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CALCULATION OF WELFARE EFFECTS OF ROAD PRICING ON A LARGE SCALE ROAD NETWORK

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Abstract. After a brief review of the theoretical principles of road pricing this paper presents the results of a modelling exercise aimed at ascertaining the effects of road pricing on a large road network. For the study area we chose an important part of the road network of Belgium, situated in the corridor between the main cities of Brussels and Ghent. Simulations were carried out using an elastic static traffic assignment method. Special care was taken to use realistic parameters for resource costs, time costs, external environmental costs and tax rates. The reduction of traffic caused by the increased trip prices as well as the route changes induced by the tolls were taken into account. The main objective of tolling as considered in this paper is the maximisation of the social welfare gain but possible adverse effects of tolling on traffic streams are also investigated. The relative merits of cordon and corridor tolling schemes are discussed. A combination of these two tolling schemes appears to give the best results, both in terms of welfare gain and traffic streams.

Keywords: road pricing, cordon toll, corridor toll, social welfare, elastic static assignment, road network.

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1. Introduction

The introduction of road pricing on a large scale national road network requires a clear definition of the objectives, for this may have important implications for the scheme characteristics, for example, in terms of the vehicles affected and the amount of toll to be charged. Different objectives can be formulated such as alleviating congestion, reducing environmental

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damage, financing of infrastructure or increasing the efficiency of using the infrastructure. This paper focuses on the last objective: increasing the efficiency of using the infrastructure. This implies that the effectiveness of the scheme will be measured by the increase in social welfare it entails.

An important and non-trivial aspect of road pricing is its technical implementation. This includes the overall system architecture, the technical design of toll plaza's, the provision of secure payment systems and the day to day operation of all the electronic systems involved. Very important are also the transaction costs, i.e. the costs of implementing the system, as these costs must be deducted from the welfare benefits of the system. In this paper we do not address those questions but a good overview of intelligent transport systems is given by Jarašūnienė (2007) and Batarlienė, Baublys (2007). Road pricing also plays an important role in the optimisation of an urban area's operating efficiency (Tanczos and Torok 2007).

This paper presents the results of a modelling exercise aimed at determining the effects of road pricing on the Belgian road network using recent Belgian data on resource costs, tax rates and external costs. Because of limitations of the used model the calculations are of an exploratory nature. Comparable work has been done by Zhang, Yang (2004) for the city of Shanghai and by Akiyama *et al.* (2004) for the city of Osaka, while in the recent MC-ICAM European project calculations were carried out for 5 European cities (MC-ICAM European Research Project 2006).

In order to place the results in their proper perspective, it is important to point out some limitations of the modelling framework. The first limitation concerns the choice behaviour of drivers. Charging a toll on a road network will change the choice patterns of drivers in different ways. The following choices will be affected:

1 – the choice of whether or not to make a trip;
2 – the choice of route from origin to destination;
3 – the choice of departure time;
4 – the choice of transport mode;
5 – the choice of origin and destination (a long term 'distributive' effect).

In this study we shall only examine the first two choices mentioned above. The other effects are also important, but are outside the scope of the model, that we describe in this paper.

The second limitation is related to the difference between passenger traffic and freight traffic. These two types of traffic will show different reactions to the charging of a toll, mainly due to the large difference in value of time. In this paper, however, we assume an average value of time for all traffic combined.

The paper starts with a brief review of the theoretical principles of road pricing. Next we present an overview of the modelling framework that we used and the values of the parameters involved. In the last section of the paper we discuss a number of simulations that were carried out on the basis of static traffic assignment. The aim of these simulations is to find, by using a trial-and-error process, an optimal pricing scheme for an important part of the road network of Belgium, situated in the corridor between the main cities of Brussels and Ghent.

2. Basic economical principles of road pricing

Pricing on a simple network (one single origin-destination pair)

We start the analysis with a very simple network. Consider a motorway between an origin O and a destination D. The road carries a flow of x vehicles per time unit. The total benefits of all drivers taken together are indicated by $B(x)$. The total social costs are given by $C(x)$. The total surplus on the market for car trips between O and D equals the difference between total benefits and total social costs. This total surplus is maximised when:

$$\frac{dB(x)}{dx} = \frac{dC(x)}{dx}. \tag{1}$$

The left-hand side of this equation represents the marginal benefit function, better known as the demand function. The right-hand side represents the marginal cost function, sometimes called the supply function. The equation shows that maximal efficiency is attained when the flow of vehicles x is such that marginal social costs equal marginal benefits (or are equal to the demand function evaluated at x). In ordinary circumstances (i.e. without tolls) this is never the case: an equilibrium flow will arise where marginal social costs exceed marginal benefits, leading to a so-called dead-weight welfare loss caused by an overproduction of traffic.

The total social costs (expressed in monetary units) caused by the x vehicles using the road are:

$$C(x) = a\,x + x\,c(x) + m\,x, \tag{2}$$

where

a – resource costs ("real" production costs excluding tax) for car ownership and car use per time unit;

$c(x)$ – travel time costs per vehicle for a flow of x vehicles per time unit;

m – environmental and other social costs per vehicle per time unit.

