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Second-best urban tolling with distributive concerns

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Second-best urban tolling with distributive concerns

(Draft version)

Andrea Diaz^{1,2,*} and Stef Proost²

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Abstract

This paper analyzes the optimal configuration of urban congestion tolls on work-related traffic, in a second-best setting where only one road in a network can be tolled. Both heterogeneity in labor productivity and income distribution concerns are considered. The optimal toll balances two types of considerations. First, the efficiency in correcting the marginal external congestion cost on the tolled road, given the distortion on non-tolled roads. Second, the equity consideration that takes into account who uses the tolled road and how toll revenues are spent. Both separating and pooling equilibriums are analyzed for two alternative uses of the toll revenues: poll transfers or labor-tax cuts. Using numerical simulations, we show that the equity concern can lead a government to prefer recycling via poll transfers rather than via labor tax reductions.

Key words: tax reform, congestion pricing, urban tolls.

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1. Introduction

Academic interest in curbing urban congestion has increased considerably in the last few decades as this problem has moved up the political agenda. Economists advocate road pricing as an efficient instrument to use infrastructures. Indeed, imposing a road toll that reflects marginal external congestion costs makes consumers use the road up to the point where marginal social costs equalize marginal social benefits. Optimal road pricing therefore ensures that the only trips made are those that bring the highest benefits for society. This is only true, however, as long as tolling is analyzed in a first-best framework. Additional conditions, e.g. not being able to toll all roads in a network and pre-existing distortions on the labor market, complicate the optimal design of urban congestion tolls.

The related literature is mainly focused on the interaction of road taxes with taxes on labor income (see: Mayeres and Proost, 1997; Parry and Oates, 2000; Parry and Bento, 2001; Van Dender, 2003; Parry and Small, 2005; De Borger, 2009). Road taxes have a positive welfare impact by reducing congestion externalities. But at the same time they have a negative welfare impact, since an increase in commuting costs discourages agents to supply labor. Which effect (externality reduction or reduced labor supply) prevails has become a central question in transport economics. Parry and Bento (2001) showed that the welfare impact of a road tax differs according to the use of the tax revenues. According to them, using revenues raised from road taxes to reduce tax rates on labor increases social welfare. This is because reduced congestion and reduced labor taxes compensate workers for the congestion toll. Other revenue uses, such as the classic case of making poll transfers, do not compensate the negative labor supply impact and reduce welfare. On the other hand, Mayeres and Proost (1997) demonstrated that as long as equity objectives are relevant, obtaining significant welfare gains from recycling tax revenues requires a careful balance of several options. They show that imposing a tax on congestion externalities may need a reconfiguration of all taxes, and that a reduction of labor taxes is not necessarily the best option.

Thus, although urban congestion tolls have gained importance during the last decade, they require further investigation before being broadly recommended. Differences across road users and the composition of the economy (proportion of low-income groups) might change the effect of this instrument on social welfare. Similarly, the use of toll revenues and the distributive objectives of the transport policy could benefit certain consumer groups at the expense of others.

This paper contributes to this line of research by analyzing the optimal design of urban tolls to address work-related traffic congestion in a second-best setting that considers tolling a single road in a network and the use of distortive taxes in the labor and transport markets. Our approach is close to that of Parry and Bento (2001) but we add two dimensions to their model.

First, instead of a congested road and uncongested public transit, we model two congested transport options. They can be both roads or one of them can be public transit. Considering the tax interaction problem in a two-road framework is particularly interesting since Parry and Bento (2001) find that the optimal congestion toll should equal marginal external congestion costs, whereas the two-route literature indicates that when just one of the roads can be taxed, the optimal toll should be set below marginal external costs (see e.g. Rouwendal and Verhoef, 2004). Second, Parry and Bento consider homogeneous consumers without paying attention to income distribution issues. However, we know that at the origin of labor taxes there is often the income distribution objective. We consider heterogeneity in labor productivity, in order to take into account differences across commuters. Differences in productivity imply differences in values of time. This in turn determines the sorting of commuters over the tolled and the untolled route. Tolling the faster route will tend to attract the most productive commuters. Therefore, the tax can act as an instrument imposed on high-income consumers and used either to redistribute resources to low-income consumers or to obtain additional efficiency gains by lowering labor taxes for all commuters.

Our analysis shows that the optimal toll differs from the Pigouvian tax. The toll can be lower or higher than the marginal external cost of the tolled road. The magnitude of the deviation depends on several aspects: the government distributive concerns, who uses the tolled road, who benefits from redistribution, how easily consumers switch to other alternatives. The marginal external cost takes into account not only congestion on the tolled road but also the increase of congestion on non-tolled alternatives caused by the tolling policy. It also takes into account the values of time of the different commuters that use the road.

A numerical exercise shows that the impact of an urban toll differs among drivers. Those who cannot afford to pay for the toll are obligated to seek other alternatives that can be welfare reducing (if limited and expensive). On the other hand, consumers that can pay the toll benefit from the reduction of congestion generated by those who leave the tolled road. The social impact of this instrument depends, therefore, not only on the use of the toll revenues but also on the distributive concern of the transport policy. Low-productivity

households benefit from toll transfers but take no advantage of labor tax reductions. On the other hand, high-productivity consumers benefit from both policies, but they can gain more from labor tax reductions. If income distributional concerns seek to favor low-productivity workers, the policymaker would prefer to recycle toll revenues through toll transfers. Increasing the toll and reducing labor taxes is not necessarily welfare optimal because poor can gain more from toll transfers.

This paper is organized as follows. In Section 2, we develop an analytical model and analyze the problem faced by homogeneous households. In Section 3, we introduce heterogeneity in labor productivity and establish four different equilibriums of road use given the types of consumers. In Section 4, we analyze the social planner's problem and derive the optimal toll rules for the different equilibriums and two ways of recycling the toll revenues: toll transfers and labor tax cuts. In section 5, we present a numerical illustration. In the last section, we present some conclusions.

2. Analytical model: the household's problem

We start with a simple model of a representative household whose utility function depends on aggregate consumption of market goods (X , whose price is normalized to one), leisure time (t_L), and the number of days devoted to work (D).

$$\mathcal{U}(X, t_L, D) = U(X, t_L) + C(D). \quad (1)$$

The representative household owns a car and uses it to commute to work by taking either one of the two parallel congested roads (of given capacities) that connect residential areas to workplaces, as illustrated in Figure 1. A congestion toll (τ) related to distance (d) is applied on one of the two roads (route T), while the other (route U) remains untolled.

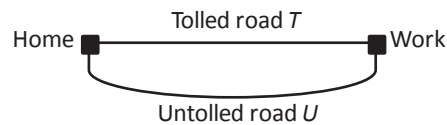


Figure 1. The two-route problem

Households choose which route to use to commute to work, U or T . Total number of worked days in a period (D) is the sum of the number of days the household commutes by the untolled road D_U and by the tolled road D_T . Thus, the budget constraint is:

$$X + p_g g d_U D_U + (p_g g d_T + \tau d_T) D_T \leq \varepsilon W (1 - \tau_w) (D_U + D_T) + G. \quad (2)$$

The right-hand side of (2) corresponds to total household's income composed of work income and lump-sum government transfers (G). Work income in a period is the product of the daily net wage and the number of days worked in the period, where \mathcal{E} is labor productivity, W is the gross daily wage and τ_w is a tax levied on wage. We assume that households are homogeneous in all respects except that they exhibit different exogenous levels of labor productivity. Thus, for the same level of labor supplied, high-productivity households get a higher work income than low-productivity households.

The left-hand side of (2) corresponds to household expenditures on aggregate consumption and commuting. Each day of work requires a commuting round trip which requires time and monetary costs. When commuting by the untolled road, only fuel costs are relevant³, p_g represents fuel price (such that $p_g = k_g(1 + \tau_g)$, where k_g is the resource fuel cost and τ_g the fuel tax), and g car (or fuel) efficiency. Commuting by the tolled road implies paying for the fuel consumption plus the toll. However, this road allows faster trips, while the untolled road requires more time and higher fuel consumption due to a longer distance: $d_U = \beta d_T$ with $\beta > 1$.

Households also face a time constraint:

$$\bar{t} = D_U + D_T + t_U d_U D_U + t_T d_T D_T + t_L. \quad (3)$$

This indicates that the household's time endowment in a period (\bar{t}) equates the sum of labor supplied ($D_U + D_T$), commuting time (by the untolled or by the tolled road) and leisure time. t_U is the time per unit of distance when using the untolled road (the inverse of the speed –h/km) and t_T the time per unit of distance required when using the tolled road.

Households choose how many days to work in a period (hours of work per day are fixed), and how to commute to work in those days (by the tolled or the untolled road). Note that by choosing the optimal number of workdays (D_T and D_U) in a period, households indirectly set total income and total leisure time in the period.

