Why modeling of heavy goods vehicles matters when designing congestion pricing schemes

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Introduction

Distance-based pricing, for heavy goods vehicles (HGVs) is today reality in several European countries, and congestion pricing is currently implemented in London, Stockholm and Gothenburg. While road pricing in urban areas are commonly focused on reducing the negative effect of congestion, distance-based pricing schemes on highways are mainly a way for the road authorities to finance infrastructure investments. Thus, it is not a farfetched idea that in the future we will see common road pricing schemes, including both of these objectives, as well as including both urban and rural parts of the road network.

In all three previously mentioned European cities, cars and HGVs pay the same fee in the implemented congestion pricing scheme. In general, one additional truck will contribute to the congestion more than one additional car. Also, private trips by car and commercial activities by HGV differ in how the time is valued by the user/operator. Thus, it can very well be argued that the pricing scheme for the two types of vehicles should be differentiated. A pricing scheme differentiated based on vehicle type would make is possible to improve the efficiency of the pricing scheme. There are, however, difficulties in evaluating the effect on congestion in urban areas, and ultimately the potential improvement in social surplus, from introduction of such a differentiated pricing scheme. In practical applications, the contribution to congestion from HGVs are commonly modeled as either background traffic without incorporating route choice and demand modeling, or in best case by applying a passenger car equivalence (PCE) factor, turning HGV demand into passenger car demand. Partly, this is due to the lack of data in terms of origin destination matrices and demand models for HGVs, but also since the introduction of a more realistic modeling of HGVs in the transportation models introduces mathematical difficulties in the assignment procedure.

This paper considers a multiclass assignment model, which incorporates both private cars and HGVs, with class specific travel time functions. The model will be used for comparing distance-based and cordon-based road pricing schemes for all vehicles, with the tolls being differentiated both in terms of vehicle and road type. First we will show how alternative modeling approaches for describing demand and route choice for HGVs will affect the evaluation of a pricing scheme in terms of the change in social surplus. Secondly, results will be presented for a Stuttgart model, for which different modeling approaches have been used when evaluating congestion pricing schemes.

A small example

The user equilibrium multiclass assignment problem with common travel time functions can be formulated as an optimization problem and solved by standard methods. The optimization based formulation relies on that the integral of the travel time function is well defined. This is unfortunately not necessarily true when introducing class specific travel time functions. The multiclass user equilibrium problem with class specific travel time functions can, however, be formulated as a variational inequality (VI). Solving the VI is difficult for larger networks, but for this small network the VI-based formulation can be used for computing equilibrium flows. For large networks heuristic approaches have been developed (Noriega and Florian, 2007). It should, however, be noted that while the single class user equilibrium problem has a unique link flow solution, this is not necessarily true for the multiclass user equilibrium.

Consider the small network with one origin and destination pair, and two alternative links connecting them. There are two classes of users in the network, private cars and HGVs, with value of time (α) equal to 100 SEK/h and 400 SEK/h respectively. Link flows are given by v^c and v^h for cars (c) and HGVs (h) respectively. The travel cost function is for each link a and class i given by

$$c_a^i(v_a^c, v_a^h) = t_a^i(v_a^c, v_a^h) + \frac{1}{\alpha_i}\tau_a^i,$$

where $t_a^i(v_a^c, v_a^h)$ is the class specific travel time function

$$t_a^i(v_a^c, v_a^h) =) = \beta_i \cdot d_a \cdot (t_a^0 + 0.15 \cdot ((v_a^c + 3v_a^h)/k_a)^4).$$

The class specific travel delay component is described by β_i (see e.g. Noriega and Florian, 2007), and reflects that HGVs have a slower speed, and for this example the values are set to $\beta_c = 1$ and $\beta_h = 1.1$. The parameters d_a, t_a^0 and k_a are link specific parameters related to the length of the link, free flow travel time, and capacity respectively, with $d_1 = 5$, $d_2 = 10$, $t_1^0 = 1.2$, $t_2^0 = 0.5$, $k_1 = 800$ and $k_2 = 1800$. For cars, the demand is given by the inverse demand function $D_c^{-1} = 22 - 0.005q^c$ (resulting in a point elasticity of -0.67 in the non-tolled equilibrium), with $q^c = v_1^c + v_2^c$.

