A Bimodal Model for Road Transportation Tolling in Europe[1]

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1 Introduction

The object of this paper is to investigate a bimodal model (private cars and trucks) for transportation tolling. Long distance trips are estimated by a deterministic path based Wardrop assignment model, whereas shorter distance trips are modeled by local flows, which are arc based. In this fashion the model recaptures the full scale of trip lengths while retaining a simple structure. Link costs are partly based on travel times, thus the link costs for cars and trucks share common components and are not monotone. Nevertheless it is shown that local flows are uniquely determined, given global flows, and several procedures for calculating the global network equilibrium are described.

Elements of application to a real network in Europe centered on Belgium are given, including calculations of various marginal costs for several tolling policies, as well as social optima and average speeds. The impact of tolling cars is shown to be modest while the impact of tolling on trucks seems to be significant.

[1] This paper is an outgrowth of the first author's work during a post-doctoral research project at the Department of Economics of the Catholic University in Leuven (Belgium).

2 The model

The Network

The network considered in this study consists of major highways connecting four countries of France, Belgium, Germany, and the Netherlands. The origins are: Calais, Paris, Lyon, Lille in France, and Köln in Germany. The origins in France capture the freight traffic from southern Europe, England and Switzerland. The freight traffic from Eastern Europe can be captured from entry points to Belgium and the Netherlands, such as Köln.

There are 2 designated destinations: Antwerp in Belgium, and Rotterdam in the Netherlands. There are 46 links, and 52 paths in the network. There is a minimum of four paths and a maximum of seventeen paths between each origin-destination pair. The numbers of paths between O-D pairs are dictated by the criteria of reasonable accessibility for freight and car traffic. A simplified representation of the network is given in Figure 1

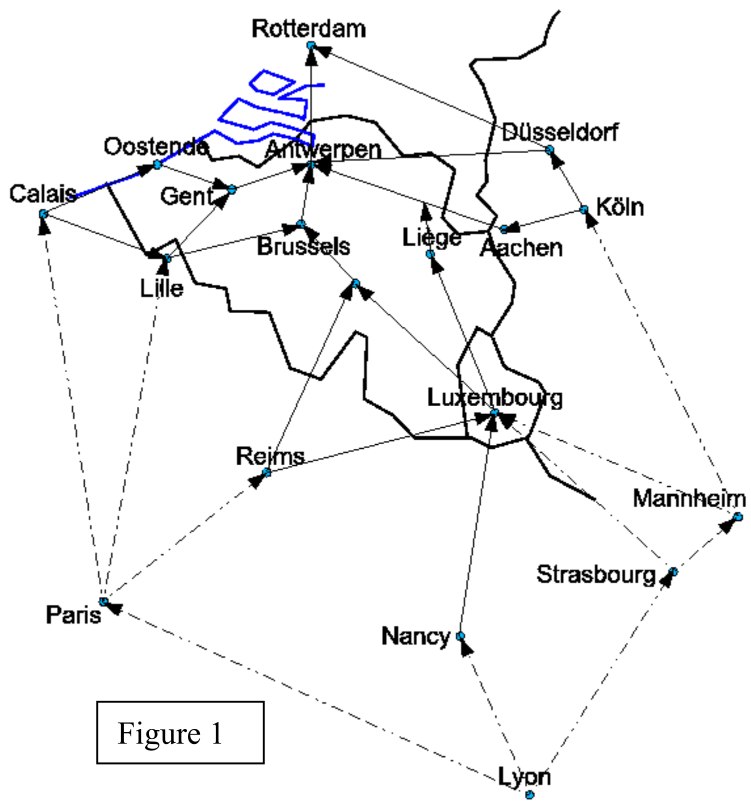

Figure 1

General description

The model consists of two components: network equilibrium, economic analysis. *Inputs* into the network equilibrium are: reference link flows, reference origin flows, link and origin inverse demand functions. The input network attributes are: number of origins and destinations, number of links, number of paths, list of links on each path, free flow speeds, road length, number of lanes, truck – car equivalency factor, and link congestion cost functions. The economic input data per link are: fuel tax rate (trucks, cars), wage and depreciation costs, value of time (VOT), (trucks, cars), MEC (*marginal environmental costs*) of environmental pollution, MEC of road accident risk, MEC of damage to infrastructure (trucks), toll level by origin, and by link, and demand elasticity. Values for these parameters were found in De Borger and Proost 2001.