The first-order conditions of maximizing utility (1) subject to (2) and (3) are (see Appendix A for detailed derivations):

$$\mathcal{E}W(1 - \tau_w) = p_g g \beta d_T + (1 + t_U \beta d_T) \frac{U_{t_L}}{U_X} - \frac{C_{D_U}}{U_X}, \quad (4)$$

$$\mathcal{E}W(1 - \tau_w) = p_g g \beta d_T + (1 + t_U \beta d_T) \frac{U_{t_L}}{U_X} - \frac{C_{D_U}}{U_X}, \quad (5)$$

³ We consider that costs such as maintenance, insurance, vehicle ownership taxes, etc., are constant, since they do not vary with the level of congestion.

These expressions equate the private benefit from an extra day of work (net wage) with the private cost of working (monetary and time costs) plus the marginal disutility from commuting. The monetary cost of transport consists of the fuel consumption charge in the case of commuting by the untolled road (4), whereas it consists of the fuel consumption charge plus the road toll charge when commuting by the tolled road (5). The total time cost includes both daily hours spent at work and daily time lost on commuting.

As a result of considering time as a resource, we get the monetary value of time for each household (U_{t_L}/U_X). This is the ratio between the Lagrange multiplier of the time constraint and the Lagrange multiplier of the income constraint (see Appendix A). The value of spending time in transport⁴ (Value of Transport Time –VTT) is represented in (4) and (5) by the value of time foregone by commuting minus the marginal disutility of commuting ($VTT = t_R d_R (U_{t_L}/U_X) - (C_{D_R}/U_X)$, where $R=U,T$). We could also express (4) and (5) as:

$$\varepsilon W(1 - \tau_w) - \frac{U_{t_L}}{U_X} = p_g g \beta d_T + \beta d_T t_U \frac{U_{t_L}}{U_X} - \frac{C_{D_U}}{U_X}, \quad (4')$$

$$\varepsilon W(1 - \tau_w) - \frac{U_{t_L}}{U_X} = (p_g g + \tau) d_T + d_T t_T \frac{U_{t_L}}{U_X} - \frac{C_{D_T}}{U_X}. \quad (5')$$

That is, the daily net wage minus the value of daily leisure time foregone by working equals the daily total cost of commuting. The right-hand side of (4') and (5') represents the *generalized private cost of commuting* by the untolled and tolled road respectively. Equating (4') and (5') yields the Wardrop equilibrium condition⁵ in which the two roads have equal generalized prices⁶:

$$\tau = p_g g (\beta - 1) + (\beta t_U - t_T) \frac{U_{t_L}}{U_X} + \frac{1}{d_T} \left(\frac{C_{D_T}}{U_X} - \frac{C_{D_U}}{U_X} \right). \quad (6)$$

This expression indicates that households are indifferent between taking either of the two roads when the toll imposed on road T equals the extra-cost of commuting by road U . That is, the extra-gasoline and the extra travel time costs plus the difference between the marginal disutility of commuting by each road⁷ (per distance traveled a day).

⁴ For a detailed explanation of travel time valuation, see Small and Verhoef (2007) and Jara-Diaz (2000).

⁵ Wardrop principle: "For a given origin-destination pair of substitute roads, all used routes should have equal average cost and there should be no unused routes with lower costs" (Small and Verhoef, 2007).

⁶ We assume we can exclude corner solutions where only one of the two roads is used.

⁷ If the marginal disutility of commuting were the same by the two roads ($C_{D_T}/U_X = C_{D_U}/U_X$) such as if the household has no particular preference for one of the roads, condition (6) would be reduced to: $\tau = p_g g (\beta - 1) + (\beta t_U - t_T)(U_{t_L}/U_X)$, so that the household would take into consideration only the extra-gasoline and extra-time costs.

Household's individual decision depends on its own value of time (U_{t_L}/U_X), which also determines its willingness to pay for a trip. The opportunity cost of time indirectly depends on labor productivity. As high-productivity households will normally get higher wages, they should exhibit higher values of leisure time, whereas low-productivity households exhibit lower values ($U_{t_L}^h/U_X > U_{t_L}^l/U_X$). Thus, a sufficiently high toll should make high-productivity households stay on the tolled road and therefore save high-valued time. In contrast, as low-productivity households have lower budgets, they should be more sensitive to monetary cost and should prefer taking the untolled road in order to save money.

We finally define the differentiable demand functions for each road $D_U^* = D_U(P_g, \tau, t_U, \tau_w, W, \mathcal{E})$, $D_T^* = D_T(P_g, \tau, t_T, \tau_w, W, \mathcal{E})$. Assuming that they exist allows us to get the household's indirect utility function $v(P_g, \tau, t_U, t_T, \tau_w, W, \mathcal{E}, G)$ as a function of exogenous parameters (see Appendix A).

3. Use of the congested roads by heterogeneous households

Increases in road use create congestion by reducing average travel speed and raising commuting time for all road users. When deciding which road to use, households do not take into account their impact on raising the commuting time of all other users, thus congestion externalities appear. The average number of cars using each road every day depends on the number of days in a period the representative household decides to commute. Thus, travel time on both routes is endogenous $t_U(D_U)$ and $t_T(D_T)$, such that time required to commute depends on the number of trips households decide to make by each road in a period, with $\frac{\partial t_T}{\partial D_T} > 0$, and $\frac{\partial t_U}{\partial D_U} > 0$.

In the presence of congestion, households take into account the average congestion and weight it at their own value of time. However, they do not take into account the value of time of their co-travelers, on whom they impose a congestion externality. First-best pricing calls for tolling both roads. The tolls should reflect the marginal external costs of each road, such that households face the marginal social cost of their trips. However, we are interested in analyzing the second-best configuration where a single road can be tolled.

We assume that the economy is populated by high-productivity and low-productivity households in a known share ℓ, h (such that $\ell + h = N$). Both kinds of households

independently choose the number of trips they make in a period D_R^i ($i = \ell, h$ and $R = U, T$). As households differ in their willingness to pay for commuting, differentiating them according to the road used may be useful.

As a start, we may expect consumers with higher values of time taking road T while consumers with lower values of time taking road U ⁸. From the right-hand side of equations (4') and (5') we can get the expressions to compare the generalized cost of commuting by each road per type of household:

$$p_g g + \tau + t_T(hD_T^h) \frac{U_{t_L}^h}{U_X} - \frac{1}{d_T} \frac{C_T^h}{U_X} \leq \beta p_g g + \beta t_U(\ell D_U^\ell) \frac{U_{t_L}^h}{U_X} - \frac{1}{d_T} \frac{C_U^h}{U_X}, \quad (7)$$

$$p_g g + \tau + t_T(hD_T^h) \frac{U_{t_L}^\ell}{U_X} - \frac{1}{d_T} \frac{C_T^\ell}{U_X} \geq \beta p_g g + \beta t_U(\ell D_U^\ell) \frac{U_{t_L}^\ell}{U_X} - \frac{1}{d_T} \frac{C_U^\ell}{U_X}. \quad (8)$$

These conditions compare total generalized cost of commuting by T (left hand-side) with the cost of commuting by U (right hand-side) for a high-productivity household (7) and for a low-productivity household (8). When a household takes the decision to commute by one of the roads, it already knows the cost of time it will face: total time required times its own value of time⁹. Time required (per unit of distance) by each road is an increasing function of total traffic volume. $t_T(hD_T^h)$ is the time required by road T when all high-income households commute by T , and $t_U(\ell D_U^\ell)$ is the time required by road U when all low-income households use road U . $U_{t_L}^h/U_X$ and $U_{t_L}^\ell/U_X$ represent the value of time for high and low-productivity households, respectively.

From (7) and (8) we can establish four different equilibriums of use of the roads by the households, similar to those established in Small and Yan (2001). Let us assume for a moment that there is not specific preference for a road. That is, $C_T^\ell/U_X = C_U^\ell/U_X$ and $C_T^h/U_X = C_U^h/U_X$. Thus, conditions (7) and (8) become:

$$\underbrace{\tau + p_g g + \frac{U_{t_L}^h}{U_X} t_T(hD_T^h)}_{c_T^h} \leq \underbrace{\beta p_g g + \beta \frac{U_{t_L}^h}{U_X} t_U(\ell D_U^\ell)}_{c_U^h}, \quad (7')$$

$$\underbrace{\tau + p_g g + \frac{U_{t_L}^\ell}{U_X} t_T(hD_T^h)}_{c_T^\ell} \geq \underbrace{\beta p_g g + \beta \frac{U_{t_L}^\ell}{U_X} t_U(\ell D_U^\ell)}_{c_U^\ell}. \quad (8')$$

Equilibrium 1. *High-income households commuting by T and low-income households by U :* If equations (7') and (8') hold both with inequality, high-income households will strictly

⁸ As road T attracts consumers who are willing to pay more for faster commuting.