Marginal social costs are found by taking the derivative of this expression with respect to x:

$$MSC(x) = a + c(x) + x\,\frac{d(c(x))}{dx} + m. \tag{3}$$

The existing market equilibrium

The marginal social costs MSC are depicted in the diagram in Fig. 1. They are equal to the sum of marginal resource costs, marginal time costs and marginal environmental costs. The traffic demand is represented by the demand function or marginal benefits function.

Usually the market equilibrium is found by equating demand to total marginal costs. But in deciding on his trip a car driver only considers his *private* marginal costs (MPC), which are less than total marginal costs and are equal to the sum of marginal resource costs a, marginal tax costs b and marginal private time costs $c(x)$:

$$MPC(x) = a + c(x) + b. \tag{4}$$

The demand function intersects the MPC function at E. The corresponding vehicle flow for the existing market equilibrium is x_2.

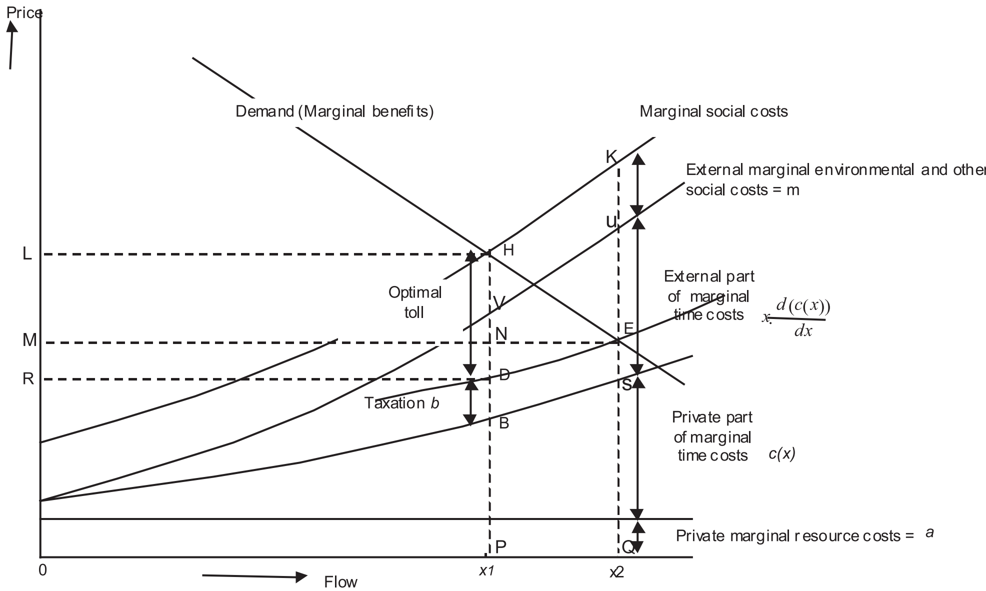


Fig. 1. Existing and optimal equilibrium for a simple network

The optimal market equilibrium

The equilibrium point E in Fig. 1 is undesirable from a social point of view. The optimal equilibrium point is H, where marginal benefits equal marginal social costs. The number of cars using the road in this optimal market equilibrium has dropped to x_1. By imposing a levy equal to the marginal external costs prevailing in the optimal equilibrium we can shift the equilibrium point from E to H. This levy is represented by HB in Fig. 1. A part of this levy, depicted by BD, is already charged by the existing taxation. In addition to the tax, we need to charge a toll equal to DH in Fig. 1.

The transition from the existing market equilibrium E to the optimal market equilibrium H leads to a gain in social welfare. The gain in welfare is represented by the area of triangle HEK, and is the result of avoided costs PQKH minus lost benefits PQEH.

An alternative way of determining the welfare gain is by making a profit and loss account for all relevant actors. We distinguish the following groups: the drivers who continue driving despite the toll, the drivers who stop driving because of the toll, the social groups suffering from the environmental damage brought about by the traffic and finally the government charging the toll:

1. The x_1 drivers, who continue driving, will experience a time gain of ND, but they are paying a toll of HD. Their loss corresponds to the area MNHL.

2. The x_2–x_1 drivers, who stop driving, loose benefits amounting to the area of PQEH, but they are saving expenses corresponding to PQEN. Their ultimate loss in welfare is equal to the area of triangle NEH.
3. The social groups suffering from the environmental damage enjoy a gain in welfare represented by the area HKUV.
4. The government, finally, collects a toll of DH from x_1 drivers (area RDHL), but losses tax revenues from x_2–x_1 drivers (area BSED).

Of course, the sum of all these gains and losses equals the above-mentioned 'gain triangle' HEK, as can be demonstrated by some mathematical manipulation.

