benefit of travel. Since congestion is currently unpriced, this will occur at a traffic flow lower than the current flow. Thus a model showing the reaction of users to alternative levels of congestion and to prices for the use of the road is needed to compute the optimal congestion charge. The need to calculate congestion charges at this point of equilibrium implies the need for an iterative process in determination of the optimal charge.

As well as the expected delay, congestion can lead to variability in travel time, or in other words unreliability. Valuation of unreliability is discussed below, but the bigger difficulty is forecasting its increase as congestion builds up. Ideally this requires a micro simulation model, which simulates the journey times of individual vehicles and which can be run for a large number of

days, so that distributions of travel time for different levels of traffic may be estimated, or extensive observations to estimate such a relationship from real data.

RECOMMENDATIONS

- 1.1 Wherever possible, external road congestion costs should be estimated from a model which simulates the interaction of demand and supply on the road network. The model can then be used to approximate the marginal external costs of congestion by rerunning it with small changes in traffic volumes, and examining the effects on journey time for existing traffic. This model would ideally incorporate a detailed network description, with both speed/flow relationships and junction delays, and allow for user behaviour in terms of rerouting, retiming, changing destination or mode or changing frequency of travel, in order to obtain a new set of flows and journey times following imposition of a charge. Data is therefore required on the base O/D matrix, base generalised costs and responses to changes in these values. The calculation of generalised cost requires knowledge of operating costs, values of time and vehicle occupancy rates. Only when the charge is equal to the marginal external cost in this new position has the optimal level of charge and traffic been found
- 1.2 Where this is not possible, we recommend that calculations are undertaken for typical inter urban or rural roads at alternative traffic levels and mixes of types of vehicle using link speed/flow relationships. Separate calculations will be needed according to the type of road (number of lanes; motorway or conventional road). Again, data on base traffic flows and generalised costs are needed, and traffic volumes should again be adjusted for the introduction of charges, if necessary by means of a simple price elasticity of demand, in order to obtain an equilibrium value.
- 1.3 For urban areas, the degree of interaction between roads means that such an approximation will be particularly crude. If a full network model is not available, the use of area speed/flow relationships relating to the entire network for central, inner and outer urban areas is likely to be preferable to link based speed/flow relationships.
- 1.4 Forecasting the impact of increased traffic on unreliability is more difficult, but given the importance of the issue it should be attempted wherever possible. A variety of approaches exists, including the use of micro-simulation models which model individual vehicles and can thus estimate the spread of journey times, and purely empirical approaches, which require data on unreliability and on traffic flows for a set of roads over time.
- 1.5 All the above relationships should relate to local conditions in the area concerned, and relate to conditions such as driving styles and typical speeds in that location. It would be counter-productive therefore to attempt to specify Europe-wide relationships, although results may with care be transferred from comparable situations elsewhere in Europe if local information is not available.

2. CONGESTION AND SCARCITY COSTS OF RAIL

In principle, the approach we take to estimating the social marginal cost of rail traffic is consistent with that for road - namely, we try to estimate the additional costs imposed on society by the use of the infrastructure by an additional train. However the methodology for rail is quite different from that for road transport. The reason is that for rail the volume of traffic is directly controlled by allocation of slots, so capacity should never be exceeded. Nevertheless, as traffic approaches capacity, so delays become more frequent. Where one operator delays trains of another through unscheduled departure from the timetable, compensation may be paid directly

for increased costs and passengers' time, provided that adequate records are kept of amounts and causes of delay. This is a feature of the 'performance regime' embodied in track access agreements in Great Britain. However, this is only likely to measure the delays directly caused by the train in question. Simulation modelling, using a model such as the MERIT model used by Railtrack, which simulates a large number of days operations using probability distributions of the various causes of delay, will estimate the full effect of running additional trains, including the worsening of delays from other causes by the reduction of the recovery margin in the system.

But the main consequence of full utilisation of capacity is that users simply cannot get the capacity they want when they want it; they have to run their trains at times and possibly speeds different to their preferred alternative, or to give up the journey.