⁹ It implicitly assumes consumers are informed about current traffic congestion conditions on both roads, by for example, electronic bulletin boards or services such as traffic forecast, and of course, by their own experience.

commute by road T and low-income households by road U . In this case, road T should be less expensive than road U for high-income consumers. That is, the cost of an extra-trip on T should be lower than the cost of an extra-trip on U for a high-income commuter, $c_T^h < c_U^h$. Moreover, as road U should be less expensive than road T for low-income commuters, the cost of an extra-trip on T should be higher than the cost of an extra-trip on U for a low-income commuter, $c_T^l > c_U^l$. These equations can hold simultaneously since the cost of time is different for each type of consumer and normally $U_{t_L}^h/U_X > U_{t_L}^l/U_X$.

Equilibrium 2. *High-income households commuting by T and U , and low-income households commuting by U :* If equation (7') holds with equality and (8') with inequality, high-income households will be indifferent towards the two roads and low-income households will strictly commute by road U . In this equilibrium the cost of an extra-trip on road T for a high-income consumer equals the cost of an extra trip on road U , $c_T^h = c_U^h$ and $c_T^l > c_U^l$.

Equilibrium 3. *High-income households commuting by T , and low-income households commuting by T and U :* If equation (7') holds with inequality and (8') with equality, high-income households will strictly prefer road T and low-income households will be indifferent towards taking either of the two roads. In this equilibrium the cost of an extra-trip on road T for a low-income consumer equals the cost of an extra-trip on road U , $c_T^h < c_U^h$ and $c_T^l = c_U^l$.

Equilibrium 4. *High-income households commuting by T and U , and low-income households commuting by T and U :* If both equations hold with equality, both types of households will be indifferent towards taking either of the two roads. In this equilibrium the cost of an extra-trip on road T for both kinds of consumers equals the cost of an extra-trip on road U , $c_T^h = c_U^h$ and $c_T^l = c_U^l$.

4. Optimal toll: the social planner's problem

The government raises revenues, to finance a fixed set of public goods F , and a head subsidy G , from three tax instruments: fuel taxes (τ_g), tolls (τ) and wage taxes (τ_w). The government maximizes social welfare¹⁰ $\mathbb{W} = \sum_{i=1}^N \theta^i v^i(p_g, \tau, t_U, t_T, \tau_w, W, \mathcal{E}, G)$, subject to the following budget constraint:

¹⁰ This is a purely utilitarian social welfare function where increases or decreases in individual utilities translate into identical changes in social utility. Aversion to income inequality is introduced via the social weight given by the government to each kind of household θ (with $\sum_{i=1}^N \theta^i = 1$).

$$W\tau_w \sum_{i=1}^N \mathcal{E}^i(D_U^i + D_T^i) + \tau_g k_g g \sum_{i=1}^N (d_U D_U^i + d_T D_T^i) + \tau d_T \sum_{i=1}^N D_T^i = F + NG. \quad (9)$$

Note that total budget collected by the government depends on household decisions: D_U and D_T .

The social welfare function for our two groups of consumers becomes $\mathbb{W} = \theta h v^h + (1 - \theta) \ell v^\ell$. In what follows, we analyze the welfare improving changes of the four possible equilibriums studied in the previous section. For each case, toll revenues are returned to the individuals either through poll transfers or recycled through labor-tax cuts.

4.1 High-income households commuting by T , and low-income households commuting by U

Assume that the economy is at the equilibrium where high-income households take only road T and low-income households take only road U . Each household chooses the optimal number of commuting trips (D_R^i) that maximizes its individual utility. We assume that an increase of the toll reduces the number of trips high-income commuters make on road T . As road U is not priced, users on this road keep the number of trips fixed. Assuming equal labor tax rates for both types of households, the government's budget constraint becomes:

$$\tau_w W(h\mathcal{E}^h D_T^h + \ell\mathcal{E}^\ell D_U^\ell) + \tau_g k_g g d_T(hD_T^h + \beta\ell D_U^\ell) + \tau d_T h D_T^h = F + NG. \quad (10)$$

4.1.1 Toll revenues used to finance poll transfers

The welfare impact of an increase in the congestion tax is obtained by maximizing the social welfare function subject to the budget constraint (10) (see Appendix B for detail). The optimal toll per unit of distance, when revenues are returned to households as poll transfer is given by:

$$\tau_{pt}^* = \theta_{pt} \underbrace{\frac{U_{t_L}^h}{U_X^h} \frac{\partial t_T}{\partial D_T^h} D_T^h}_{mecc} - \theta'_{pt} \underbrace{\left(\tau_g k_g g + \tau_w \frac{W\mathcal{E}^h}{d_T} \right)}_{\text{Other taxes per trip}}, \quad (11)$$

where $\theta_{pt} = \frac{\theta}{\theta + (\ell/N)\hat{\theta}\xi}$, $\theta'_{pt} = \frac{\theta + (\ell/N)\hat{\theta}}{\theta + (\ell/N)\hat{\theta}\xi}$, $\hat{\theta} = \alpha(1 - \theta) - \theta$, $\alpha = \frac{U_X^\ell}{U_X^h}$, $\xi = 1 + 1/\epsilon_{D_T^h}^\tau$, and $\epsilon_{D_T^h}^\tau$ is the elasticity of demand of high-income households for the tolled road.

The optimal congestion toll has two main components. The marginal external congestion cost (*mecc*) and other taxes levied per trip. The *mecc* measures the increase in traffic-time cost

to all road users caused by congestion arising from an extra trip per period. In equation (11), it is represented by the product of the increase in commuting time per distance from an additional trip ($\partial t_T / \partial D_T^h$), the value of time of the commuter (U_{tL}^h / U_X^h) and the number of trips made per period D_T^h . Other taxes per trip appear in (11) as the complementary relationship between work-related trips and the labor market makes that all the taxes (per kilometer) levied per day of work serve to tackle the externality caused by each day of work, namely congestion. Thus, for example, if the sum of the fuel and the labor tax exceeds the *mecc*, rather than taxing road T commuters, the government should subsidize them. Equation (11) therefore suggests an optimal combination of the toll, the fuel tax and the labor tax, rather than a unique optimal toll level.

Each term in (11) is multiplied by a factor that depends on the government distributive concerns (θ_{pt} and θ'_{pt}). They depend on the social weight given to the groups (θ) and on the ratio of the marginal utility of income of both types of consumers (U_X^ℓ / U_X^h). This component captures the value that the government attaches to a unit of income of low-productivity households with respect to a unit of income of high-productivity households. This involves trading off the utility of one group against that of the other group. Normally, $U_X^\ell / U_X^h > 1$ when the decision maker attaches a higher weight to a unit of income of a low-productivity consumer, thus $\alpha > 0$. Conversely, if the government attached the same weight to both groups ($U_X^\ell = U_X^h$), we would have $\alpha = 1$, and $\theta_{pt} = \theta'_{pt} = 1$. Thus the government would not be concerned with redistribution.

If $\alpha > \frac{\theta}{1-\theta}$ we have that, if the demand for the tolled road is inelastic ($|\epsilon_{D_T^h}^\tau| < 1$), θ_{pt} and θ'_{pt} are higher than one, so that the optimal toll level could be higher than the *mecc* if the government cannot raise enough revenues from other taxes. In this case, the toll becomes an instrument to distribute income among consumers. On the contrary, if the demand for the tolled road is elastic, θ_{pt} and θ'_{pt} are lower than one and the toll have to be set lower than the *mecc*. In this case, the toll cannot longer be used as an instrument to distribute income, as every euro of tax revenues then has a high efficiency cost. When the government gives the same weight to both kinds of consumers, $\theta_{pt} = \theta'_{pt} = 1$, so that the optimal toll equal the difference between the *mecc* and the sum of the other taxes.