This alternative derivation of the welfare implications of charging a toll clearly demonstrates that drivers always suffer a loss in welfare, but that their losses are more than compensated for by the gains of the toll-charging authority and the environmental gain. (Naturally individual welfare implications depend on individual valuations of time.). For further details we refer to De Borger and Proost (2001).

Pricing on realistic networks (many origin-destination pairs)

Above we have considered only one market consisting of one origin-destination (OD) pair. As indicated, maximum efficiency occurs on this market when marginal benefits are equal to marginal social costs, a situation that may be obtained by imposing a levy (toll plus possibly existing taxation) equal to the marginal external costs. Realistic networks, however, usually have a large number of OD pairs. Every OD-pair can be seen as a separate market with an accompanying demand function. Moreover, because paths between different OD-pairs partly overlap, there is a strong interaction between these markets.

It can be shown (Verhoef 2000), that analogously to a network with one origin-destination pair, for a network with many origin-destination pairs, maximum efficiency is obtained by imposing a levy (toll plus possibly existing taxation) on every used route between all OD-pairs. The levy should equal the sum of the marginal external costs on all links used in that route. This, in turn, can always be realised by imposing a levy on each link equal to the marginal external costs on that link. The external costs concerned are the external costs that apply in the optimal equilibrium, not the external costs in the existing untolled equilibrium.

A so-called first-best optimum is obtained if marginal benefits are equal to marginal costs on all markets concerned. Because charging a toll on each and every link in a network is almost impossible, obtaining a first-best optimum on a real road network is practically unfeasible. However, the first-best optimum may serve as a benchmark because it gives some idea about the maximum efficiency increase that is attainable.

If a first-best optimum is not feasible, one has to resort to a so-called second-best optimum. Finding a second-best optimum means maximising total surplus subject to certain constraints. The constraints could, for example, involve a restriction on the links where toll may be charged or a restriction to the available budget.

Finding second-best optima for realistic traffic networks is difficult. Exact analytical solutions, obtained, for example, by applying Lagrange multipliers, quickly become intractable. Networks discussed in the literature are generally small-size networks. In this paper we examine a very large network. We use realistic values for important parameters such as resource costs, taxes, price elasticity etc, and apply a trial-and-error method in searching for a tolling scheme that maximises social welfare, restricting tolling generally to main highways.

3. Modelling framework

OmniTrans

We used the traffic modelling software OmniTrans for our simulations (OmniTrans Transportation Software). Calculations were done on the basis of static assignments. OmniTrans has a built-in job-engine enabling the analyst to extend the functionality of the package. We used this facility to write two programs: a program to do elastic assignments and a program to calculate the welfare effects of a certain tolling scheme.

Elastic assignment

Traffic assignment in OmniTrans (and in many other traffic modelling packages) is based on inelastic demand, i.e. the OD-matrix is considered to be constant and invariable. Generally, however, increasing the price of a trip between an origin and a destination, for example, by charging a toll, will entail a reduction in the number of trips undertaken. The developed program calculates, starting from the initial OD matrix without tolls and on the basis of a value for the price-elasticity, the new OD matrix (with generally lower values) arising after the charging of tolls. This means that we essentially preserve the existing general structure of the OD matrix, i.e. we disregard the possibility that people will change their destination (or even their origin) in response to the toll. In the long term it is likely that distributive effects (meaning a different general structure of the OD matrix) will also take place, but, as mentioned in the introduction, we have not taken these effects into account.

Calculation of welfare effect

In a previous section of this paper we indicated 2 alternative ways of calculating the welfare effect of a toll measure. In fact, we considered the optimal market equilibrium but the calculation of the effects of a sub-optimal tolling scheme essentially follows the same lines. Because the effects of a local toll measure can potentially be sensed throughout the whole network, the welfare calculations have to be carried out for every OD relation.

As previously explained, drivers will as a rule always suffer a loss in welfare. But in exceptional circumstances charging a toll on some links may actually improve driving circumstances and lead to new drivers on certain OD relations. For example, a cordon toll around a city may lead to a welfare gain for some drivers, namely those car drivers having their origin within the cordon. They benefit from the lower traffic volumes within the city without actually paying for it.

Network and OD demand

The network we studied covers an area of approximately 20 by 40 kilometres around the main motorway between the large cities of Brussels and Ghent. Apart from the motorway two important main highways and a number of lower order roads can be found in this corridor. The data in the OD-table date from the beginning of 2005. They apply to the period between 8 and 9 o'clock in the morning peak. The dominant traffic streams are in the direction of Brussels at that time. The data are expressed in passenger car units (pcu), where lorries count for 2 passenger cars. In the calculations no distinction is made between different types of vehicles; averages over all vehicles are used.

Parameters

Value of time

The value of time (VOT) plays a central part in the calculations. As mentioned, we use an average value over all vehicles. Common values for VOT given in literature (De Ceuster 2004) are about 9 euro/hour for passenger cars (average over all trip purposes) and 45 euro/hour for lorries. Counts on the motorways in the study area indicate that about 85% of traffic consists of passenger cars and 15% of lorries. Applying these percentages would suggest an average VOT of about 14 euro/hour per vehicle for the study area. Possibly a higher value would be more appropriate, considering that traffic in the morning peak will probably contain a high proportion of business travellers.