The model uses a fixed-point method to achieve network equilibrium both for trucks and cars, and both for local and transit traffic. The model produces two types of output per link; one is traffic related, and the other is economics related. The traffic related output per link is: equilibrium path choice flows ((truck, car), (local, transit)) (vh/Pk.hr), origin and path costs (€), link costs (€), average speed (truck, car (km/hr)), number of trips per origin-destination pair. The economic related output per link is: generalized costs (€/vh), external congestion cost (€/vh), welfare (truck, car) (€/hr), link tolls (€), environmental costs (local, transit (€/hr)), pollution, accidents, road damage, toll revenue ((truck, car), (local, transit) (€/hr)), consumer surplus ((truck, car), (local) (€/hr)).

Network equilibrium and tolling model

The model is bimodal (truck, car), path oriented. The total demand at origins is given by an inverse demand function calibrated on the available data (flows, elasticities). There are two possible destinations (Antwerp, Rotterdam). Preference for each destination is modeled by adding two dummy links joining the two destinations to a dummy node. The costs of these dummy links reflect the disutility of each possible destination. Another possible model would be a fully logit inverse demand model, as described in Fernandez *et al*. 1994 and Bellei *et al*. 2002. Assignment is deterministic user optimal (Wardrop principle), and optimal tolls are calculated (uniform first best or first best).

On each arc two types of flow coexist: origin based flows (*global flows*) which are path specific, and *local flows* (trucks and cars) which are arc specific, and result from arc inverse demand functions. They account for local traffic, i.e. the short to medium distance traffic. Global flows account for long distance traffic. Local flows constitute a distinctive feature of the model, they were introduced in Khoshyaran 2002.

Arc travel times are modeled as linear functions of the total equivalent flow (local + global, truck + car); modal arc cost is equal to modal arc travel time times VOT. It can be shown that given global flows, local flows are unique and determined by a finite algorithm, although the variational inequality yielding local flows is not monotone.

At this point the model is solved iteratively: path flows (global flows) are calculated in turn for cars and trucks, and local flows are determined given global flows. The calculation of modal global flows, also a fixed point problem (Cantarella 1997) can be carried out by iterations of a fixed step projected dynamical system (Nagurney and Zhang 1997). The scheme is Gauss-Seidel like, close to a diagonalization scheme, Wu *et al*. 1994, Nagurney 1999. Optimal tolls are determined by heuristic schemes (Verhoef 2002, Yang and Bell 2001). Indeed the completely linear case is well understood (Brotcorne et al. 2001), but this is not the case of the nonlinear case. Even unicity of the optimal solution is not guaranteed for all tolling schemes. Methods such as Friesz *et al*. 1992 could also possibly be considered.

The model could be made more realistic by introducing capacity constraints, Huang and Yang 1997. The reader is referred also to this reference for a definition of the bi-level problems related to optimal tolling on capacitated networks, and also for a simple definition of such quantities as social economic benefit, user surplus etc. De Borger and Proost 2001 provide a more economic oriented outlook on this material. Alternative definitions are discussed in Bellei *et al.* 2002.

3 Results

All results in this section are from Khoshyaran 2002.
The model is tested using a benchmark case. In the benchmark, we include existing fuel excises. Only France has tolling policies. Therefore, France is chosen as the benchmark. A uniform toll of 8€ per 100 km per truck, and 4€ per 100 km per car is applied to all highways in France. The other three countries do not toll.