4.1.2 Toll revenues used to cut labor taxes

Following the same procedure, we obtain the optimal toll when the incremental toll revenues are used to cut labor tax rates (see Appendix B.1):

$$\tau_{lt}^* = \theta_{lt} \frac{U_{tL}^h}{U_X^h} \frac{\partial t_T}{\partial D_T^h} D_T^h - \theta'_{lt} \left(\tau_g k_g g + \tau_w \frac{W \mathcal{E}^h}{d_T} \right), \quad (12)$$

where $\theta_{lt} = \frac{\theta}{\theta + (\ell \mathcal{E}^\ell D_U^\ell / (h \mathcal{E}^h D_T^h + \ell \mathcal{E}^\ell D_U^\ell)) \bar{\theta} \xi}$, $\theta'_{lt} = \frac{\theta + (\ell \mathcal{E}^\ell D_U^\ell / (h \mathcal{E}^h D_T^h + \ell \mathcal{E}^\ell D_U^\ell)) \bar{\theta}}{\theta + (\ell \mathcal{E}^\ell D_U^\ell / (h \mathcal{E}^h D_T^h + \ell \mathcal{E}^\ell D_U^\ell)) \bar{\theta} \xi}$. This expression differs from (11) in that θ_{lt} and θ'_{lt} take into account the proportion of labor supplied by low-productivity households. Therefore, labor productivity enters in the distributive concern term, so that redistributing income through the labor tax implies that what drives the toll level is the proportion of labor supplied by low-productivity consumers $\left(\frac{\ell \mathcal{E}^\ell D_U^\ell}{h \mathcal{E}^h D_T^h + \ell \mathcal{E}^\ell D_U^\ell} \right)$ rather than their proportion in the economy (ℓ/N).

4.2 High-income households commuting by T and U , and low-income households commuting by U

In this subsection, we assume that the economy is at the second type of equilibrium, where high-income households take road T and road U , and low-income households take only road U . As the roads are substitutes, we assume that if the toll increases, high-income consumers reduce the number of trips they make by road T and increase the number of trips they make by road U . To keep things simple we assume that low-income users do not change their number of trips by road U as the toll increases¹¹. Thus, the government's budget constraint becomes:

$$\tau_w W (h \mathcal{E}^h (D_T^h + D_U^h) + \ell \mathcal{E}^\ell D_U^\ell) + \tau_g k_g g d_T (h (D_T^h + \beta D_U^h) + \beta \ell D_U^\ell) + \tau d_T h D_T^h = F + NG. \quad (13)$$

4.2.1 Toll revenues used to finance poll transfers

Here, we consider the case where the incremental toll revenues are used to finance lump-sum transfers (see Appendix B.2):

$$\tau_{pt}^* = \theta_{pt} \underbrace{\frac{U_{tL}^h}{U_X^h} \left(D_T^h \frac{\partial t_T}{\partial D_T^h} + D_U^h \beta \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \right)}_{mecc\ T + mecc\ U} - \theta'_{pt} \left(\tau_g k_g g (1 + \beta \Delta D_{TU}^h) + \tau_w \frac{W \mathcal{E}^h}{d_T} (1 + \Delta D_{TU}^h) \right). \quad (14)$$

¹¹ This assumption will be relaxed in the numerical illustration.

Because in this case high-income commuters have the possibility to exchange trips on road T for trips on road U as the toll increases, we get the term $\Delta D_{TU}^h = \partial D_U^h / \partial D_T^h < 0$, which gives the number of trips added to U per trip removed from T ¹². Although equation (14) has the same structure as (11), it incorporates the marginal external congestion cost caused on road U by the fraction of trips removed from T and added to U .

As before, (14) implies that the optimal toll should be set as the difference between a fraction of the *mecc* and other taxes per trip. The externality-correction term refers to the difference between the marginal cost of congestion on road T and the marginal cost of congestion imposed on road U by commuters that change roads to avoid the toll. This is a typical second best result: mitigate the distortion on one market only to the extent that it does not aggravate the distortion on the other market (Small and Verhoef, 2007 p. 140).

4.2.2 Toll revenues used to cut labor taxes

The optimal toll when the incremental toll revenues are used to cut labor taxes is given by (see Appendix B.2):

$$\tau_{lt}^* = \theta_{lt} \underbrace{\frac{U_{tL}^h}{U_X^h} \left(D_T^h \frac{\partial t_T}{\partial D_T^h} + D_U^h \beta \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \right)}_{mecc\ T+mecc\ U} - \theta'_{lt} \left(\tau_g k_g g (1 + \beta \Delta D_{TU}^h) + \tau_w \frac{W \mathcal{E}^h}{d_T} (1 + \Delta D_{TU}^h) \right). \quad (15)$$

This equation has the same structure as (14) and contains the externality-correction term. Again, the only difference between (14) and (15) is the redistributive term, which takes into account the proportion of labor supplied by low-productivity households as in (12).

Equations (14) and (15) imply therefore a toll level lower than that implied by (11) and (12), respectively, as the former includes a *mecc* that is reduced by the effect of traffic diversion.

4.3 High-income households commuting by T , and low-income households commuting by T and U

Let us assume that the economy is at the third type of equilibrium, where high-income households take road T , and low-income households take both road T and road U . As before,

¹² This trade-off between roads ($\partial D_U^h / \partial D_T^h$) affects the *mecc* as well as the second part of (14) since revenues collected from other taxes also depend on the road used.

we assume that if the toll increases, low-productivity consumers reduce the number of trips they make by road T and increase the number of trips they make by road U . In addition, we assume that high-productivity consumers reduce their number of trips by road T only as result of the toll increase. However, they do not move to road U . Thus, the government's budget constraint becomes:

$$\tau_w W \left(h \varepsilon^h D_T^h + \ell \varepsilon^\ell (D_T^\ell + D_U^\ell) \right) + \tau_g k_g g d_T \left(h D_T^h + \ell (D_T^\ell + \beta D_U^\ell) \right) + \tau d_T (h D_T^h + \ell D_T^\ell) = F + NG. \quad (16)$$

The optimal toll when revenues are used to make poll transfers is as follows (for detail see Appendix B.3):

$$\begin{aligned} \tau_{pt}^* = & \theta \bar{E}_{D_T^h}^\tau \frac{U_{X^h}^h}{U_X^h} \frac{\partial t_T}{\partial D_T^h} D_T^h + (1 - \theta) \bar{E}_{D_T^\ell}^\tau \frac{U_{X^\ell}^\ell}{U_X^\ell} \left[D_T^\ell \frac{\partial t_T}{\partial D_T^\ell} + D_U^\ell \beta \frac{\partial t_U}{\partial D_U^\ell} \Delta D_{TU}^\ell \right] \\ & - (\theta + (\ell/N)\hat{\theta}) \left(\tau_g k_g g \left[\bar{E}_{D_T^h}^\tau + \bar{E}_{D_T^\ell}^\tau (1 + \beta \Delta D_{TU}^\ell) \right] + \tau_w \frac{W}{d_T} \left[\bar{E}_{D_T^h}^\tau \varepsilon^h + \bar{E}_{D_T^\ell}^\tau \varepsilon^\ell (1 + \Delta D_{TU}^\ell) \right] \right). \end{aligned} \quad (17)$$

where $\bar{E}_{D_T^h}^\tau = \frac{h D_T^h \varepsilon_{D_T^h}^\tau}{\bar{E}^T}$, $\bar{E}_{D_T^\ell}^\tau = \frac{\ell D_T^\ell \varepsilon_{D_T^\ell}^\tau}{\bar{E}^T}$ and $\bar{E}^T = h D_T^h \left[(\theta + (\ell/N)\hat{\theta}) (1 + \varepsilon_{D_T^h}^\tau) - \theta \right] + \ell D_T^\ell \left[(\theta + (\ell/N)\hat{\theta}) (1 + \varepsilon_{D_T^\ell}^\tau) - (1 - \theta) \right]$. Although (17) is more complex than previous equations, we can identify the same structure. The optimal toll should be set as the difference between a fraction of the externality-correction term and the level of other taxes per trip. The externality-correction term here consists of three terms: the *mecc* imposed on road T by both high-income and low-income households and the *mecc* imposed on road U by low-income households. In this case, the value of time of both types of consumers appears in the equation as they both take the tolled road. As indicated by Small and Verhoef (2007 p. 145), when tolls cannot be differentiated among user groups, the second-best toll depends on a weighted average (by the price sensitivity of demand) of the marginal external costs for the different groups.

The price elasticity of demand of both groups appears in (17) as both kinds of consumers take road T . Each term in this expression is weighted by the price elasticity of each type of household, as the response of consumers to toll increases depends on their price elasticity.

In this section we only derive the expression for the optimal toll when revenues are used to finance poll transfers. The complexity of the expression makes that deriving the second case does not add any further insight other than the already found in (17). That is, when both kinds of individuals use the tolled road, the price elasticity of both groups should be taken into account.

