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UNITE Case Studies 7A to 7D: Inter-Urban Road and Rail User Costs

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Executive Summary

1. Goal and Structure of the Paper

The present paper presents the case studies 7A to 7D on marginal social user costs of inter-urban road and rail transport of the UNITE project. The aim of these four case studies is to describe and quantify the driving factors of congestion on a functional basis and to demonstrate the impact of marginal social cost pricing at four Trans-European corridors. Each of those corridors represents one of the case studies 7A to 7D. For each of the case study corridors a market segment, on which the investigations will focus, is defined. Table S-1 gives an overview of the four corridors and their definition.

Table S-1: Case Study Descriptions

Case Study	Corridor	Transport Market
7A	Paris – Brussels	Passenger transport
/b	Paris – Munich	Passenger transport
7C	Cologne – Milan	Container freight transport
7D	Duisburg - Mannheim	Bulk goods transport

The paper is structured in three parts:

- The functional analysis of the influence of various cost drivers on welfare-optimal road user congestion charges.
- The application or the selected model of congestion costs to the four case study corridors 7A to 7D.
- The investigation of rail traffic congestion.

2. Methodology

In road transport congestion costs are calculated by a modified version of the European multi-modal network model VACLAV. The model allows a multi-user assignment of congestion costs to passenger cars and HGVs according to their specific cost functions, values of travel time and demand elasticities. The user cost functions are composed of the speed-flow curves and fuel consumption functions of the German manual for road investments (EWS). The value of travel time per passenger car hour was set according to the UNITE values of time per passenger and travel purpose in combination with an average European car occupancy rate, an average mix of travel purposes and national adjustment factors. Values of time per HGV are given directly by the UNITE valuation conventions. Values of demand elasticity are estimated per country on the basis of available results of the VACLAV model and considerations of the users' time and destination choice.

Marginal social user costs in rail transport were determined on the basis of a database on train movements, delays and passenger trips of January 2001 in Switzerland. Out of this database it was possible to estimate a linear relationship between the number of passenger trips per hour and the average train delay. The marginal External user costs then were determined in the common manner as a liner function of the number of trips, the coefficient between trips and average delay and the value of time. For the valueation of delays two models were considered:

- Model 1 takes all delays against the scheduled arrival of trains into account.
- Model 2 considers only delays equal and above 5 minutes against scheduled arrival.

In both models the value of time was increased by 50% in the case of delays of five minutes and more compared to normal travel or small delays.

3. Results

In the first part of the paper, functions of welfare-optimal congestion charges in road transport have been determined by computing the equilibrium of traffic demand and marginal social user costs of a single road link. For a two lane motorway with a HGV-share of 15% and a demand elasticity of -0.35 congestion charges of 0.15 Euro / km for passenger cars and 0.34 Euro / km for HGVs were found. These have been checked against the following driving factors:

(1) Road type or speed-flow function.
(2) HGV share and.
(3) The demand elasticity.

Among these, the demand elasticity is found to have the greatest impact on the level of congestion charges for all vehicle types. The impact of the HGV-share and the road type are only considerable for congestion costs of heavy traffic. Table S-2 presents the variations in congestion charges found for the three driving factors.

Table S-2: _Variations of congestion costs by cost driver

	Maximum congestion costs for passenger cars (Euro / km)	Congestion costs for HGVs (Euro / km)
Standard conditions: (2-lane motorway, HGV-share: 15%, Elasticity: -0.35)	0.15	0.35
Variation of road type: (2-lane rural road - 4-lane motorway)	0.15 - 0.16	0.48 - 0.33
Variation of HGV-share: (p = 10% - 30%)	0.15 - 0.15	0.32 - 0.72
Variation of demand elasticity: (Eta(P) = Eta(G) = -0.1 - -1)	0.26 - 0.10	0.61 - 0.20

The congestion functions have been applied to the four case study corridors 7A to 7D presented in Table S-1, were 7A and 7B focus on passenger transport and 7C and 7D focus on goods transport. Network definition, demand data and demand elasticities are based on the European network model VACLAV. For each corridor, average user costs and optimal congestion charges have been computed for several departure times.

Table S-3 summarises the congestion costs for passenger cars (corridors 7A and 7B) and for HGVs (corridors 7C and 7D) for different departure times.

Table S-3: Summary results by corridor for different departure times

Corridor and considered vehicle class	Average marginal external costs by departure time (Euro per km)			
	6:00	08:00	14:00	20:00
7A: Passenger car Paris - Brussels	0.12	0.10	0.19	0.01
7B: Passenger car Paris - Munich	0.14	0.16	0.03	0.00
7C: HGV Cologne - Milan	0.58	0.52	0.47	0.04
7D: HGV Duisburg - Manhheim	0.83	0.78	0.89	0.16

The main findings from the corridor application are:

- Congestion charges vary strongly with the departure time. For journeys during night-time congestion charges for passenger cars might be reduced by 95% or even 100% compared to daytime travel. For HGVs a reduction of charges during the night up to 90% was found

- In most cases of passenger travel congestion pricing reduces the travel costs perceived by car users significantly (up to 25%). However, in some cases of passenger travel and in all cases of freight transport travel costs increase after the introduction of congestion pricing due to network effects.

For the two models of delay valuation, in Swiss rail passenger transport Table S-4 presents the main results:

Table S-4: Summary of results for rail congestion costs

Time period		External congestion costs (Euro / trip)	
		Model 1: consideration of all delays	Model 2: Delays >5 min. only
Before morning peak	06.00-06.59	0,0361	0,0149
Morning peak	07.00-07.59	0,0942	0,0388
Noon	12.00.12.59	0,0334	0,0138
Afternoon peak	17.00-17.59	0,0950	0,0391
Evening	20.00-20.59	0,0248	0,0102
Night	23.00-23.59	0,0145	0,0060

Average	0,0321	0,0132

- For model 1 (all delays), congestion externalities of .010 Euro per trip in the morning and the afternoon peak are calculated. In the off-peak period the marginal external user costs range around 0.03 Euro per trip.

- Model 2 (only valuation of delays above 5 minutes) delivers congestion externalities of roughly 40% of those presented by Model 1. This ratio is pre-determined by the ratio of the coefficient *b* of the delay curve and thus holds for all times of day.

4. Generalisation

Under the condition, that the functional form of the German EWS speed-flow relationships is considered as valid, the welfare-optimal congestion charges of road transport derived in this paper are considered to be transferable between different local contexts. However, a number of influencing factors need to be considered. These are:

- The demand elasticity needs to be set very carefully by considering all possible travel alternatives of users (e.g. route choice, mode choice, flexibility in departure time shifts and the possibility for omitting trips). for this task, the consultation of network models is strongly recommended.

- The impact of varying HGV-shares and different road types on HGV congestion costs can be taken out of the sensitivity analyses presented in Table S-2 and Section 5.1 of this paper. In first order, the congestion charges for passenger cars are invariant against road types and varying HGV-shares.

- The value of travel time, which influences the level of congestion costs directly, can be transferred between geographical contexts as proposed by the UNITE valuation conventions. In addition, national compositions of travel purposes and vehicle load factors in passenger travel need to be considered.

In case other speed-flow functions than the presently used German EWS functions are to be taken as a basis for the calculation of marginal congestion costs a generalisation of the present results is not possible. Different speed-flow functions will strongly impact the slop and the level of congestion costs and the ratio between congestion costs of HGVs and passenger cars.

1 Introduction

1.1 Overview

The present paper presents the case studies 7A to 7D on marginal social user costs of inter-urban road and rail transport of the UNITE project. The aim of these four case studies is to describe and quantify the driving factors of congestion on a functional basis and to demonstrate the impact of marginal social cost pricing at four Trans-European corridors. Each of those corridors represents one of the case studies 7A to 7D. For each of the case study corridors a market segment, on which the investigations will focus, is defined. Table 1 gives an overview of the four corridors and their definition.

Table 1: Case Study Descriptions

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7A	Paris - Brussels	Passenger transport
/b	Paris - Munich	Passenger transport
7C	Cologne - Milan	Container freight transport
7D	Duisburg - Mannheim	Bulk goods transport

The four case studies are presented jointly in a single paper as they are based on a common methodological framework and thus, a separate presentation would imply a great number of repetitions.

1.2 Goal of the Case Studies

The determination of marginal social congestion costs under current traffic conditions and in the equilibrium of demand and supply (optimality condition) is well examined in theory and demonstrated in very many model calculations. Nevertheless, the effect of a number of cost drivers - in particular the mutual disturbance of different vehicle types - is sometimes ignored. Thus, the first goal of the present series of case studies is to identify these cost drivers and to estimate their influence on the slope and the level of marginal social congestion costs.

The second goal of the present paper is to demonstrate the variation of external congestion costs in time and location along selected Trans-European passenger and freight corridors. The paper is clearly focussed on road transport, as detailed data on marginal cost functions of rail transport is not available for the corridors investigated. Rail transport can be investigated for Swiss passenger services only.

The third goal of the paper is to demonstrate the impact of a congestion pricing system, which is based on external marginal cost prices on a particular traveller or haulier along the selected corridors. It will be investigated to what extend and under which circumstances traffic will shift from one mode to another and what this will mean for the resulting social costs for the society and for the affected user. The output of this analysis is expected to provide a basis for estimating in advance the reactions of winners and losers generated by the introduction of marginal social congestion prices.

Bringing these three goals under one umbrella it can be formulated that the visualisation of the effects of congestion pricing depending on various input parameters is the central goal of the present series of inter-urban user cost case studies. To achieve this goal, link-based as well as corridor-based calculations and sensitivity test are carried out by applying the functional definition of the inter-urban traffic model VACLAV.

1.3 Structure of the Paper

Chapter 2 of the present paper contains a theoretical introduction into the nature of congestion costs in road and rail transport. Further the chapter enumerates the various driving factors of private and social travel costs and identifies those, which will be examined in more detail throughout the Case Studies 7A to 7D.

Chapter 3 gives an overview of the basic methodology and of the modelling framework applied for the examination of link-based effects and the computation of corridor-specific results.

Chapter 4 contains a description of the corridors investigated and of the data used.

Chapter 5 presents the results for single road segments as well as for the corridors as a whole. In the first case the chapter describes the influence of various driving factors on the level of congestion charges, while the corridor results take the viewpoint of a particular traveller of haulier driving along the whole corridor.

Chapter 6 finally summarises the results, gives and interpretation of the level of congestion-based user charges and an analysis of potential user reactions on their introduction. Special emphasis is put on the question of generalisation of results for different spatial locations and traffic patterns.

2 Theoretical Background

2.1 The Role of Marginal Social Congestion Costs

In the recent discussion on transport externalities there is a common agreement that congestion costs must not be added up with other "classical" externalities in order to produce an all-embracing value of the external costs of transport. The reason for this special role of congestion twofold: First the definition of total congestion costs is different from cost categories such as air pollution or noise. Second, congestion is a mainly system-internal problem, while classical externalities such as noise, air pollution or accidents are affecting third parties and consequently are system-external.

Total social congestion costs are an artificial measure of ineffective infrastructure use, which can only be based on theoretical reflections on marginal social cost functions rather than on the physical measurement of economic or social damages. There is a number of approaches existing, which can either not be entitled as scientific measures or which conclude with figures which are useful, but do not describe congestion effects. The first category are engineering-style calculations like the total costs of users above a particular (arbitrary) level of road quality, but these costs are mainly user-internal and hence not relevant for pricing. Examples for interesting and useful figures in the light of traffic congestion are the revenues, which need to be collected in order to reach the optimal level of demand Q^* or the scarcity costs of infrastructure, which describe the production losses of economy due to the non-availability of transport options due to congestion.

Marginal user costs are the basis for any economic determination of congestion costs or congestion-cost based user charges. Thus, the investigation of marginal social user costs and of its driving factors is decisive for setting up a welfare-optimal pricing system. The nature of marginal user costs can be described as follows:

When the density of traffic is increasing, vehicles start to disturb each other and possible travel speeds are decreasing which is resulting in increasing time and operating costs. While individuals usually only consider their private cost function, they do not take into account the additional costs they impose on others when they decide to enter a non-empty system. These unconsidered effects are called **marginal external congestion costs** and are determined by the users' private operating costs as a function of traffic density. The sum of (internal) private operating costs a user bears and the external costs he imposes on others is entitled as **marginal social** costs (upper curve in Figure 1).

When the marginal external congestion costs are levied on the users, then traffic demand will react by shifts in travel time, routes, modes or by omitting less important trips. As traffic volumes decrease, also the marginal external costs and hence the internalisation charge are declining and respectively a part of the displaced traffic demand will return to its former behavioural pattern. The resulting equilibrium (*Q** in Figure 1) is called the **optimal traffic demand** and the respective marginal external costs is the **optimal user charge**.

According to economic welfare theory, the total costs of traffic congestion are defined by the cumulated difference between the marginal social (private plus external) user costs and the willingness of users to pay for a particular level of infrastructure quality of that traffic demand, which is exceeding the optimal level *Q**. This measure (which is depicted by the grey area ABC in Figure 1) is entitled as the **dead-weight loss** of infrastructure use, which is considered as the only correct economic definition of congestion. It can be interpreted as the loss in social efficiency because we are not using the existing infrastructure properly (Prud’home 1998).

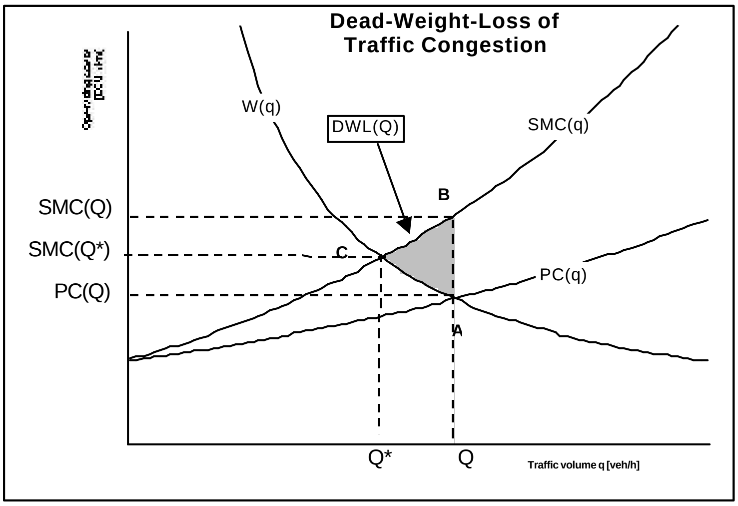

Figure 1: Economic definition of total congestion costs (Source: INFRAS/IWW 2000)

This definition of congestion implies, that those means of transport, where the allocation of infrastructure is planned by a higher instance are not subject to congestion in the above definition (INFRAS/IWW 2000). It can be argued, that in scheduled transport the network operators (railway track operators or Air Traffic Control) are totally aware of the effects, which an additional train or aircraft has on the whole network. Thus, there are no user-external effects which could be internalised by a congestion charges.

However, this is a bit too simple. Slots in rail and air are not requested by the operator, but by transport companies on demand of their customer. The operator only supplies slots according to pre-defined rules. In this chain of demand and supply it will in practice not be possible to identify all impacts caused by an additional unit of demand. Consequently, some kind of congestion charges on scarce slots could well improve the efficiency capacity demand by the transport companies.

2.2 Determinants of Road Traffic Congestion

Although road transport allows a much more simple estimation of marginal social external congestion costs than rail (or scheduled transport in general) does, a number of cost drivers need to be considered. The following determinants of road congestion costs shall be examined in more detail here.

- User Cost Functions.
- Demand curves
- Capacity demand factors
- The Value of Travel Time

2.2.1 Supply-Side Cost Drivers

2.2.1.1 The role of the shape of user cost functions

The estimation of a Pigu-style optimal user charge requires the existence of monotonic, user cost curves. Ideally, user costs are a convex increasing function of traffic density, while demand is a convex falling function of average costs. In this case we find the situation depicted in figure 1, were we have only one intersection between demand and supply. Accordingly, a computable general equilibrium between demand and supply, and thus a optimal congestion charge, exists.

However, user cost functions do not necessarily have to be convex and steadily increasing. An example for a concave cost function would be traffic noise. Caused by the logarithmic relation between traffic volume and noise levels (in dB(A)) each additional vehicle will have less impact on the total noise exposure level alongside traffic infrastructure than the previous one. In Christensen (1998) it was shown, that even it we value the exposure level with an exponentially increasing cost function, the marginal external costs per additional vehicle in road traffic is declining. The result of marginal social cost theory applied to noise effects then is, that if we have to add an additional traffic unit, we should put it on an already loaded peace of infrastructure. This makes sense when we consider peoples' sensitivity towards noise disturbance in quiet residential areas or at night, when traffic activities are low. However, this outcome is contradictory to congestion prices, which are highest when infrastructure is fully loaded.