The carrying capacity of a railway link is the maximum number of physical transport units which can use the link, and can be expressed as a function of the number of tracks in a section, average train speeds, geometry, signalling and safety systems, section lengths, length of trains, etc. (Rothengatter et al, 1996). However, over and above all these factors, the mix of train speeds and the precise order in which trains are run is crucial. For instance, on a predominantly high speed line an additional slow freight train may remove the paths of several high speed passenger trains; on a heavy freight route the reverse may be true. Capacity is also maximised by grouping trains of like speeds, so that a 'flight' of fast passenger trains is followed by a 'flight' of slow freights and vice versa. However, this conflicts with providing a good service of well spaced trains at regular intervals for the public. More complicated still is the interaction of trains on different routes or between different origins and destinations; as with roads, junctions and other bottlenecks (e.g. speed restrictions) are key factors determining capacity.

The result of all these considerations is that it is impossible to come to a ready definition of the capacity of a rail route corresponding to that for roads. More seriously, the impact of an additional train of a particular type on the paths available to other trains will differ enormously according to the precise mix of traffic on the line. At the same time, the value of a slot to other commercial operators or to government bodies providing social services will also differ enormously in time and space. It does not therefore seem possible to come to a general methodology to estimate scarcity values for rail slots in a variety of typical circumstances, in the way in which we have for road.

There are other ways of seeking to derive scarcity values. One is by competitive bidding for the slots. However, in rail systems capacity can be used in such a wide variety of ways to produce different mixes of trains of different types, origins and destinations that any bidding exercise is likely to be very complex. Moreover the value of a particular slot depends very much on what other slots are obtained, in order to put together a commercially attractive service. We see some scope for bidding processes for alternative packages of slots in a pre-planned timetable, but in general we do not consider bidding processes as a practical way of revealing scarcity values.

We see it as inevitable that the use of rail infrastructure will be planned by the infrastructure manager rather than being determined by a purely market process. The most efficient mechanism for revealing scarcity values is probably to allow the infrastructure manager to negotiate with the potential users about their willingness to pay for alternative slots in determining that plan. This allows for negotiation over desired packages of access rights and iteration to improve upon the initial solution. It might work in terms of train operators first registering their wishes, the infrastructure manager using these to produce packages of paths and charges and further negotiation then taking place to determine whether operators would be prepared to pay more to

improve their package, or to surrender some of their paths in return for a reduced charge. Such negotiations would also naturally encompass investment in expanded or enhanced capacity and the sharing of the development costs.

It does raise fears that the infrastructure manager or the larger train operating companies may exert undue monopoly power over the process (particularly when the two are part of the same organisation), and calls for an independent regulator to intervene where that happens. However, in a situation in which there is no ideal solution, it does appear to be the best way forward.

RECOMMENDATIONS

- 2.1 Estimation of the scarcity value of specific slots on rail infrastructure requires a way of revealing the value placed on the slots by alternative possible users, both in terms of commercial rail operators and in terms of government bodies wishing to provide social services. It may be possible in some cases to reveal these values by auctioning the slots, but given the complexities involved in terms of the alternative ways in which the infrastructure may be used, this is difficult. Some pre-packaging of slots is probably necessary, in order to offer attractive combinations to alternative bidders. In general, a process of negotiation appears the most practicable way forward. This might work in terms of train operators first registering their wishes, the infrastructure manager using these to produce packages of paths and charges and further negotiation then taking place to determine whether operators would be prepared to pay more to improve their package, or to surrender some of their paths in return for a reduced charge. Such negotiations would also naturally encompass investment in expanded or enhanced capacity and the sharing of the development costs.

- 2.2 Unscheduled delays imposed by one train operator on another may be measured ex post if adequate monitoring is undertaken to measure both the extent and the cause of delays. However, this will only measure the delays directly caused and not those where the presence of the additional train has worsened the consequences of other delays by absorbing part of the recovery margin. It is therefore more accurate to measure anticipated delays by simulation modelling and charge these as part of the tariff. Of course these additional delays will vary by route, type of train and time of day.

3. MONETARY VALUATION

In general it is found that the external costs of congestion are dominated by time losses (rather than effects on operating costs) and thus are extremely sensitive to the value of time. In order to estimate the marginal cost of congestion, it is necessary to choose monetary valuations to be used in the evaluation of increased journey time and congestion in both the passenger and freight markets. Valuations are required for private car, bus, van, HGV, train, and aircraft.

In addition, disaggregations by journey purpose for passenger travel would be desirable, so that the differing mix of journey purposes by time and location can be allowed for. A distinction according to the duration of trip may also be made since it could well have a bearing on time constraints and disutility of the journey.