4.4 High-income households commuting by T and U , and low-income households commuting by T and U

Finally, assume that the economy is at the fourth type of equilibrium, where both kinds of households take both roads. Next, assume that if the toll increases, both groups reduce the number of trips they make by road T and increase the number of trips they make by road U . Moreover, assume that road users reduce the number of trips they make on this road only as a result of the toll increase. The government's budget constraint becomes:

$$\tau_w W \left(h \mathcal{E}^h (D_T^h + D_U^h) + \ell \mathcal{E}^\ell (D_T^\ell + D_U^\ell) \right) + \tau_g k_g g d_T \left(h (D_T^h + \beta D_U^h) + \ell (D_T^\ell + \beta D_U^\ell) \right) + \tau d_T (h D_T^h + \ell D_T^\ell) \quad (18)$$

$$= F + NG.$$

The optimal toll when the incremental toll revenues are used make poll transfers is as follows (see Appendix B.4):

$$\begin{aligned} \tau_{pt}^* = & \theta \tilde{E}_{D_T^h}^\tau \frac{U_{tL}^h}{U_X^h} \left[D_T^h \frac{\partial t_T}{\partial D_T^h} + D_U^h \beta \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \right] + (1 - \theta) \tilde{E}_{D_T^\ell}^\tau \frac{U_{tL}^\ell}{U_X^\ell} \left[D_T^\ell \frac{\partial t_T}{\partial D_T^\ell} + D_U^\ell \beta \frac{\partial t_U}{\partial D_U^\ell} \Delta D_{TU}^\ell \right] \\ & - (1 + (\ell/N)\hat{\theta}) \left(\tau_g k_g g \left[\tilde{E}_{D_T^h}^\tau (1 + \beta \Delta D_{TU}^h) + \tilde{E}_{D_T^\ell}^\tau (1 + \beta \Delta D_{TU}^\ell) \right] \right. \\ & \left. + \tau_w \frac{W}{d_T} \left[\tilde{E}_{D_T^h}^\tau \mathcal{E}^h (1 + \Delta D_{TU}^h) + \tilde{E}_{D_T^\ell}^\tau \mathcal{E}^\ell (1 + \Delta D_{TU}^\ell) \right] \right). \end{aligned} \quad (19)$$

where $\tilde{E}_{D_T^h}^\tau = \frac{h D_T^h \epsilon_{D_T^h}^\tau}{\tilde{E}^T}$, $\tilde{E}_{D_T^\ell}^\tau = \frac{\ell D_T^\ell \epsilon_{D_T^\ell}^\tau}{\tilde{E}^T}$ and $\tilde{E}^T = \ell D_T^\ell \left[\theta + \epsilon_{D_T^\ell}^\tau + (\ell/N)\hat{\theta} (1 + \epsilon_{D_T^\ell}^\tau) \right] + h D_T^h \left[1 - \theta + \epsilon_{D_T^h}^\tau + (\ell/N)\hat{\theta} (1 + \epsilon_{D_T^h}^\tau) \right]$. Equation (19) is the more general equation derived in this analysis. It takes into account the use of the roads by both kinds of consumers. Interpretation is as explained before.

4.5 Optimal tolling rule: summary

The optimal tolling rule can be formulated as an optimal deviation from the marginal external congestion costs as follows:

$$\tau^* = \theta \overline{m\epsilon c\bar{c}} - \theta' \bar{\tau}^\circ$$

where θ and θ' stand for distributional concerns (a combination of the social weights given to each group, the marginal utility of income of each group, the proportion of low-income households in the economy, the price elasticity of demand), $\overline{m\epsilon c\bar{c}}$ stands for the marginal external congestion cost and $\bar{\tau}^\circ$ for the preexisting taxes in the economy.

The urban toll on work-related traffic differs from the Pigouvian tax given the second-best conditions considered in the analysis. These can be summarized as: (i) When only a single road in a network can be tolled, the marginal external cost induced on substitute roads by

traffic diversion should be subtracted from the marginal external cost of congestion on the tolled road. (ii) When the toll cannot be differentiated among heterogeneous drivers, the marginal external cost should be an elasticity-weighted average of the marginal external cost for all the drivers using the tolled road. (iii) When patterns of traveling interfere with other markets' equilibriums, the taxes levied (per trip) on the other markets should be considered in the tolling rule.

5. Numerical illustration

This section presents the results of a numerical simulation¹³ of a road network such as illustrated in Figure 1. The average distance of a daily (round) commuting trip is 40 Km if using the tolled road and 60 Km if using the untolled road. The maximum commuting demand in a period (a year) is 200 000 trips. The slope of the congestion function is such that the free-flow speed is 60 Km/h, which is reduced to 30 Km/h when total number of trips is equally divided between the two roads. Thus, travel time increases linearly with increasing traffic volume. Both roads exhibit the same congestion functions.

We define a household's utility function¹⁴ separable in two terms, the utility of consumption/leisure and the disutility of travelling:

$$U(X, t_L, D_U, D_T) = (\alpha_X X^{\sigma_U} + (1 - \alpha_X) t_L^{\sigma_U})^{\frac{1}{\sigma_U}} - \sigma_C (D_U + D_T). \quad (1')$$

We choose $\sigma_U=0.33$ and $\alpha_X=0.4$ to be consistent with values of consumption/leisure elasticity of the related literature¹⁵. We set $\sigma_C=1$ ¹⁶ and give no particular weight to any of the roads, so that the marginal disutility of traveling for any of the routes is the same¹⁷. In other words, preferences with respect to the use of the two roads are symmetric, such that households do not systematically prefer one road to the other.

We introduce two groups of households (in equal proportion in the economy) that only differ in their labor productivity. Labor productivity factor of high-income households is

¹³ The algorithm was written in Wolfram Mathematica 7.0.

¹⁴ Similar functions are used in Parry and Bento (2001) and Van Dender (2003).

¹⁵ See Parry and Bento (2001) p. 658 for a discussion of empirical evidence of these parameters.

¹⁶ In the basic setting, $\sigma_C=1$ implies a disutility of traveling around 7% (3.5%) of the total utility for low-income consumers (high-income consumers). Increasing (decreasing) this parameter raises (drops) the disutility of traveling (see the sensibility analysis).

¹⁷ This implies that the roads are perfect substitutes from the consumer perspective. This reflects the consumer taste and has no relation with the characteristics of the roads.

around five times the productivity factor of low-income households¹⁸. This implies that the gasoline expenditures represent around 20% of the after tax wage of a low-productivity household and around 5% of the after tax wage of a high-income household. We assume a wage tax rate of 20% and 8 hours of work per day.

The constraints of this maximization problem are those described in (2) and (3). Thus, each household individually chooses, with perfect knowledge of the travel conditions on the road network, the route and the number of commuting trips.

When we use a toll, the toll revenues can be recycled in two ways: (1) recycling through poll transfers, and (2) recycling through labor tax reductions.

Figure 2 depicts the number of trips that a representative household of each type makes in a period on each of the roads in function of the toll when toll revenues are recycled through labor tax cuts (recycling through poll transfers gives similar results in terms of road use). The point where the toll is zero in Figure 2 gives the no-toll equilibrium. At the no-toll equilibrium, the tolled road is intensively used by both types of consumers. Low-income consumers make around 70% of their trips by road *T*, whereas high-income consumers make around 60% of their trips by this road.

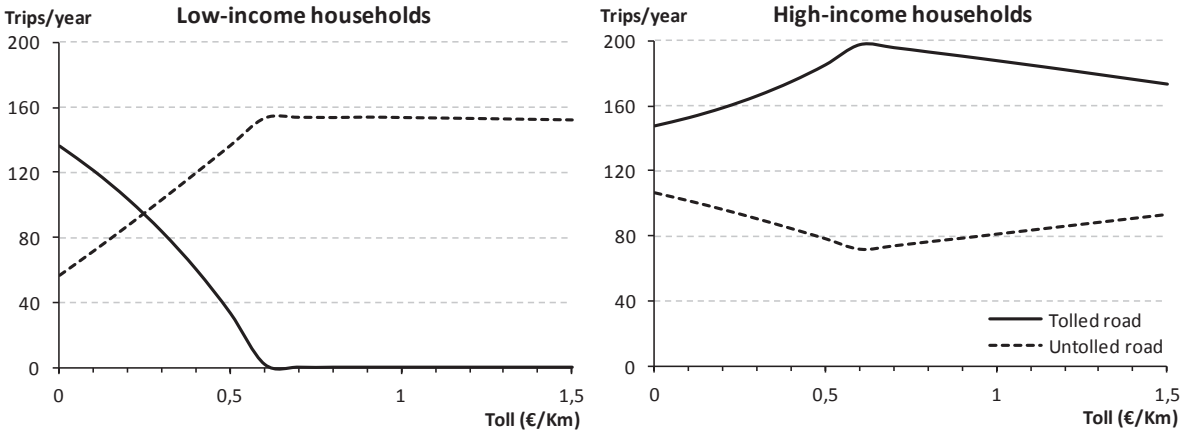


Figure 2. Trips per household per road (labor tax cut case)

If the toll increases, low-income consumers reduce the number of trips they make and exchange some of the trips on road *T* by trips on road *U*. On the contrary, high-income consumers increase the number of trips they make and exchange trips on road *U* by trips on

¹⁸ We consider total disposable income, without distinguishing the source of income. Income data were taken from INSEE (2009); according to them, the best-off of households have five times as much disposable income as the most modest.

road *T*. As they can pay for the toll, they can take advantage of the reduction of congestion on road *T* caused by low-income commuters leaving this road.

