Pergamon

Transpn Res.-D, Vol. 2, No. 2, pp. 77–87, 1997

1361-9209/97 $17.00+0.00

PII: S1361-9209(96)00018-1

OPTIMAL ROAD-PRICING: SIMULTANEOUS TREATMENT OF TIME LOSSES, INCREASED FUEL CONSUMPTION, AND EMISSIONS

OLOF JOHANSSON
Department of Economics, Göteborg University, Vasagatan 1, S-41180 Göteborg, Sweden

(Received 12 June 1996; accepted 11 November 1996)

Abstract—In this paper, optimal road-charges are derived with respect to congestion, emissions, and the corresponding excessive fuel consumption and emissions due to the congestion. It is shown that a road-user should then pay a charge corresponding not only to its own emissions, but also to the increased emission and fuel consumption of other road-users. It is demonstrated in a numerical example that these 'system effects' may be significant. Furthermore, a new flexible speed–flow relationship is introduced which incorporates the linear speed–flow relationship as well as the linear speed–density relationship (for different parameter values). The optimal pure congestion charge is then expressed solely by the equivalent congestion factor, the average vale of time, the actual speed, and the speed at which the maximum flow occurs. © 1997 Elsevier Science Ltd

Keywords: road-pricing, congestion, speed–flow relationship, environmental costs, externalities, air pollution.

1. INTRODUCTION

The objective of this paper is to derive optimal speed-depending charges due to congestion and emissions, and to determine whether or not the excessive fuel consumption and emissions caused by additional congestion should affect the optimal charge. In general, should the fact that other cars' emissions increase with the degree of congestion suggest a corresponding increase of the optimal charge? If so, would such considerations imply a significant change in the optimal charge?

Road-pricing is a notion which still, more than 30 years after the seminal papers by Walters (1961) and Vickrey (1963), is used primarily in relation to congestion problems; see Morrison (1986), Hau (1992), Lewis (1993) and Johansson and Mattsson (1995) for surveys. It is also sometimes used as a means to raise revenues for infrastructure improvements, such as road investments. However, the latter use is often not based on any economic efficiency concept, but rather on 'pure political' reasoning.* For example, the proposed road-toll systems in Stockholm and Göteborg in Sweden are designed primarily to raise revenue for investments for new roads, and not to improve economic efficiency.

The interest in pricing traffic in an efficient way with respect to all kinds of externalities, such as health effects, regional environmental effects, global warming, noise, barrier effects, road damage and accidents, has recently increased dramatically; see De Borger *et al.* (1996), Kågeson (1993), Maddison *et al.* (1996), Mayeres (1993), Newbery (1988), Rothengatter (1994), and Verhoef (1994). The reasons for this lie in a general increased environmental awareness and the fact that modern information technology has made various road-pricing systems realistic possibilities, at least in the near future. Still, each element in the optimal externality correcting tax has typically been treated separately.

In this paper, however, the (external) time losses, the increased fuel consumption, and the increased emission/km due to congestion are treated *simultaneously*, which will have some perhaps unexpected policy implications. The optimal road-charge is derived in a standard cost–benefit framework, based on the Hicks/Kaldor efficiency criteria, in which we explicitly maximize the net benefit per time unit. Thus, as is common in the road-pricing literature, all distributional considerations are neglected.†

*See Lave (1994) and Verhoef (1995) for recent contributions to the important and complicated issue of political feasibility.
†See Nowlan (1993) for a recent treatment of road-pricing and distributional considerations.

Furthermore, only the static deterministic equilibrium solution for a given infrastructure will be considered. Hence, all the obviously important dynamics and uncertainties of the system is neglected.* We will focus solely on pricing and no attempt is done to quantify the potential efficiency gains from the introduction of a road-pricing system.† The model is described in Section 2, where a general tax expression is also derived. The tax is expressed as a function of the speed, and not, as in most studies, as a function of the flow, which simplifies the interpretation.

Section 3 introduces a new, rather general, speed–flow relationship, which includes the linear speed–flow relationship as well as the linear speed–density relationship.‡ However, as noted by many, there is of course no reason to believe that there is a single, unique relationship between speed and the representative flow in a given network. Disturbing elements include the interaction between different links at crossings, spill-overs from bottlenecks and so forth. Hence, generally, the speed on a given link is not independent of the current flow of surrounding links. To comprehensively deal with these issues one would need more powerful tools such as simulation methods to calculate the appropriate charges, see for instance Dewees (1979). Still, it seems useful to set-up a unique speed–flow relationship, at least for the purpose of illustration, to get an approximate picture of the situation. The speed used in the speed–flow relations might then in a network context be interpreted as some representative speed index in an urban area, rather than the momentary speed on the actual link.

Section 4 describes the speed-dependency relation of fuel consumption and emissions and derive the final optimal tax expression with respect to the speed. Section 5 is a numerical illustration using some Swedish data and Section 6 provides some concluding remarks.

2. THE MODEL

Assume n different types of road users in a given transportation network. They differ with respect to their equivalent congestion factor, time values, emissions, fuel consumption and the benefit derived from the trips. We will derive the social optimum as the maximum of the social net benefit per time unit in a steady-state solution, i.e. a situation where all variables are constant over time. Without loss of generality, we assume that the road length in the network is normalized to 1 km, which implies that the (equivalent) flow, in terms of number of vehicles passing a certain point/time unit, can also be interpreted as the (equivalent) volume, i.e. as the number of vehicle kilometer (vkm) per time unit in the network. The social net benefit (total benefit minus total cost) per time unit from transportation on a given road network, NB (SEK/h; 10 SEK$\simeq$1£), may then be written as:

$$\mathrm{NB} = \sum_{i}^{n} \int_{0}^{Q_i} \Big[\mathrm{MB_i}(\tilde{Q}_i) - \mathrm{MC_i^0} - \mathrm{MC_i^e}(V(Q_r)) - \mathrm{MC_i^f}(V(Q_r)) - \mathrm{MC_i^t}(V(Q_r))\Big]\mathrm{d}\tilde{Q}_i \tag{1}$$