A remarkable project in San Diego (Seiji *et al.* 2004) produced much higher values for VOT than the usual values. For home-work travel a value of $30 /hour/person was found. Possibly, in this particular case, factors that are difficult to quantify such as comfort during travel, safety etc. played an important part.

After considering the available information we decided to use an average VOT value of 20 euro/hour/pcu for all the simulations. (In addition, in one of the simulations we studied the sensitivity of the results for the VOT parameter.)

Price elasticity

There is a large variation in the values of price elasticity reported in the literature. For an extensive review see (Victoria Transport Policy Institute). Additional complexity is caused by the fact that elasticities are determined with respect to different bases. Travel time is often used as the basis, but the use of elasticity with respect to fuel price is also widespread.

For our investigation we need the elasticity value with respect to generalised price. The generalised price includes resource costs and taxation (containing an important fuel component), travel time and possibly toll costs. The elasticity with respect to generalised price is higher than the elasticity with respect to all these separate components.

On the basis of available information we decided to apply a price elasticity value with respect to generalised price of – 1.0 (Here also we studied the sensitivity of the results for this parameter in one of the simulations).

Resource costs and taxation

A recent study of external costs in transport carried out in Flanders (De Ceuster 2004) produced the values displayed in Table 1a for resource costs (pure 'production' costs) and the taxation component in the total costs faced by the car users.

The table contains average values weighed according to vehicle-kilometres over all vehicles. A more detailed investigation of the values found in the above-mentioned study reveals large differences between diesel and petrol cars and also between passenger cars and lorries. A diesel passenger car costs 18.30 euro per 100 kilometres on average of which 6.90 euro tax. Petrol cars come to 28.40 euro inclusive of 11.60 euro tax. Diesel cars are much cheaper in running because of lower taxation and because of higher annual mileage. The price for light diesel lorries amounts to only 14.50 euro per 100 kilometres. Heavy lorries and buses can go up to 50 euro, of which 15 euro is tax.

On the basis of the values in Table 1a, we decided to use a value of 0.13 euro/km/pcu for the average resource costs and 0.07 euro/km/pcu for taxation on resource costs.

Table 1. Average cost parameters used in simulations (euro/100 km), weighed according to vehicle-km over all vehicle types in Flanders 2002: a) User costs; b) External costs (excl external time cost). Source (De Ceuster 2004)

a) User costs

Item	*Resource costs*	*Taxation*	*Total*
Fuel	2.90	4.54	7.44
Purchase	8.51	1.42	9.93
Maintenance and insurance	2.77	2.54	5.31
Total	*14.18*	*8.50*	*22.68*

b) External costs (excluding external congestion costs)

Item	*External costs*
Damage to road surface	0.01
Accidents	2.38
Noise hindrance	0.97
Climate change	0.47
Air pollution	1.98
Total	*5.81*

External costs (excluding external time costs)

Here we also used the recent study of external costs in transport carried out in Flanders (De Ceuster 2004). Table 1b originates from that publication. Note that the existing taxation (Table 1a) already covers the total current external costs as given in Table 1b. But the external costs given in Table 1b do not include the external time (or congestion) costs and it are precisely these external time costs that are the most important.

On the basis of the data in Table 1b we selected a value of 0.05 euro/km/pcu for the external costs (excluding external time costs).

Parameters of the travel time performance function

The travel time performance function expresses the relation between the flow and the travel time on a link. We applied the usual BPR (Bureau of Public Roads) function:

$$t = t_0 (1 + \alpha (Q / Cap)^{\beta}, \tag{5}$$

where t_0 is the travel time in free flow conditions, Q is the flow across the link and Cap – the practical capacity of a link. Depending on the type of road we use $\alpha = 0.5$ (motor ways, main roads) or $\alpha = 2.0$ (local roads). For β a value of 4 is taken.

4. Analysis of tolling schemes

In this section we will attempt to develop an optimal tolling scheme in an heuristic way. We also consider the effect of the different tolling schemes on the traffic flows.

We distinguish 3 different types of tolling scheme (Deloitte Business Advisory 2005):

1. *Corridor toll.* Examples are the traditional toll roads found in many countries. The objective of these traditional toll roads usually consists of generating revenues for the (mostly) private investors in these roads. However, in our case it is the growth in social welfare that prevails.
2. *Cordon toll.* A cordon may be located around an important city. As with corridor tolls the objective may be to generate revenues, but often the objective is to 'improve' the traffic flow pattern.
3. *Combined system.* These often are national or regional tolling schemes. They are complex systems but there is an increased probability of inducing a more efficient use of the road network.