When the toll approaches 60 cents/Km, the cost of commuting by road *T* exceeds the cost of commuting by road *U* for low-income commuters. Consequently, from that point onwards they only use road *U*. On the other hand, high-income consumers, instead of decrease, increase the number of trips on road *T* until that point. From that point onwards they start switching to the other road since paying for the toll does not compensate the gain in time anymore as low-income consumers have completely abandoned that road.

This exercise shows that if the tolled road allows faster and less fuel-consuming trips than the alternative roads, imposing a toll can reduce congestion on the tolled road. However, the negative impact of this reduction is mainly borne by low-income consumers that have to reduce their number of trips and bear the extra-time and extra-fuel costs implied by the alternative roads. The welfare effect of the two policies is depicted in Figure 3. The vertical axis shows the change of individual welfare per policy (in units of utility), where zero corresponds to the welfare level at the no-toll equilibrium.

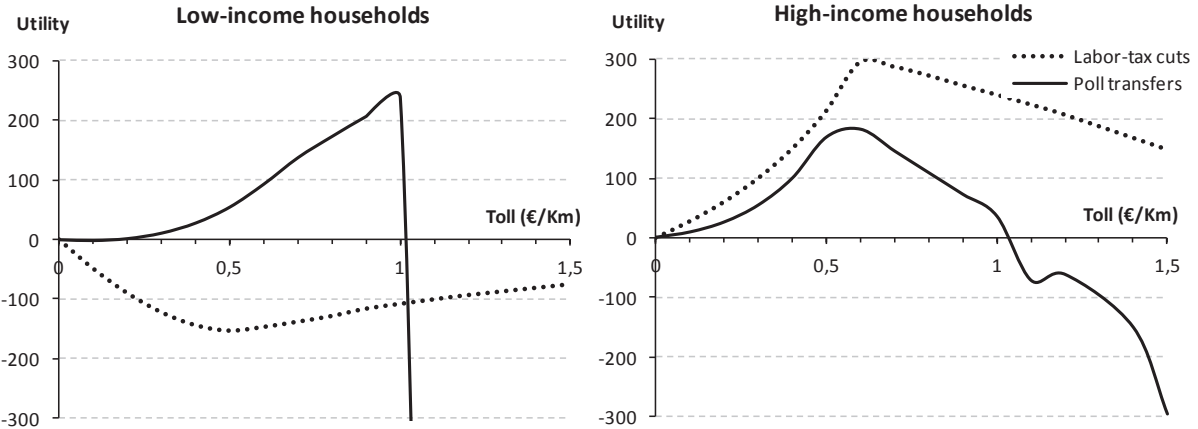


Figure 3. Utility per type of household

Low-income consumers benefit only with head transfers. Recycling through labor-tax cuts is welfare reducing for them. On the other hand, high-income consumers benefit from both measures but they gain more when revenues are redistributed through labor-tax cuts. There are two reasons for these effects. First, an equal head transfer represents a higher percentage of the after-tax income of a low-productivity consumer than of a high-productivity one. Second, the reduction that high-productivity workers obtain from a labor tax cut is higher than the reduction obtained by low-productivity workers.

The social welfare of both kinds of recycling measures, when the distributive weight to the low-income group is higher (the revealed policy preference in the basic setting gives $\theta=0,6$), is shown in Figure 4.

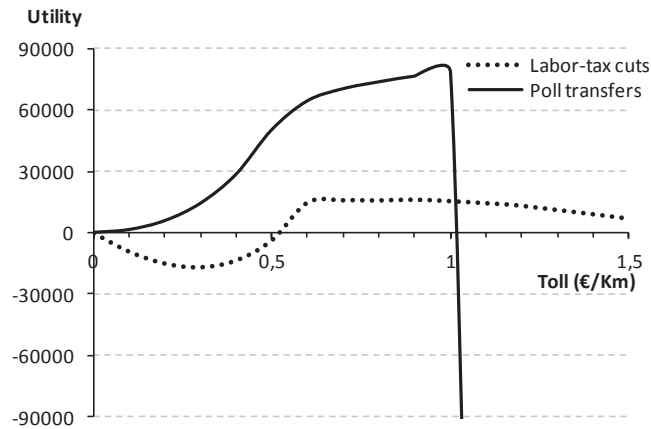


Figure 4. Social welfare

Poll payments do better than labor tax cuts at the social level as this measure advantages low-income consumers. If income distributional concerns seek to favor low-productivity workers, the policymaker would prefer to recycle toll revenues through poll transfers. Increasing the toll and reducing labor taxes is not necessarily welfare optimal because poor can gain more from poll transfers.

6. Conclusion

In this paper, we have derived an optimal toll rule that can be used for a government that, in order to reduce traffic congestion, charges commuters for the use of a road and uses the revenues to redistribute wealth among all commuters. The tolling rule goes beyond the simple external congestion cost. Issues as the governmental distributive concerns, who uses the tolled road, who benefits from redistribution, how easily consumers switch to other alternatives, move away the toll from the marginal external congestion cost.

A numerical illustration shows that, in general, the implementation of a toll makes high-income consumers to win and low-income consumers to lose when other transport options (free roads or public transit) are costly and limited. On the other hand, if toll revenues are to be distributed among commuters, low-productivity commuters take better advantage of head transfers, while high-productivity commuters take better advantage of labor tax reductions.

However, the choice of the policy largely depends on the characteristics of the economy and the weight that the decision maker gives to redistribution.

We conclude our analysis by drawing attention to some caveats. A differentiated labor tax between income groups could for instance change the results. Implementation costs of tolling systems can also be important. Other interesting considerations include the introduction of environmental externalities related to the use of motor fuels as well as the differentiation of fuel or car technology according to consumers groups. A more comprehensive analysis would also include tolling leisure-related traffic.

7. Acknowledgements

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Appendix A. The households' problem

The household's problem defined by (1), (2) and (3). can be solved by maximizing the following Lagrangian function:

$$\begin{aligned} \mathcal{L} = & U(X, t_L) + C(D_U, D_T) - \lambda_c [X + P_g g \beta d_T D_U + (P_g g + \tau) d_T D_T - \varepsilon W(1 - \tau_w)(D_U + D_T) - G] \\ & + \mu_c [\bar{t} - D_U(1 + t_U \beta d_T) - D_T(1 + t_T d_T) - t_L] \end{aligned}$$

λ_c is the Lagrangian multiplier related to the income constraint, called the "marginal utility of income". μ_c is the Lagrangian multiplier related to the time constraint, called the "resource value of time". For $X > 0$, $D_U > 0$, $D_T > 0$ and $t_L > 0$, the system of first-order conditions can be written as:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial X} = U_X - \lambda_c = 0 & \Rightarrow \lambda_c = U_X \\ \frac{\partial \mathcal{L}}{\partial t_L} = U_{t_L} - \mu_c = 0 & \Rightarrow \mu_c = U_{t_L} \\ \frac{\partial \mathcal{L}}{\partial D_U} = C_{D_U} - \lambda_c [P_g g \beta d_T - \varepsilon W(1 - \tau_w)] - \mu_c (1 + t_U \beta d_T) = 0 \\ \frac{\partial \mathcal{L}}{\partial D_T} = C_{D_T} - \lambda_c [(P_g g + \tau) d_T - \varepsilon W(1 - \tau_w)] - \mu_c (1 + t_T d_T) = 0 \end{aligned} \tag{A.1}$$

Using these conditions and the budget constraint, we obtain the demand functions for X^* , D_U^* , D_T^* and t_L^* . Replacing these functions into the utility gives the indirect utility function $v(P_g, \tau, t_U, t_T, \tau_w, G)$ which allows rewriting the household's problem as:

$$\begin{aligned} \mathcal{L} = & v(P_g, \tau, t_U, t_T, \tau_w, G, \varepsilon) + \lambda_c [X + P_g g d_U D_U + (P_g g + \tau) d_T D_T - \varepsilon W(1 - \tau_w)(D_U + D_T) - G] \\ & - \mu_c [\bar{t} - D_U(1 + t_U d_U) - D_T(1 + t_T d_T) - t_L] \end{aligned}$$

F.O.C.:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \tau} = v_\tau + \lambda_c d_T D_T = 0 & \Rightarrow v_\tau = -U_X d_T D_T \\ \frac{\partial \mathcal{L}}{\partial \tau_g} = v_{\tau_g} + \lambda_c k_g g d_T (\beta D_U + D_T) = 0 & \Rightarrow v_{\tau_g} = -U_X k_g g d_T (\beta D_U + D_T) \\ \frac{\partial \mathcal{L}}{\partial \tau_w} = v_{\tau_w} + \lambda_c \varepsilon W (D_U + D_T) = 0 & \Rightarrow v_{\tau_w} = -U_X \varepsilon W (D_U + D_T) \\ \frac{\partial \mathcal{L}}{\partial t_U} = v_{t_U} + \mu_c d_U D_U = 0 & \Rightarrow v_{t_U} = -U_{t_L} d_U D_U \\ \frac{\partial \mathcal{L}}{\partial t_T} = v_{t_T} + \mu_c d_T D_T = 0 & \Rightarrow v_{t_T} = -U_{t_L} d_T D_T \\ \frac{\partial \mathcal{L}}{\partial G} = v_G - \lambda_c = 0 & \Rightarrow v_G = U_X \end{aligned} \tag{A.2}$$

Note that the marginal disutility of a toll increase (v_τ) is the marginal utility of income (U_X) multiplied by the optimal number of trips (D_T). Similarly, the marginal disutility of an increase of travel time on road T (v_{t_T}) is the resource value of time (U_{t_L}) multiplied by the optimal number of trips.