where $\mathrm{MB_i}$ (SEK/vkm) is the marginal benefit per kilometer at the vehicle flow (or volume) Q_i (vkm/h) for group i, $\mathrm{MC^0}$ (SEK/vkm) is a fixed marginal cost per kilometer, $\mathrm{MC^e}$ (SEK/vkm) is the marginal environmental cost per vehicle kilometer at the current speed V (km/h), which in turn is assumed to be a function of the current *passenger car equivalent* flow in the network Q_r (vkm/h). $\mathrm{MC^f}$ (SEK/vkm) is the fuel cost per kilometer at the actual speed and $\mathrm{MC^t}$ (SEK/vkm) is equal to the marginal time cost per kilometer. The equivalent flow Q_r is given by

$$Q_r = \sum_{i}^{n} \alpha_i Q_i \tag{2}$$

where α_{i} (no dimension) is equal to a passenger car equivalent congestion factor for vehicles of type i. For example, Viton (1980) assumes α to be 2.2 for trucks. If we assume that the different

*See for instance Small (1992), Arnott *et al.* (1993) or Mun (1994) for recent discussions of the dynamics and D'Ouville and McDonald (1990) for the treatment of congestion tolls and uncertainty.

†These gains depend strongly on the amount of re-scheduling, re-routing, switching of mode etc. that will take place.

‡We will, as is common, assume that all vehicles travel with the same speed. See Tzedakis (1980) for congestion resulting from slowly moving vehicles.

marginal cost elements are constant with respect to the driven distance within each group,* we may write:

$$\mathrm{NB} = \sum_i^n \left[\mathrm{TB_i}(Q_i) - Q_i\left(\mathrm{MC_i^0} + \mathrm{MC_i^e}(V(Q_r)) + \mathrm{MC_i^f}(V(Q_r)) + \frac{P_i^t}{V(Q_r)} \right) \right] \tag{3}$$

where $\mathrm{TB_i}$ (SEK/h) is equal to *total* benefit per time unit and P_i^t (SEK/vh) is equal to the value of time for road-users of group *i*. The first order conditions for an interior solution of the social maximization problem with respect to the flow of (an arbitrary) group *k* are then given by:†

$$\begin{aligned} \frac{\partial \mathrm{NB}}{\partial Q_k} &= \mathrm{MB_k}(Q_k) - \alpha_k \frac{\mathrm{d}V}{\mathrm{d}Q_r} \sum_i^n Q_i \left(\frac{\partial \mathrm{MC_i^e}}{\partial V} + \frac{\partial \mathrm{MC_i^f}}{\partial V} - \frac{P_i^t}{V^2} \right) \\ &\quad - \mathrm{MC_k^0} - \mathrm{MC_k^e} - \mathrm{MC_k^f} - \frac{P_k^t}{V} = 0\ \forall k \end{aligned} \tag{4}$$

However, the individual road users will maximize only their own net benefit. The individual first order conditions for road users of group *k* may be written:

$$\mathrm{MB_k}(Q_k) - \mathrm{MC_k^0} - \mathrm{MC_k^f} - \frac{P_k^t}{V} - t_k = 0\ \forall k \tag{5}$$

where t_k (SEK/km) is a road tax (or charge) imposed by the government. Hence, it is assumed that the road users' own contributions to the emissions will affect their own utility to only a negligible extent, i.e., that the number of road users is large. The same assumption applies to the changes in fuel and time costs due to the marginal change in speed. The road users of type *k* with a higher marginal benefit of traveling than the critical level will then travel, and the others will not. By combining eqns (4) and (5), the optimal tax expression per distance unit may be written:

$$t_k = \mathrm{MC_k^e} - \alpha_k \frac{\mathrm{d}V}{\mathrm{d}Q_r} \sum_i^n Q_i \left(\frac{\partial \mathrm{MC_i^e}}{\partial V} + \frac{\partial \mathrm{MC_i^f}}{\partial V} - \frac{P_i^t}{V^2} \right) \forall k \tag{6}$$

In other words, the tax is equal to the marginal environmental costs plus increased time and fuel costs for other road users plus the increase in environmental costs that are due to the decreased speed, which results from the additional vehicle kilometer from road users of type *k*. To be able to rewrite this expression in terms of more easily observable variables, we need to impose some additional assumptions.

3. SPEED–FLOW RELATIONSHIP

First, to replace $\mathrm{d}V/\mathrm{d}Q_r$ from eqn (6) we need to introduce an explicit speed–flow relationship. Economists have in empirical studies largely focused on linear (or close to linear) speed–flow relationships‡ of the form $V = V_0 - bQ_r$, where V_0 is the free-flow speed and b is a road-specific constant; see e.g. Newbery (1990), Evans (1992), Mayeres (1993), and Harrison *et al.* (1986). Proponents of an 'engineering approach', however, seems generally to conclude that linear (or close to linear) speed–*density* (or occupancy) relationships, of the form $V = V_0 - b\frac{Q_r}{V}$, are superior for specific links; see Hall and Hall (1990), Hall *et al.* (1992), and Fritzsche (1994). According to

*Thus, for simplicity it is assumed that the marginal environmental cost is not dependent of the emission level *per se*. The marginal environmental cost per kilometer is then equal to the average environmental cost. This assumption, although not correct in an absolute way, seems plausible and is defended by Small and Kazimi (1995) among others. It would not be very difficult to generalize the model to take non-linearities into account.

†It is assumed that the functions involved are sufficiently 'well-behaved' for the 2nd order condition to be fulfilled and for the solution to be unique.