Current situation

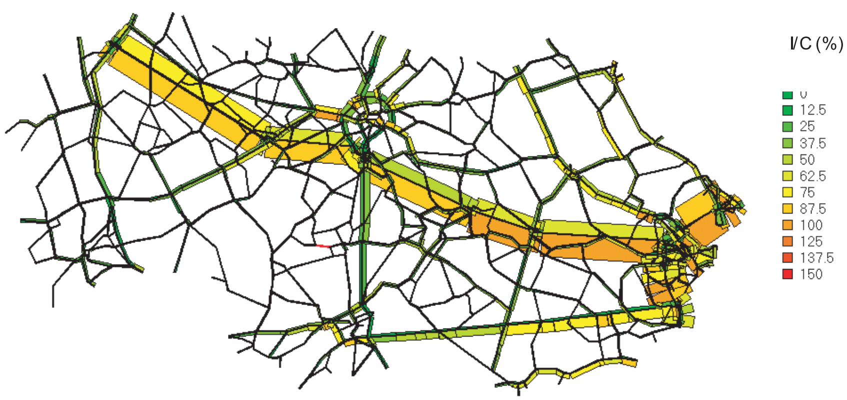


Fig. 2. Current situation, bandwidth = load in morning peak, colour = I/C ratio (see the text for further information)

Our exploration of tolling schemes starts by studying a corridor system, next we investigate a toll cordon around Brussels and we conclude with the consideration of a combined system. In this paper we only give a summary of the large number of simulations that we have carried out.

The current load of the network in the morning peak is depicted in Fig. 2. In this figure Ghent is located just past the left-hand side of the diagram while on the right part the Brussel Ring Road is just visible. The wide band in the middle represents the E40 motorway. About halfway between Brussels and Ghent the important market town of Aalst is situated. Apart from the E40 some other important entry roads into Brussels (such as the N8 at the bottom of the figure and the N9 alongside the E40 near Brussels) are discernible in the figure.

The bandwidth indicates the current flow in the morning peak. The highest volume of 6600 pcu/hour occurs on the E40, just before Brussels. The band colour indicates the ratio between flow and capacity (I/C); the darker the colour, the higher this ratio. Just before Brussels the I/C ratio reaches a value of about 100%.

The figure clearly shows where the largest external costs are incurred, namely on the E40 motorway, and to a lesser extent on the N8 and N9. We therefore start our exploration by investigating the effects of a single toll point on the E40 motorway just before Brussels.

Toll at one point on the E40, just before Brussels

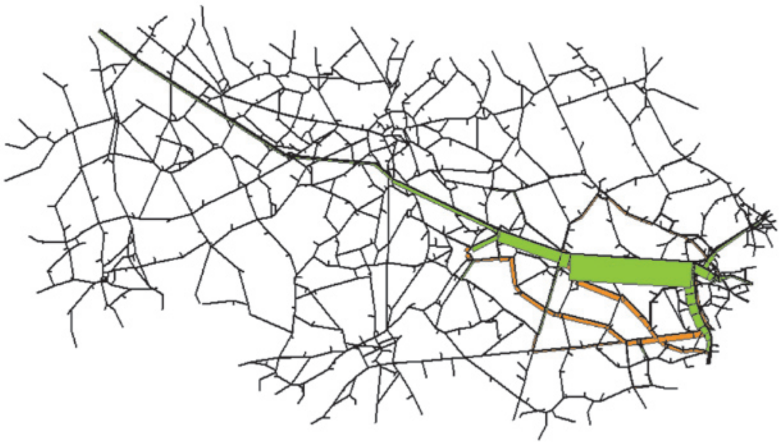
If we desire to charge a toll at a single point in the network it is important to influence those road users causing the largest external costs in the study area. We reach this group of road users by charging a toll on the E40 motorway just before it enters Brussels. We computed the effect on social welfare for different levels of the toll charge.

Some comments are in order before we start the discussion of the results:

1. The real accuracy of the results is (evidently) less than the number of significant digits in the results might suggest.
2. The welfare effects are expressed in euro/hour. To get a clearer picture one would have to multiply the results by the number of hours in a peak period.
3. The transaction costs (i.e. the costs for building the tolling system) have *not* been included. These costs should be deducted from the indicated welfare gains.

The results (see the table in Fig. 3b) show the optimal toll level to be about 2 euro. The toll revenues in that case amount to 10534 euro/hour, of which 887 euro/hour should be deducted because of lost tax revenues due to lower traffic volumes. This means that the real revenues come to 9647 euro/hour. But this is not the real gain of the toll system. The real welfare gain comes to slightly less than half this amount, namely 4122 euro/hour.