The monotonic growth of the user cost function is not necessarily a pre-requirement for the applicability of the marginal social cost pricing theory. To demonstrate this, we consider a public transport system, were supply is adopted to the current level of demand. Here, the service quality, the average waiting time of passengers due to higher frequencies or even the average fares per passenger might decrease when new passengers user the system. In this case, additional traffic units would cause benefits to others. The theoretical background of this concept was first described by Mohring (1972) in the context of urban bus transit and was further developed by Jansson (1984). In the terminology of social welfare theory, an optimal condition is received by paying a subsidy to the users in order to make more of them use the system and thus cause more benefits to everyone. However, increasing costs for the system operator for extending his services beyond a particular level of quality will put an end to this development. Besides the fact that in practice it is not possible to determine the entrepreneurial costs associated with the extension path o the operator, in the case of economies of density we run into the problem that there might be multiple intersection points between the demand and the supply curve. Thus, a unique optimum does not necessarily exist (Neuenschwander, 1990). An in-depth discussion of the Mohring effect in the case of Swedish rail transport is presented in the case study 7G.

2.2.1.2 Supply curves and marginal social cost functions

Supply curves describe the dependency of average user costs from the level of demand. Therefore, we also talk of private - or average cost functions *AC(Q)* of the traffic volume (or demand) *Q*. In individual road transport, *AC(Q)* is composed of users' time costs, fuel costs and other vehicle operating costs. The latter is usually neglected as there costs are not directly perceived by perceived by the users. Time and fuel costs per kilometre vary both with travel speed and thus with the quality of capacity supply. In scheduled transport services we need to consider the dependency of access- and waiting times with service quality in addition.

If we simplify the term "user costs" and consider time costs only, the supply curve is determined by the value of travel time and the speed-flow relationship. Marginal social user costs then are computed by deriving the quotient of the Value of Time (VOT) and the travel speed (v(Q)) with respect to traffic volume Q. Formally we get:

$$MC(Q) = \frac{\partial \frac{VOT}{v(Q)}}{\partial Q} = -\frac{VOT}{v(Q)^2} \cdot \frac{\partial v(Q)}{\partial Q}$$

Accordingly, the shape of the speed flow relationship determines the slope and the level of the marginal social user costs. To illustrate this, Figure 2 presents three different speed-flow relationships and the corresponding marginal social user costs. The selected speed-flow relationships are:

- The official German EWS speed-flow curve for a motorway with 3 lanes per direction and separated carriageways.
- A TRENEN-style function, were the travel time is expressed by a simple exponential function of traffic volume.
- A linear relationship between travel speed and traffic volume.

In all cases it is assumed that - even under heavy congestion - a minimum speed v_{end} = 20 kph is maintained. This attribute is justified when of speed-flow curves are assumed to express average travel speeds observed over a non-infinite time interval or a longer stretch of road. In other words: Even under the most severe congestion vehicles will carry on driving after a particular time and in many cases not the total length of a road segment will be captured by congestion. The latter statement in particular holds true for long segments of inter-urban roads.

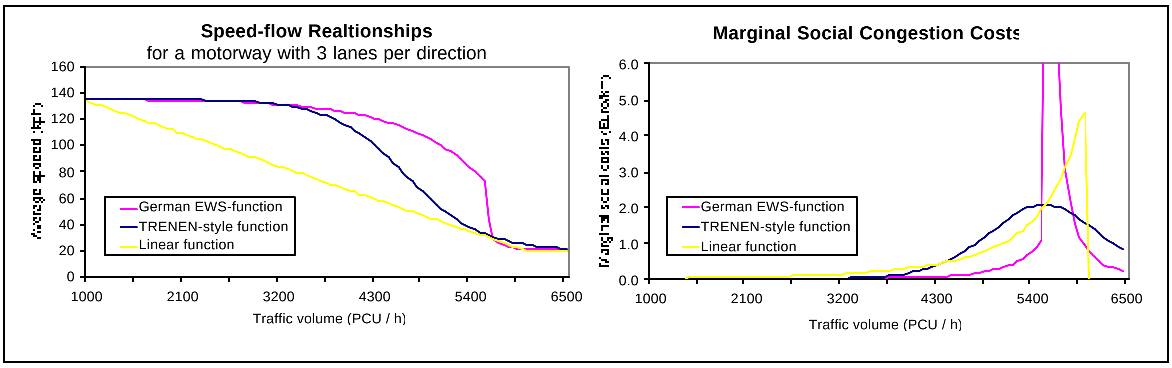

Figure 2: Speed-flow relationships (left) and marginal social user costs (right)

Figure 2 illustrates, that the non-continuos slope of the EWS speed-flow functions cause an extreme increase in the marginal social congestion costs in the transition phase from fluent driving conditions to stop-and-go traffic. The most moderate slope of the marginal social costs is shown by the TRENEN-style curves. The reason for this behaviour is, that the TRENEN-curves smoothly approach the minimum speed. Contrasting this, the marginal cost function derived from the linear speed-flow relationship increases with Q^2 in order to instantly fall back to zero when the minimum speed v_{end} is reached.

In all three cases the marginal social cost functions fall back to (or approach -) the x axes because of the assumption of a non-zero minimum travel speed $v_{end}>0$. If we would allow the speed-flow curves to decrease to zero, of course the marginal social time costs would get infinite. Thus, the existence of a minimum speed is a very strong and decisive assumption for the level of congestion costs.

As will be elaborated in the sections below, the right segment of the speed-flow curves, where travel speed rapidly falls in order to approach a minimum travel speed are hardly predictable and thus of questionable value for the determination of marginal cost based user charges. The minimum travel speed will strongly vary with small changes in the users' driving behaviour and in the length of the time interval used to determine the speed-flow curves. In order to avoid such uncertainties, the British COBA-manual uses an liner trend to describe speed-flow characteristics to be used in transport models beyond the transition from fluent traffic to congestion. As this approach can be criticised being too pragmatic, it will be concluded in the following sections, that only the deterministic left part of the speed-flow curves are considered to det4ermine martinal-social costs of traffic congestion.

The practical relevance of the speed and cost curves shown in Figure 2 are discussed briefly in turn:

The linear relationship between traffic demand on a particular link and the resulting travel speed represents a very pragmatic engineering approach. The assumption behind such type of cost functions is, that roads have got a fixed capacity, which is approached equally by adding a single traffic unit, regardless of the underlying traffic situation. The travel speed according to the linear speed flow relationship takes the form:

$$v_{Linear} = a - b \cdot Q$$

Were a and b are model parameters. Although there is no empirical evidence for a linear dependency of travel speed and road occupancy, this functional form is applied in a number of European studies (e.g. the PETS project, Christensen et al. 1998). Linear functions are also used for cost-benefit analyses in the UK and to derive recommended levels of road user charges in the reports of the High Level Group on transport pricing of the European Commission (Nash, Sansom 1999).

In the TRENEN model (Proost and Van Dender 1999) average user time costs AC(Q) are described by a exponential function of traffic volume, which takes the following form:

$$AC(Q) = a + b \cdot \exp(c \cdot Q)$$

The speed-flow functions derived out of this form are computed by VOT/AC(Q). This function approaches zero for traffic volumes Q increasing beyond the infrastructure capacity. In order to come closer to the EWS functions we have added a minimum speed v_{end}, which results in the following definition of the TRENEN-style speed-flow functions:

$$v_{TRENEN}(Q) = \frac{1}{a + b \cdot \exp(c \cdot Q)} + v_{end}$$

This functional form takes into account, that the level-of-service due to an additional vehicle is only decreasing slowly in the case of low traffic volumes, but is decreasing drastically when the road occupancy is close to its capacity limit. Accordingly, the external marginal social costs of an additional traffic unit remain close to zero until a particular level of capacity use and rises to its maximum level when traffic conditions get worse. In case of $v_{end}=0$ the marginal user cost function rises to infinity if Q is increased beyond the capacity limit. Otherwise, if v_{end} is positive, the marginal cost function falls to zero.

The advantage of the TRENEN-style speed-flow relationships are, that their slope represents observed speed-flow relationships much better than the linear function. Moreover, the TRENEN-style functions are defined by a simple mathematical expression with a small number of parameters to be estimated. This feature is very convenient for the derivation of cost functions and for modelling purposes.

The EWS speed flow curves, which are appl8ied to cost-benefit analyses in Germany are defined for 24 road types on the basis of traffic observations. The are defined in three parts:

- Part 1: Traffic conditions from free flow to beginning mutual disturbance of vehicles.
- Part 2: Transition from beginning disturbance of vehicles to heavy congestion.
- Part 3: Constant speed from stop-äand-go conditions onwards.

For inter-urban roads the EWS manual distinguishes between speed-flow relationships for passenger cars ($v_P(Q)$) and for goods vehicles ($v_{GV}(Q)$). For motorways, the function of $v_P(Q)$ takes the following form:

$$v_{P,EWS}(Q) = \begin{cases} a_1 - a_2 \cdot \exp(a_3 \cdot s) - a_4 \cdot \exp(a_5 \cdot Q) & \text{for } Q < Q_1 \\ \coth\left(\left(Q - b_1\right) \cdot b_2\right) + b_3 & \text{for } Q_1 < Q < Q_2 \\ v_{end} & \text{for } Q > Q_2 \end{cases}$$

$v_{P,EWS}(Q)$: Speed of passenger cars (kph).
Q : Traffic volume (passenger car units / hour).
Q_1 : Transition from fluent to disturbed traffic conditions.
Q_2 : Transition from disturbed to stop-and-go traffic conditions.
v_{end} : Average speed under stop-and-go conditions.
a_i, b_i : Model parameters
s : Gradient

The speed-flow relationships for goods vehicles and for passenger and goods vehicles on rural and urban roads look slightly different. on urban roads a unique function is applied for all vehicle types.

The general shape of the EWS functions is the same as that of the TRENEN-style cost functions. However, due to the partial definition the function can not be derived by traffic volume at the transition phase from fluent to congested driving conditions. In the left part of Figure 2 this point of discontinuity of the EWS-functions for 6-lane motorways is at $Q1=5600$ *PCU/h*. At this traffic volume the marginal cost function makes an extreme peak. For optical reasons this peak is cut off in the right graph of Figure 2.

2.2.1.3 The dynamic aspect

Traditional speed flow relationships can only give a static explanation of the interdependency of infrastructure occupancy, measured in vehicles passing a specific point per hour, and the possible travel speed. In these models it is assumed that the relation between traffic volume and speed is unequivocal and that (under which conditions ever) total demand for using infrastructure capacity can be satisfied. It is an old and common knowledge in traffic engineering science, that these simplifications do not hold true in practice. In the subsequent paragraphs it will be verified, whether or not for the purpose of determining optimal congestion tolls, the application of traditional speed-flow relationships is admissible.

First, we need to start from the consideration that there is a difference between present (or momentary) demand Q_D for passing a particular point and satisfied demand or the momentary throughput Q_S. Both are measured in vehicles (or passenger car units) per hour. The demand, which can not be satisfied instantly $Q_W = Q_D - -Q_S$ needs to queue and therefore holds on demanding in later time periods until it can be served. In order to determine correct marginal social cost prices, we have to look not only at the additional costs an extra vehicle causes to other users within the system, but also to the extra costs he (or she) causes to those, who want to enter the system.

The relevance of these queuing costs caused by an additional vehicle can be estimated as follows: If l denotes the length of the waiting queue (in km) and s the space occupancy per vehicle (in m) then the number of vehicles queuing $n = l*1000/s$. If further v is the speed in which the queue is served (in km/h) and VOT denotes the value of time per vehicle (Euro/h) then we can say that each vehicle behind the marginal one is delayed by dt = (s/1000)/v (in h), which is to be valued by VOT in order to receive the additional costs perceived by each of them. We assume that our marginal car is located in the middle of the queue, such that the number of affected vehicles is $n/2 = l*500/s$. The marginal external queuing costs MEC_{queue} finally are determined by subtracting the private queuing costs $(s/1000)/VOT$ from the social queuing costs. We receive:

$$MEC_{Queue} = \left(\frac{n}{2} - 1\right) \cdot VOT \cdot \Delta t = \left(\frac{l \cdot 1000}{2 \cdot s} - 1\right) \cdot VOT \cdot \frac{s/1000}{v} \approx \frac{l \cdot VOT}{2 \cdot v}$$

The örivate costs can be neglected for long queues, which simplifies the expression for MEC_{Queue} according to the right term of the previous equation. In a traffic jam of 1 km length and a average minimum speed of 20 km/h we receive a total time loss of 1.5 minutes for all users in common. With an average value of time of 13.0 Euro/PCU (used in Banfi, Doll et al. 2000) we receive marginal entrance costs of 0.33 Euro per vehicle.

In the traditional definition of marginal external user time costs, this queuing effect is not considered. The above estimate shows, that its monetary value is considerable. As the queuing costs directly depend on the length *l* of the traffic jam it could add a simplified representation dynamic component of traffic congestion to the static Pigou-style user charges.

2.2.1.4 Speed-flow curves under heavy congestion

One question still remains: What happens when and after traffic flow is breaking down and what does this imply for the determination of marginal social cost prices? The speed-flow relationships shown in Figure 2 show an extreme drop in veh8icle speeds in the transition phase from fluent traffic to congestion, but the curves are designed such, that traffic volume can be increased up to any desired level. Contrasting this, common engineering-style diagrams of vehicle flows and travel speeds as shown in the left part of Figure 3 show, that there *is* a maximum capacity of road space. In Figure 3 this capacity limit is labelled with Q_T, which means the point of transition of road conditions, were traffic flow breaks down and congestion starts.

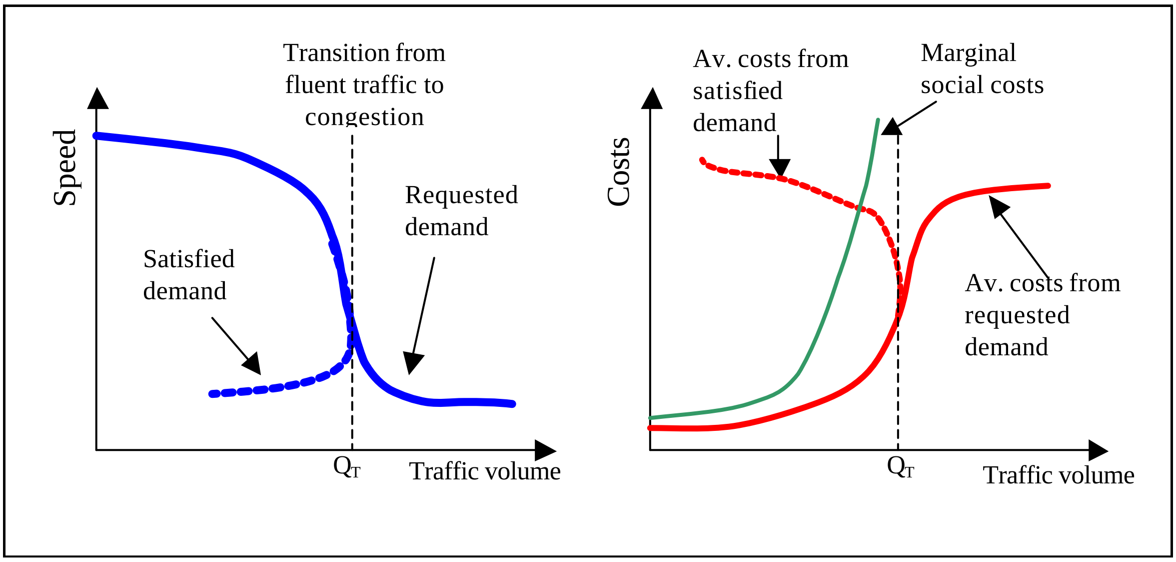

Figure 3: Scheme of a speed-flow relationship (left) and average / marginal social costs (right) for requested and satisfied demand for road space.

In general we can state, that near and beyond the maximum capacity Q_T of a road segment, speed-flow relationships are hardly predictable as traffic reacts extremely sensitive to small disturbances or irregularities. This indicates, that for the determination of cost-based road user charges only the predicable part of speed-flow relationships (for traffic volumes up to Q_T) are valid. This demand hoods true for the official German speed-flow-curves in FGSV (1997) in their first partial definition until Q_1. Beyond Q_1 the determination of cost-based congestion charges is not possible any more. In this segment of infrastructure occupancy demand-based prices are recommended. One could for instance imagine to define a minimum Level-of-Service, which is to be maintained by means of pricing.

The level and slope of optimal congestion charges will be analysed in Chapter 5.1 for various types of inter-urban roads, were each of them has its characteristic speed-flow relationship.

2.2.1.5 Capacity requirements by vehicle

In first order, the amount of road capacity occupied by each vehicle class determines its impact on all other vehicles and thus on the marginal external costs caused by it. As congestion curves show a convex slope in the part relevant for congestion analysis, the congestion externality of a vehicle is assumed to raise faster than the capacity demand. In other words: A double-size vehicle will cause more than 200% of the congestion costs of a single-size vehicle.

The question of capacity use is further closely related to traffic rules and driving behaviour. This statement is illustrated by the following common situation on motorways with two or more lanes per direction: The right lane is used by lorries and, in case of free capacity, by passenger cars. The left lane(s) instead are used by passenger cars only. Thus, the number of lorries on the road influences the available road capacity for passenger cars, but the volume of passenger cars is irrelevant for the speed of the lorries. This changes if lorries start to use the left lane(s). In case of urban roads, were we do not have a separation of vehicle types, all vehicle types influence each other according to their capacity demand.

For inter-urban roads, the effect of variations on the share of heavy traffic on optimal congestion charges will be determined in Section 5.1.2.