Uniform first best tolls for Belgium are determined in a second step, i.e. a uniform toll rate for Belgium optimizing social welfare. Other uniform tolling schemes for Belgium were also tested (a fraction of the uniform first best toll). First best tolls for Belgium were also calculated. The rationale for tolling in Belgium is the following. France is already tolling its motorways, and the Dutch part of the motorway network is small. On the other hand tolling in Germany would be of interest. Uniform first best tolls are calculated because they are easier to implement.
Figure 2 shows the level of welfare gain for each link in Belgium, which is positive but eventually small for certain links, both for trucks and cars.

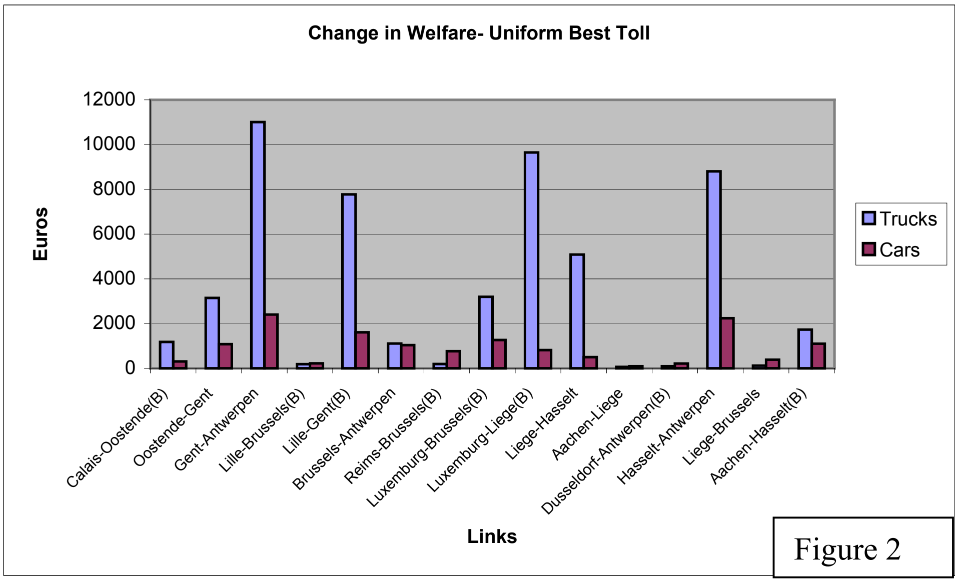

Figure 2

Toll revenue due to uniform tolling is shown in Figure 3. There is a gain in toll revenue after the application of the uniform toll. This toll revenue is higher from trucks than cars, and is concentrated on a few links

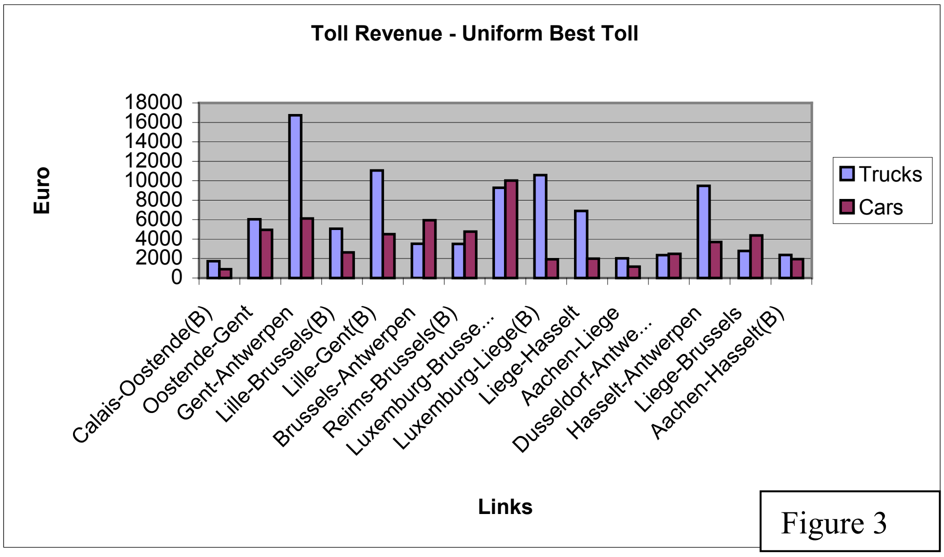

Figure 3

The change in consumer surplus is shown in Figure 4. Overall, there is a drop in local consumer surplus, both trucks and cars. On average this drop in consumer surplus is more significant for cars than trucks.