As was indicated earlier in this paper, the welfare can be computed in 2 alternative ways. Above we have shown the profit and loss account for all involved parties. The other method consists of a comparison of the costs and benefits before and after toll charging. The change in real costs (time, resource and environmental costs) at a toll level of 2 euro is shown in the table in Fig. 3c. The results are instructive. It appears that the saved costs are relatively low when compared to the costs incurred over the entire network. At 11069 euro/hour they are only in the order of 2% of total real costs before toll was charged.



a) Change in traffic flow for a toll of 2 euro on E40 at single point just before Brussels
light colour (green) is decrease; dark colour (red) is increase

Toll	**1 euro**		**2 euro**		**3 euro**	
Car drivers:						
- Continuing to drive	–2789		–5965		–9512	
- Quitting drivers	–42		–197		–497	
- New drivers	+1		+3		+7	
Total car drivers		*–2830*		*–6159*		*–10002*
Government:						
- Toll revenues	+5970		+10534		+13314	
- Tax revenues	–410		–887		–1387	
Total government		*+5560*		*+9647*		*+11927*
Environmental gain		*+293*		*+634*		*+990*
Change in social welfare		*+3023*		*+4122*		*+2915*

b) Welfare effects (euro/hour) for different toll levels

Network costs	*Time costs*	*Resource costs*	*Environmental costs*	*Total*
before toll	381739	149122	57355	588216
after toll	372951	147475	56721	577147
Saving	*8788*	*1647*	*634*	*11069*

c) Saving of real costs for a toll of 2 euro on E40 at single point just before Brussels

Fig. 3. One single tolling point on the E40 near Brussels: a) change in traffic flow, b) welfare effects, c) saving of real costs

Note that the savings in the table in Fig. 3c are not the real gain of the system! Calculation shows that the reduction of car drivers due to tolling leads to a loss of benefits of 6947 euro/hour. The ultimate welfare gain therefore comes to 11069 – 6947 = 4122 euro/hour, a result that we also found in the table in Fig. 3b.

Note also that in this method of calculation toll and tax revenues play no part. Toll and tax are transfer payments to government. Society as a whole does not lose or gain any welfare by these transfer payments, apart from a possible difference in production efficiency between the public and private sector. The real significance of charging a toll is that it functions as an incentive to change driving behaviour. The ensuing change of traffic flows induces a change of time costs, resource costs and environmental costs and user benefits on the network. The gross effect of these changes in this particular case is a gain in social welfare.

Although the effects in terms of aggregated values of gains and losses relative to the entire network are relatively small, this does not hold true if we study the effects of tolls on a more local level. Near the points where toll is charged the effects are substantial (Fig. 3a). The light colour indicates a reduction of traffic, the dark colour an increase of traffic. Note that only the difference between flows before and after tolling are represented.

On the link where the toll is charged traffic volume decreases by 21%. Only a small part of this reduction is caused by people who decide not to make their trip because of increased costs. The majority of car drivers that decide not to take their old route along the motorway are the drivers that look for bypasses to arrive at their destinations. If the toll level is very high, the time losses along minor roads rise disproportionately reducing possible welfare gains.

Sensitivity of results for varying values of the parameters

The value of time (VOT) and the price elasticity are important parameters when calculating the effects of tolling. For the case 'one single tolling point on E40 just before Brussels' we varied these parameters and checked the effect this had on the welfare results.

If we decrease the VOT parameter, this also has a decreasing effect on the attainable welfare gain, as Table 2a shows. Although the precise interactions between the traffic flows are difficult to trace, the results indicate that a variation of 20% in VOT leads to a variation in welfare gain of roughly the same order. The effect of a variation of elasticity values on the value of attainable social welfare is less pronounced than the effect of a variation in VOT (Table 2b). A variation in the value of elasticity of 20% leads to a variation in welfare gain of only 5 to 10%.

Tolls along the full length of the E40 motorway

Introducing only one single tolling point on the E40 motorway already leads to social welfare gains. But there are some undesirable side effects:

- All users passing the tolling point pay the same toll amount, independent of the distance already covered, and therefore also independent of the external costs that they have already caused.
- The high volumes of rat-run traffic generated on the minor roads are unsafe and cause environmental and other problems.

Table 2. Welfare effect of one single tolling point on E40 near Brussels (euro/hour) for a) varying values of VOT and b) varying values of elasticity

a) Varying values of VOT

Toll on E40 near Brussels	**2 euro VOT = 16 euro**		**2 euro VOT = 20 euro**		**2 euro VOT = 24 euro**	
Welfare of car drivers		*–6720*		*–6159*		*–5934*
Welfare of government		*+8795*		*+9647*		*+10241*
Environmental gain		*+729*		*+634*		*+534*
Change in social welfare		*+2804*		*+4122*		*+4841*

b) Varying values of elasticity

Toll on E40 near Brussels	**2 euro elasticity = –0.8**		**2 euro elasticity = –1.0**		**2 euro elasticity = –1.2**	
Welfare of car drivers		*–6626*		*–6159*		*–5864*
Welfare of government		*+9874*		*+9647*	*+9482*	
Environmental gain		*+543*		*+634*		*+693*
Change in social welfare		*+3791*		*+4122*		*+4311*

From a number of simulations that we carried out (for example, reducing the number of on- and off-ramps from the motorway and charging tolls on other main and minor roads) it appeared that the problem of rat-run traffic is more or less persistent when applying corridor tolls. As will be explained later in this paper, the problem of rat-run traffic is best dealt with by introducing a cordon toll around the city of Brussels.