‡Alternatively, they focus on the bottleneck situation (where the flow is limited by a specific section of the road) and the corresponding build-up of queues, see Vickrey (1963), or Arnott *et al.* (1990) for a more recent contribution.

the engineering approach, the 'supply curves' (the private marginal cost curves) will then be backward bending, since the same flow may be obtained at two different levels of the generalized cost.

One reason, as argued by Newbery (1988, 1990) and Evans (1992), why many economists have shown little interest in these engineering results is that they are obtained from single links and are therefore not applicable to urban networks where most of the congestion occurs. Newbery and Evans argue that on such networks linear speed–flow relationships are better suited. However, they show little empirical evidence for this conclusion. Both refer to the Harrison *et al.* (1986) study from Hong Kong, which does indeed indicate that a linear relation seems appropriate. However, Harrison *et al.* propose a 'kinked' linear relation where the speed is equal to the uncongested speed until a certain level of the vehicle flow. Furthermore, there seem to be no really low-speed observations in their data-set, which severely limits the possibility to generalize their results.

Another possible, more pragmatic, reason has to do with the calculation of the optimal congestion charge in practice, which is often based on the *present* traffic situation. It is straightforward to show that the optimal congestion tax will go to infinity when the speed decreases to a certain level (half of the uncongested speed in the linear speed–density case). This is illustrated in Fig. 1 where the optimal charge is shown both (as is most common) in the cost–flow dimension and in the cost–speed dimension.

Hence, it will always be inefficient (in Hicks/Kaldor sense) to have a speed lower than the one at which the maximum flow occurs, which corresponds to the 'backward-bending' region of the MPC–curve, and the tax should then correspondingly prevent this.* Newbery (1988, 1990) calculated optimal congestion charges in the U.K. based on the *present* flow and a linear speed–flow relationship. The flow-weighted average was found to be 3.4 pence/vkm (passenger car equiv.). It is clear then that if Newbery instead had chosen a speed–flow relationship where the maximum flow is obtained at a certain speed level, which is equal to (or higher than) the actual speed at peak-hour, then the optimal charge would be infinite! Consequently, the flow-weighted average congestion charge in the U.K. should also reach infinity instead of 3.4 pence/vkm. This seemingly

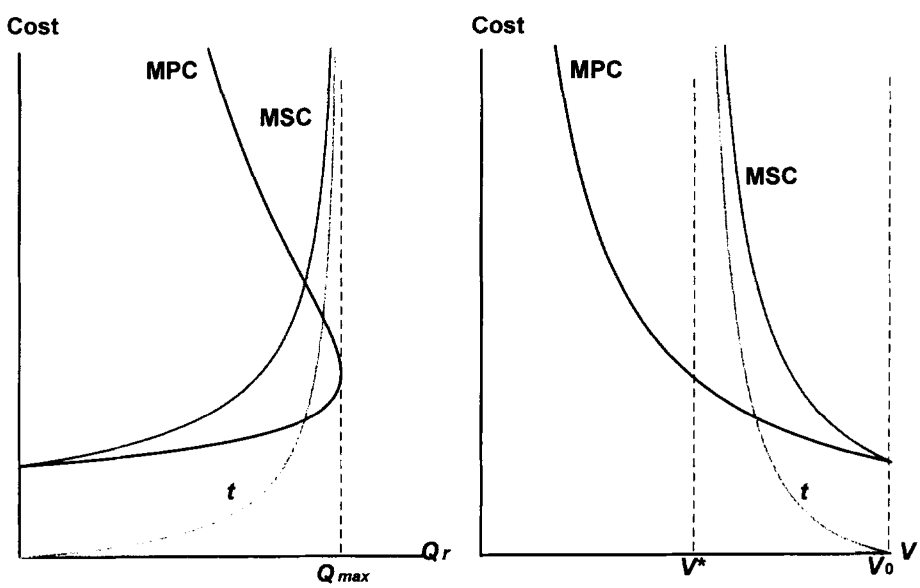

Fig. 1. Illustration of how the marginal private cost (MPC), the marginal social cost (MSC), and the optimal tax (t = MSC−MPC) varies with respect to the flow and the speed (in equilibrium). V^* is the speed where the maximum flow $Q_{\max}$ occur.

*See e.g. Walters (1961) and eqn (10) in this paper. Else (1981, 1982) questioned this 'conventional' view and claimed that a social optimum may be located in the backward-bending region. However, Nash (1982), in a reply to Else, argued that Else was wrong in this respect and that "the conventional analysis is correct whenever the flow on a road may be assumed to be at a steady state" (p. 299).

odd result derives from the fact that the optimal charge calculations are based on the *present* (i.e. before the charge is implemented) traffic situation. But, of course, in reality the optimal charge would never reach infinity, since the (optimal) speed would never be equal to or lower than this critical speed (in equilibrium).

The linear speed–flow approach has been criticized strongly by transport engineers, perhaps especially for the unpleasant feature that the flow is maximized when the speed is zero, which is of course not reasonable; see the discussion between Evans (1992, 1993) and Hills (1993).

Recently, Olszewski *et al.* (1995) presented an "area-wide traffic speed–flow relationship for the Singapore CBD", where CBD is known as the restricted zone in their Area Licensing Scheme. They estimated a non-linear relationship between *average* speed and *average* density in the area based on a functional form suggested by Drake and Schofer (1967). Expressed in the speed–flow dimension, their estimated result is:

$$Q_r = V(44.9 - 12.0 \ln V)^{1.563} \tag{7}$$

The maximum flow is found at a speed of 8.82 km/h which thus is lower than what would have been the case with a linear speed–density relationship, and higher than with a linear speed–flow relationship (which is zero). However, an unpleasant feature associated with this functional form is that the slope of the speed–flow curve goes to infinity when the flow goes to zero, i.e. $(dQ_r/dV)_{Q_r=0} = 0$, which is not intuitively plausible.

