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Public transport subsidies and the marginal cost of public funds: An interpretative review

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ABSTRACT

This paper examines the rationale for public transport subsidies when revenues are raised through distortionary taxation, captured by the Marginal Cost of Public Funds (MCF). While first-best arguments such as scale economies and the Mohring effect justify subsidies, their relevance in second-best settings depends on the fiscal cost of raising funds. We compare general and partial equilibrium approaches, highlighting their advantages and limitations in incorporating key efficiency arguments, externalities, and labor market effects. Building on this, we develop a unified analytical framework that derives second-best pricing rules for public transport and assesses the welfare implications of subsidies under different conditions of scale economies, congestion, and labor taxation. Our framework clarifies when subsidies increase welfare and when the fiscal cost of financing them outweighs efficiency gains, providing both theoretical insights and policy-relevant guidance.

1. Introduction

Public transport subsidies represent one of the largest government expenditures in urban areas, yet their economic justification remains debated once the distortionary cost of raising public funds is considered. Subsidies cover about 64% of operating costs in the United States and range from 20% to 80% in Europe and Latin America (EMTA, 2020; FTA, 2019; Rivas et al., 2020). They are typically justified by price distortions, car externalities, and equity concerns (Basso and Silva, 2014; Matas et al., 2020; Adler et al., 2021). From the standpoint of efficiency, however, two arguments dominate: (i) scale economies, where average costs fall as demand rises, and (ii) the Mohring effect, where higher demand justifies greater service frequency, lowering waiting times for all users (Mohring, 1972; Jansson, 1980, 1984).[1] Both imply that first-best fares lie below average cost, requiring subsidies.

At the same time, subsidies must be financed through distortionary taxation, raising the Marginal Cost of Public Funds (MCF). When MCF is higher than 1, each additional unit of revenue imposes efficiency losses in the labor or consumption markets, pushing optimal fares upward (Laffont and Tirole, 1993). These opposing forces are summarized in Table 1, contrasting the main efficiency arguments for and against public transport subsidization.

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[1] The origin of the term “Mohring effect” is the article “Optimization and Scale Economies in Urban Bus Transportation” published by Herbert Mohring (1928–2012) in the *American Economic Review* in 1972. See Silva (2021) for a discussion about the effect.

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Table 1
Main arguments for and against public transport subsidies.

Argument	Mechanism	Implication for fares
Scale economies	Larger vehicle capacity, denser networks, or adoption of high fixed-cost technologies reduce average costs as demand grows.	First-best fares fall below average cost, requiring subsidies.
Mohring effect	Higher demand justify a higher service frequency, thereby lowering user waiting times.	Optimal fares below average cost; subsidies internalize this effect, analogous to a positive externality.
Car negative externalities relief	Modal shift from cars reduces road congestion, pollution, crashes and other negative externalities.	Lower fares can increase welfare if car travel is underpriced.
Agglomeration and density economies	Increased labor supply increases productivity through positive externalities in matching, sharing and learning in the labor market	Lower fares induce more commuting, which generates a positive productivity externality, captured by increased wages.
Equity	Lower-income groups disproportionately use public transport.	Subsidies may improve distributional outcomes.
Marginal Cost of Public Funds (MCF > 1)	Raising revenue through distortionary taxation reduces labor supply and efficiency.	Optimal fares increase relative to marginal cost; subsidies may lower welfare.
Capacity limit	When capacity cannot be increased, the Mohring effect is blocked and scale economies are lost.	Fare increases to ration demand.
Negative externalities	Crowding, Bus stop congestion.	Pricing externalities increases fares.

Despite the importance of this trade-off, the literature has developed along two separate strands. General equilibrium (GE) models capture interactions with labor supply, taxes, and congestion pricing, but usually ignore the Mohring effect and scale economies. By contrast, partial equilibrium (PE) models incorporate these transport-specific mechanisms but abstract from fiscal distortions and labor markets. Each approach, therefore, provides only a partial view.