For the moment we focus on the first undesirable side effect mentioned above. The simulation results for a tolling scheme consisting of a number of tolling points along the entire length of the E40 motorway are shown in Fig. 4b.

We obtain a maximum welfare gain of 6724 euro/hour by spreading out a total toll of 5 euro evenly along the full length of the E40 in the study area. That means a rise in welfare gain of nearly 65% compared to the situation with only one single toll point. Car drivers originating in the Ghent region are now charged a toll of 5 euro instead of 2 euro, while drivers originating nearer to Brussels pay proportionally less.

Fig. 4a shows that, as expected, traffic flow decreases evenly along the entire E40 motorway. The reduction amounts to about 23% on average. The rat-run traffic near Brussels has also diminished somewhat, mainly because the toll on the road stretch just before Brussels has decreased in comparison to the previous simulation. But, on the other hand, traffic on the other main roads has gone up appreciably. This could be rectified by charging toll on those roads also. We shall return to this issue when looking at a combined corridor/cordon tolling scheme later. First we shall study the effects of a cordon toll around Brussels.

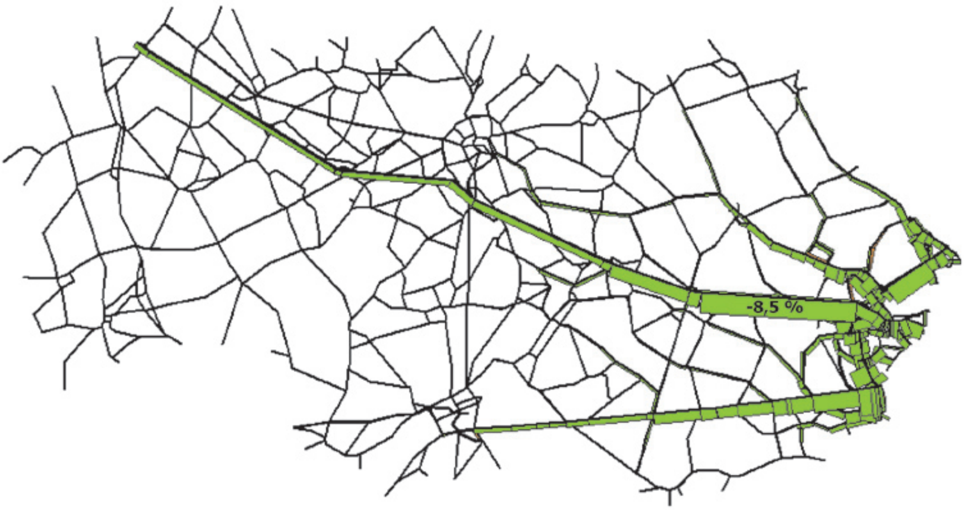
a) Change in traffic flow for tolling points (total toll 5 euro) along entire length of E40 motorway. Light colour (green) is decrease; dark colour (red) is increase. Average decrease flow on E40 is about 23%

Toll	2.50 euro		5 euro		7.50 euro	
Car drivers:						
- Continuing to drive	–6668		–13505		–20353	
- Quitting drivers	–205		–923		–2416	
- New drivers	0		+2		+5	
Total car drivers		*–6873*		*–14426*		*–22764*
Government:						
- Toll revenues	+12697		+21799		+26718	
- Tax revenues	–1064		–2273		–3625	
Total government		*+11633*		*+19526*		*+23093*
Environmental gain		*+760*		*+1624*		*+2589*
Change in social welfare		*+5520*		*+6724*		*+2918*

b) Welfare effects (euro/hour) for different total toll along E40

Fig. 4. Tolling points along entire length of E40 motorway: a) change in traffic flow, b) welfare effects

Cordon toll around Brussels



a) Change in traffic flow for cordon toll (2 euro) around Brussels Light colour (green) is decrease; dark colour (red) is increase

Toll	1 euro		2 euro		3 euro	
Car drivers:						
- Continuing to drive	–9225		–15474		–19715	
- Quitting drivers	–934		–3595		–7608	
- New drivers	+9		+31		+61	
Total car drivers		*–10150*		*–19038*		*–27262*
Government:						
- Toll revenues	+14047		+24046		+31032	
- Tax revenues	–1355		–2738		–4107	
Total government		*+12692*		*+21308*		*+26925*
Environmental gain		*+968*		*+1956*		*+2934*
Change in social welfare		*+3511*		*+4226*		*+2597*

b) Welfare effects (euro/hour) for different cordon toll around Brussels

Fig. 5. Cordon toll around Brussels: a) change in traffic flow, b) welfare effects

The advantage of a cordon tolling scheme is that it discourages rat-run traffic. No car driver that has Brussels as a destination can evade paying toll by choosing a detour route.

The table in Fig. 5b shows that the optimal cordon toll is around 2 euro. The table also shows that toll revenues are quite high in comparison to a corridor toll. But, in proportion to the toll revenues, the welfare gain is relatively modest. When charging a toll along the whole E40 motorway the welfare gain amounts to 34% of the government revenues, for a cordon toll this share decreases to only 20%.