On the basis of the above discussion, a simple but still rather flexible speed–flow relationship, which includes both of the above mentioned most common functional forms, is proposed. The speed will then be a linear function of some 'weighted product' of the flow and the density and it could be written as follows:

$$V = V_0 - bQ_r^{\gamma}\left(\frac{Q_r}{V}\right)^{1-\gamma} = V_0 - b\left(\frac{Q_r}{V^{1-\gamma}}\right) \tag{8}$$

where V_0 is equal to the free-flow speed, V is the actual speed, Q_r/V is equal to the (equivalent) density, and b is a road specific constant. $\gamma = 1$ will then imply a pure linear speed–flow relationship and $\gamma = 0$ implies a linear speed–density relation. In Fig. 2, different speed–flow relationships are shown for a typical road with a maximum capacity of 1200 passenger car equiv. vehicles/h, and an uncongested speed of 40 km/h.

It should be noted that the shape of the 'lower parts' (where the slope is positive) of these speed–

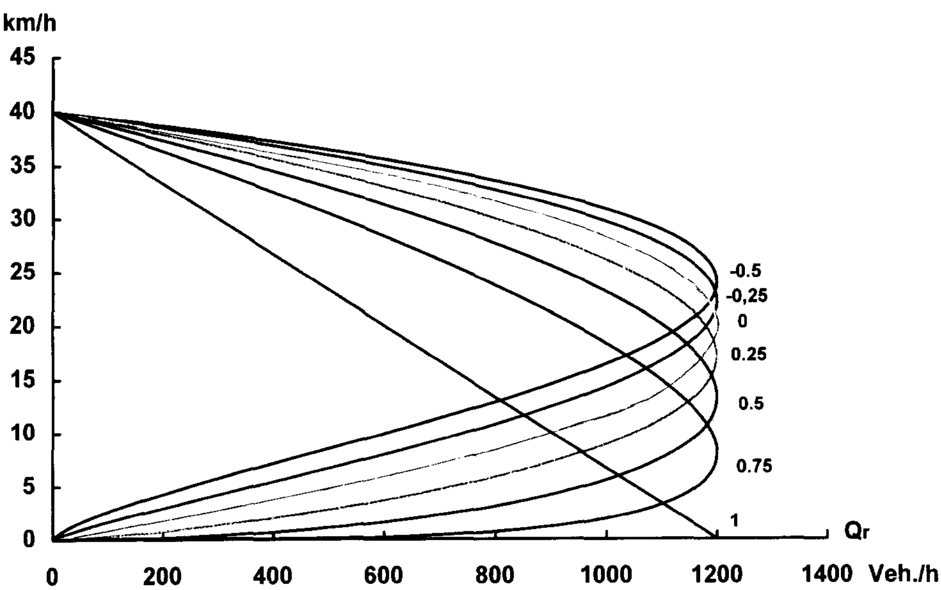

Fig. 2. Speed–flow relationships for different values of γ (varying between −0.5 and 1).

flow curves is irrelevant from the perspective of an optimal congestion charge. What matters is whether such a lower part exists or not, i.e. if the maximum flow will be obtained at zero speed or at a positive speed and, if so, at what speed. The discussion between Hills (1993) and Evans (1992, 1993) regarding the need for a lower part to go through the origin is then not important for this purpose.

It may seem reasonable that the maximum flow in a typical urban network would occur at a lower speed than on a specific link without much traffic on intersections. Drawing on the recent results by Olszewski *et al.* (1995), a crude estimate may be to assume a maximum flow to occur at about 25% of the free flow speed, i.e. γ would be equal to 2/3.* The derivative of the speed with respect to the representative vehicle flow, which is needed for the optimal tax expression (6), can be written in terms of the speed:

$$\frac{\mathrm{d}V}{\mathrm{d}Q_r} = \frac{-b}{V^{-\gamma}[V(2-\gamma) - V_0(1-\gamma)]} \tag{9}$$

eqn (9) in eqn (6) then gives the optimal tax as:

$$t_k = \mathrm{MC}_\mathrm{k}^\mathrm{e} - \frac{\alpha_k b}{V^{-\gamma}[V(2-\gamma) - V_0(1-\gamma)]} \sum_i^n Q_i\left(\frac{\partial \mathrm{MC}_\mathrm{i}^\mathrm{e}}{\partial V} + \frac{\partial \mathrm{MC}_\mathrm{i}^\mathrm{f}}{\partial V} - \frac{P_i^t}{V^2}\right) \forall k \tag{10}$$

We know that the maximum flow occurs at the representative flow where $\mathrm{d}V/\mathrm{d}Q_r = 0$, i.e. where the denominator of eqn (9) is equal to zero. It is easy to see that this occurs when the speed V goes to $\frac{1-\gamma}{2-\gamma}V_0$. The optimal tax would then correspondingly converge to infinity. In the linear speed–density case ($\gamma = 0$), this will occur when the speed goes to half of the free-flow speed; in the linear speed–flow case ($\gamma = 1$), the same applies when the speed goes to zero.

4. RELATION BETWEEN FUEL CONSUMPTION, EMISSIONS AND SPEED

The next step is to introduce expressions for how the fuel costs, the environmental costs, and the time costs vary with the speed, which corresponds to the three terms in parentheses in eqns (6) and (10). The fuel consumption per kilometer will typically increase when the speed decreases due to congestion.† Fwa and Ang (1992) present the result of several estimated relations of the type:

$$q^f = \beta^f + \frac{\epsilon^f}{V} \tag{11}$$

where q^f (l/vkm) is the specific fuel consumption per kilometer, β^f and ϵ^f are constants and V is the average speed which varies due to varying traffic conditions. The fuel cost per kilometer would then be possible to write as

$$\mathrm{MC}_\mathrm{i}^\mathrm{f} = P_i^f\left(\beta_i^f + \frac{\epsilon_i^f}{V}\right) \tag{12}$$

where P^f (SEK/l) is the price of fuel. A decrease from 40 km/h to 20 km/h implies an increase in fuel consumption of between 26–45% with an average of 37% for 10 different estimated relations (our own calculations based on the results in Fwa and Ang).