The value of time represents the maximum amount an individual is prepared to pay for a time saving or the minimum acceptable amount to compensate for an increase in journey time. The marginal value of time is made up of two components:

- the marginal utility of time; and,
- the marginal utility of money.

Hence variations in the value of time can arise from variations in the marginal utility of time or in the marginal utility of money. Variations in the former will depend on the conditions in which travel time is spent and on the opportunity cost of travel time. Variations in the latter depend on personal characteristics and particularly on income. Congestion may impact on the conditions of travel and thus may affect the value of time.

For car, van and HGV users, the impacts of increased congestion can be expected to be:

- increases in the average journey time, with the additional time being spent in congested traffic which can be expected to be more highly valued than time spent in free flow traffic because of the greater stress, frustration and unpleasantness involved; and,
- increases in the variability of travel time, with a wider distribution around average travel time. This is measured by the standard deviation of travel times or a proportion of vehicles arriving late.

For public transport users, the situation is a little different because of the fixed schedules involved. Congestion may again lead to increases in both the mean and the variability of in vehicle time, but it will also lead to more waiting time, as vehicles became bunched and fail to arrive at stops on schedule.

For values of time it is desirable to use values selected for the specific context concerned as far as possible, since values of time will vary with income and other characteristics of the travellers concerned. For many purposes this means that values estimated for the country concerned will be the best choice. On international routes, it will be necessary to use a weighted average of the values for the countries from which the travellers come.

There are established values of working time for passenger travel, based on the cost of employing workers, (which reflects the wage rate and an overhead). These are appropriate for workers whose job is actually driving. However, this approach may not be appropriate where passengers may work en route, as is the case of many business travellers when travelling by rail, or where much of the journey takes place outside normal working hours. Hensher (1977) outlines an approach which may be used to estimate values empirically in such circumstances, but few countries have applied this, perhaps because many of the elements are difficult to value in practice. However, a number of studies are available which have taken this approach, using surveys to quantify elements such as the gain in subsequent productivity as a result of faster journeys leading to the traveller arriving at a meeting feeling more refreshed. The equation to be estimated is the following:

Equation 6 $V_B = (1 - r - p.q)MP + (1 - r)v_w + rv_l + MP_F$

where:

V_B = value of business time savings

r is share of saved time used for leisure
p is share of saved time used productively
q is relative productivity of time saved that was used for work
MP is marginal productivity of labour
 v_w is employee value of saved time otherwise spent in work
 v_l is employee value of saved time otherwise spent in leisure
 MP_F is the value of increased productivity from reduced fatigue

For passenger travel in non-working time, the general approach is to use behavioural values estimated from either revealed preference or stated preference data. In general, revealed preference models have the benefit of being based on actual data, but stated preference models allow much more precise estimation with a given sample size. There is some evidence that a well designed stated preference survey is relatively free from bias, but this issue remains controversial. A fair amount of evidence suggest that the value of time for leisure purposes is related to income, and a figure of the order of 25% of the wage rate is often used.

There is evidence that inter-urban travel is valued higher than urban travel, on which most values of time are based. Wardman (1998) provides this evidence on the basis of regression analysis of the inter-urban and urban values of time of over 100 revealed preference and stated preference studies. The principal reason for this distinction appears to be the higher relative income levels of inter-urban travellers. Time spent in congested road conditions is also valued more highly, because of the discomfort of driving in stop-start conditions and the uncertainty associated with the journey.

For rail, the appropriate values for in-vehicle time should be used for scheduled travel time, for 'late' time for delays and for wait time for any additional waiting time involved. Where scarcity of capacity requires a change in departure time, the value per minute of switch in departure time is also needed. All of these values may in principal be estimated by either revealed or stated preference methods, although in practice their estimation by stated preference methods is much more straightforward, as appropriate trade-offs may be postulated without having to find them in practice.