Appendix B. The social planner's problem

B.1 High-income households commuting by T and low income households by U

In this case, $D_U^h = 0$ since high-income households only use road T . And $D_T^l = 0$, since low-income households only use road U .

Revenues used to make lump-sum transfers to the individuals:

Differentiating the social welfare function with respect to τ , when $d\tau$ affects dG , we have:

$$\frac{d\mathbb{W}}{d\tau} = \theta h \left(v_{\tau}^h + v_{t_{\tau}}^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} + v_G^h \frac{dG}{d\tau} \right) + (1 - \theta) \ell v_G^{\ell} \frac{dG}{d\tau} \quad \text{B.1}$$

With $\frac{\partial t_{\tau}}{\partial D_T^h} > 0$, $\frac{dD_T^h}{d\tau} < 0$ and $\frac{dG}{d\tau} > 0$. Replacing A.2 into B.1 we have:

$$\frac{d\mathbb{W}}{d\tau} = -\theta h d_{\tau} D_T^h \left(U_X^h + U_{t_L}^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} \right) + (\theta h U_X^h + (1 - \theta) \ell U_X^{\ell}) \frac{dG}{d\tau} \quad \text{B.2}$$

Differentiating (10) with respect to τ gives the change in the transfer dG associated with a change in the toll $d\tau$:

$$\frac{dG}{d\tau} = \frac{h d_{\tau}}{N} \left[\left(\tau + \tau_g k_g g + \tau_w \frac{W \mathcal{E}^h}{d_{\tau}} \right) \frac{dD_T^h}{d\tau} + D_T \right] \quad \text{B.3}$$

Inserting B.3 into B.2 and dividing by U_X^h , we have:

$$\frac{d\mathbb{W}/d\tau}{U_X^h} = \left(\theta \frac{h}{N} + (1 - \theta) \frac{\ell U_X^{\ell}}{N U_X^h} \right) \left(\tau + \tau_g k_g g + \tau_w \frac{W \mathcal{E}^h}{d_{\tau}} \right) \frac{dD_T^h}{d\tau} + \left(\theta \frac{h}{N} - \theta + (1 - \theta) \frac{\ell U_X^{\ell}}{N U_X^h} \right) D_T^h - \theta \frac{U_{t_L}^h}{U_X^h} D_T^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau}$$

Setting $\frac{d\mathbb{W}/d\tau}{U_X^h} = 0$, defining $\alpha = \frac{U_X^{\ell}}{U_X^h}$ and the elasticity of demand of high-income consumers for the tolled road as

$$\epsilon_{D_T^h}^{\tau} = \frac{dD_T^h}{d\tau} \frac{\tau}{D_T^h}, \text{ we get (11).}$$

Revenues used to cut labor taxes:

The welfare impact when the incremental toll revenues $d\tau$ are used to cut labor tax rates $d\tau_w$.

$$\frac{d\mathbb{W}}{d\tau} = \theta h \left(v_{\tau}^h + v_{t_{\tau}}^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} + v_{\tau_w}^h \frac{d\tau_w}{d\tau} \right) + (1 - \theta) \ell v_{\tau_w}^{\ell} \frac{d\tau_w}{d\tau} \quad \text{B.4}$$

With $\frac{d\tau_w}{d\tau} > 0$. Replacing A.2 into B.5 we have:

$$\frac{d\mathbb{W}}{d\tau} = -\theta h d_{\tau} D_T^h \left(U_X^h + U_{t_L}^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} \right) - (\theta h \mathcal{E}^h D_T^h U_X^h + (1 - \theta) \ell \mathcal{E}^{\ell} D_U^{\ell} U_X^{\ell}) W \frac{d\tau_w}{d\tau} \quad \text{B.5}$$

Differentiating (10) with respect to τ and solving for $W \frac{d\tau_w}{d\tau}$ gives:

$$W \frac{d\tau_w}{d\tau} = \frac{-h d_{\tau}}{h \mathcal{E}^h D_T^h + \ell \mathcal{E}^{\ell} D_U^{\ell}} \left[\left(\tau_w \frac{W \mathcal{E}^h}{d_{\tau}} + \tau_g k_g g + \tau \right) \frac{dD_T^h}{d\tau} + D_T^h \right] \quad \text{B.6}$$

Inserting B.6 into B.5, dividing by U_X^h , setting $\frac{d\mathbb{W}/d\tau}{U_X^h} = 0$, and using α and $\epsilon_{D_T^h}^{\tau}$ we get (12).

B.2 High-income households commuting by T and U , and low-income households commuting by U

Revenues used to make lump-sum transfers to the individuals:

Differentiating the social welfare function with respect to τ , when $d\tau$ affects dG , gives:

$$\frac{d\mathbb{W}}{d\tau} = \theta h \left(v_{\tau}^h + v_{\tau}^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} + v_{t_U}^h \frac{\partial t_U}{\partial D_U^h} \frac{\partial D_U^h}{\partial D_T^h} \frac{dD_T^h}{d\tau} + v_G^h \frac{dG}{d\tau} \right) + (1 - \theta) \ell v_G^{\ell} \frac{dG}{d\tau} \quad \text{B.7}$$

Replacing A.2 into B.7 we have:

$$\frac{dV}{d\tau} = \theta h \left(-U_X^h d_{\tau} D_T^h - U_{t_L}^h d_{\tau} D_T^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} - U_{t_L}^h \beta d_{\tau} D_U^h \frac{\partial t_U}{\partial D_U^h} \frac{\partial D_U^h}{\partial D_T^h} \frac{dD_T^h}{d\tau} + U_X^h \frac{dG}{d\tau} \right) + (1 - \theta) \ell U_X^{\ell} \frac{dG}{d\tau} \quad \text{B.8}$$

Differentiating (13) with respect to τ and solving for $\frac{dG}{d\tau}$, gives:

$$\frac{dG}{d\tau} = \frac{h}{N} \left[\tau_w W \mathcal{E}^h \left(\frac{dD_T^h}{d\tau} + \frac{\partial D_U^h}{\partial D_T^h} \frac{dD_T^h}{d\tau} \right) + \tau_g k_g g d_{\tau} \left(\frac{dD_T^h}{d\tau} + \beta \frac{\partial D_U^h}{\partial D_T^h} \frac{dD_T^h}{d\tau} \right) + d_{\tau} D_T^h + \tau d_{\tau} \frac{dD_T^h}{d\tau} \right] \quad \text{B.9}$$

Inserting B.9 into B.8, dividing by U_X^h , setting $\Delta D_{TU}^h = \partial D_U^h / \partial D_T^h$, and using α we get:

$$\begin{aligned} \frac{d\mathbb{W}/d\tau}{U_X^h} &= \left(\theta \frac{h}{N} + (1 - \theta) \frac{\ell}{N} \alpha \right) \left(\tau + \tau_g k_g g (1 + \beta \Delta D_{TU}^h) + \tau_w \frac{W \mathcal{E}^h}{d_{\tau}} (1 + \Delta D_{TU}^h) \right) \frac{dD_T^h}{d\tau} + \left(\theta \frac{h}{N} - \theta + (1 - \theta) \frac{\ell}{N} \alpha \right) D_T^h \\ &\quad - \theta \frac{U_{t_L}^h}{U_X^h} \left(D_T^h \frac{\partial t_{\tau}}{\partial D_T^h} + \beta D_U^h \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \right) \frac{dD_T^h}{d\tau} \end{aligned}$$

Setting $\frac{d\mathbb{W}/d\tau}{U_X^h} = 0$ and using $\epsilon_{D_T^h}^{\tau}$ we get the optimal toll in (14).