According to a Danish study, Krawack (1993), the emissions of CO and VOC from catalyst equipped passenger cars in urban traffic will be about 100% higher per kilometer at an average speed of 20 km/h (rush-hour) than at off-peak hours at an average speed of 40 km/h. NO_x emissions are 50% higher at rush hour. The corresponding emission increase for non-catalyst equipped

*Is directly obtained by setting the denominator of eqn (9) equal to 0, and V equal to 0.25 V_0. On links without much traffic on intersections, it may be more reasonable to assume γ to be zero or even negative; cf. Hall and Hall (1990), Hall *et al.* (1992) and Fritzsche (1994).

†However, as is well known, the fuel consumption and some emissions will increase per kilometer beyond a certain speed level. But these levels will in general not be reached in urban traffic.

cars is somewhat lower. The Swedish AIG model proposes a more than 100% increase of CO emissions and almost 100% increase of the NO_x emissions at these speed changes (not specified type of cars) according to the manual, Trivector (1992). It seems not too unreasonable to assume that a representative emission index could be written in a way similar to the fuel consumption relationship. If this is so, we may write:

$$\mathrm{MC}_i^e = P^e\left(\beta_i^e + \frac{\epsilon_i^e}{V}\right) \tag{13}$$

where P^e (SEK/g) is the monetary valuation of the equivalent emissions, β^e (g/vkm) is the emissions per kilometer which are independent of the speed and ϵ^e is a parameter related to the speed-dependency of the emissions.

We may now differentiate eqns (12) and (13) and substitute them into eqn (10) to obtain:

$$t_k = P^e\left(\beta_k^e + \frac{\epsilon_k^e}{V}\right) + \frac{\alpha_k}{V^2}\frac{b}{V^{-\gamma}[V(2-\gamma) - V_0(1-\gamma)]}\sum_i^n Q_i(P^e\epsilon_i^e + P_i^f\epsilon_i^f + P_i^t)\ \forall k \tag{14}$$

Hence, again, the optimal tax is equal to the marginal environmental cost from your own emissions, plus a congestion tax equal to the marginal external time cost imposed on others, plus a charge corresponding to the increases in emission and fuel consumption of the other vehicles that an additional vehicle kilometer will cause. In order to obtain a more practically useful expression, flow-weighted averages of the terms in parentheses are introduced. Then we have:*

$$t_k = P^e\left(\beta_k^e + \frac{\epsilon_k^e}{V}\right) + \frac{\alpha_k}{\bar{\alpha}}\frac{(V_0 - V)/V}{V(2-\gamma) - V_0(1-\gamma)}(P^e\overline{\epsilon^e} + \overline{P^f\epsilon^f} + \overline{P^t})\ \forall k \tag{15}$$

where a bar denotes the weighted average (by the vehicle flow) of each variable. It should be emphasized that the speed-level in this expression serves solely as an indication of the level of congestion, and the charge should of course not be related to the *individual* speed of cars in this way (which would presumably be disastrous for road safety).

Note that this charge is not expressed as a function of the vehicle flow (other than indirectly through the weighted averages), nor does it depend on the factor b.† This is important from a policy perspective, since it is generally much easier, especially for the road-users themselves, to observe the current speed than the current flow, or some parameter in the speed–flow relationship which is typical for the specific road. The tax does, nevertheless, depend on the γ-factor which may not be easily observable either. On the other hand, the speed of which the flow is maximized, say V^*, may be possible to estimate. Then eqn (15) can be re-written as a function of V^* instead as of γ:‡

$$t_k = P^e\left(\beta_k^e + \frac{\epsilon_k^e}{V}\right) + \frac{\alpha_k}{\bar{\alpha}}\frac{V_0 - V}{VV_0}\frac{V_0 - V^*}{V - V^*}(P^e\overline{\epsilon^e} + \overline{P^f\epsilon^f} + \overline{P^t})\ \forall k \tag{16}$$

where V_0 is equal to the uncongested speed, V^* is the speed at which the maximum flow occurs and V is the actual speed.

The result implies that so called zero emission vehicles (ZEVs) should optimally pay both a charge corresponding to the increased emissions from other vehicles that will be the result of the marginally increased representative flow, as well as pay the 'standard' congestion charge.§ This is so even though each other vehicle, on its own, should also pay the increased cost per kilometer due to their emission increase at the lower average speed.

*For example, $\overline{\epsilon^e} = \frac{\sum_i Q_i\epsilon_i^e}{\sum_i Q_i} = \frac{\sum_i Q_i\epsilon_i^e}{\sum_i \alpha_i Q_i}\frac{\sum_i \alpha_i Q_i}{\sum_i Q_i} = \frac{\sum_i Q_i\epsilon_i^e}{Q_r}\bar{\alpha}$ Hence, $\sum_i Q_i\epsilon_i^e = \frac{\overline{\epsilon^e}}{\bar{\alpha}}Q_r = \frac{\overline{\epsilon^e}}{\bar{\alpha}}\frac{V_0 - V}{b}V^{1-\gamma}$, where the last step makes use of eqn (8). In reality, we may have many types of emissions. Then this term should be replaced by as many terms as we have emission types.

†The crucial condition for this is that $\frac{dV}{dQ_r}Q_r$ is independent of b.

‡Using that $\gamma = \frac{V_0 - 2V^*}{V_0 - V^*}$ and some algebraical manipulations.

§Given of course that ZEVs exist at all. Some recent evidence indicate that particulate matters from tires and brakes may be considerable.