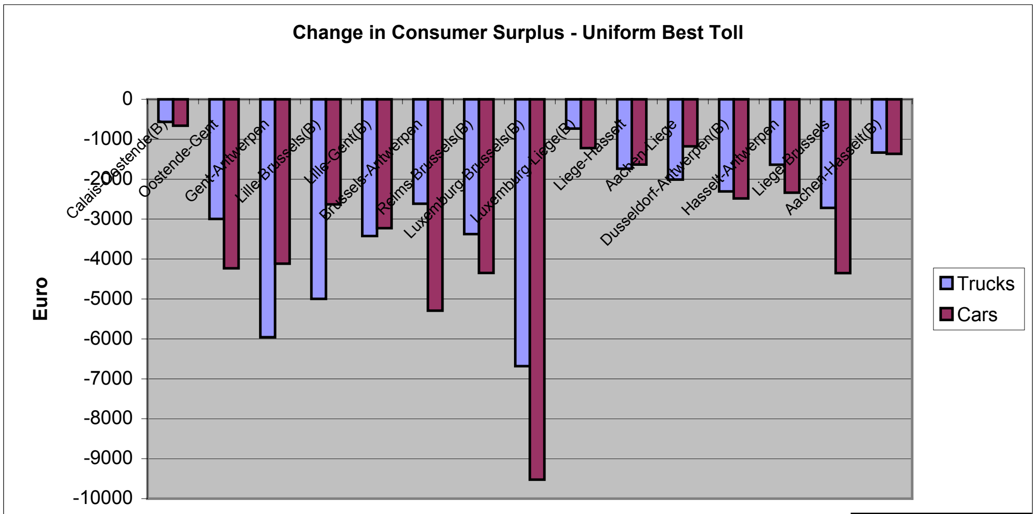

Figure 4

In Figure 5, we observe a drop in external costs due to uniform tolling as compared to the benchmark. For the majority of links, this drop in external costs is more significant for cars than trucks. On two links “Luxemburg-Liège”, and “Liège-Hasselt” there is an increase in externalities due to trucks.