Revenues used to cut labor taxes:

Differentiating the social welfare function with respect to τ , when $d\tau$ affects $d\tau_w$, gives:

$$\frac{d\mathbb{W}}{d\tau} = \theta h \left(v_{\tau}^h + v_{\tau}^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} + v_{t_U}^h \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \frac{dD_T^h}{d\tau} + v_{\tau_w}^h \frac{d\tau_w}{d\tau} \right) + (1 - \theta) \ell v_{\tau_w}^{\ell} \frac{d\tau_w}{d\tau} \quad \text{B.10}$$

Replacing A.2 into B.10 we have:

$$\begin{aligned} \frac{d\mathbb{W}}{d\tau} &= \theta h \left(-U_X^h d_{\tau} D_T^h - U_{t_L}^h d_{\tau} D_T^h \frac{\partial t_{\tau}}{\partial D_T^h} \frac{dD_T^h}{d\tau} - U_{t_L}^h \beta d_{\tau} D_U^h \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \frac{dD_T^h}{d\tau} - U_X^h \mathcal{E}^h W (D_T^h + D_U^h) \frac{d\tau_w}{d\tau} \right) \\ &\quad - (1 - \theta) \ell U_X^{\ell} \mathcal{E}^{\ell} W D_U^{\ell} \frac{d\tau_w}{d\tau} \end{aligned} \quad \text{B.11}$$

Differentiating (13) with respect to τ and solving for $W \frac{d\tau_w}{d\tau}$ gives:

$$W \frac{d\tau_w}{d\tau} = \frac{-h d_{\tau}}{h \mathcal{E}^h (D_T^h + D_U^h) + \ell \mathcal{E}^{\ell} D_U^{\ell}} \left[\tau_w \frac{W \mathcal{E}^h}{d_{\tau}} \left(\frac{dD_T^h}{d\tau} + \Delta D_{TU}^h \frac{dD_T^h}{d\tau} \right) + \tau_g k_g g \left(\frac{dD_T^h}{d\tau} + \beta \Delta D_{TU}^h \frac{dD_T^h}{d\tau} \right) + D_T^h + \tau \frac{dD_T^h}{d\tau} \right] \quad \text{B.12}$$

Inserting B.12 into B.11, dividing by U_X^h , using α and $\epsilon_{D_T^h}^{\tau}$, and solving for τ we get (15).

B.3 High-income households commuting by T , and low-income households commuting by T and U

Revenues used to make lump-sum transfers to the individuals:

Differentiating the social welfare function with respect to τ (when $d\tau$ affects dG) and replacing A.2 gives:

$$\begin{aligned} \frac{dW}{d\tau} = & \theta h \left(-U_X^h d_\tau D_T^h - U_{t_L}^h d_\tau D_T^h \frac{\partial t_\tau}{\partial D_T^h} \frac{dD_T^h}{d\tau} + U_X^h \frac{dG}{d\tau} \right) \\ & + (1 - \theta) \ell \left(-U_X^\ell d_\tau D_T^\ell - U_{t_L}^\ell d_\tau D_T^\ell \frac{\partial t_\tau}{\partial D_T^\ell} \frac{dD_T^\ell}{d\tau} - U_{t_U}^\ell \beta d_\tau D_U^\ell \frac{\partial t_U}{\partial D_U^\ell} \frac{\partial D_U^\ell}{\partial D_T^\ell} \frac{dD_T^\ell}{d\tau} + U_X^\ell \frac{dG}{d\tau} \right) \end{aligned} \quad \text{B.13}$$

Differentiating (16) with respect to τ and solving for $\frac{dG}{d\tau}$ gives:

$$\begin{aligned} \frac{dG}{d\tau} = & \frac{1}{N} \left\{ \tau_w W \left[h \varepsilon^h \frac{dD_T^h}{d\tau} + \ell \varepsilon^\ell \left(1 + \frac{\partial D_U^\ell}{\partial D_T^\ell} \right) \frac{dD_T^\ell}{d\tau} \right] + \tau_g k_g g d_\tau \left[h \frac{dD_T^h}{d\tau} + \ell \left(1 + \beta \frac{\partial D_U^\ell}{\partial D_T^\ell} \right) \frac{dD_T^\ell}{d\tau} \right] + d_\tau [h D_T^h + \ell D_T^\ell] \right. \\ & \left. + \tau d_\tau \left[h \frac{dD_T^h}{d\tau} + \ell \frac{dD_T^\ell}{d\tau} \right] \right\} \end{aligned} \quad \text{B.14}$$

Inserting B.14 into B.13, dividing by U_X^h , using α and setting $\Delta D_{TU}^\ell = \partial D_U^\ell / \partial D_T^\ell$ we get:

$$\begin{aligned} \frac{dW/d\tau}{U_X^h} = & (\ell D_T^\ell + h D_T^h) \left[\theta + \frac{\ell}{N} (\alpha(1 - \theta) - \theta) \right] - \theta h D_T^h - (1 - \theta) \ell D_T^\ell \\ & + \left[\theta + \frac{\ell}{N} (\alpha(1 - \theta) - \theta) \right] \left\{ \tau_w \frac{W}{d_\tau} \left[h \varepsilon^h \frac{dD_T^h}{d\tau} + \ell \varepsilon^\ell (1 + \Delta D_{TU}^\ell) \frac{dD_T^\ell}{d\tau} \right] + \tau_g k_g g \left[h \frac{dD_T^h}{d\tau} + \ell (1 + \beta \Delta D_{TU}^\ell) \frac{dD_T^\ell}{d\tau} \right] \right. \\ & \left. + \tau \left[h \frac{dD_T^h}{d\tau} + \ell \frac{dD_T^\ell}{d\tau} \right] \right\} - \theta h \frac{U_{t_L}^h}{U_X^h} D_T^h \frac{\partial t_\tau}{\partial D_T^h} \frac{dD_T^h}{d\tau} - (1 - \theta) \ell \frac{U_{t_L}^\ell}{U_X^h} \left(D_T^\ell \frac{\partial t_\tau}{\partial D_T^\ell} + D_U^\ell \beta \frac{\partial t_U}{\partial D_U^\ell} \Delta D_{TU}^\ell \right) \frac{dD_T^\ell}{d\tau} \end{aligned} \quad \text{B.15}$$

Setting B.15 equal to zero, using $\varepsilon_{D_T^h}^\tau = \frac{dD_T^h}{d\tau} \frac{\tau}{D_T^h}$ and $\varepsilon_{D_T^\ell}^\tau = \frac{dD_T^\ell}{d\tau} \frac{\tau}{D_T^\ell}$, we get the optimal toll in (17).

B.4 High-income households commuting by T and U , and low-income households commuting by T and U

Revenues used to make lump-sum transfers to the individuals:

Following the same procedure, we obtain the two basic equations to get (19):

$$\begin{aligned} \frac{dW}{d\tau} = & \theta h \left(-U_X^h d_\tau D_T^h - U_{t_L}^h d_\tau D_T^h \frac{\partial t_\tau}{\partial D_T^h} \frac{dD_T^h}{d\tau} - U_{t_U}^h d_\tau D_U^h \frac{\partial t_U}{\partial D_U^h} \Delta D_{TU}^h \frac{dD_T^h}{d\tau} + U_X^h \frac{dG}{d\tau} \right) \\ & + (1 - \theta) \ell \left(-U_X^\ell d_\tau D_T^\ell - U_{t_L}^\ell d_\tau D_T^\ell \frac{\partial t_\tau}{\partial D_T^\ell} \frac{dD_T^\ell}{d\tau} - U_{t_U}^\ell \beta d_\tau D_U^\ell \frac{\partial t_U}{\partial D_U^\ell} \Delta D_{TU}^\ell \frac{dD_T^\ell}{d\tau} + U_X^\ell \frac{dG}{d\tau} \right) \end{aligned} \quad \text{B.16}$$

$$\begin{aligned} \frac{dG}{d\tau} = & \frac{1}{N} \left\{ \tau_w W \left[h \varepsilon^h (1 + \Delta D_{TU}^h) \frac{dD_T^h}{d\tau} + \ell \varepsilon^\ell (1 + \Delta D_{TU}^\ell) \frac{dD_T^\ell}{d\tau} \right] + \tau_g k_g g d_\tau \left[h (1 + \beta \Delta D_{TU}^h) \frac{dD_T^h}{d\tau} + \ell (1 + \beta \Delta D_{TU}^\ell) \frac{dD_T^\ell}{d\tau} \right] \right. \\ & \left. + d_\tau [h D_T^h + \ell D_T^\ell] + \tau d_\tau \left[h \frac{dD_T^h}{d\tau} + \ell \frac{dD_T^\ell}{d\tau} \right] \right\} \end{aligned} \quad \text{B.17}$$

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