5. A NUMERICAL ILLUSTRATION OF THE OPTIMAL PIGOVIAN TAX

In order to investigate the order of magnitude of the different tax elements, a simple numerical illustration will be undertaken, based on some data for Göteborg, which is Sweden's second biggest city with a population size of about 450,000. The following assumptions are used:

The traffic consists of 10% heavy vehicles with a passenger car equivalent of 2.5, and 90% passenger cars, implying that $\bar{\alpha}=1.15$ ($\alpha=1$ for a passenger car). A speed–flow relationship according to eqn (8), with a free-flow speed of 40 km/h and a maximum flow occurring at 10 km/h, is assumed.

The emissions from a passenger car equipped with a catalytic converter are on average 0.6 g NO_x/km, and 0.6 g VOC/km, at an average speed of 40 km/h.* The corresponding CO_2 emissions are approximately 2.4 kg CO_2 per liter of fuel consumed.† We obtain a *flow weighted* average of about 6.7 g/km of NO_x and the same specific amount of VOC, based on data about total emissions of NO_x and VOC from the road transport sector in Göteborg 1991 [Göteborgsregionen (1993)] and the total vehicle flow the same year [Ekberg, 1995, Traffic Office in Göteborg, personal communication]. The flow-weighted average emission factors at 40 km/h are assumed to be 5 g/km for both VOC and NO_x. Furthermore, the emissions at 20 km/h are conservatively estimated to be 50% higher than the emissions at 40 km/h. The economic valuation of the health effects in Göteborg are assumed to be, on average, 48 SEK/kg NO_x or VOC, based on Leksell and Löfgren (1995). The associated valuations for the regional and global environmental effects are commonly assumed to be 40 SEK/kg NO_x, 20 SEK/kg VOC and 0.33 SEK/kg CO_2 in Sweden; see e.g. Maddison *et al.* (1996).

The flow-weighted average fuel consumption is assumed to be 0.1 l/km at 40 km/h, and 37% higher at 20 km/h, which implies that $\bar{\epsilon}^f=0.148$. The fuel price $\bar{P}^f$ is equal to 3 SEK/l (net of all taxes except for VAT based on the net price). The average time valuation $\bar{P}^t$ is 72.5 SEK/h [Swedish Road Administration (1993)]. We can then substitute these numbers in eqn (16), which implies that we can plot the optimal charge as a function of the current speed (Fig. 3).

As can be seen from the diagram, on average, the external time component seems to dominate the others. In particular, the costs related to the increased fuel consumption for others seems to be small compared to the time losses. The optimal charge increases dramatically when the speed decreases and is, in our example, more than 20 times larger at a speed of 20 km/h than at a speed

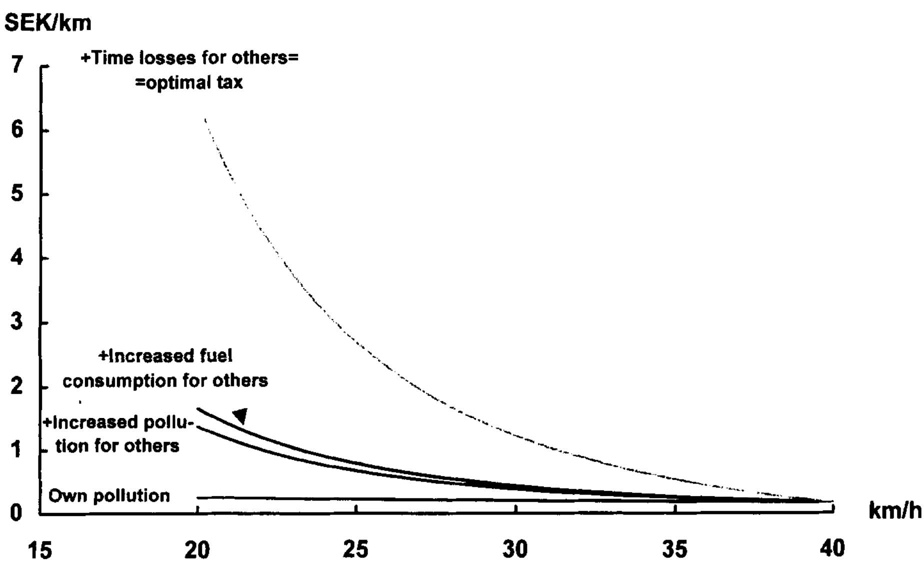

Fig. 3. Optimal road charge for a passenger car with catalytic converter with respect to the equilibrium speed divided (cumulatively) on different elements. Average conditions in Göteborg; assumptions described in text; 10 SEK≃1£.

*In reality, these emissions differ dramatically between different cars and with respect to cold-start effects, driving behavior and weather conditions; see the references in Maddison *et al.* (1996).

†The CO_2 emissions are determined (almost solely) by the fuel use, irrespective of control equipment. For simplicity, we neglect for such other emissions as sulphur and particulate matters.

of 40 km/h. It is particularly interesting to note that although the charge related to the own emissions increases when the speed decreases (since these emissions will increase, but from a low level), the amount related to the increased emissions for others will increase much more rapidly. The tax will increase asymptotically to infinity when the speed goes to 10 km/h.

However, it should be emphasized that the optimal emission charges vary dramatically with respect to other variables such as the population density in the neighborhood (the health costs are low in the countryside but very high outside a hospital in an urban area) and the weather conditions. Leksell and Löfgren state that the health costs during unfavorable weather conditions on a central street might be more than 15 times higher than the average figures for Göteborg.* If we multiply the health costs per emission unit by a factor of 15 (but keep the other environmental costs constant), the relative size of the tax elements will change as is shown in Fig. 4. The tax element related to the own pollution will again of course increase when the speed decreases, but in highly congested traffic, the elements related to increased emissions for others will dominate strongly.