2.2.2 Demand-Side Cost Drivers

2.2.2.1 The Shape of the Demand Curve

The price elasticity of traffic demand is a direct determinant of optimal congestion charges as they result from the equilibrium of the demand-dependent user costs and the demand as a function of user costs. In other words: If traffic reacts in a very sensitive way on price increases the traffic volume, and thus the optimal congestion charges, will be well below the actual situation. If, in the other extreme, traffic does hardly react on higher costs, the optimal user charge will be close the current marginal external costs.

Different elasticities of demand with respect to user costs, and thus different gradients of the demand curve, are subject to sensitivity tests of marginal social user costs to be presented in Section 5.1.3

2.2.2.2 The Value of Travel Time

The level of external user costs is determined directly by the value of travel time. Especially for goods vehicles, which influence other goods vehicles as well as passenger cars, also the ratio of the VOT of both vehicle types is relevant. It is common practice to consider a mixed travel time (Euro per PCU), which already presumes a particular mix of travel purposes and vehicle types (compare e.g. Banfi, Doll, Maibach et al. 2000). The present paper follows this approach for the mix of travel purposes in passenger transport and types of goods transported in road haulage. However, goods vehicles and passenger cars are considered separately. The marginal external user costs caused by each of these user groups are determined my a multi-user assignment technique.

Apart from the consideration of different vehicle types, the paper does not carry out explicitly sensitivity tests of marginal user costs with respect to varying values of travel time. However, implicitly, differences in the VOT due to regional contexts are notified in the corridor studies presented in Section 5.2.

2.3 Congestion in Rail Transport

2.3.1 The Difference between Road and Rail

While the definition of marginal social congestion costs in road transport is more or less clear, the case is much more tricky for rail and for all other public transport services. Here, the interdependency between user costs and traffic demand is not clear from the start or is at least very difficult to be determined. The reasons for this inconvenient attribute of mass transport is:

- The interdependency of trains in a network is very high. Thus, delays along a particular line does not only affect the passengers in the delayed train, but also other trains possibly at very different parts of the network and after a long time.

- The most important component of user costs are additional waiting times and arrival delays. They are not only determined by the pure length of the travel time, but also by the shift of the travel time against a published schedule. Thus, the design of time tables itself strongly impacts delays and delay costs.

- Due to the danger of missing connections to other trains, flights or important meetings, user costs will not increase proportionally with train delays.

- Apart from the pure waiting time travellers will also value the comfort of travel, can be expressed in the availability of a seat. However, the value of these crowding effects have been determined in yet in detail.

- In the medium or long term, increasing delay costs might cause positive effects on the users in case the operator expands the density of service. This so-called ”Mohring effect” is subject to case study 7g.

- Train delays very often have multiple causes, of which many have nothing to do with the level of demand. The most important are bad weather conditions, accidents, technical problems, track maintenance and - very important - suicides. These effects, which might easily count up to 60% to 70% of all delays, must be eliminated from delay statistics for the purpose of determining marginal social user costs.

In IFRAS/IWW (2000) the existence of external marginal congestion costs in rail transport is denied with the argument, that the infrastructure operator is aware of the effects, which an additional train has on the whole system. Thus, delays caused by one train to others are willingly accepted and consequently they are not external. This holds true in the case of a single operator and of a user cost based framework of providing track access.

In most countries both re-conditions are not totally fulfilled. Following the EC directive 1991/440 in a number of countries companies for passenger, freight and local traffic are competitors for rail infrastructure and as such do not take into consideration the costs they cause for others when using an additional slot. Further, the provision of slots by the operator follows pre-defined rules, which are hardly based on a welfare optimisation of the whole system. Consequently, the existence of congestion externalities in rail transport can not be completely denied, but they must be treated with care.

If we say, that services are installed by the service operator on demand of his (future) passengers and if we further assume that those suffering from delays are not compensated either by ”their” operator or by someone else, also rail congestion can be considered as an interaction between users. The service operators do only determine the mechanism between additional demand and additional delays, wait time or crowding of vehicles. Unfortunately, due to the interdependencies scratched above, this mechanism is very complex. Figure 4 tries to summarise possible decision situations for the service operator and their effects on the user costs and benefits.

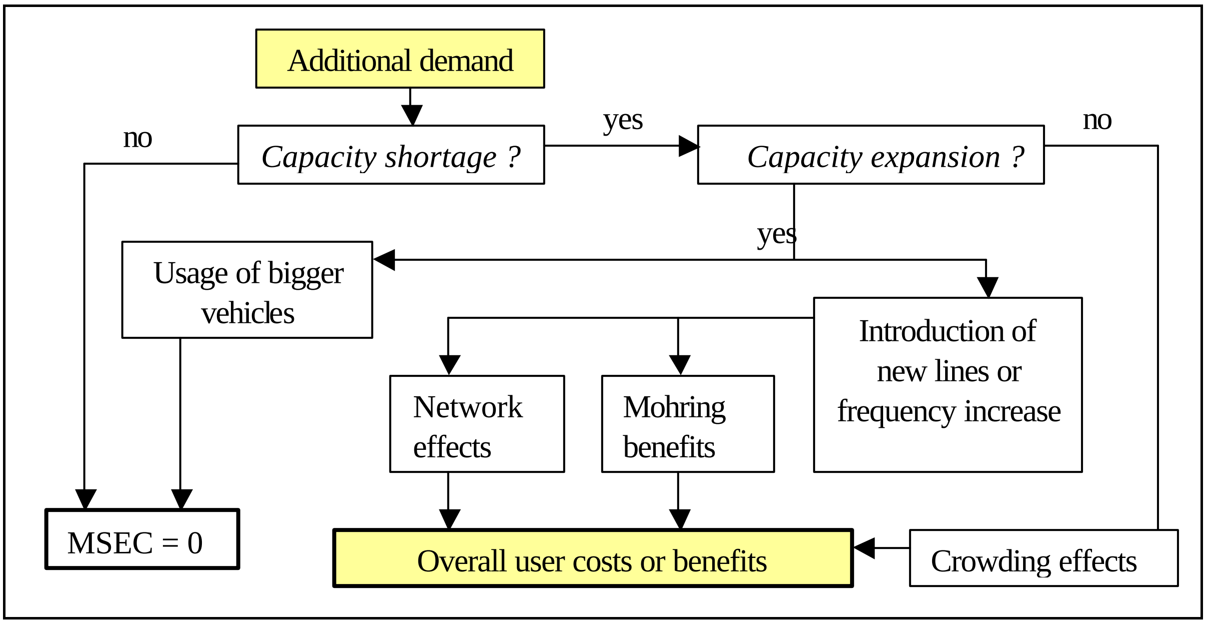

Figure 4: Simplified decision scheme of operators and the resulting user costs and benefits

2.3.2 Approach towards the Measurement of Rail Congestion

Within the present paper it is not possible to analyse the various effects presented in Figure 4 for the European or national rail networks in an analytical manner. Instead, a database on the development of train loads, the number of trips and delay probabilities in Switzerland will be used for a top-down estimate of marginal social user costs in rail passenger services.

Further, rail services are considered as an alternative to road and thus the costs of using rail and its service quality do influence the demand elasticity for road. This is considered in a qualitative way when defining the case studies (Chapter 4).

The most appropriate way of determining optimal congestion charges and their results would be to compute the equilibrium of demand and supply within an intermodal traffic network model. Even though this is not possible within the present series of case studies, from the perspective of a road user, who finds himself in front of a new situation due to the introduction of welfare-optimal congestion charges, the costs occurring for him when using rail instead of road, are of interest. In general the road users' decision problem can be formulated as follows:

- User your pervious route, pay the congestion charges and benefit from the improved traffic situation.
- Use another route, which is now more occupied than before the introduction of the congestion charges and

- Shift to public transport, which has enough capacity to handle the additional demand due to the increasing road costs.

The third bullet is a very strong assumption, which says, that the various types of user interactions drafted in Figure 2 do not exist. This might hold true for small changes in demand. As well as the saturation of the network capacity of alternative routes, the saturation of the carrying capacity of public transport services needs to be taken into consideration when changes in demand are big enough to influence the operators' decision situation.

3 The Modelling Framework

For road traffic, the modelling framework applied in the four case studies on inter-urban traffic is based on the IWW network model VACLAV (Schoch et al. 1998). For the UNITE project the model definition was extended in order to make it capable to compute the external marginal user costs different user groups in road transport impose on each other. The approach towards the consideration of a heterogeneous composition of road users in general follows the economic principles presented in Chapter 2 above; however, as it is a direct extension of the VACLAV model capabilities, the formal structure of the problem is worked out in Section 3.1.4 below.

The estimation of marginal social congestion costs in rail transport follows a different approach. Appropriate data is only available for passenger services in Switzerland. Thus, for rail transport the corridor approach can not followed. From a theoretical point of view this is not considered a problem as in rail transport the inter-dependency of different network parts is much more distinct than it is in road traffic. Thus, the network approach is preferred against a link- or corridor-based computation of marginal social congestion costs in rail transport. For rail freight traffic no information is available at present.

3.1 Specification of the Road Model

3.1.1 Overview

The modelling framework applied in the present series of case studies is a partly simplified and partly extended version of the IWW passenger transport model VACLAV.

”Simplified” because the general network has been reduced to the corridors Paris - Brussels (7A), Paris -Munich (7B), Cologne - Milan (7C) and Mannheim - Duisburg (7D). The simplification of the transport network database was necessary because additional functions for the calculation of user costs had been added (see below), which was not possible within the existing model shell. Thus, parts of the model had to be translated into Microsoft Excel.

”Extended” because an equilibrium-based computation module for optimal marginal social costs and respective traffic volume corrections for passenger and freight road traffic had been added to the model functionality.

For each link, the module successively calculates the current marginal social costs of an additional traffic unit and computes the traffic demand in the equilibrium of marginal social user costs and the users’ willingness-to-pay for (or willingness-to-accept) the resulting user costs. In the equilibrium process, two user groups, which are competing for the same infrastructure and which have different WTP functions and capacity demand requirements, are considered.

The modified model uses the following input data:

- Link-based information on road types and traffic volumes.
- Variation of traffic volume over day.
- Traffic demand elasticity, influenced by the travel alternatives available.
- Departure time of the traveller / haulier at the origin of the corridor.

Starting at the departure time set externally, the model goes along the road links of the corridors and computes travel time and marginal external costs in both, the current and the optimally priced situation. The time when the traveller / haulier then enters the succeeding link is determined by the travel time used so far.

3.1.2 Selection of Speed-Flow functions

In INFRAS/IWW (2000) as well as in the UNITE case studies 7A to 7D the official German speed-flow relationships (FGSV 1997) are used. These functions are defined for 24 road categories for passenger cars and for goods vehicles. As derived in the sections above only the first partial definition of these functions, which are composed of three partial functions, is considered as relevant for the determination of social marginal costs and thus for setting congestion tolls.

As mentioned above, the EWS speed flow functions consider the mutual influence of traffic volumes and travel speeds between two groups of vehicles: light vehicles and heavy traffic. As light vehicles are mainly composed of passenger cars they are entitled as group ”P” , while heavy traffic (goods vehicles and coaches) are entitled as group ”G” in the following text. For each group of vehicles a passenger car unit factor is given, which describes the relative impact of this group on its own travel speed and on the speed of other vehicle groups. Table 2 presents the mutual influence matrix of passenger and goods vehicles:

Table 2 : Mutual influence of travel speeds by vehicle group

Influencing vehicle group	Affected vehicle group	
	”P” (Passenger cars, vans)	”G”(HGVs, coaches)
”P” (Passenger cars, vans)	1	0
”G” (HGVs, coaches)	2	1

Table 2 is to be read as follows: The travel speed of passenger cars is influenced by both, passenger cars and goods vehicles, while the influence of goods vehicles is equal to the influence of two passenger cars. On the other hand, the speed of goods vehicles is not affected by the number of passenger cars.

3.1.3 Monetary Valuation

3.1.3.1 The Value of Time

The value of travel time used in the Case Studies 7A - 7D are set in accordance with the UNITE valuation conventions (Nellthorp et al. 2001). In passenger travel occupancy of vehicles and the mix of travel purposes is consistent with the assumptions of the German pilot accounts in Deliverable 5. For other countries respective information is currently not available. With the input data presented in Table 3 an average European Value of Time in passenger transport of 11.87 Euro/vkm is determined.

Table 3 : Input data for determining av average VOT in passenger tranpsrt

Travel purpose	European VOT per pass. hour (Euro/person-h)	Average veh. occupancy (Germany) (Persons/Veh.)	Share of vkm (Germany)
Business	21.82	1.20	0.18
Commuting	6.23	1.40	0.33
Private	4.16	2.10	0.49

In freight transport the average Euoprean Value of 43 Euro/vkm stated in Nellthorp et al. (2001) is used. The Values of Time in passenger and freight transport are transferred to the countries involved in the Case Studies 7A to 7D by the VOT transfer factors given in the UNITE valuation conventions. The resulting values of Time per country are shown in Table 4.

Table 4: Values of Time per country

Country	Adjustment factor	National VOT for p.cars	National VOT for HGVs
Germany	1.04	12.33	44.68
Belgium	1.07	12.69	45.97
France	0.95	11.32	41.02
Switzerland	1.22	14.52	52.59
Italy	0.97	11.54	41.80

These values are valid for uncongested driving conditions. In the case of congestion the commonly used multiplier of 1.5 is used to adjust the VOT. This factor is unique for all modes and countries.

3.1.3.2 Other operating costs

Load-dependent travel speeds do not only influence the time costs of travellers, but also the fuel consumption of vehicles. In first order, other operating costs, such as the wear and tear of tyres and other expendable parts of the vehicles can be regarded as varying only with the mileage driven. A number of fixed costs of vehicle fleets (e.g capital costs) are frequently allocated to the time consumed by the use of the respective asset. Such operating cost elements are part of the factor costs of the vehicle operator and thus are already considered his (or her) time preference.

Speed-depending fuel consumption functions are also provided by the German manual on road-side cost benefit analyses. From here it can be derived, that the fuel consumption of light vehicles are rising by a factor 2 under congested conditions. For heavy vehicles (group ”G”: HGVs and coaches) an increase by a factor 1.5 can be assumed. Starting from an initial consumption of 8 l/100 km for vehicle group ”P” and 35l/100 km for group ”G” and assuming an average fuel price of 1 Euro, Table 5 shows the relation between extra travel time and extra fuel costs for both vehicle groups.

Table 5: Relevance of time and fuel costs by vehicle group and traffic situation

Cost category	Unit	Vehicle group "P"		Vehicle group "G"	
		Free flow	Stop & go	Free flow	Stop & go
travel speed	kph	120	20	80	20
VOT	Euro/v-hour	16,45	24,68	43,2	43,2
Time costs	Euro/vkm	0,14	1,23	0,54	2,16
Fuel consumption	l/100km	8	16	35	70
Fuel price	Euro/l	1,00	1,00	1,00	1,00
Fuel costs	Euro/vkm	0,08	0,16	0,35	0,70
Share of total costs					
Time costs		63%	89%	61%	76%
Fuel costs		37%	11%	39%	24%

Table 3 indicates, that for both vehicle groups under free flow conditions fuel costs are an important cost factor as they count up to around 38% of the total of time and fuel costs. Under Stop-&-go-conditions, however, the relevance of fuel costs drops considerably. Due to the increased VOT in congested passenger traffic fuel costs account only for 11% while they still count up to 24% for heavy vehicles (group ”P”).

Consequently, fuel costs must not be neglected totally. For a rough estimation of total social costs arising from road congestion, the approach of INFRAS/IWW (2000) is followed and the fuel cost element is added to the Value of Time per vehicle category.

3.1.4 The Problem of Heterogeneous User Groups

Optimal road user charges based on the theory of short-run marginal cost prices are derived from the costs a member of a specific user group imposes on all other users (or user groups) currently using the same system. Starting from the definition of speed-flow relationships in FGSV (1997) this means, that the charges for passenger cars only take into consideration the impact of an additional passenger car on the travel speed of other passenger cars. The charges for HGVs, however, must include the impact of an additional HGV on passenger cars (which is twice the impact of a passenger car on passenger cars) and on other HGVs (compare Table 2). For the quantification of these impacts in monetary units information on the traffic mix and on the values of travel time per vehicle of passenger cars and HGVs is required.