If we examine the effect on traffic flows (Fig. 5a), then it appears that, as expected, the problem of rat-run traffic is largely solved. Traffic flow decreases evenly along all arterial roads leading to Brussels. But traffic flow on the E40 motorway does not decrease as much as it does with a corridor toll. While a corridor toll on the E40 showed a reduction in flow of about 20%, for a cordon toll the reduction amounts to only 10%. On the other main roads the decrease in flow comes to about 15%.

Combined system: corridor toll on E40 and a cordon toll around Brussels

When comparing a cordon tolling scheme around Brussels to a corridor toll along the E40 motorway, the following advantages and disadvantages can be noticed:

- A cordon tolling scheme prevents rat-run traffic and generates relatively high revenues, but the disadvantages are that the welfare gains are relatively low and that car drivers living near to the attraction pole are affected in a disproportional way.
- A corridor toll gives relatively large welfare gains and distributes costs more evenly over the population, but it offers possibilities to evade the toll and therefore promotes rat-run traffic.

In this last section the aim to investigate what happens if we combine both tolling schemes. In order to discourage rat-run traffic on the other main roads we add a tolling point on the main road upstream (west) of Aalst. Many tolling schemes, in terms of locations and levels of tolling charge, are now possible. We present the results of one particular scheme that yielded a relatively high welfare gain (see the table in Fig. 6b).

The welfare gain in this case is the highest of all simulations and the proportion between toll revenues (minus lost tax revenues) and welfare gain is acceptable. Furthermore it appears that the rat-run traffic around Brussels has disappeared while the main road upstream from Aalst also does not show any detour traffic. Downstream of Aalst we now observe some new problems, that could be suppressed by specific measures. However, we prefer to conclude our exposition at this point.

5. Conclusion

The objective of the study described in this paper was to develop, by heuristic methods, an optimal tolling scheme for a complicated road network. Realistic parameters for resource costs, time costs, external environmental costs and tax rates were used. The reduction of traffic caused by increased prices as well as route changes induced by tolls were taken into account, but some other effects, such as travellers changing their destinations or shifting to another

a) Change in traffic flows for a cordon toll of 1 euro around Brussels, a corridor toll on E40 (5 euro) and a tolling point (1 euro) near Aalst. Light colour (green) is decrease, dark colour (red) is increase in traffic flow

Car drivers:		
- Continuing to drive	–20400	
- Quitting drivers	–2058	
- New drivers	+11	
Total car drivers		*–22447*
Government:		
- Toll revenues	+31027	
- Tax revenues	–3301	
Total government		*+27726*
Environmental gain		*+2358*
Change in social welfare		*+7637*

b) Welfare effects (euro/hour) for combination of cordon and corridor toll

Fig. 6. Combination of cordon and corridor toll: a) change in traffic flows; b) welfare effects

mode, were not included. The main objective was to maximise the social welfare gain but possible adverse effects of tolling on traffic streams were also investigated.

We studied the pros and cons of a cordon tolling scheme and a corridor toll. A combination of these two tolling schemes gives the best results, both in terms of welfare gain and traffic streams. The welfare gain, for that matter, appears to be rather modest. The more so if one keeps in mind that the implementation costs of the tolling schemes have not been deducted from these welfare gains.

Static traffic assignment was used in this study. Moreover, we averaged over all types of vehicles. It would be interesting to see, if dynamic traffic assignment using multiple user classes (passenger cars and lorries) would lead to essentially different results.

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KELIŲ APMOKESTINIMO DIDELIO MASTELIO KELIŲ TINKLE SOCIALINĖS GEROVĖS EFEKTO APSKAIČIAVIMAS

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Santrauka

Po trumpos teorinės kelių apmokestinimo apžvalgos aprašomi kelių apmokestinimo didelio mastelio kelių tinkle efekto nustatymo rezultatai. Analizei atlikti buvo pasirinkta svarbi Belgijos kelių tinklo dalis – koridorius tarp pagrindinių Briuselio ir Gento miestų. Ypatingas dėmesys kreiptas į tai, kad buvo panaudoti realūs išteklių, išorinės aplinkos sąnaudų ir mokesčių parametrai. Modeliuota pagal lankstųjį statinį eismo nustatymo metodą. Nustatyta, kad eismas sumažėjo padidėjus kelionių kainoms, įvedus rinkliavą už kelius. Aprašomas rinkliavos poreikis socialinei gerovei ir galimas nepalankus poveikis. Aptariami santykiniai privalumai, užkardos ir koridoriaus rinkliavų schemos. Šių dviejų rinkliavų schemų derinys duoda geriausių rezultatų tiek socialinei gerovei, tiek eismo srautams.

Reikšminiai žodžiai: kelių mokestis, užkardos mokestis, koridoriaus mokestis, lankstus pastovus priskyrimo metodas, kelių tankis.

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