Consider now a situation in which a zero-emission vehicle is driving in the Göteborg-network in peak-hour. Optimally, it should then not pay for any emissions created by that car, but it should pay all the other tax components, including the one associated with increased emissions for others. Consider as a comparison a standard petrol-fuel passenger car which is driving in a network with only zero-emission vehicles (except for this vehicle). It should then pay for the 'own-emission' element, but not for any increased pollution for others (since there would not be any). Hence, a 'dirty' car in an otherwise 'clean' traffic environment should optimally pay less than a 'clean' car in dirty environment! However, these perhaps unexpected results may be of limited value for policy in practice. Furthermore, of course, a 'dirty' car should always pay more per km than a clean one, irrespective of whether the traffic environment is 'dirty' or not. It is more important to stress that the indirect external costs may be considerable, especially during unfavorable conditions.

It should also be noted that a fuel tax is generally a rather poor measure in order to deal with urban air pollution. This is because such a tax will neither take into account the strongly varying emission characteristics of different cars, nor the differences in population density etc. which implies that the health cost per unit of emission may be very different in different areas. Furthermore, contrary to the common view, it is not even an ideal measure to deal with the global warming problem since it fails to take into account the indirect carbon emission increase of others, which results from increased traffic.

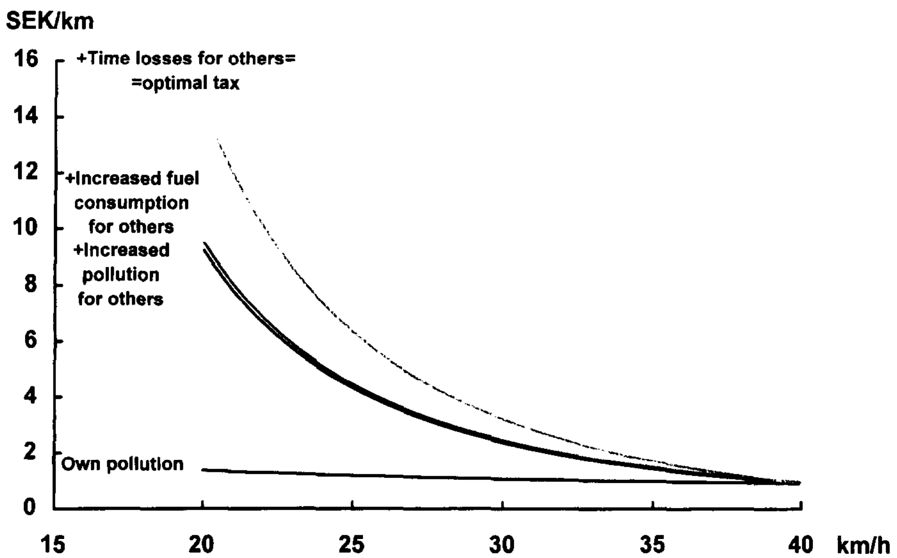

Fig. 4. Optimal road charge for a passenger car with catalytic converter with respect to the equilibrium speed divided (cumulatively) on different elements. Central street in Göteborg and unfavorable weather conditions; assumptions described in text; 10 SEK≃1£.

*However, the regional and (especially) the global cost elements will not be affected equally strong by the weather. Here it is assumed that they will not be affected at all.

6. CONCLUSION

This paper has focused on some important external costs associated with road transport in urban areas. It has been shown that indirect external effects of transportation may constitute important non-negligible elements in an optimal pricing schedule. As mentioned in the introduction, there are of course other important externalities such as noise, accidents and increased maintenance costs. These latter can probably be treated in a way similar to the increased fuel consumption element and can perhaps also be assumed to be proportional to the fuel consumption. The accident element seems to be more complicated and the accident risk might perhaps decrease in congested situations, which would then imply a possible negative charge component. Clearly, more research is needed in this field, and in the *simultaneous* study of other road transport externalities.

It is also demonstrated that the optimal road charge can be expressed as a function of the current speed instead of (as is more common) as a function of the vehicle flow. The 'pure congestion charge' could then, for a certain class of speed–flow relationships, be expressed solely by the equivalent congestion factor, the average vale of time, the actual speed, and the speed at which the maximum flow occurs. One can then illustrate (in a way which is easy to interpret) how quickly the optimal road charge increases when the (equilibrium) speed decreases.

By way of conclusion, it should be emphasized that the results obtained here are based on a highly stylized theoretic model and therefore, of course, should be used with great care for policy purposes. For example, we know that no ideal road-pricing system exist anywhere in the world, and it is not likely that it ever will exist. In reality, one will have to weight the advantages with refined systems against the associated increase of the investment and managing costs. But since the development of information technology is very rapid, it seems likely that this trade-off will go in the direction of more sophisticated systems over time, where the charges in a not too distant future will be differentiated with respect to time (peak/off-peak, inversion/'normal' climatological conditions), space (e.g. population density), type of car (environmental and congestion characteristics), and possibly also other variables. Still, of course, there are large uncertainties in this process, including political feasibility and public acceptance.

Acknowledgements—I am grateful to Thomas Sterner, Henk Folmer, and two referees for useful comments. Of course, none of them are responsible for remaining errors. Financial support from the Swedish Transport and Communications Research Board (KFB) is gratefully acknowledged.

REFERENCES

Arnott, R., de Palma, A. and Lindsey, R. (1990) Economics of a bottleneck. *Journal of Urban Economics* **27**, 111–130.

Arnott, R., de Palma, A. and Lindsey, R. (1993) The welfare effects of congestion tolls with heterogenous commuters. *Journal of Transport Economics and Policy* **27**, 139–161.

De Borger, B., Mayeres, I., Proost, S. and Wouters, S. (1996) Optimal pricing of urban transport — A simulation exercise for Belgium. *Journal of Transport Economics and Policy* **30**, 31–54.

Dewees, D. N. (1979) Estimating the Time cost of highway congestion. *Econometrica* **47**(6), 1499–1512.

D'Ouville, E. L. and McDonald, J. F. (1990) Effects of demand uncertainty on optimal capacity and congestion tolls for urban highways. *Journal of Urban Economics* **28**, 63–70.