If $Qm=Q_P+2Q_G$ denotes the decisive traffic volume determining the speed of passenger cars, the total social costs per kilometre can be written as:

$$TC(Q_P,Q_G)=\frac{Q_P\cdot VOT_P}{v_P(Q_P,Q_G)}+\frac{Q_G\cdot VOT_G}{v_G(Q_G)}$$

The marginal social congestion costs passenger cars mutually impose on each other $MC_p(Q_P,Q_G)$ then are computed by deriving $TC(Q_p,Q_{G'})$ by Q_P The marginal external costs then are determined by subtracting the average costs $AC(Q_P)=VOT_P/v_P(Q_P,Q_G)$. This leads to:

$$\begin{aligned}MEC_P(Q_P,Q_G)&=VOT_P\cdot\frac{v_P(Q_P,Q_G)-Q_P\cdot\dfrac{\partial v_P(Q_P,Q_G)}{\partial Q_P}}{(v_P(Q_P,Q_G))^2}-\frac{VOT_P}{v_P(Q_P,Q_G)}\\&=VOT_P\cdot\frac{-Q_P}{(v_P(Q_P,Q_G))^2}\cdot\frac{\partial v_P(Q_P,Q_G)}{\partial Q_P}\end{aligned}$$

The external marginal social costs for HGVs $MEC(Q_p,Q_G)$ = $MEC(Q_p,Q_G)$ - $AC(Q_G)$ is as follows:

$$\begin{aligned}MEC_G(Q_P,Q_G)&=VOT_P\cdot\frac{-Q_P\cdot\dfrac{\partial v_P(Q_P,Q_G)}{\partial Q_G}}{(v_P(Q_P,Q_G))^2}+VOT_G\cdot\frac{v_G(Q_G)-Q_G\cdot\dfrac{\partial v_G(Q_G)}{\partial Q_G}}{v_G(Q_G)^2}-\frac{VOT_G}{v_G(Q_G)}\\&=MEC_{GP}(Q_P,Q_G)+VOT_G\cdot\frac{-Q_G}{(v_G(Q_P,Q_G))^2}\cdot\frac{\partial v_G(Q_G)}{\partial Q_G}=MEC_{GP}+MEC_{GG}\end{aligned}$$

The traffic volume Q_m determining $v_P(Q_Q,Q_G)$ is given as $Q_m=Q_?+kQ_G$ with $K=2$. Then, the marginal external costs imposed on passenger cars by goods vehicles $MEC_{GP}(Q_P,Q_G)$ is given by the simple expression:

$$MEC_{GP}(Q_P, Q_G) = k \cdot MC_P(Q_P, Q_G)$$

The term $MEC_{GP}(Q_P,Q_G)$ is often neglected (compare e.g. Bandi, Doll, Maibach et al. (2000)) as for reasons of simplicity a homogeneous group of road users is assumed. However, from the above equation it can be seen, that the ratio between charges for HGVs and for light vehicles are heavily depending on Q_P and Q_G and thus on the share of heavy traffic. The relevance of the different terms MEC_{GP} and MEC_{GG} for optimal congestion charges are presented in Section 5.1.2.

3.1.5 The Price Elasticity

When the marginal social external costs of traffic congestion are imposed on road infrastructure users in the form of congestion charges, traffic volumes will react. Possible reaction patterns are modal shift, route shift, departure time shifts, omitting of less important trips, car pooling or maintaining the previous behaviour. The degree to which these alternatives are realised is heavily depending on the local circumstances (availability of alternative modes, network density) and the travel purpose. A change in the level of traffic demand then will impact the level of the external marginal social costs caused by an additional traffic unit, and thus will alter the congestion charges themselves. The solution of this feedback circle is the equilibrium Q^* in Figure 1, where total user costs $MSC(Q)$ - including the internalisation charge - meet the usrs' willingness to pay for a specific traffic quality W(Q).

However, the goal of the present case studies is to present reaction potentials of traffic on the introduction of congestion charges as well as to determine an equilibrium charge. In practice, demand elasticities will hardly be constant over demand for significant changes of user costs, but information on the slope of demand levels by user costs is not available at present. Thus, we fall back to the simple assumption of iso-elastic demand curves.

The demand elasticities chosen depend on the traffic composition and the availability of route and mode alternatives along each corridor. In each corridor both, passenger and freight transport are priced and thus for each mode the price elasticity must be determined. For this purpose, the intermodal network model VACLAV is applied.

The VACLAV model determines the allocation of passenger and freight traffic demand to the road and rail network by a iterative assignment of a fixed demand matrix to a inter-modal network. By the dynamic creation of local traffic loads VACLAV is capable to simulate induced congestion effects on all road links important for inter-regional traffic. However, the simulation of earlier or later departure times or the omitting of trips is not possible by the

VACLAV model. For this reason a demand elasticity of abut -0.2 is added to the model results. Table 6 shows the elasticities by country used for the corridor estimates:

Table 6: Average Demand Elasticities

Country	Demand Elasticity	
	Passenger car	HGV
Belgium	-0.50	-0.50
Switzerland	-0.35	-0.15
Germany	-0.50	-0.50
France	-0.25	-0.25
Italy	-0.25	-0.25
Average	-0.30	-0.30

For reasons of simplicity it is assumed, that the entire inter-urban main road network is subject to congestion pricing and that the existing road user charges remain as they were in 1998. Cross-section effects, such as induced passenger traffic due to reductions in freight traffic are not investigated here. It is also not accounted for

The VACLAV model is not able to simulate congestion effects in the rail network as rail services are included by timetable information in the model. Therefore, the elasticity values delivered for rail traffic by VACLAV only refer to the modal choice decision of passengers.

3.2 Specification of the Railway Model

3.2.1 Formal definition

For rail passenger transport speed-flow relationships similar to the ones used in road transport do not exist. Moreover, due to the interdependency of different parts of the rail network considerations of single links would not be appropriate to describe the problem of rail congestion. The most appropriate way to determine congestion effects in rail transport is the application of a micro-simulation model, which covers the entire network. Such a model is not available for the present case studies.

The approach followed here is to determine rail congestion costs by using aggregated data of hourly train loads, trips and delay probabilities. Out of this data a network-wide demand-delay-relationship is estimated. The marginal external congestion costs then can be estimated in the common manner by deriving total user costs by the number of users. We get the following formal structure of model for rail congestion costs:

The average delay $D(Q_t)$ per train arrival is estimated as a function of the hourly traffic volume Q_t. Q_t describes the development of the number of trips over day and is given as input data. t denotes the hour of day.

The average user costs $AC(Q_t)$ per passenger trip are composed of the waiting time costs at the begin of the journey, the fare, the time costs without delays and the time costs of the delay $D(Q_t)$. The waiting time costs are determined by the average waiting time T_{wait} times the value of travel time VOT. The fare is determined by the tariff per kilometre C_{Fare} times the average length of the journey L. The normal travel time results from multiplying the value of time VOT with the average travel time, which is average journey length L divided by the average train speed v. All these cost components are independent of the traffic load and thus summarised as C_{Fix}.

The delay costs $C_{Delay}(Q_t)$ are defined by the product of the value of time VOT and the average train delay $D(Q_t)$, which is a function of the hourly number of passenger trip. As described in the UNITE valuation conventions (Nellthorp et al. (2001)), the value of time depends on the degree of delay. In rail transport we put a factor of 1.5 on the VOT for all delays of 5 minutes or more. In the present model we put the 1.5-factor on the delay times of all arrivals within the delay class >4 minutes and thus operate with a constant VOT. Using this notation the average costs per passenger trip can be written as:

$$AC_t(Q_g) = \underbrace{l \cdot c_{Fare} + \left(t_{Wait} + \frac{l}{v}\right) \cdot VOT}_{C_{Fix}} + \underbrace{D(Q_t) \cdot VOT}_{C_{Delay}(Q_t)}$$

The marginal social time costs then are determined by deriving the total social costs per hour $(Q_t{*}AC(Q_t))$ by Q_t. Subtracting the average user costs from the marginal social costs we get the marginal external costs $MEC(Qt)$ as a function of traffic demand as follows:

$$MEC(Q_t) = \frac{dAC(Q_t)}{dQ} - AC(Q_t) = Q_t \cdot \frac{dD(Q_t)}{dQ_t} \cdot VOT$$

Without foreclosing the results of the calculations we can say, that the increase of user costs due to the internalisation of external rail congestion costs is very small. Thus, demand reactions and the determination of an optimal congestion charge by finding the equilibrium of supply and demand can be neglected.

3.2.2 The Value of Time

The value of travel time in rail traffic is set in accordance with the UNITE valuation conventions for the year 1998. Considering the share of travel purposes in Germany we get the following values for normal and delayed travel time (Table 7). Delayed travel time values are put on all delays exceeding 5 minutes.

Table 7: Values of Time in Rail Transport

VOT by type of service and travel purpose	**VOT per p-hour** Euro/p-hour		**Share of purpose**	**Average VOT** Euro/p-hour	
	Normal	Delayed		Normal	Delayed
Local traffic					
Business	21.82	32.73	6%	21.82	32.73
Private / Commuting	5.56	8.34	71%	5.56	8.34
Leisure	4.88	7.32	23%	4.88	7.32
Total			100%	**6.38**	**9.57**

3.2.3 Other determinants of the Fixed Travel Costs

The waiting time t_{Wait} denotes the average time passengers wait for the departing train at the beginning of the journey. We estimate an average of 6 minutes (0.1 hours) per trip. Departure delays, interchanges and differences in the value of time for wait and for travel time are not considered.

The average length per journey is given by the Swiss data for the years 1995 to 2000 for different train classes. For 1998 the distances range between 23 km (urban light train) and 69 km (IC). In average 39.2 km are given. This value is used for within the present model.

The speed of different train classes are determined by the consultation of time tables. We use an average of 60 Kph across all train classes. This results in an average time per trip of 39 minutes.

4 The Case Study Corridors

4.1 Corridor Description

The paper embraces the four corridor case studies 7A to 7D of the UNITE project, Work Package 7 (User Costs and Benefits). The corridor studies focus clearly on road transport as the estimation of marginal external user costs in public transport requires demand- and supply side data, which is presently not available. Rail transport thus is treated in a final step to compare it to time costs plus congestion charges in road traffic

For each of the four road corridors a main route and a alternative route vial the trunk road network is identified by the VACLAV traffic model. Data on road types, number of lanes, gradients, curvature and traffic loads are provided by the digitised road network, which is included in the VACLAV model. The number of vehicles is modelled as an average volume for cars and trucks per working day, based on UN traffic census data. An overview of aggregated corridor characteristics is given by Table 8.

Table 8: Corridor definition (overview)

Case Study	Route	Main Route Distance (km)	Travel time (hours)	Alternative Route Distance (km)	Travel time (hours)
7A	Paris - Brussels	282	3,4	246	3,6
7B	Paris - Munich	795	11,1	759	12,8
7C	Cologne - Milan	839	12,2	804	14,7
7D	Duisburg - Mannheim	251	4,6	245	4,7

The Corridors 7A and 7B deal with passenger transport. Here, the effect of pricing passenger cars according to the principles of marginal social cost pricing on the user costs in passenger transport is investigated.

- In Corridor 7A we have a medium-distance route from Paris to Brussels, which is characterised by a high share of business travel and the existence of a well developed high speed rail alternative. The latter is assumed to have a great influence on users’ behaviour (or price reaction potential).

- Corridor 7B represents a fairly long route from Paris to Munich, which consists of two major parts which each having its own traffic characteristics. On the French side, Paris - Strassbourg consists of a rather thin network of alternative routes and only a conventional rail connection. The German part from Strassbourg to Munich then consists of a very dense network of motorways and high quality trunk roads, and of a well developed high speed rail system.

The potential effects of congestion charging on road freight traffic is investigated by the corridors 7C and 7D. According to the model definition, the MC-prices for HGVs consider not only the delay effect of an additional heavy vehicle on other heavy vehicles, but also on light vehicles. The changes in average travel costs, which are resulting from the respective congestion internalisation, however, are shown for freight vehicles only.

- Corridor 7C (Container shipment Cologne - Milan) is probably one of the most frequently investigated routes in Europe. It is characterised by a heavily congested motorway network on the one hand and attractive alternatives by combined rail transport on the other hand. The majority of goods carried along this Trans-Alpine corridor are high quality goods.

- In contrast, Corridor 7D between the central German industrial areas Duisburg (Ruhrgebiet) to Mannheim represents a typical national transport market with a high level of competition among hauliers and between modes. On such relatively short distances rail is only competitive for bulk goods, while consumer goods are shipped within a network of highly interconnected industries.

Figure 5 gives a graphical overview of the four corridors. Numerical details (traffic loads, road parameters, etc.) for the main and alternative lines are provided in the annex to this paper.

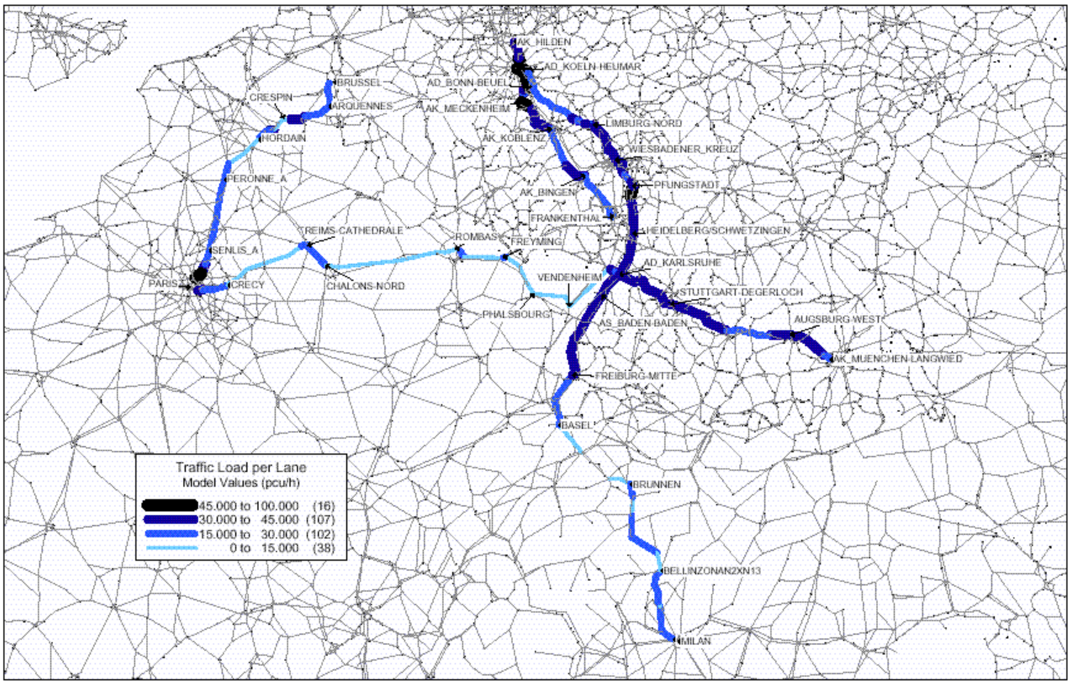
Traffic Load on Corridors 7A - 7D

Figure 5: Traffic Load on the Case study corridors 7A to 7D
Source: IWW

4.2 Road Traffic Input Data

4.2.1 Network Data

The road network database is extracted from the IWW network model VACLAV. The road links in here are attributed by:

- road type (motorway, trunk road, county road, urban road, etc.)
- number of lanes per direction,
- existence of line separators or side lanes and
- curvature and gradient.

These road attributes define the speed flow function applied for calculating travel speeds, congestion costs and optimal traffic volumes.

4.2.2 Traffic Volume Data

The traffic volume data is based on UN traffic count information for the year 1995, which was used to calibrate the traffic generation and assignment modules of the VACLAV model. This modelled core transport data is given as average annual daily traffic (for working days only). The values for 1998 are derived by assuming an average annual growth of passenger transport of 1% and an increase of road freight transport of 3%. These figures are consistent with the assumptions of the German Transport Investment Plan 1997 to 2015.

The traffic loads of the four corridors (in vehicles per day) are depicted in Figure 5. A list of the traffic volumes by road link on the main routes of the corridors 7A to 7D is provided in the annex.

4.2.3 Hourly Traffic Pattern by Travel Purpose

The German Highway Research Institute (Bundesanstalt für Strassenwesen, BASt) periodically analyses traffic volume patterns measured by automatic counting posts alongside different roads in Germany. The data provided for 1998 in BASt 2001 does report the number of vehicles only; a separation of heavy traffic is not possible on this basis. The hourly traffic flow data per road direction is categorised into six types of traffic demand pattern A to F. The share of average daily traffic per hour and the description of these demand patterns are given in Figure 6 below.