In this paper, we offer a general framework to investigate the relationship between the welfare-maximizing pricing of public transport and the MCF. Throughout the development of this framework, we review relevant literature to identify the conditions under which the model is applicable and to quantify its components. We mainly focus our analysis on a single-line type of model; i.e., we ignore network effects and other spatial features. This allows for a clean comparison between General and Partial equilibrium models and estimations. We begin by examining the MCF, the two mainstream approaches to model it, the available empirical estimations, and the implications for transport policy.

We then develop a GE framework that integrates the main efficiency arguments for public transport subsidies together with the MCF. We derive analytical pricing rules for public transport within a setting where fares are optimized jointly with labor taxation. The results show that while efficiency arguments for subsidization may lower fares below average cost pricing, the extent of subsidization ultimately depends on the fiscal cost of raising public funds. As public transport revenues can help mitigate distortions in the markets where the government collects taxes, it works as an opposing force.

We then address a closely related question: whether a revenue-neutral tax reform that raises labor taxes to reduce public transport fares improves welfare. We show that the social cost of raising labor taxation must be weighed against three forces favoring subsidies: the efficiency arguments stemming from the Mohring effect and increasing returns to scale, the congestion relief from modal shifts to public transport, and the increase in labor supply resulting from lower commuting costs. A drawback of the general equilibrium models is that they typically do not allow for a detailed modeling of externalities. As the focus is on broader questions, such as determining the gasoline tax at the national level, public transport waiting times, in-vehicle crowding, and network design, among others, are neglected. Yet, these are important determinants of welfare-maximizing fares.

We continue developing a PE model that allows for a detailed modeling of the phenomena mentioned above. We derive an expression for the second-best fare and subsidy that relates the MCF to the degree of scale economies of public transport, the Mohring effect, and urban transport externalities. We illustrate our model's main implications for policy with a twofold methodology. First, we provide a theoretical analysis without making strong assumptions regarding functional forms. When the MCF is significant, the social cost of raising distortionary taxes may be greater than the benefits of subsidizing it (e.g., due to economies of scale), and public transport subsidization may decrease welfare. While these results are intuitive, we are the first to provide a formal theoretical analysis consistent with the public transport literature.[2] We also consider the relevant case when car travel is available as an underpriced imperfect substitute.

The second part of the methodology, within the PE framework, is to review the literature that assesses each of the determinants of the fare to provide a general picture of when subsidies are desirable. We also develop an empirical application by extending the model proposed by Basso and Silva (2014) to examine the conditions under which subsidies are justified from a welfare perspective. The setting is based on a representative corridor, where individuals are located and choose to travel or not, between public transport and car, if they do, and the time of day (peak or off-peak). The public transport provision is modeled with the choice of bus stop spacing, frequency, and vehicle size. There is congestion on the roads, between buses and cars, and on bus stops (crowding). Through

[2] In a simultaneous but independent work, Jara-Díaz et al. (2023) discuss the design, scale, and optimal pricing of public transportation. They also discuss the role of the marginal cost of public funds in the design and subsidy, but with a subtly different approach. Our work considers welfare maximization instead of minimizing the Value of the Resources Consumed (VRC).

all these components, the cost function allows for increasing and decreasing returns to scale. By analyzing different conditions, we clarify the magnitude of the benefits of subsidizing compared to the associated costs, negative externalities, and the impact of the MCF.

This paper contributes to two strands of the literature. First, it advances the GE analysis of transport pricing under distortionary taxation (see, e.g., Mayeres, 2000; Mayeres and Proost, 2001; Parry and Bento, 2001; Tirachini and Proost, 2021; Tikoudis and Van Dender, 2021). As most studies focus on congestion tolls (see, e.g., Mayeres and Proost, 1997; van Dender, 2003; De Borger, 2009; De Borger and Wuyts, 2011; Calthrop et al., 2007; Rizzi, 2014; Tikoudis et al., 2018; Tikoudis, 2020), this paper bridges a crucial gap by developing the first, to our knowledge, general equilibrium framework that integrates the Mohring effect—a primary justification for subsidies—with a rigorous treatment of distortionary taxation, thereby providing a more complete second-best analysis.