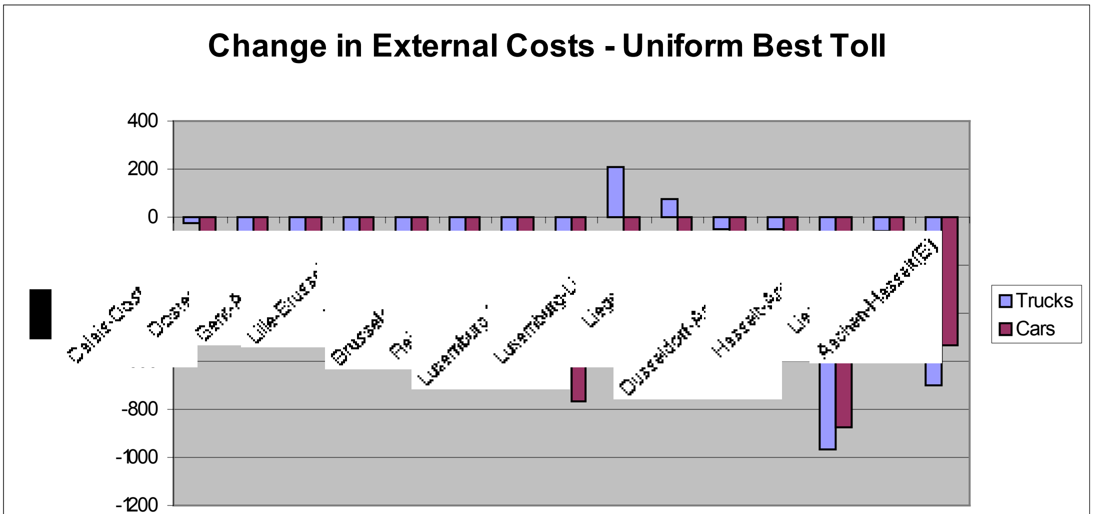

Figure 5

4 Conclusion

Concerning the network equilibrium problem, unicity issues are not yet completely solved. Nevertheless the numerical results as well as the theoretical analysis of the projected dynamical system associated to the network equilibrium problem strongly suggest that the network equilibrium is unique. Although there is no monotonicity, unicity should be a consequence of the structure of arc costs. Ongoing research aims at taking advantage of the simple structure of lower level constraints (applying to flows) to construct algorithms for solving the bilevel problem.

The economic benefits of uniform first best tolling schemes are clear notably from Figure 5 (externalities) and Figure 2 (welfare increase, concerning mainly trucks), but limited. Adverse effects, loss in consumer surplus (Figure 4) and reduction in demand (not documented in this paper), cannot be ignored. The increase of average speed is moderate, and also of limited social benefit, as excessive speed has been identified as the cause of accidents.

References

Bellei G., G. Gentile, N. Papola (2002). "Network pricing optimization in multi-user and multimodal context with elastic demand". *Transportation Research B*, 779-798.

Brotcorne L., M. Labbé, P. Marcotte, G. Savard (2001). "A bi-level model for toll optimization on a multicommodity transportation network". *Transportation Science* **35**, 3, 345-358.

Cantarella G.E. (1997). "A general fixed-point approach to multimode multi-user equilibrium assignment with elastic demand". *Transportation Science* **31**, 2, 107- 128.

De Borger B., S. Proost (2001). *Reforming transport pricing in the European Union, a modelling approach*. Edward Elgar Publishing.

Fernandez E., J. de Cea, M. Florian, E. Cabrera (1994). "Network equilibrium models with combined modes". *Transportation Science* **28**, 3, 182- 192.

Friesz T., H-J. Cho, N.J. Mehta, R.L. Tobin, G. Anandalingam (1992). "A simulated annealing approach to the network design problem with variational inequality constraints". *Transportation Science* **26**, 1, 18-26.

Khoshyaran, M.M. (2002). "Decisions on freight tolls: country versus EU perspectives". *3rd MC-ICAM Seminar*, Helsinki. http://www.strafica.fi/mcicam/3rdseminar.html.

Nagurney A. and D. Zhang (1997). "Projected dynamical systems in the formulation, stability analysis and computation of fixed-demand traffic network equilibria". *Transportation Science* **31**, 2, 147- 158.

Nagurney A. (1999). *Network economics: a variational inequality approach* (2nd ed.). Kluwer Academic Publishers.

Nguyen S., S. Pallottino, M. Gendreau (1998). "Implicit enumeration of hyperpaths in a logit model for transit networks". *Transportation Science* **32**, 1, 54- .

Verhoef, E.T. (2002). "Second best congestion pricing in general networks. Heuristic algorithms for finding second-best optimal toll levels and toll points". *Transportation Research* B, **35**, 707-730.

Yang H. and M. Bell (2001). "Transport bi-level programming problems: recent methodological advances". *Transportation Research* B, **35**, 1-4.

Yang H. and H-J Huang (1998)." Principle of marginal-cost pricing: how does it work in a general road network?" *Transportation Research* B, **32**, 45-54.

Wu J.H., M. Florian, P. Marcotte (1994). "Transit equilibrium assignment: a model and solution algorithms". *Transportation Science* **28**, 3, 193- 203.