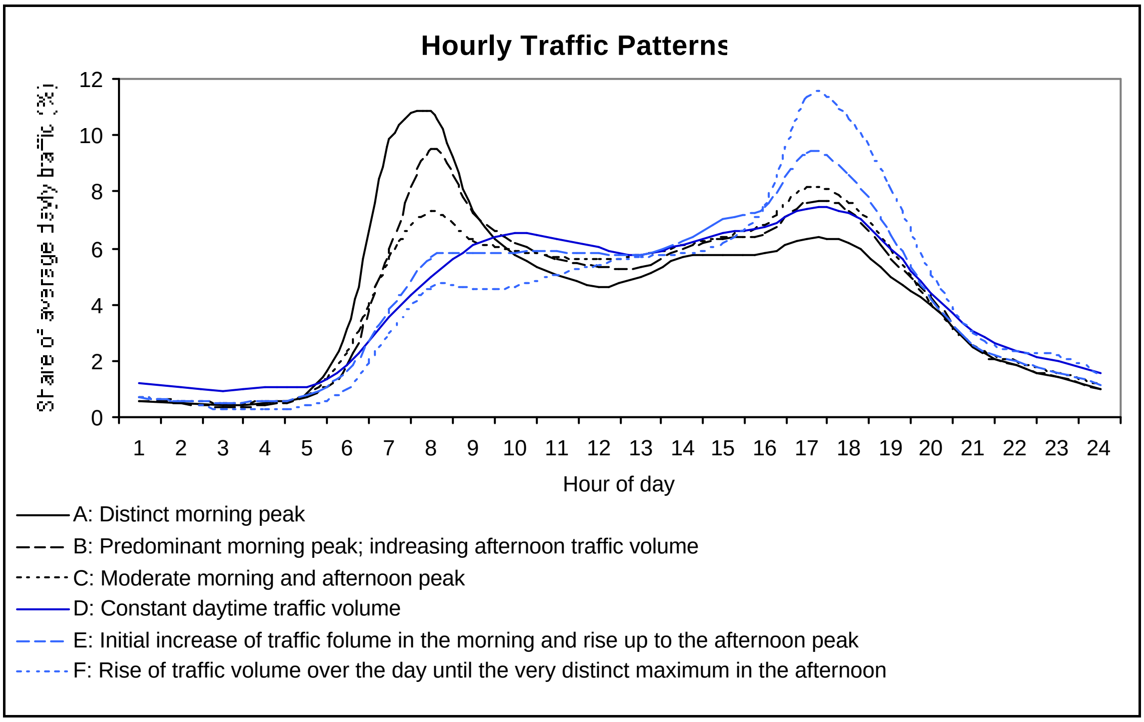

Figure 6: Hourly traffic pattern by type of road and vehicle class
Source: BASt (2001)

In particular close to urban centres traffic patterns are different for each direction for the road. Patterns with a distinct morning peak (e.g. A) are typical for roads towards the city centre, while patterns with a distinct afternoon peak (e.g. F) are typical for traffic leaving the urban area. Unfortunately, the available road network model does not distinguish between different directions. In this case mixed traffic patterns has to be used. Table 9 shows the number of counting posts in the federal states of Bavara, Baden-Wuerttemberg and Nordrhein-Westfahlen by the combination of traffic flow patterns A to F in both directions.

Table 9: Observed combinations of traffic demand patterns in selected federal states of Germany

Observed traffic pattern in direction 1	Observed traffic pattern in Direction 2											
	Motorways						Other federal roads					
	A	B	C	D	E	F	A	B	C	D	E	F
A	0	0	1	3	18	28	0	0	1	1	3	39
B		1	26	11	32	3		0	6	0	18	22
C			36	25	6	1			11	5	34	5
D				32	4	0				2	3	2
E					0	0					5	0
F						0						0

Source: BASt (2001)

For motorways we select traffic pattern C (Moderate morning and afternoon peak). For freight transport we assume a more equally distributed traffic load. This is given by Type-D pattern (constant daytime traffic volume). Under the assumption of an average tHGV share on German motorways of 15% the traffic pattern for passenger cars is derived by

For other federal roads (Bundesstraßen) there is a clear indication, that traffic volumes are extremely different in both directions. Table 9 shows by far the most observations for the combination of Type A (Distinct morning peak) and F (Distinct afternoon peak). Averaging these two patterns we get a distribution of demand over day, which is a bit more extreme in the morning and afternoon peak than the Type-C curve. We use this curve for all other inter-urban roads except for motorways.

4.3 Data Sources for Estimating Rail Congestion

The estimation of marginal external congestion costs in rail passenger transport is based on a data set of January 2001 for Switzerland. This data set provides the following information:

- Arrivals and departures of trains by hour and degree of delay
- Number of passenger trips by train class
- Distribution of passenger trips in inter-urban and regional traffic over day.

Out of this data a demand-delay relationship for the entire rail network of Switzerland is estimated. The steps towards its estimation and the underlying data sources are described in turn.

4.3.1 Data on Train Movements

Data on train arrivals and departures are given for January 2001 for 21 hours per day and for three delay classes. The delay classes are:

- 0 to 1 minute
- 2 to 4 minutes.
- More than 4 minutes.

The type of train is not encoded in the data set. The train movements are further only given as aggregated figures for the whole month. For the following determination of delay costs, only the train arrivals are considered. These are presented in Figure 7.

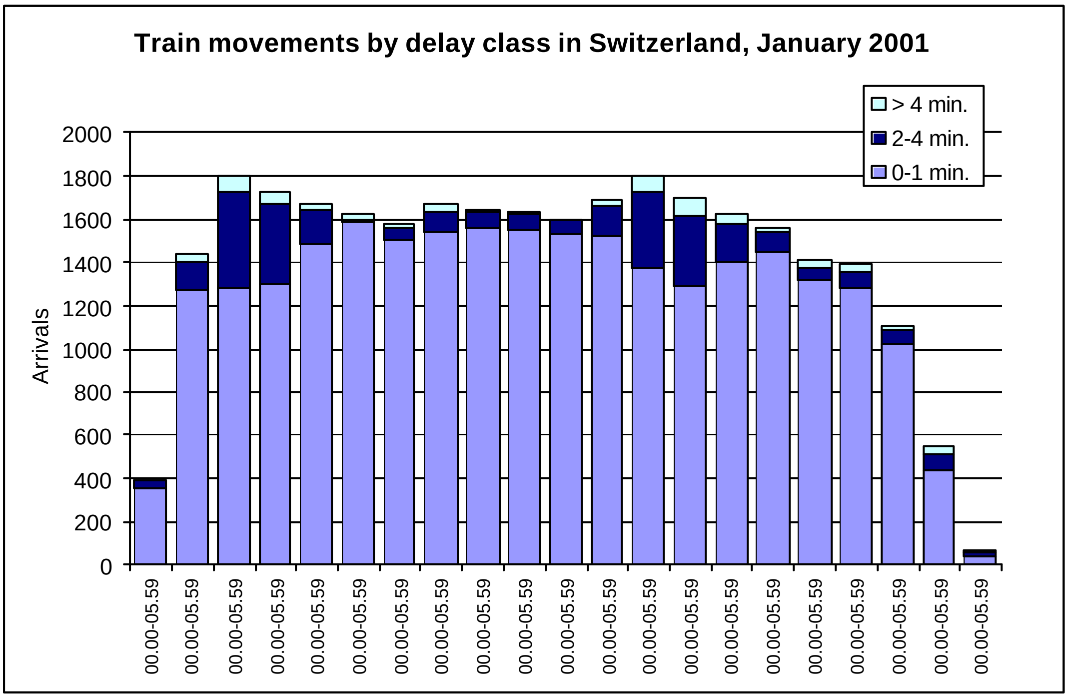

Figure 7: Train arrivals in Switzerland, January 2001
Source: Based on data from INFRAS / Link et al. (2002)

Figure 7 indicates clearly, that the punctuality of trains decreases when the hourly number of arrivals exceeds 1600. From this data of Swiss rail passenger services we can conclude that there is a direct interrelationship between exceeding the capacity limit of a rail network and the degree mutual interference of trains.

For freight transport no comparable data set is available and thus the dependency of demand and train delays can not be estimated. Moreover, in freight traffic the use of fixed time tables is less common than in passenger services. For this reason it is much more vague to define the term congestion.

4.3.2 Data on passenger movements

The development of passenger movements by time of day is much more distinct than the movement of trains. From the UNITE accounts for Switzerland (Link et al. 2002) data estimates of passenger movements by four train classes are provided per month. The distribution of the number of trips over the day is only available for two types of service: Fast long distance services and regional and urban services. These daily traffic patterns were applied to the four levels of demand in order to estimate the number of passenger trips made per hour in the Swiss rail network. The results of the estimates are presented in the following diagram:

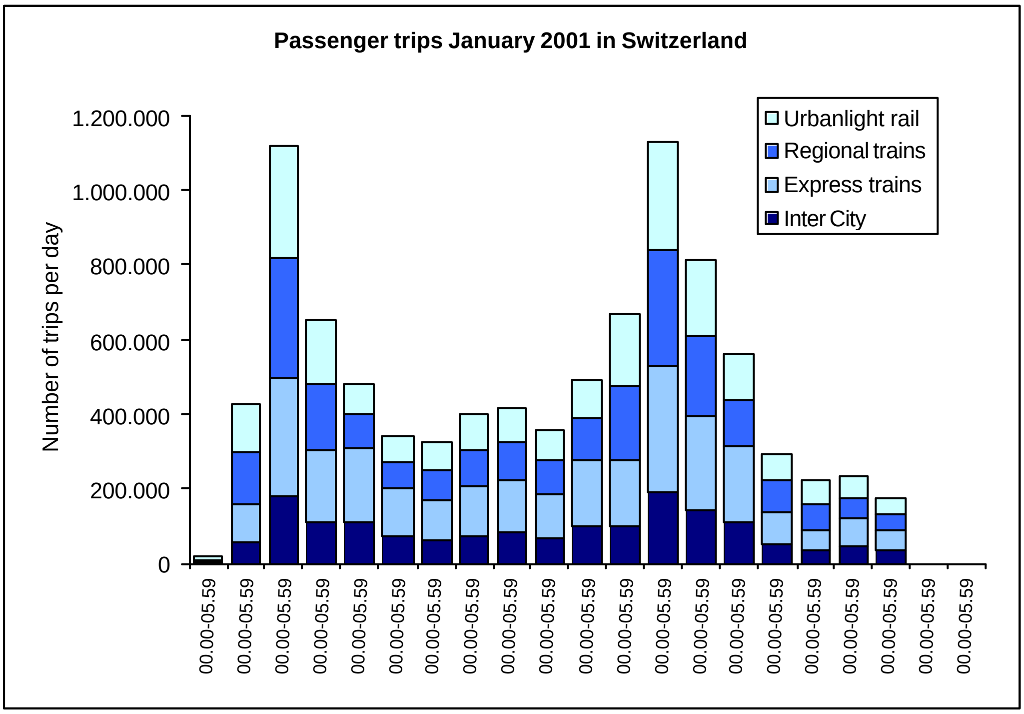

Figure 8: Passenger trips by hour
Source: Data from Link et al. (2002)

For the time midnight and 2:00 a.m. no information on passenger movements is available.

4.3.3 The Demand-Delay Relationship

The relationship between demand and delay is estimated by the hourly data on train delays presented above. From a systematic point of view we would argue that delays in rail transport are caused by the number of trains operated rather than by the number of passengers. However, there are two arguments for setting average delays in relation to the number of passenger trips: First, the number of trains operated by the rail company is requested by the number of passengers and second, the goal of the present case studies is to quantify user externalities. Moreover, at least a small proportion of delays is caused by the time required by passengers to enter and exit trans at the stations.

The following Figure 9 gives an impression of both relationships. In the left part the average train delays (in hours) are plotted over the hourly number of train arrivals. In the right part they are plotted over the number of passenger trips per hour. In both figures the delays are shown as total delays (dark squares, left axes) and delays exceeding of five minutes and more (light circles, right axes). These two cases are considered as the UNITE valuation conventions define rail congestion as arrivals, which are more than 5 minutes behind schedule.

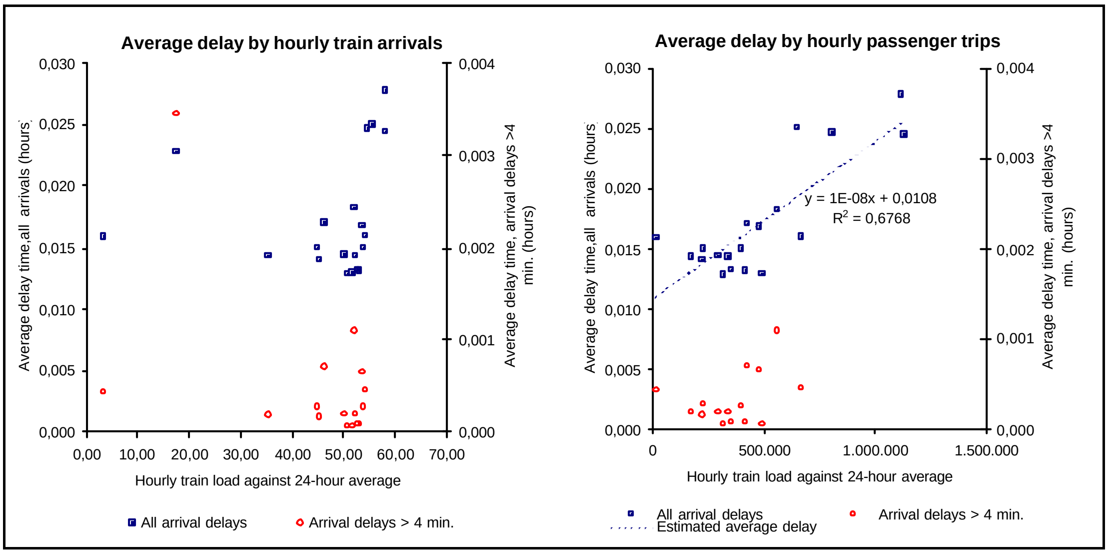

Figure 9: Average delays in relation to train arrivals (left) and to passenger trips (right)

Source: Data from Link et al. (2002)

The available data indicates, that the relationship of average hourly delay and the number of passenger trips is more significant than the relationship of delay and the number of train arrivals. Keeping in mind the goal of the present UNITE case studies, the first mentioned relationship is used for the definition of demand-delay curves in rail transport.

Figure 9 indicates clearly, that a linear relationship between passenger movements and delay is most appropriate. Thus, the functional form for the demand-delay curve $D(Q_t)$ is defined by:

$$D(Q_t) = a + b \cdot Q_t$$

The model parameters a and b are estimated by linear regression. The results are presented in the following table:

Table 10: Regression parameters of the delay curve in rail transport

Model of delay valuation	Parameter a (Constant)	Parameter b (Linear coefficient)
Model 1: Consideration of all delays	0,01078	1,31E-08
Model 2: Restriction to delays > 4 minutes	-0,00102	5,42E-09

The comparison of the parameters shows, that the increase of average delays with demand is much less and the level of delay is lower if only delays above 5 minutes are valued (model 1). The consequence of this result for the marginal external costs of rail usage will be presented in chapter 5.3.

5 Results

The results of the four case study corridors are presented as the development of

- total marginal social costs,
- total user costs and
- congestion externality charges

for the type of traffic specific to each corridor (passenger car for the Corridors 7A and 7B; HGVs for the Corridors 7C and 7D) For the main routes along the corridors the development of costs is presented before and after the users are reacting ont he introduction of the congestion tolls. For the alternative road corridors and the rail services only the initial state is presented as an additional information, which was used to estimate the price elasticities of traffic along the main route.

5.1 Link-Specific Results

The present first part of Chapter 5 presents a number of general results, which have been obtained from a link-specific application of the modelling framework described above. These results are particularly important for the assessment of the possibility to generalise the cost values presented for the selected corridors. Furthermore, due to the absolute limitation of the congestion phenomenon in space and time the link-based local view is much more important for the understanding of congestion in road traffic than the corridor perspective. In rail transport things are different because congestion at one part of the network usually causes effects throughout a wilder part of the network.

According to the identification of cost drivers in Section 2.2 the variation of external marginal social congestion costs (in the equilibrium) with the following parameters will be demonstrated:

- Road type,
- traffic volume and traffic mix,
- demand elaticities and
- the structure of the values of travel time by user group.

The influence of speed flow curves, which is much decisive for the slope of the congestion cost function, is not demonstrated explicitly. However, some indication can be found in the discussion on road types.

5.1.1 The Influence of the Speed-Flow Curve

The dynamics of transport flows is determined by traffic regulation measures, permitted speeds, the number of disturbing objects (such as junctions, curves or non-motorised traffic participants) and by the pavement quality. While motorways are designed such, that the disturbance of flowing traffic is avoided as much as possible, the secondary road network needs to give access to all types of users. Thus, most crossings are not level-free, curves and gradients are more distinct than at motorways and a considerable share of secondary roads lead through built-up areas. Consequently, it can be expected that the slope and the level of congestion charges vary significantly between different road types.

The following graphs illustrate the development of marginal social congestion costs for cars and HGVs for motorways and other inter-urban roads. The main difference between these two types of roads is the separation of carriageways. Further, for motorways and for other roads (here entitled as rural roads) different numbers of lanes per direction are investigated.