For freight transport, values of time need to take account not just of the additional operating costs and drivers' wages caused by congestion, but also of the value to the consignor of receiving the goods more quickly and - perhaps even more important - more reliably. A traditional approach is to look at the value of the goods, and then consider the interest charges on the additional time the stock is in transit. Except for very long journeys (e.g. inter continental sea transits) this gives very low valuations. Empirical evidence suggests that consignors typically value journey time more highly, presumably because slow transits make it more difficult to cope with short term fluctuations in demand, and thus increase the amount of buffer stock held in the system. But much more important still is reliability. Given the spread of 'just in time' distribution and production systems, failures in reliability may be very expensive, in again leading to additional buffer stock or to failures to supply goods at the promised time. Obviously all these values will vary with the commodity but also with other factors. For instance the values of time and reliability for transits to depots holding buffer stock are typically below those applying to the journey to the final customer.

Again values of time for freight may be estimated by either revealed or stated preference analysis. There is a growing trend towards the use of stated preference analysis, because

appropriate revealed preference data is hard to obtain (both due to issues of confidentiality and because of a lack of real alternatives for a lot of freight - road is dominant on all criteria).

Current evidence is not conclusive but suggests that values of time may rise over time in proportion to income. Of course, this is not the only factor that needs updating over time; changes in traffic levels, infrastructure capacity and operating costs all also need to be taken into account.

RECOMMENDATIONS

- 3.1 For staff working in the transport industry, the usual approach of estimating the marginal cost of their time as their wage rate plus an allowance for the overhead costs of employing labour is generally appropriate. Similarly, the costs of poorer vehicle utilisation may be estimated by calculating the impact on fleet size of the delay, and the additional interest and depreciation costs of a larger fleet.
- 3.2 For other staff who travel in the course of their work, a more sophisticated approach, which takes account of factors such as their ability to work on route, the fact that part of their journey time may be at the expense of leisure time and the fact that the length of their journey time may affect their productivity later in the day, is needed. Appropriate formulae exist, and a number of studies have made estimates of the elements involved.
- 3.3 Values of commuting and leisure time should be based on empirical evidence, and segmented by variables such as journey purpose, length, mode and income of travellers, whenever evidence of significant variation by this variable exists. A large number of studies, using revealed and stated preference methods, exists, and both methods appear capable of producing reliable results when used with care.
- 3.4 The evidence that travelling in congested conditions produces higher values of time than in uncongested conditions requires particularly careful examination because of its importance in the current context.
- 3.5 Empirical estimates also exist, and should be used, for valuing time spent waiting for public transport, late arrivals and the difference between desired departure time and the time at which the service actually departs. All may be affected by congestion or scarcity of slots.
- 3.6 As a first approximation, values of time for passengers may reasonably be assumed to increase over time in proportion with income. The value of marginal external cost of congestion will also need to be updated for changes in traffic volumes, infrastructure capacity, technology and operating cost.
- 3.7 Valuations of time for freight consignments for which transit time is increased, or made more unreliable, are an important component of social costs, and should be based on empirical estimation (using revealed and/or stated preference methods) rather than the alternative approach which is in use, which is to make estimates of the interest cost of stock in transit.

4. CONCLUSIONS

Externalities occur between vehicles when the presence of one vehicle increases the journey time of another. The marginal external congestion cost of additional traffic comprises the additional time costs and vehicle operating costs imposed on others by an additional unit of travel. For roads the calculation of additional travel time can be done using speed flow relationships, for the country or corridor in question. However, the way in which traffic interacts in a network of roads means that really a network simulation model is needed, particularly in urban areas; the results of this may be approximated by an area/speed flow relationship. It is also necessary to remember that the optimal charge represents the marginal external congestion cost at the optimum; it is thus necessary to model the reactions of traffic to changes in road user charges and levels of congestion to find the appropriate charge.

For rail, there are important differences. Use of the system is controlled through the allocation of slots and the main consequence of full capacity is the inability to run the train when desired. The costs of congestion and scarcity are only external when imposed by one train operator on another; costs imposed on other trains of the same operator are already internalised. The complexities of rail systems are such that no simple formula can be found to estimate scarcity values of slots for a variety of typical circumstances. We recommend that negotiation between infrastructure managers and train operating companies is the best way to reveal scarcity values of rail slots.

For values of time we recommend the use of values related to local conditions as far as possible. There are established values of working time for passenger travel, based on the cost of employing workers, (which reflects the wage rate and an overhead.), but for business travel the alternative of empirical estimation is to be preferred. For passenger travel in non-working time, values based on analysis of revealed or stated preference data and disaggregated in a number of dimensions such as purpose, trip length and degree of congestion, are needed. There is evidence that inter-urban travel is valued more highly than urban travel, on which most of the values of time are based. Time spent in road congestion is also valued more highly. For rail and air public transport the appropriate values for delay/late and wait time are also required.