Our paper is closely related to Tikoudis et al. (2015), who relaxed the assumption of constant returns to scale in public transport provision. They showed that the welfare gains from using congestion toll revenues to fund transit depend on whether the initial fare is above or below the first-best, marginal-cost level. However, their framework is limited in two key ways. First, it assumes subsidies are financed by congestion tolls, which is rarely the case in practice, rather than by more common distortionary taxes. Second, their model does not endogenously optimize service frequency and thus omits the Mohring effect. These omissions reveal a crucial gap in the literature: the lack of analysis of the interaction between the Mohring effect and second-best pricing in an economy with distortionary taxation, which this paper aims to fill.

Second, it contributes to the debate on public transport subsidies by clarifying the conditions under which they remain welfare-improving once tax distortions are considered. Earlier studies highlight scale economies and the Mohring effect as efficiency arguments for subsidies (see, e.g., Hörcher and Tirachini, 2021; Börjesson et al., 2017; Parry and Small, 2009; Basso and Silva, 2014; Basso et al., 2011; Jara-Díaz and Gschwender, 2003, 2009; Jara-Díaz et al., 2023). More recent studies have analyzed the impacts and desirability of introducing fare-free public transport (e.g., Bull et al., 2021; Lehe and Pandey, 2025) and the role of stop spacing and optimal frequencies in the debate (e.g., Fielbaum, 2024). However, their interaction with the MCF has seldom been analyzed systematically. We develop a unified framework that weighs the efficiency gains from scale economies and frequency optimization against the fiscal costs of distortionary taxation.

Our paper also contributes to the theoretical literature that employs PE models to show that the MCF raises the welfare-maximizing public transport fare (Batarce and Galilea, 2018; Sun et al., 2016; Palma et al., 2017; Zhang et al., 2018; Jørgensen and Pedersen, 2004) and to the literature that studies the impact on the welfare-maximizing frequency (Ramos and Silva, 2023; Hörcher et al., 2020; Zhang et al., 2020). We also contribute to the literature that uses numerical simulations to assess the effect of the MCF on transport prices (Proost et al., 2002; Asplund and Pyddoke, 2020). For example, in Brussels, an MCF of 1.066 raises the optimal bus and metro (peak) fares by 130% and 455%, respectively, while an MCF of 1.035 increases them by 44% and 180% in London (Proost and van Dender, 2008). Similarly, in Karlstad and Stockholm, Sweden, an MCF of 1.2 raises the optimal bus fares by 500% and 183%, respectively (Börjesson et al., 2019).

Our paper also relates to the literature that empirically assesses the Mohring Effect. Most studies estimate an aggregation of all the effects that could justify using public funds to cover operating costs (see, e.g., Börjesson et al., 2017). One study that measured the specific impact of the Mohring Effect was conducted in Washington, Los Angeles, and London by Parry and Small (2009). They report that the marginal welfare gains of increasing the subsidy due to the Mohring effect appear significant. For off-peak services, the proportion of the optimal subsidy explained by the Mohring effect is about 60%. For peak services, this proportion ranges from 15% to 46%. We add to this literature by deriving general analytical expressions and assessing the impact of the Mohring Effect isolated from other forces.

The paper is organized as follows. Section 2 introduces the two accepted definitions of the MCF and its relation with the optimal provision of public goods such as public transport. Section 3 proposes a GE model to study public transport pricing and reviews the relevant literature. Section 4 proposes the PE model and revision, while Section 5 concludes by discussing the models' capability in incorporating additional components and its potential in addressing unanswered questions.

2. The marginal cost of public funds

Taxes affect resource allocation within an economy by altering individual decisions regarding consumption, labor supply, and investment. The degree of this distortion varies depending on the type of tax. For instance, lump-sum taxes, which are fixed and are not directly influenced by taxpayer behavior, and taxes on goods with inelastic demand do not introduce distortions. Conversely, taxes on wages, consumption, and investments can substantially distort decisions related to labor supply, personal savings, and investment.