Drake, J. S. and Schofer, J. L. (1967) A statistical analysis of speed–density hypotheses. *Proc. Third International Symposium on Theory of Traffic Flow*. Elsevier, New York.

Ekberg, U. (1995) Traffic in Göteborg. Personal communication.

Else, P. K. (1981) A reformulation of the theory of optimal congestion taxes. *Journal of Transport Economics and Policy* **15**, 217–232.

Else, P. K. (1982) A reformulation of the theory of optimal congestion taxes: rejoinder. *Journal of Transport Economics and Policy* **16**, 299–304.

Evans, A. W. (1992) Road congestion pricing: when is it a good policy? *Journal of Transport Economics and Policy* **26**, 213–243.

Evans, A. W. (1993) Road congestion pricing: when is it a good policy? Rejoinder. *Journal of Transport Economics and Policy* **27**, 99–105.

Fritzsche, H.-T. (1994) A model for traffic simulations. *Traffic Engineering and Control* **35**(5), 317–321.

Fwa, T. F. and Ang, B. W. (1992) Estimating automobile fuel consumption in urban traffic. *Transportation Research Board Record* **1366**, 3–10.

Göteborgsregionen (1993) *Luftmiljöanalys för Göteborgsregionen*. GöteborgsRegionens Kommunalförbund.

Hall, F. L. and Hall, L. M. (1990) Capacity and speed–flow analysis of the Queen Elizabeth way in Ontario. *Transportation Research Board Record* **1287**, 108–118.

Hall, F. L., Hurdle, V. F. and Banks, J. H. (1992) Synthesis of recent work on the nature of speed–flow and flow–occupancy (or density) relationships on freeways. *Transportation Research Board Record* **1365**, 12–18.

Harrison, W. J., Pell, C., Jones, P. M. and Ashton, H. (1986) Some advances in model design developed for practical assessment of road pricing in Hong Kong. *Transportation Research* **20A**, 135–143.

Hau, T. (1992) Congestion charging mechanisms for roads. World Bank, Working Paper WPS 1071.

Hills, P. (1993) Road congestion pricing: when is it a good policy?: Comment. *Journal of Transport Economics and Policy* **27**, 91–99.

Johansson, B. and Mattsson, L.-G. (eds) (1995) *Road Pricing: Theory, Empirical Assessment and Policy*. Kluwer, Amsterdam.

Kågeson, P. (1993) *Getting the Prices Right. A European Scheme for making Transport Pay its True Costs*. Transport and Environment 93/6.

Krawack, S. (1993) Traffic management and emissions. *The Science of the Total Environment* **134**, 305–314.

Lave, C. (1994) The demand curve under road pricing and the problem of political feasibility. *Transportation Research* **28A**, 83–91.

Leksell, I. and Löfgren, L. (1995) *Värdering av lokala luftföroreningseffekter*. KFB-rapport 1995:5. In Swedish but with an English summary of 6 pages: Valuation of the local effects of air pollution. How to place monetary values on health effects of exhaust emissions in urban areas. Swedish Transport and Communication Research Board.

Lewis, C. (1993) *Road Pricing: Theory and Practice*. Thomas Telford, London.

Maddison, D., Pearce, D., Johansson, O., Calthrop, E., Litman, T. and Verhoef, E. (1996) *The True Cost of Road Transport, Blueprint 5*. CSERGE, Earthscan, London.

Mayeres, I. (1993) The marginal external cost of car use—with an application to Belgium. *Tijdschrift voor Economie en Management* **38**(3), 225–258.

Morrison, S. A. (1986) A survey of road pricing. *Transportation Research* **20A**, 87–97.

Mun, S.-, II (1994) Traffic jams and the congestion toll. *Transportation Research* **28A**, 365–375.

Nash, C. A. (1982) A reformulation of the theory of optimal congestion taxes: Comment. *Journal of Transport Economics and Policy* **16**, 295–299.

Newbery, D. M. (1988) Road user charges in Britain. *Economic Journal* **98**(Conference), 161–176.

Newbery, D. M. (1990) Economic Principles relevant to pricing roads. *Oxford Review of Economic Policy* **6**(2), 22–39.

Nowlan, D. M. (1993) Optimal pricing of urban trips with budget restrictions and distributional concerns. *Journal of Transport Economics and Policy* **27**, 253–276.

Olszewski, P. H., Fan, S. L. and Tan, Y.-W. (1995) Area-wide traffic speed–flow model for the Singapore CBD. *Transportation Research* **28A**, 273–281.

Rothengatter, W. (1994) *External Effects of Transport*. Project for the UIC, Paris, Interim report, Infras Zürich, IWW Karlsruhe.

Small, K. A. (1992) *Urban Transportation Economics*. Harwood, Switzerland.

Small, K. A. and Kazimi, C. (1995) On the costs of air pollution from motor vehicles. *Journal of Transport Economics and Policy* **29**, 7–32.

Swedish Road Administration (1993) *EVA, Effektberäkning vid VägAnalyser*, version 1.1. Borlänge.

Trivector (1992) *Användarmanual för AIG/S*. VTI Linköping and Trivektor Lund.

Tzedakis, A. (1980) Different vehicle speeds and congestion costs. *Journal of Transport Economics and Policy* **14**, 81–103.

Verhoef, E. (1994) External effects and social costs of road transport. *Transportation Research* **28A**, 273–287.

Verhoef, E. (1995) The demand curve under road pricing and the problem of political feasibility. *Transportation Research* **29A**, 459–465.

Vickrey, W. S. (1963) Pricing in urban and suburban transport. *American Economic Review* **59**, 251–261.

Viton, P. A. (1980) Equilibrium short-run-marginal-cost pricing of a transport facility: the case of the San Francisco Bay Bridge. *Journal of Transport Economics and Policy* **14**, 185–203.

Walters, A. A. (1961) The theory and measurements of private and social cost of highway congestion. *Econometrica* **29**, 676–699.