For freight transport the value of time should cover not just drivers' wages and operating cost savings, but also the value to the consignor of receiving the goods more quickly and/or reliably. Freight values of time vary by commodity and other relevant factors, although a simple mean will often suffice.

A comprehensive survey of the evidence on values of time for passenger and freight traffic, including all the separate values discussed above, is given in PETS deliverable D7 (See Annex B).

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ANNEX A: EXAMPLES OF SPEED FLOW RELATIONS AND CONGESTION COSTS

A.1 Speed-Flow Relationships

This annex gives examples of speed-flow relationships for inter-urban motorways. These relate to Austria, Germany, the UK and the USA.

A1.1 Austrian Example (from DIW et al, 1998)

The following formula was referenced in DIW et al. 1998:

$$V = v_k + (v_G - v_k) * (1-a)^\alpha$$

with: a traffic volume / capacity

v_k speed, if a --> 1:

dual carriage way	55 km/h
normal road	50 km/h if > 3.00 m lane width
	45 km/h if < 3.00 m lane width

v_G speed, if a --> 0

A1.2 Example of Speed-Flow Relationships from the German EWS Manual³

The function that relates to car speeds in free-flow conditions can be expressed as:

$$V_p = c_0 + c_1 * \exp(c_2 * (Q_p + 2 * Q_G))$$

where:

- V_p : Speed passenger car
- Q_p : Flow passenger car
- Q_G : Flow heavy goods vehicle
- c_0 : Constant, depending on road type, gradient and curvature
- c_1, c_2 : Constant, depending on road type ($c_1 < 0, c_2 > 0$)

³ EWS (1997) Forschungsgesellschaft für Straßen- und Verkehrswesen, 1997: *Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Strassen (EWS)*. Aktualisierung der RAS-W '86, Köln, 1997. This text provided by Michael Schoch, IWW, Karlsruhe University).

The slope of this function, a fundamental part of the marginal external congestion cost function is then given by:

$$dV_p/dQ_p = c_1 * c_2 * \exp(c_2 * (Q_p + 2*Q_G))$$

A1.3 UK COBA Curves

This was the type of relationship adopted in the DIW et al (1998) study. It is referenced in PETS D7 (1998), from which the following text comes. The following examples relate to light vehicles only.

➤ **Speed of a light vehicle on a two-lane motorway.**

The speed-flow relationship provided by COBA is of the form $v = a - \beta q$. When the flow level is less than 1200 veh/hour/lane the following expression provides speed:

$$v = 107 - 0.006 Q$$

The discontinuity point is given at $Q=1200$ veh/hour/lane. When flow levels are higher than 1200 vehs/hour/lane then

$$v = 139 - 0.033 Q$$

Note that flow Q in this relationship is measured in vehs/hour/lane, and speed v in km/hour`.

Table A1.1: Parameters of the Speed-Flow Relationships for Light vehicles

Type of Road	Q _B (veh/hour/lane)	Constant a before Q _B	Constant a after Q _B	β before Q _B	β after Q _B
Rural single carriageways	80% of capacity ¹	77	-	0.015 ²	0.050 ²
All-purpose dual carriageways	1080	Two lane: 103 Three lane: 110	Two lane: 132 Three lane: 139	0.006	0.033
Motorways	1200	Two lane: 107 Three lane: 114 Four lane: 114	Two lane: 139 Three lane: 147 Four lane: 147	0.006	0.033

¹ The capacity of rural single carriageways depends on road width and the percentage of heavy vehicles.

² Assuming a 15% of heavy vehicles.