As first argued by Pigou (1920), the distortionary cost of taxation plays a fundamental role in assessing the benefits and costs of public expenditures:

> Where there is indirect damage, it ought to be added to the direct loss of satisfaction involved in the withdrawal of the marginal unit of resources by taxation before this is balanced against the satisfaction yielded by the marginal expenditure. It follows that, in general, expenditure ought not to be carried out so far as to make the real yield of the marginal unit of resources expended by the government equal to the real yields of the last unit left in the hands of the representative citizen (Pigou, 1920, p. 34).

This concept was further refined by Stiglitz and Dasgupta (1971) and Atkinson and Stern (1974), who adapted Samuelson's rule (Samuelson, 1954) to account for the impact of tax distortions on public goods provision. According to the original Samuelson rule, the government should provide public goods until the marginal benefits to consumers equal the marginal production costs. However, when public goods are financed through distortionary taxes, the associated costs increase by a factor equal to the marginal cost of public funds (MCF) (Ballard and Fullerton, 1992). Therefore, the MCF measures the societal loss incurred from raising additional revenue through taxation to fund government spending (Gahvari, 2006). Consequently, if the MCF exceeds one, the optimal provision of public goods should be lower than what the standard Samuelson rule suggests.

Following this modification of the Samuelson rule for public goods provision, many cost-benefit analyses now incorporate an MCF greater than one, multiplying the net cost of public projects. This adjustment accounts for the cost of raising public revenues, making it less likely for public projects to meet cost-benefit criteria. This principle is fundamental across various economic disciplines. For example, in the procurement and regulation literature, an MCF exceeding one increases the importance of rent extraction over providing incentives to reduce costs (Laffont and Tirole, 1993; Gagnepain et al., 2013; Gagnepain and Ivaldi, 2002). Similarly, in transport pricing, incorporating an MCF greater than one in partial equilibrium (PE) models assessing the economic efficiency of transport policies results in welfare-maximizing transport fares that exceed the standard marginal-cost pricing (see, e.g., Sun et al., 2016; Hörcher et al., 2020; Zhang et al., 2020; Börjesson et al., 2019; Asplund and Pyddoke, 2020).

Despite the significant influence of the MCF on cost-benefit analysis and public policy evaluation, considerable debate persists in the economic literature regarding whether the MCF should be less, greater or equal to one (see, e.g., Gahvari, 2006; Jones, 2005; Kreiner and Verdelin, 2012; Dahlby, 2008; Auerbach and Hines, 2002). This controversy primarily arises from the absence of a universally accepted definition of the MCF. Two main theoretical approaches dominate the literature: the Pigou-Harberger-Browning approach and the Atkinson-Stern-Ballard-Fullerton approach. We begin our review by differentiating the two methods and discussing their implications.

2.1. The Pigou-Harberger-Browning approach

The Pigou-Harberger-Browning approach (Pigou, 1920; Harberger, 1964; Browning, 1976, 1987) defines the MCF as one plus the marginal excess burden of taxation, often referred to as the shadow cost of public funds (usually denoted by λ). The excess burden, also known as the deadweight loss, represents the difference between the welfare loss caused by taxation and the revenue collected by the government. Accordingly, the marginal excess burden quantifies the rate at which this excess burden increases with each additional unit of tax revenue collected (Dahlby, 2008). In simpler terms, it reflects the marginal welfare loss associated with raising additional government revenues.

Due to its simplicity and straightforward interpretation, the Pigou-Harberger-Browning definition of the MCF is widely applied in the economic literature, particularly in PE models. When public projects are financed through distortionary taxes, the marginal excess burden is positive, as raising public revenues increases the deadweight losses from taxation. Consequently, the MCF exceeds one, implying that if the government allocates \$1 to finance a public project, the societal cost amounts to \$$(1 + \lambda)$. Conversely, when government expenditures are funded by non-distortionary taxes (i.e., $\lambda = 0$), the MCF equals one, meaning there is no additional cost to society. However, as Dahlby observes:

> Browning and others who followed his tradition did not develop their measures as part of an optimality condition or a condition for welfare improvement. They proposed a particular measure and left undefined how it would be used for tax policy evaluation or public expenditure (Dahlby, 2008, p. 44).