In practice, a common approach for modeling HGVs in transportation models is to consider the flow as fixed, either based on actual link counts or by performing an all or nothing assignment of the HGVs. Let us first consider a fixed demand of 250 HGVs. For this case any split of the HGV demand onto the two links will correspond to a user equilibrium for both the cars and HGV. Any equilibrium can then be described by $v^c = (1113.59; 1523.25)^T + \lambda(-750; 750)^T$ and $v^h = (0; 250)^T + \lambda(250; -250)^T$, where λ is any number between 0 and 1. Thus, any actual count of HGVs can in theory correspond to one user equilibrium. In order to illustrate how the modeling approach affect the evaluation of a pricing scheme we will first consider a pricing scheme which toll the car users 10 SEK and 5 SEK for traveling on link 1 and 2 respectively, and no toll for the HGVs. Keeping the HGV flow fixed to either all flow on link 1, all flow on link 2 or dividing the demand by half to the two links, the change in social surplus (as total change in user surplus and operator surplus added together and given in the unit of SEK) is 5561, -879 and -4 respectively. The flow of 250 HGVs on link 1 and none on link 2 correspond with the actual tolled multiclass user equilibrium. Thus it is clear that if the un-tolled HGV flows are used as a fixed background flow, a considerable error can be introduced in the social surplus measure.

Next we introduce an elastic demand model for describing the relationship between HGV demand and travel cost. The inverse demand function $D_h^{-1} = 33.95 - 0.097q^h$ results in a demand of 250 in the non-tolled equilibrium (i.e. the same demand as in the previous fixed demand case), with a corresponding point elasticity of -0.4. Considering a tolling scheme which tolls both private cars and HGVs a distance-based charge (the distance is given by d_1 and d_2), the corresponding improvements in social surplus for both the fixed and elastic demand case are given in Table 1.

Table 1: Improvment in social surplus from the distance-based pricing scheme

HGV demand modeling	Car toll in SEK/km	HGV toll in SEK/km	Social surplus
Fixed	1	from 1 up to 4	+7287
Elastic	1	1	+7005
Elastic	1	2	+7274
Elastic	1	3	+7378
Elastic	1	4	+7314

For the fixed demand case, a differentiated toll will have no impact in this example, unless the HGV toll is set to 5 SEK/km. The fixed demand model, however, results in larger improvements in the social surplus for an HGV toll up to 2 SEK/km, after which it results in smaller improvements, compared with the elastic demand model. Using a fixed demand HGV model will for this case lead to the assumption that a differentiated HGV toll gives no further improvement of the social surplus. This example only illustrates how the two modeling approaches may affect the social surplus levels, and the actual numbers are of 'course related to the demand elasticities.

Evaluation on a large scale transportation model

While the small example serves the purpose of illustrating the need to incorporate route choice and demand modeling of HGVs, an aggregated transportation model of the German city Stuttgart has been used in order to show how different approaches for modeling route choice and demand of HGVs will affect the evaluation of different road pricing scheme. The Stuttgart network model includes the highway and arterial network of Stuttgart. Private car traffic is modeled by three different classes by trip purposes; commuting trips, business trips and other trips. For commuting trips and other trips, the demand is modeled by multinomial logit models describing the choices of traveling within the morning peak, outside the morning peak or by public transport. For business trips, the demand is assumed to be fixed. The demand for HGVs is divided into the two classes distribution traffic and transit traffic. For the transit traffic a multinomial logit demand model has been developed to allow for the choice to travel in or out of the morning peak period (following the approach in Holguín-Veras and Cetin, 2009), and for the distribution traffic the demand is assumed to be fixed. The same principles for modeling HGV route choice and demand, as were used for the small example, will be adopted for evaluating distance-based and cordon-based pricing schemes on the Stuttgart model. Thus giving the possibility to compare how both the level of social surplus, as well as, the level of close to optimal tolls depend on the route choice and demand HGV model.

References

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