A1.4 USA Freeway Estimates (Highway Capacity Manual, 1994)

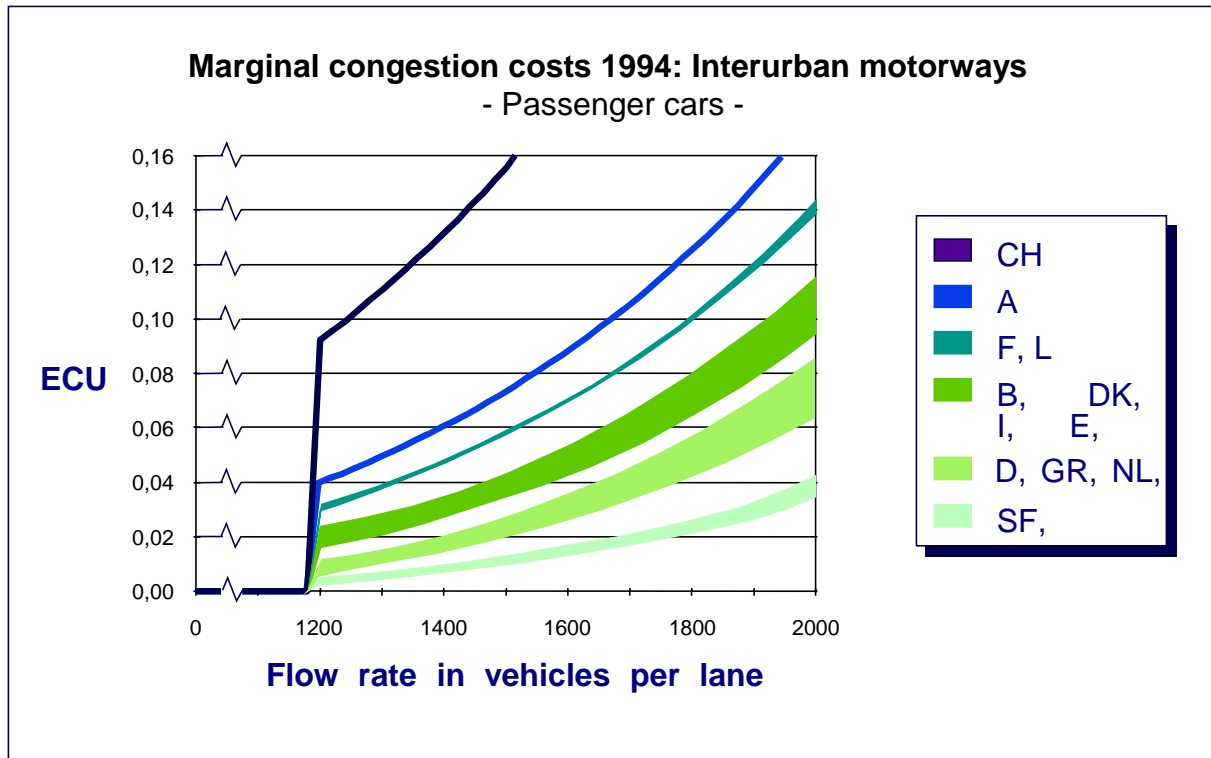
For basic freeway sections, the manual gives speed-flow curves which are characterised by:

- flows from zero to around 75% of capacity - a very flat, almost linear;
- flows from around 75% of capacity – non-linear, with slope increasing;

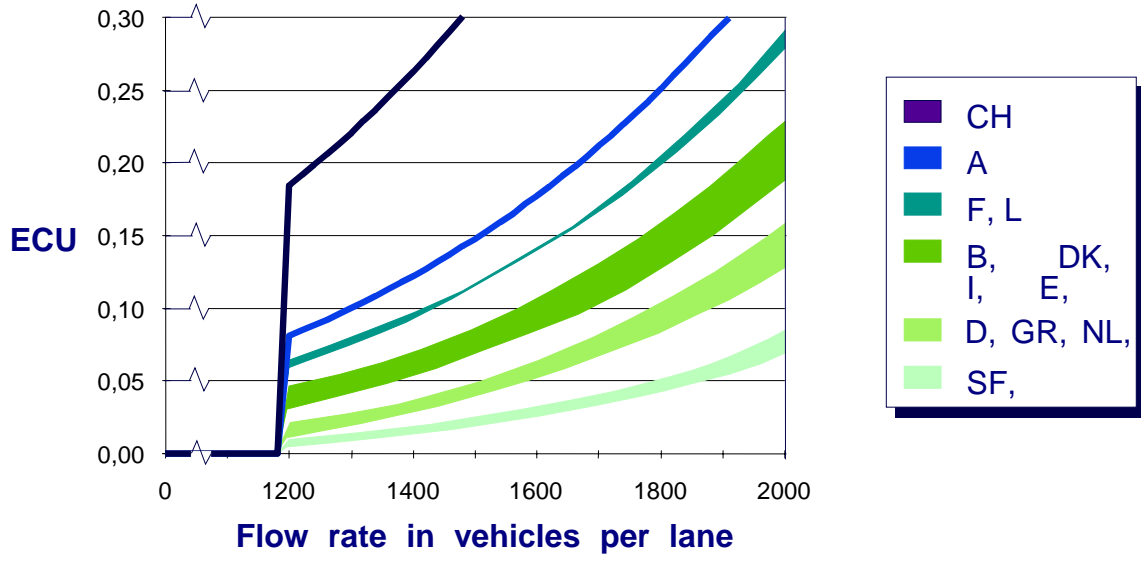
A2 Examples of Marginal External Congestion Charge Estimates