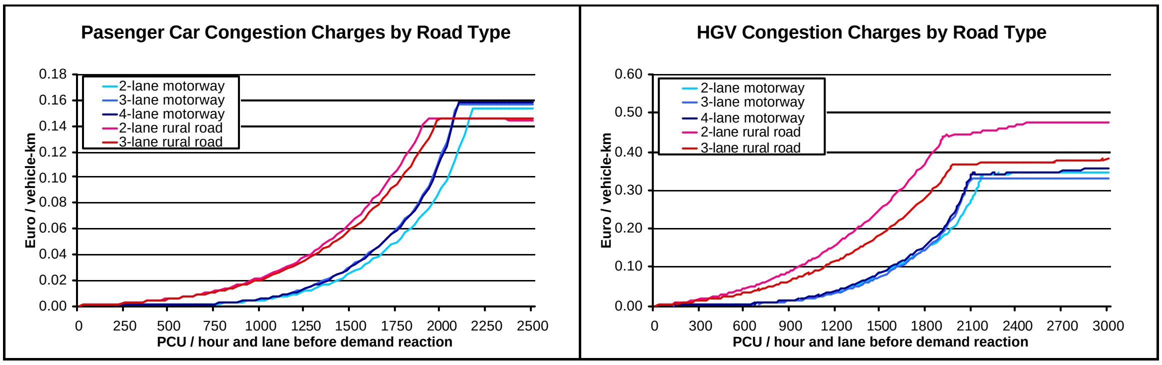

Figure 10: Marginal extermal costs for cars (left) and HGVs (right) by road type

The underlying assumptions for calculating the results shown above are: HGV-share: 15%, VOT(P) = 11.80 Euro/h, VOT(G) = 42 Euro/h, Eta(P) = Eta(G) = -0,30. The influence of the type of road, which is represented by a characteristic speed-flow curve, is found to be as follows:

- For passenger cars on motorways, an maximum congestion charges of 0.16 Euro per km is found. The respective value for rural roads is around 10% less (0.145 Euro / km).
- For HGVs two additive curves can be observed: the effect of lorries on passenger cars and the mutual disturbance of HGVs. On motorways the disturbance of cars by HGVs reaches its maximum at a traffic volume of 2100 PCU/h and lane. The respective congestion charge is roughly 0.34 Euro per vehicle-km. At rural roads the maximum level of the HGVs' influence on cars is reached slightly earlier, but the optimal congestion charge is much higher than on motorways. It is between 0.ö37 and 0.44 Euro per HGV-km. Due to the mutual disturbance of HGVs the optimal congestion charges for goods vehicles rises a bit further until its final maximum. However, for most road classes this increase is less than 3% and thus can be neglected for practical considerations.
- In both cases the congestion costs rise earlier for rural roads than they do for motorways.
- The influence of the number of lanes on congestion costs shows a less significant, and even heterogeneous picture. Under congested conditions on motorways, congestion costs are about 10% less for 2-lane motorways than they are on 4-lane ones. This holds for cars and for HGVs. For rural roads the opposite condition is the case for HGVs. Congestion costs are higher for 2-lane roads than for 3-lane roads.

We can conclude, that even though the EWS speed flow curves for different road types are of the same functional form, there are differences in the slope and the level of congestion costs. The use of totally different speed-flow curves then will end in totally different functions of marginal external user costs. As a consequence of this, we must conclude that congestion cost functions are not transferable between different national contexts.

5.1.2 The Influence of the HGV Share

The influence of the HGV share on the level and the slope of congestion charges for passenger cars and goods vehicles is tested at a two-lane motorway under the assumption of a constant demand elasticity of -0.3 for all vehicle types. The values of HGV-share investigated range from 10% to 30%. The resulting congestion cost functions are shown in Figure 11.

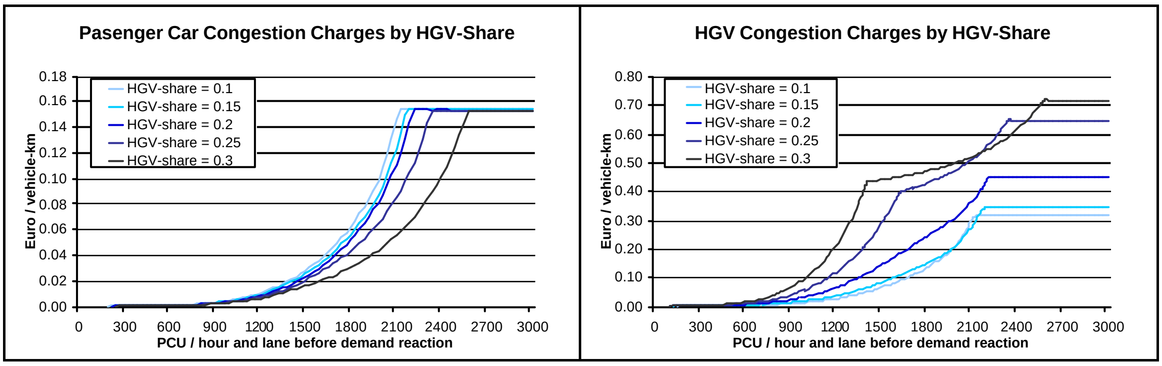

Figure 11: Marginal external costs for cars (left) and HGVs (right) by HGV share

The consideration of Figure 11 allows the following conclusions:

- The maximum congestion charge of passenger cars is not influenced by the HGV share. However, for low HGV-shares a faster rise of the congestion function for passenger cars can be observed than for high HGV shares. For a HGV-share of 10% the maximum level of passenger car congestion charges is at 2100 PCU per hour and lane, while it is at 2600 PCU for a HGV-share of 30%.

- The maximum level of congestion charges for goods vehicles is strongly influenced by the HGV-share. While it is 0.72 Euro / HGV-km in case of a HGV-share of 30%, it is only 0.32 Euro/km at 10% HGVs.

- In general we find a much faster rise of congestion costs for high shares of HGVs than for low HGV-shares.

- The higher the HGV-share is, the more distinct are the costs caused by a mutual disturbance of goods vehicles. While they are not measurable for HGV-shares up to 20%, these costs count up to more than 50% of congestion charges for shares of HGVs between 25% and 30%.

We can conclude with the constitution, that the effects of the HGV-share on the congestion costs of HGVs is much stronger than on the congestion costs of passenger cars. It can be expected, that the mutual influence of passenger cars and HGVs is the same on the main road network in all European countries. Respectively, the influence of the HGV-share on congestion costs is considered to be transferable between different national contexts.

5.1.3 The Influence of the Demand Elasticity

The selection of demand elasticities for the different types of traffic participants is usually a more or less vague task. The willingness or ability of people to pay for particular levels of service quality depend on their travel purpose, the available travel alternatives and their freedom to alter departure times or to cancel making the trip at all. Therefore it makes sense to look at the influence of different demand elasticities for the vehicle group “P” (cars) and “G” (lorries) on the level and the slope of congestion cost functions.

In the graphs of Figure 12 below various combinations of demand elaticities between Eta=-0.1 and Eta=-1 for all vehicles types are shown. The calculations have been carried out for a two-lane motorway and a HGV-share of 15%. The results found are as follows:

- For passenger cars as well as for HGVs the demand elasticity has a very strong impact on the level of congestion costs. For passenger cars the maximum congestion costs range between 0.10 Euro/km (for Eta = -1) and 0.26 Eurl/km (for Eta = -0.1). For HGVs the range is 0.20 Euro/km to 0.61 Euro/km.

- The traffic volume, where the maximum charge level is reached is infuenced only slightly by the demand elasticity.

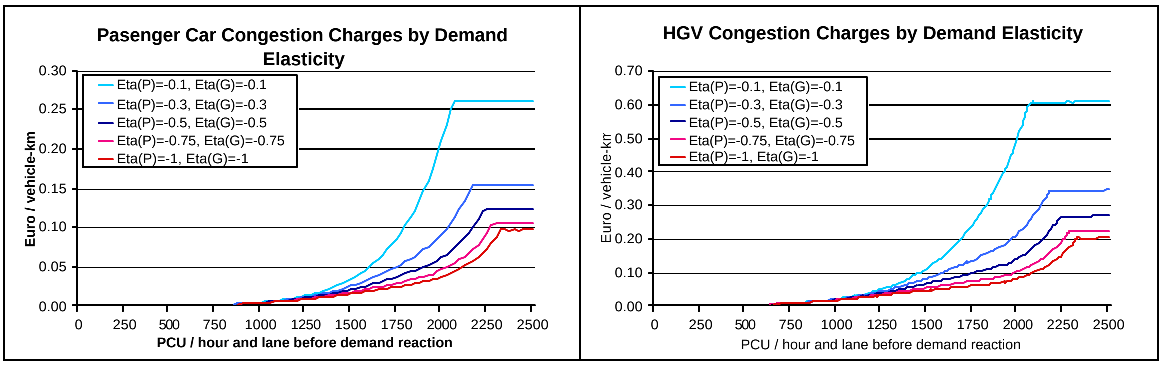

Figure 12: Marginal external costs for cars (left) and HGVs (right) by demand elasticity

Demand elasticities are the result of travel decisions taken by travellers on the basis of the available alternatives. This includes the choice between different routes or modes as well as the alternative not to travel at all. Thus, the network contes, the structure of labour markets and demand indicators need to be checked carefully before transferring estimates of optimal congestion charges between countries.

5.2 Corridor-Specific Results

5.2.1 Overview of the Corridors 7A to 7D

The aggregated results for all Case Study corridors are shown in Table 11. Here it can be seen that the user charges for passenger cars (Corridors 7A and 7B) and freight vehicles (Corridors 7C and 7D) differ extremely by a factor 15 to 30. This effect is partly due to the higher congestion externalities caused by heavy traffic (compare Chapter 5.1) and partly due to the higher traffic density on the German motorway system compared to the rest of Europe.

For the presentation of the results, four different departure times (6:00, 8:00, 14:00 and 20:00 have been chosen. Table 11 indicates, that the differences in the user charges (marginal external congestion costs) by time of day are enormous. Daytime travel costs are between 10 and 150 (!) times higher than congestion charges at night.

In the corridors 7A and 7B, average congestion charges for passenger cars up to 0.05 Euro per km during daytime are computed. For a departure at 20:00 h, for both corridors the congestion charge is found to be zero.

For HGVs average congestion charges up to 0.10 Euro/km in corridor 7C (Cologne - Milan) and up to 0.15 Euro/km for corridor 7D (Duesburg - Mannheim) for daytime travel are found. For night-time hauls, average values of 0.01 Euro/km (Cologne - Milan) and 0.03 Euro/km (Duisburg - Mannheim) are found.

In most cases of passenger travel it is found, that congestion pricing reduces the overall travel costs from the perspective of the car user. These are defined as the sum of the user's time costs and the road tolls paid by him. It is found, that this perceived cost reduction can be up to 25% for those users, which are not shifted away by the implementation of the congestion charges. However, in some cases travel costs increase in relation to a case without congestion pricing. In general we observe, that the development of travel costs strongly varies with departure time, and thus with the occurrence of high network loads in space and time along the study corridors.

Table 11: Summary results by corridor for different departure times

Corridor and departure time	Average time and operating costs (Euro)		Marginal external costs (Euro)		Average marginal external costs (Euro / km)		increase of private costs per trip
	before charging	after charging	before charging	after charging	before charging	after charging	
7A: Passenger car Paris - Brussels							
6.00	36,3	26,3	33,7	7,1	0,12	0,03	-8,1%
8.00	36,9	26,9	29,3	11,8	0,10	0,04	4,9%
14.00	53,7	27,3	52,7	13,7	0,19	0,05	-23,8%
20.00	26,5	25,0	3,7	1,1	0,01	0,00	-1,5%
7B: Passenger car Paris - Munich							
6.00	119,3	73,9	107,3	13,7	0,14	0,02	-26,6%
8.00	121,1	75,2	124,7	22,3	0,16	0,03	-19,5%
14.00	79,2	73,0	22,7	8,5	0,03	0,01	2,8%
20.00	71,1	71,1	0,5	0,3	0,00	0,00	0,4%
7C: HGV Cologne - Milan							
6.00	533,6	530,4	483,6	80,1	0,58	0,10	14,4%
8.00	533,7	530,5	434,7	71,5	0,52	0,09	12,8%
14.00	533,1	530,2	392,6	65,8	0,47	0,08	11,8%
20.00	530,6	530,2	32,7	8,1	0,04	0,01	1,4%
7D: HGV Duisburg - Manhheim							
6.00	143,2	140,5	208,1	33,3	0,83	0,13	21,4%
8.00	143,2	140,5	196,3	31,4	0,78	0,13	20,0%
14.00	143,2	140,4	222,4	36,3	0,89	0,14	23,4%
20.00	142,6	140,9	41,3	7,0	0,16	0,03	3,7%

5.2.2 Detailed Results for Corridor 7A (Paris - Brussels)

The departure time for presenting the computed results of Corridor 7A (Paris - Brussels) is 8:00 AM. According to Table 11 the journey time before user adaptation is 3.37 hours (3 hours 22 minutes). A drastic peak in external marginal congestion costs is calculated about 70 km from the Paris centre. It is remarkable, that the marginal external congestion costs are high on a longer road distance in the case of congestion pricing than they would be without congestion pricing. This can be explained by the higher travel speeds in the Paris area after congestion pricing. This means that more distance is driven within the morning peak hour. In other words: Avoiding the heavy congestion in Paris means running into congestion outside the city centre.

A similar effect can be observed at Crespin across the border to Belgium. While due to the morning delay in Paris without congestion charging the driver arrives around 10:30 in here, in the case of congestion charging he arrives about one hour earlier. At this time, the morning peak is still not over.

The journey ends in Brussels at 10:20 (after 2 hours and 20 minutes) in the case of congestion charging. Without congestion charging the journey takes 3 hours and 10 minutes. In both cases the level of congestion around Brussels is minor. Starting at 8:00 a.m. in Paris, he marginal external costs for the whole journey are 21 Euro (0.08 Euro per km) before congestion charging and 17 Euro (0.06 Euro/km) after congestion charging. This relatively moderate level of cost reduction can be explained by the traffic volume pattern along the corridor and the reaction of travel speeds on the introduction of road user charges. The model output is presented by Figure 13 below.

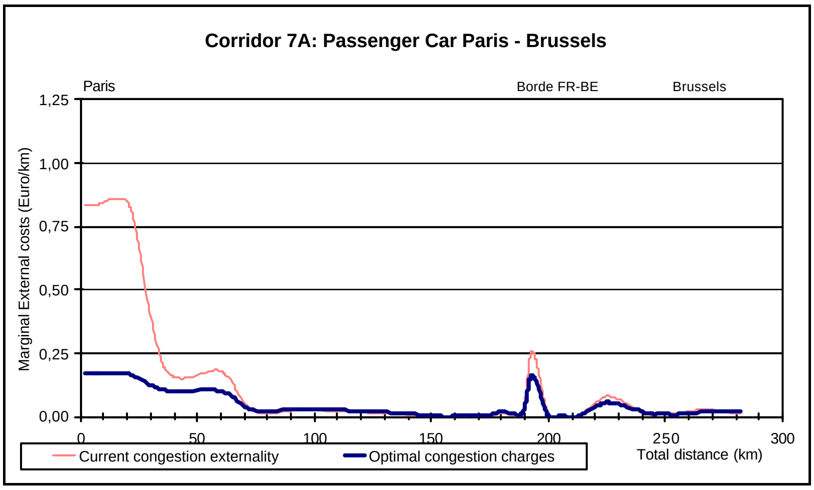

Figure 13: Detailed results corridor 7A (Paris - Brussels)

As shown in Table 11, for some departure times the introduction of a congestion pricing system might even lead to a increase in the congestion externality. On the route Paris - Brussels this the case for a departure time of 14:00 in Paris. While the afternoon congestion is avoided in the case of no road pricing system, the driver will fully step into the afternoon traffic jams around Brussels if his travel speed is increased due to congestion charges along the route.

5.2.3 Detailed Results for Corridor 7B (Paris - Munich)

The travel time along corridor 7B takes around 11 hours before demand reactions of road traffic users and around 9 hours when parts of the traffic are ”priced off”. Thus, as start time of 8:00 AM means that the morning peak as well as the afternoon peak will be met by the traveller. This is partly reflected by the results of Corridor 7B shown in Figure 16, where the afternoon peak on the route Strassbourg - Munich can be identified clearly. As west-bound traffic from Paris is not very dens in France, the effects of the morning peak only present close to the agglomeration of Paris.

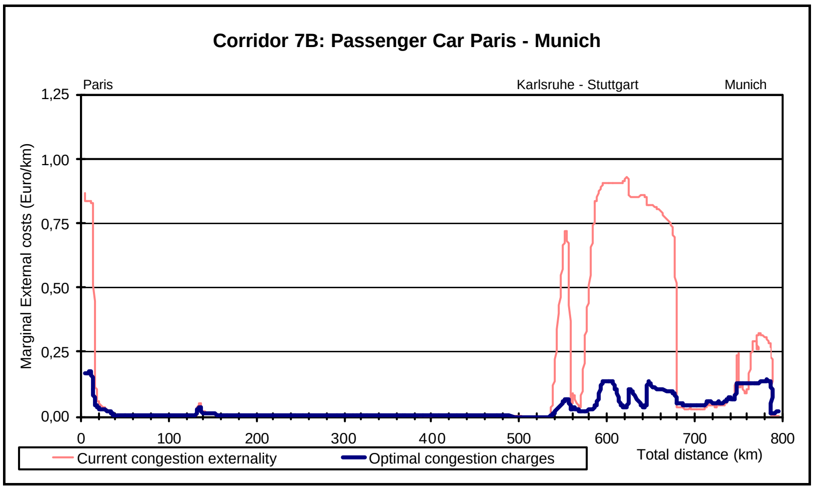

Figure 14: Detailed results Corridor 7B (Paris - Munich)

5.2.4 Detailed Results for Corridor 7C (Cologne - Milan)

The structure of the results for Corridor 7C look somewhat similar to the results found for the route Paris - Munich. The highest congestion externalities are calculated for the German road network and for border region from Switzerland to Italy. The current external congestion costs and the respective user charges (after user reaction) shown in Figure 15 are remarkably high form some route segments. This must be interpreted carefully as the speed-flow relationships out of FGSV (1997) are not continuous in every part. With a departure time of 8:00 the reference vehicle arrives at the Italian border at 19:00 h and thus the afternoon peak is over. Consequently, external congestion costs are close to zero for the Italian part of the route.