A2.1 Estimates for different European Countries (DIW et al, 1998)

The DIW et al (1998) study made use of the UK COBA speed-flow relationship, and in estimating the marginal external congestion costs took account of variation by country in the value of time and other key attributes such as road capacity.



Marginal congestion costs 1994: Interurban motorways
- Goods vehicles -



:

A2.2 USA Estimates, for 2000 (HCAS, 1997⁴)

The following table summarises values estimated for 2000 (cents per mile). It provides a clear indication of the range of variation in charges with:

- type of vehicle;
- type of road; and,
- high, medium and low levels of estimates (according to traffic volume).

	Rural Highways			Urban Highways			All Highways		
	High	Middle	Low	High	Middle	Low	High	Middle	Low
Automobiles	3.76	1.28	0.34	18.27	6.21	1.64	13.17	4.48	1.19
Pickups and Vans	3.80	1.29	0.34	17.78	6.04	1.60	11.75	4.00	1.06
Buses	6.96	2.37	0.63	37.59	12.78	3.38	24.79	8.43	2.23
Single Unit Trucks	7.43	2.53	0.67	42.65	14.50	3.84	26.81	9.11	2.41
Combination Trucks	10.87	3.70	0.98	49.34	16.78	4.44	25.81	8.78	2.32
All Vehicles	4.40	1.50	0.40	19.72	6.71	1.78	13.81	4.70	1.24

⁴ Federal Highway Cost Allocation Study (1997)

ANNEX B: TYPICAL VALUES OF TIME (PETS D7)

PETS D7 quotes the following values of working time. However, these are based on the wage rate, and should not be used for business travel for the reasons discussed above.

Country	Value†	Country	Value†	Country	Value†
Belgium	23.06	Ireland	18.69	Spain	11.15
Denmark	20.81	Italy	22.60	UK	17.63
France	26.44	Luxembourg	21.40	Finland	20.36
Germany	26.44	Netherlands	21.45	Sweden	22.92
Greece	6.90	Portugal	5.54	Average	21.02
Norway	18.4 ECU (152.50 Kr): Source Handbook 140, Public Roads Administration Norway				

† Figures were updated taking into consideration changes in GDP in the 15 countries of the European Union and the rates of inflation published by the OECD

For non working time, most empirical evidence suggests values of the order of 25% of the wage rate. There is evidence that inter-urban travel is valued more highly than urban travel, on which most of the values of time are based., with typical evidence suggesting that the value of time should be increased by 60%.

Time spent in road congestion is also valued more highly, with evidence suggesting that 'congested time' for passengers only is valued at 150% of normal time. For rail and air public transport estimates of the appropriate values for wait time, departure time shifts and late time are also recommended.

For freight transport the value of time should cover not just drivers' wages and operating cost savings, but also the value to the consignor of receiving the goods more quickly and/or reliably. Typical studies suggest that a value of around 37 ECU's per hour should be used for LGV's. The value of time for HGV's appears to be 10% more, ECU per hour, whilst the value of time for rail should be only 25% that for LGV. If the proportion of the driver costs of these recommended values can be established, then different values across countries can be used according to variations in drivers' wage rates. Freight values of time by commodity are also given.

Reliability is generally highly valued by freight operators. Evidence was found that a value of reliability (defined as a percentage of on time arrivals.) of 5% of the freight rate for a 1% improvement in reliability index used in Tweddle et al. (1995) was appropriate. The indices which most closely relate to the situations prevailing before and after the increased congestion would be used.