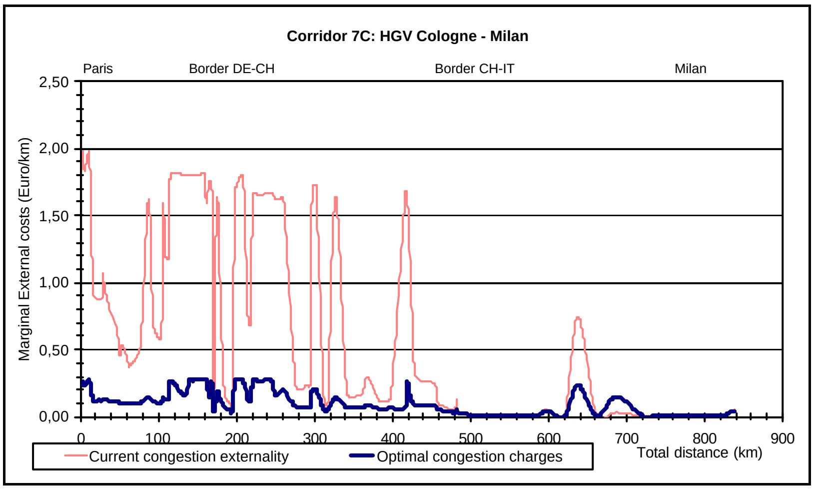

Figure 15: Detailed results Corridor 7C (Cologne - Milan)

5.2.5 Detailed Results for Corridor 7D (Duisburg - Mannheim)

The highest charges along the freight transport corridor from the Ruhr area (Duisburg) to Mannheim are located in the first half of the route from Duisburg to Cologne and further to Frankfurt. This constellation is determined by two factors:

- The departure time in Figure 16 is 8:00 AM, which means that the first part of the journey is taking place in the morning peak. Frankfurt is reached at about 11:00 AM and thus the further journey can be made before the afternoon peak is setting in.

- The motorway network in the central part of Germany around the highlyx industrialised Rohr area is more dense and more congested than the route in the southern part of the country (below Frankfurt). Thus, the marginal external congestion costs are lower in the second part of Corridor 7D.

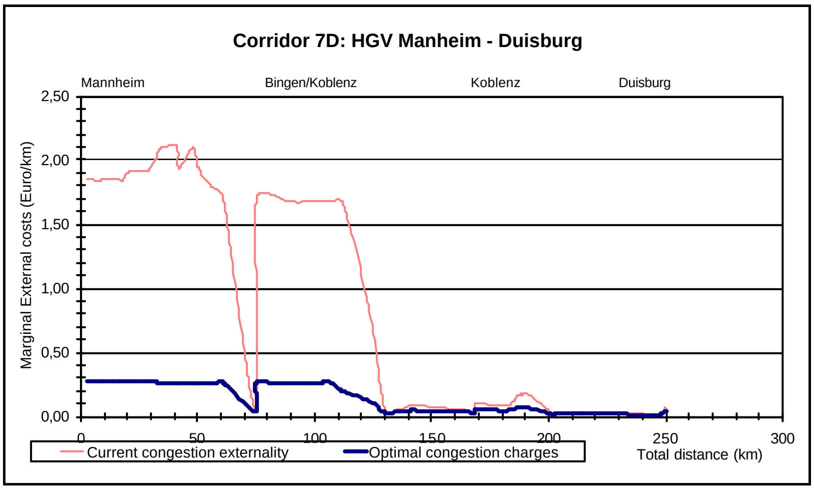

Figure 16: Detailed Results for Corridor 7D (Duisburg - Mannheim)

5.3 User costs in Rail Transport

Marginal social user costs in rail transport were determined on the basis of a database on train movements, delays and passenger trips of January 2001 in Switzerland. Out of this database it was possible to estimate a linear relationship between the number of passenger trips per hour and the average train delay. The marginal social user costs then were determined in the common manner by deriving the product of traffic volume and average user costs by the user costs. The marginal external user costs then result from subtracting the average user delay costs from these marginal social costs.

The value of time used was taken out of the UNITE valuation conventions and accordingly varied between normal travel time and small delays on the one hand and severe delays (above 5 minutes) on the other hand. The UNITE valuation conventions recommend to consider only severe delays when determining the social costs of rail congestion. However, in the determination of road congestion costs all delays, including very small changes in travel time, are considered. Thus, in the present case study on rail congestion costs both cases are considered:

- Model 1 takes all delays against the scheduled arrival of trains into account.
- Model 2 considers only delays equal and above 5 minutes against scheduled arrival.

The results of the estimate of congestion costs for Swiss passenger transport carried out by the Swiss Federal Railways (SBB) are presented in the graph below:

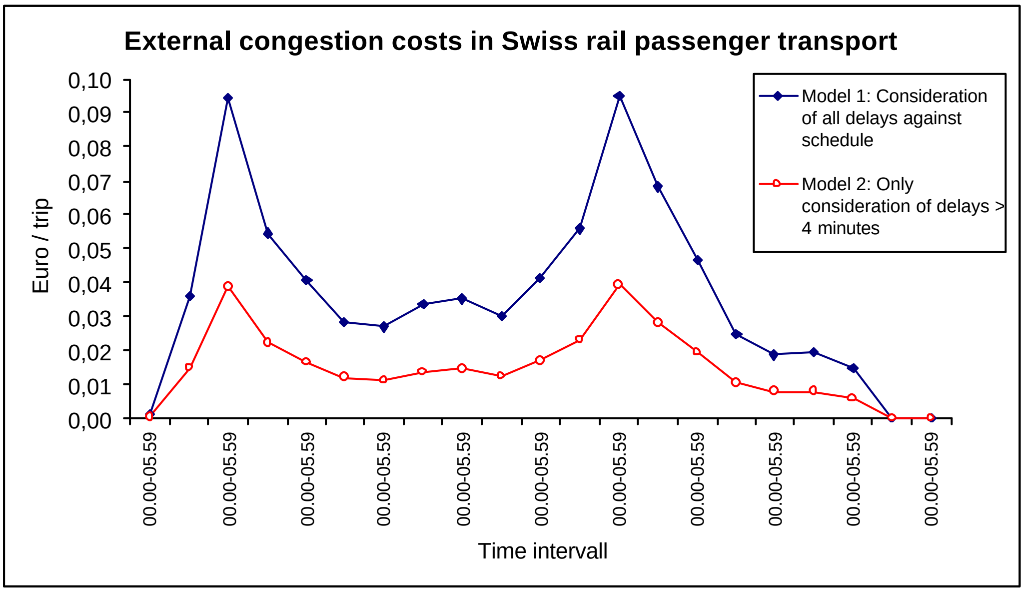

Figure 17: Results of the calculation of marginal external costs in Swiss rail passenger transport
Source: IWW

Figure 17 illustrates the development of external user costs in rail passenger transport for the two models of delay valuation. For model 1 (all delays), congestion externalities of .010 Euro per trip in the morning and the afternoon peak are calculated. In the off-peak period the marginal external user costs range around 0.03 Euro per trip.

Model 2 (only valuation of delays above 5 minutes) delivers congestion externalities of roughly 40% of those presented by Model 1. This ratio is pre-determined by the ratio of the coefficient *b* of the delay curve and thus holds for all times of day.

6 Conclusions

6.1 Summary of Results

In the first part of the paper user cost functions have been selected and transformed into congestion cost functions by computing the equilibrium of traffic demand and the sum of private user costs and internalised congestion externality of a single road link. These have been checked against the driving factors: (1) Road type or speed flow function, (2) HGV share and (3) the demand elasticity. The following results have been found:

- The general congestion level for passenger cars with a demand elasticity of -0.35 on inter-urban roads is around 0.15 Euro per vehicle kilometre at a level of traffic volume, were travel speeds start to drop dramatically. Beyond this point of transition from fluent traffic to congestion speed flow curves are not valid any more and thus the welfare-optimal definition of congestion cost functions becomes arbitrary.

- For motorways and other inter-urban roads with three and more lanes per direction maximum congestion costs between 0.35 and 0.40 Euro per km for HGVs were computed. These values are well above the simple product of congestion costs for passenger cars and the capacity demand factor for HGVs.

- The road type has only little impact on the slope and the level of congestion costs of passenger cars. In contrast, the road type is decisive for the congestion costs of HGVs. In general we can say that costs are considerably higher for roads with less capacity.

- The HGV-share does not influence the level of passenger car congestion costs, but it has a great impact on the congestion costs of HGVs themselves. While for low HGV-shares (up to 20%) mainly their influence on passenger cars is of relevance, above 20% the mutual disturbance of HGVs starts and optimal congestion costs might rise above 0.70 Euro per HGV-km.

- For passenger cars as well as for HGVs the demand elasticity has a very strong impact on the level of congestion costs. For passenger cars the maximum congestion costs range between 0.10 Euro/km (for Eta = -1) and 0.26 Eurl/km (for Eta = -0.1). For HGVs the range is 0.20 Euro/km to 0.61 Euro/km.

Table 12 gives an overview of the variations on congestion costs by cost driver.

Table 12: Variations of congestion costs by cost driver

	Maximum congestion costs for passenger cars (Euro / km)	Congestion costs for HGVs (Euro / km)
Standard conditions: (2-lane motorway, HGV-share: 15%, Elasticity: -0.35)	0.15	0.35
Variation of road type: (2-lane rural road - 4-lane motorway)	0.15 - 0.16	0.48 - 0.33
Variation of HGV-share: (p = 10% - 30%)	0.15 - 0.15	0.32 - 0.72
Variation of demand elasticity: (Eta(P) = Eta(G) = -0.1 - -1)	0.26 - 0.10	0.61 - 0.20

The congestion functions have been applied to the four case study corridors 7A to 7D, were 7A and 7B focus on passenger transport and 7C and 7D focus on goods transport. Network definition, demand data and demand elasticities are based on the European network model

VACLAV. For each corridor, average user costs and optimal congestion charges have been computed for several departure times.

Table 11 summarises the congestion costs for passenger cars (corridors 7A and 7B) and for HGVs (corridors 7C and 7D) for different departure times.

Table 13: Summary results by corridor for different departure times

Corridor and considered vehicle class	Average marginal external costs by departure time (Euro per km before (after) charging			
	6:00 h	08:00 h	14:00 h	20:00 h
7A: Passenger car Paris - Brussels	0.12	0.10	0.19	0.01
	(0.03)	(0.04)	(0.05)	(0.00)
7B: Passenger car Paris - Munich	0.14	0.16	0.03	0.00
	(0.02)	(0.03)	(0.01)	(0.00)
7C: HGV Cologne – Milan	0.58	0.52^	0.47	0.04
	(0.10)	(0l.09)	(0.08)	(0.01)
7D: HGV Duisburg - Mannheim	0.83	0.78	0.89	0.16
	(0.13)	(0.13)	(0.14)	(0.03)

The main findings from the corridor application are:

- As can be expected, the congestion charges vary strongly with the departure time. For passenger cars they can be neglected when the main part of the journey is during the night. For HGVs the difference of congestion charges by departure time is less extreme, but also significant.

- The detailed results presented in the sections above and in Appendix I show, that in most cases of passenger travel congestion pricing reduces the overall travel costs from the perspective of the car user. It is found, that this cost reduction can be up to 25%. However, in some cases travel costs increase in relation to a case without congestion pricing. In general we observe, that the development of travel costs strongly varies with departure time, and thus with the occurrence of high network loads in space and time.

- In all cases of road freight transport, congestion pricing increases the travel costs perceived by hauliers.

- In road passenger transport optimal congestion cost estimates vary between 0 and 0.17 Euro per pcu-km, whereas under the settings of Case Studies 7A and 7B the majority of distance travelled is priced by 0.05 Euro/km or less. For HGVs optimal charges are found up to 0.27 Euro/km, whereas a considerable share of distance travelled is priced above 0.20 Euro/km.

The estimation of external user costs in rail transport is restricted to passenger transport in Switzerland. Due to reasons of data availability it was not possible to compute user externalities for freight transport or along the study corridors 7A to 7D. For Switzerland two models have been applied, which are distinguished by the valuation of delay time. The main results found are summarised by …

Table 14: Summary of results for rail congestion costs

Time period		External congestion costs (Euro / trip) Model 1: consideration of all delays	 Model 2: Delays >5 min. only
Before morning peak	06.00-06.59	0,0361	0,0149
Morning peak	07.00-07.59	0,0942	0,0388
Noon	12.00.12.59	0,0334	0,0138
Afternoon peak	17.00-17.59	0,0950	0,0391
Evening	20.00-20.59	0,0248	0,0102
Night	23.00-23.59	0,0145	0,0060
Average		0,0321	0,0132

Table 14 shows the following results

- Marginal external user costs in Model 1 (valuation of all delays) vary between 0,10 Euro per trip in the peak hours, 0,30 Euro per trip on the off-peak time and 0,01 Euro per trip in night-time.

- Considering only severe delays of a minimum of 5 minutes (Model 2), external user costs vary between 0,40 and 0.06 Euro per trip, which is 41% of the external costs of Model 1.

Considering an average trip length of 39 kilometres this would mean an average charge of 0.0008 Euro per kilometre according to Model 1. For the comparison of these results to road we assume a externality charge of 0.15 Euro per car kilometre (average of corridor Paris – Brussels in Table 13) and a occupancy rate of 1.5, is 0.10 Euro per passenger kilometre. This means, rail congestion costs amount up to only 0.8% of the congestion externality found in road transport.

6.2 Generalisation

Congestion costs vary strongly by traffic demand, the constellation of traffic networks and travel alternatives and with geographical location. Under the condition, that the functional form of speed-flow relationships used in this paper is considered as valid, the welfare-optimal congestion costs found here are considered to be transferrable between different local contexts. Only a number of influencing factors need to be considered. These are:

- The demand elasticity is decisive for all vehicle types. They need to be set very carefully considering all possible travel alternatives of users, e.g. route choice, mode choice, flexibility in departure time shifts and the possibility for omitting trips. The latter depend on the composition of travel purposes and the structure of the labour market. The estimation of demand elasticities for each user group (or type of ehicle) should be supported by network models. Without such tools the generalisation of elasticities is hardly possible.

- In particular for the congestion costs of HGVs the share of heavy traffic is an important determinant. For different values of the HGV share congestion costs are shown in Section 5.1.2. These results can be used to transfer the congestion costs found in this paper to other contexts of traffic demand.

- The impact of different road types on HGV congestion costs can be taken out of Section 5.1.1 and used for generalisation.

- The value of travel time, which influences the level of congestion costs directly, can be transferred between geographical contexts as proposed by the UNITE valuation conventions. In addition, national compositions of travel purposes and vehicle load factors in passenger travel should be considered.

In case other speed-flow functions than the presently used Gernam EWS functions are to be taken as a basis for the calculation of marginal congestion costs a generalisation of the present results is not possible. Different speed-flow functions will strongly impact the slop and the level of congestion costs and the ratio between congestion costs of HGVs and passenger cars.

The congestion costs estimated for Swiss passenger rail transport can hardly be generalised for the whole of Europe. Their transfer to other countries must take into consideration:

- The buffer times the railway operator has set in for the recovery of delays.
- The inter-connection of timetables of different railway lines or between rail and other modes of transport.
- The priority rules for different train classes.
- The occupancy rate of trains.

In general we can state, that the buffer times integrated in the time tables to recover delays are longer and the railway lines are shorter than they are in other countries. Consequently, delays can be recovered much better and congestion costs are much lower than e.g. in Germany or France. However, to which degree the cost values differ from each other can not be answered without the consultation of approp0riate observation data or the application of network models.

Further, it is not possible to make any transfer from congestion estimates for rail passenger services to rail freight services is not possible. The different definitions of time tables and priority rules and the usage of different times of day for the main transport activities results in a totally different constellation of network load and train delays.

6.3 Demand for Further Research

As the most decisive factor influencing the level of congestion costs we have re-confirmed the demand elasticity. We were able to describe parts of the elasticity of road users by results of the European network model VACLAV. With this tool it is possible to describe route shift effects in road transport and modal shifts in road and rail traffic. However, the model does not allow to simulate departure time shirts or the users' decision to omit trips. For a full determination of the optimal level of congestion charges by network link and time of day a fully time-variant, behavioural model of traffic demand must replace fix O-D-matrices.

By the multi-user assignment of congestion costs on the basis of the German EWS speed-flow model we have found, that congestion charges for HGVs must be muchmore than the congestion charges for passenger cars, multiplied with the HGVs' capacity demand factor.

The basis for this is the very simplified assumption, that HGVs influence the travel speed of passenger cars, but vice versa the volume of passenger cars is irrelevant for the speed of HGVs. For further investigations of the economically correct level of congestion charges it is recommended to describe the mutual interrelationship of different vehicle classes by the results of detailed traffic flow simulation models.

The previous calculations have shown, that the internalisation of external congestion costs might remove congestion externalities by more than 90% in passenger and goods transport on road. From the perspective of a passenger car driver, however, this means only a reduction of up to 25%. Depending on network constellations in time and space, even a cost increase can be introduction of congestion pricing. For HGVs an average cost increase of 10% to 20% is caused by congestion pricing; in none of the studies corridors a cost reduction for the hauliers could be observed. Consequently, the vast majority of social surplus is caused by those, who have changed their former travel behaviour. The users' costs of changing departure times, transport modes or destinations, however, are not considered by common transport models. Given the high share of benefit caused by displaced users found in the present corridor studies, without this information we can not be sure that marginal social cost prices will really lead to an overall welfare optimum.

Especially in the rail sector the availability of detailed data on train and passenger movement by time of day or days of a year or the accessibility of network-wide railway models, which are appropriate for estimation relationships between transport demand and delays is poor. Thus, there is only little knowledge about the level of external user costs. In the case of rail transport the application of a full-scale transport model. Which is based on network information as well as on behavioural patterns of different user groups is decisive for the understanding of the reaction of users on the introduction of rail congestion charges. In the present case study on the Swiss market we have assumed, that there will be no user reaction. But in particular in the railway sector a price elasticities are higher than in road transport – especially if the alternatives by road or ther models are attractive.

References

Banfi S, Doll C, Maibach M, Rothengater W, Sieber N, Zuber J (2000): *External Costs of Transport*. Study on behalf of the International Union of Railways (UIC). Zurich, Karlsruhe, Paris,April 2000.

BASt (2001): Vereinfachtes Hochrechnungsverfahren für Außerorts-Straßenverkehrs-zählungen. Report of the Bundesanstalt für Straßenwesen, volume V84. Bergisch-Gladbach, June 2001.

EC (2001a) *Pricing European Transport Systems (PETS)*, Final Report. Study financed by the 4th RTD Framework Programme of the Commission of the European Communities. Project co-ordinated by the Institute of Transport Studies, University of Leeds. Leeds, Brussels, 2001.

Christensen C, Beaumont H, Dunkerly C, Lindberg G, Otterstrom T, Gynther L, Rothengatter W, Doll C (1998) *Summary of Internalisation of Externalities*. PETS (Pricing European Transport Systems) deliverable 7. Funded by the 4th RTD framework program of the European Commission, Leeds, September 1998.

ECMT 1998: User Charges for Railway Infrastructure; Round Table 107. Economic Research Centre of the European Conference of Ministers of Transport. Paris, 1998.

ECMT 1999: Traffic Congestion in Europe; Round Table 100. Economic Research Centre of the European Conference of Ministers of Transport. Paris, 1999.

FGSV (Forschungsgesellschaft fuer Strassen- und Verkehrswesen) (1997) Empfehlungen fuer Wirtschaftlichkeitsstudien an Strassen (EWS), Bad Godesberg.

Hohmayer, O., Ottinger, R. Rennings, K. (ed.) 1997: Social costs and Sustainability; Berlin, Heidelberg, 1997.

INFRAS 1998, *Staukosten im Strassenverkehr*; study for the Swiss Office for Road Transport (ASTRA), Bern, 2000.

Jansson J.O. 'Marginal Cost Pricing of Scheduled Transport Services' *Journal of Transport Economics and Policy vol. XIII no. 3, pp 268-294.*

Jansson JO, Lindberg G (1998) *Pricing Principles.* PETS (Pricing European Transport Systems) deliverable 2. Funded by the 4th RTD framework program of the European Commission. Leeds, July 1998.

Link H, Steward HL, Bickel R, Doll C, Maibach M, Schreyer C, Suter S (2002): Pilot Accounts for Germany and Switzerland. Deliverable D5 of the project UNITE (Unification of Accounts and Marginal Costs for Transport Efficiency), financed by the 5th framework programme of the European Commission. Berlin, 2002.

Maibach, M, Rothengatter W, Sieber N, Doll C, Banfi S, Schenkel P, Zuber J (2000) *External Costs of Transport*. Study on behalf of the UIC (Internaltional Railway Union). Paris, April 2000.

Nash C, Sansom T (1999) Calculating Transport Congestion and Scarcity Costs. Final Report of the Expert Advisors to the High Level Group on Infrastructure Charging (working group 2). Leeds, May 1999.

Neuenschwander R, Walter F (1990) *Optimale Tarife im öffentlichen Personenverkehr am Beispiel der Stadt Bern*. Bern, March 1990.

Proost, S., Van Dender, K. (1999), *TRENEN II STRAN – Final Report for Publication*. Project funded by the EC, Contract no: ST.96.SC.116. Brussels, 1999.

Rothengatter W, Doll C, Sansom T, Maccario R, Goller L, Maibach M, Otterström, T, Laurikka H. Jansson K (1998) *Guide for the Evaluation of Real Transport Costs.* FISCUS (Cost Evaluation and Financing Schemes of Urban Transport Systems) deliverable 3. Funded by the 4th RTD framework progrem of the European Commission. Lisbon, April 1999.

Sansom T, Still B, Nash C (1999) *The Cross Channel Case Study*. PETS (Pricing European Transport Systems) deliverable 9, draft report. Funded by the 4th RTD framework program of the European Commission, Leeds, June 1999.

UBA 1996: Mobilität um jeden Preis? – Expertenworkshop zu externen Kosten des Verkehr und den Möglichkeiten sie zu verringern; Fortbildungszentrum Umwelt- und Gesundheitsschutz Berlin e.V. im Auftrag des Umweltbundesamtes; Berlin, September 1996.

Wardmann, (1998), *British Evidance on the valuation of Time ...*

Appendix: Distribution of Charge Levels by Road Corridor

Table 15: Distribution of charge levels for Corridor 7A

Charge level (Euro / km)		Distance travelled by charge level by departure time				Share of distance travelled by charge level by departure time			
from	up to	6:00 h	8:00 h	14:00 h	20:00 h	6:00 h	8:00 h	14:00 h	20:00 h
0,00	0,02	176,10	139,40	91,70	275,00	62,4%	49,4%	32,5%	97,5%
0,02	0,04	39,00	63,20	96,90	0,00	13,8%	22,4%	34,4%	0,0%
0,04	0,06	41,90	15,40	14,00	0,00	14,9%	5,5%	5,0%	0,0%
0,06	0,08	14,00	0,00	0,00	4,00	5,0%	0,0%	0,0%	1,4%
0,08	0,10	0,00	0,00	39,00	0,00	0,0%	0,0%	13,8%	0,0%
0,10	0,12	0,00	39,00	0,00	0,00	0,0%	13,8%	0,0%	0,0%
0,12	0,14	0,00	0,00	15,40	0,00	0,0%	0,0%	5,5%	0,0%
0,14	0,16	0,00	0,00	0,00	0,00	0,0%	0,0%	0,0%	0,0%
0,16	0,18	11,00	25,00	25,00	3,00	3,9%	8,9%	8,9%	1,1%
0,18	0,20	0,00	0,00	0,00	0,00	0,0%	0,0%	0,0%	0,0%

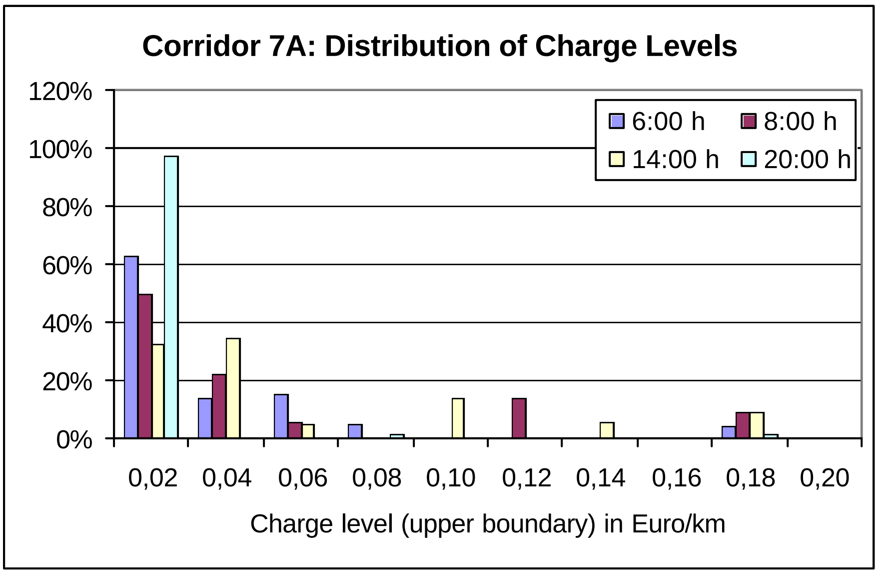

Figure 18: Distribution of charge levels for Corridor 7A

Table 16: Distribution of charge levels for Corridor 7B

Charge level (Euro / km)		Distance travelled by charge level by departure time				Share of distance travelled by charge level by departure time			
from	up to	6:00 h	8:00 h	14:00 h	20:00 h	6:00 h	8:00 h	14:00 h	20:00 h
0,00	0,02	565,50	503,00	683,50	770,50	72,8%	64,8%	88,0%	99,2%
0,02	0,04	85,00	58,50	51,00	6,00	10,9%	7,5%	6,6%	0,8%
0,04	0,06	80,00	75,50	4,50	0,00	10,3%	9,7%	0,6%	0,0%
0,06	0,08	0,00	29,00	19,50	0,00	0,0%	3,7%	2,5%	0,0%
0,08	0,10	18,00	23,00	4,00	0,00	2,3%	3,0%	0,5%	0,0%
0,10	0,12	0,00	10,50	2,00	0,00	0,0%	1,4%	0,3%	0,0%
0,12	0,14	22,00	65,00	0,00	0,00	2,8%	8,4%	0,0%	0,0%
0,14	0,16	0,00	0,00	0,00	0,00	0,0%	0,0%	0,0%	0,0%
0,16	0,18	6,00	12,00	12,00	0,00	0,8%	1,5%	1,5%	0,0%
0,18	0,20	0,00	0,00	0,00	0,00	0,0%	0,0%	0,0%	0,0%

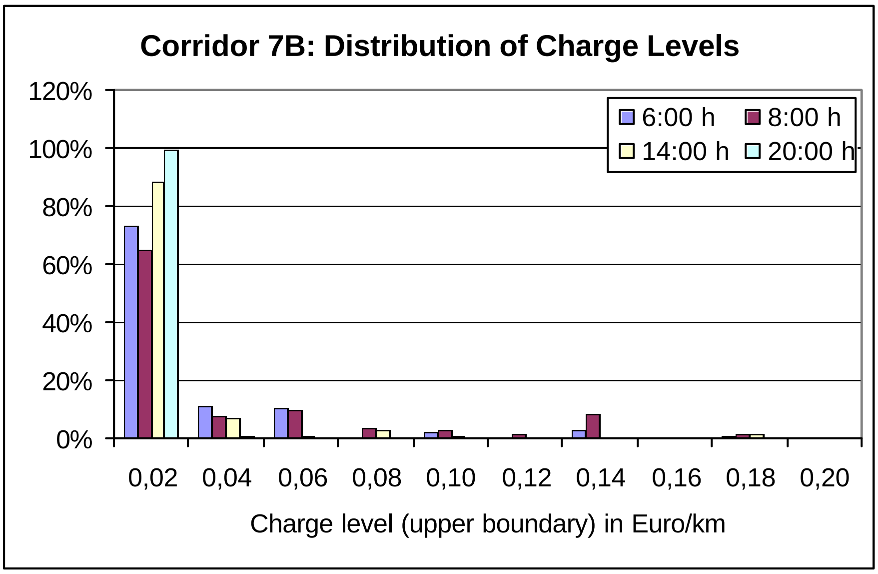

Figure 19: Distribution of charge levels for Corridor 7B

Table 17: Distribution of charge levels for Corridor 7C

Charge level (Euro / km)		Distance travelled by charge level by departure time				Share of distance travelled by charge level by departure time			
from	up to	6:00 h	8:00 h	14:00 h	20:00 h	6:00 h	8:00 h	14:00 h	20:00 h
0,00	0,03	329,00	294,00	420,00	815,00	39,2%	35,1%	50,1%	98,3%
0,03	0,06	113,00	90,50	106,00	0,00	13,5%	10,8%	12,6%	0,0%
0,06	0,09	92,50	141,50	42,00	0,00	11,0%	16,9%	5,0%	0,0%
0,09	0,12	35,50	76,00	72,50	0,00	4,2%	9,1%	8,6%	0,0%
0,12	0,15	29,00	60,00	10,50	9,50	3,5%	7,2%	1,3%	1,1%
0,15	0,18	46,50	55,50	6,00	5,00	5,5%	6,6%	0,7%	0,6%
0,18	0,21	0,00	19,00	21,50	0,00	0,0%	2,3%	2,6%	0,0%
0,21	0,24	17,00	19,00	5,50	0,00	2,0%	2,3%	0,7%	0,0%
0,24	0,27	155,00	68,00	145,00	0,00	18,5%	8,1%	17,3%	0,0%
0,27	0,30	21,00	15,00	9,50	0,00	2,5%	1,8%	1,1%	0,0%

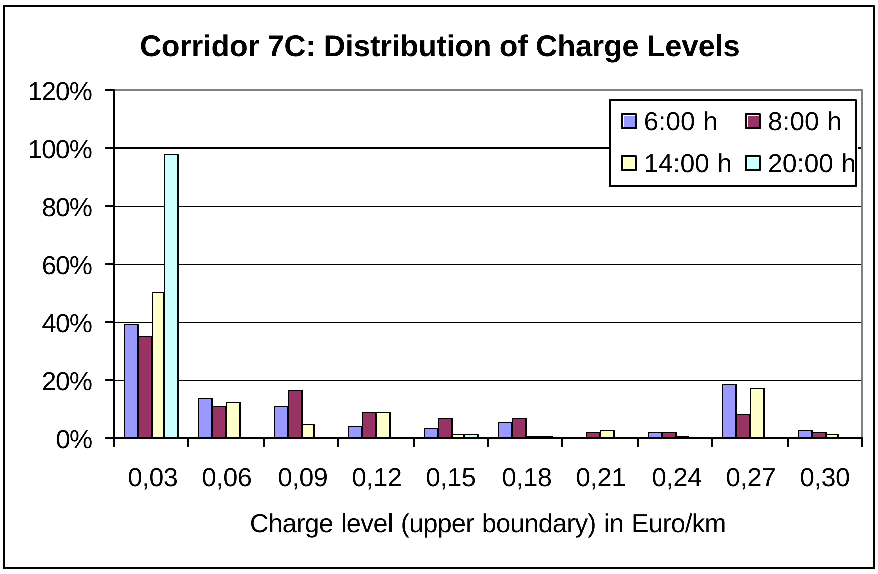

Figure 20: Distribution of charge levels for Corridor 7C

Table 18: Distribution of charge levels for Corridor 7D

Charge level (Euro / km)		Distance travelled by charge level by departure time				Share of distance travelled by charge level by departure time			
from	up to	6:00 h	8:00 h	14:00 h	20:00 h	6:00 h	8:00 h	14:00 h	20:00 h
0,00	0,03	58,00	57,00	57,00	182,60	23,1%	22,7%	22,7%	72,9%
0,03	0,06	57,50	75,10	16,50	21,50	22,9%	30,0%	6,6%	8,6%
0,06	0,09	3,00	8,50	48,10	8,50	1,2%	3,4%	19,2%	3,4%
0,09	0,12	28,60	11,50	14,50	16,00	11,4%	4,6%	5,8%	6,4%
0,12	0,15	0,00	0,00	4,50	18,50	0,0%	0,0%	1,8%	7,4%
0,15	0,18	8,50	0,00	0,00	3,50	3,4%	0,0%	0,0%	1,4%
0,18	0,21	5,50	5,50	0,00	0,00	2,2%	2,2%	0,0%	0,0%
0,21	0,24	2,00	0,00	0,00	0,00	0,8%	0,0%	0,0%	0,0%
0,24	0,27	57,50	93,00	110,00	0,00	22,9%	37,1%	43,9%	0,0%
0,27	0,30	30,00	0,00	0,00	0,00	12,0%	0,0%	0,0%	0,0%

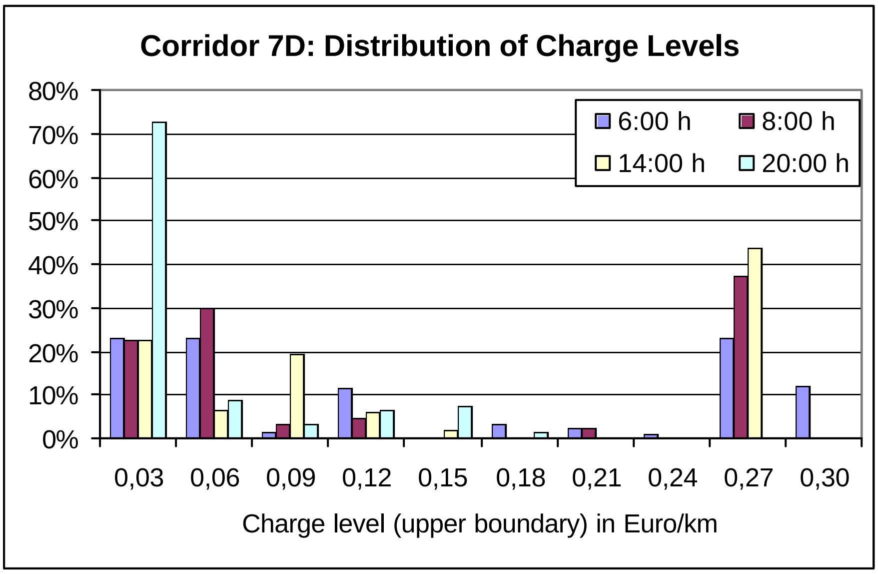

Figure 21: Distribution of charge levels for Corridor 7D