2.2. The Atkinson-Stern-Ballard-Fullerton approach

The Atkinson-Stern-Ballard-Fullerton approach (Atkinson and Stern, 1974; Ballard and Fullerton, 1992) is currently considered the standard approach in general equilibrium (GE) models. It defines the MCF as the ratio of the marginal value of income in the public sector to that in the private sector. Essentially, the MCF is the ratio of the marginal societal cost of raising \$1 in tax revenues -the value of the Lagrange multiplier on the government budget constraint, also known as the shadow price of public funds- to the private cost of having \$1 less to spend, represented by the marginal utility of income.

Nevertheless, while this definition is widely used in economic literature, it exhibits undesirable properties that complicate its application in social cost-benefit analysis (Bos et al., 2019; Jacobs, 2018). First, the MCF for lump-sum taxes does not generally equal one. Second, estimates of the MCF for distortionary taxes can, counterintuitively, be lower than one. Lastly, the MCF is sensitive to tax normalization, which depends on the choice of the untaxed *numéraire* good in the modeling framework.

For example, in a context where the government collects lump-sum, income, and consumption taxes, Jacobs (2018) demonstrates that under the standard MCF definition, with the consumption tax normalized to zero, the MCF for lump-sum taxes can be less than one if a positive income tax exists and leisure is a normal good. Additionally, the MCF for income taxes is not directly linked to the marginal excess burden and can also be less than one if the labor supply curve bends backward. However, these findings do not hold when the income tax is normalized to zero instead of the consumption tax.

2.3. Equity concerns

The two approaches mentioned above assume homogeneous agents, thereby overlooking a vital reason why distortionary taxes, such as those on wages and investment, are often preferred over less distortionary alternatives: their distributional benefits (Jacobs, 2018). Taxes with minimal distortionary effects usually place a disproportionate burden on lower-income households. To address this, most significant taxes are levied on income, wealth, or consumption, which, although more distortionary, help reduce inequality. Therefore, in the context of optimal taxation and the assessment of the MCF, distortionary taxation should be considered a necessary cost for achieving distributional objectives aimed at reducing inequality (Bos et al., 2019).

The trade-off between equity and efficiency in taxation has been extensively analyzed in the MCF literature using the Atkinson-Stern-Ballard-Fullerton approach (Sandmo, 1998; Slemrod and Yitzhaki, 2001; Boadway, 1976; Kaplow, 1996, 2004; Jacobs and de Mooij, 2015). It is now widely accepted that the MCF must also account for the social benefits of redistribution. For example, Jacobs (2018) demonstrates that optimal public good provision follows a modified version of Samuelson's rule, which accounts for the distributional characteristics of public goods and their impact on marginal social benefits.[3]

This adjustment implies that if poorer individuals derive greater utility from a public good than wealthier individuals, its provision should be increased. This argument is frequently cited to support public expenditures on policies such as public transport subsidization. However, the cost component of Jacobs' rule does not explicitly include a measure of the MCF when taxes are optimally set. In such cases, tax distortions are offset by the distributional gains from taxation, effectively making the MCF equal to one. In contrast, in scenarios where the tax system is suboptimal, the MCF may be either less than or greater than one, depending on whether the distributional benefits outweigh the marginal excess burden.

2.4. Estimating the MCF

Broadly speaking, the MCF seeks to represent the cost of raising additional tax revenue. As summarized by Bastani (2024), it traditionally reflects three key aspects: the deadweight loss of using a distortionary tax instead of a lump-sum tax; the income loss incurred due to increased taxes that makes people poorer; and the impact on individuals of the increased provision of public goods.

The problem with estimating the MCF is that it involves several definitions by the modeler about the economy and the planner's valuation of heterogeneous individuals. Examples include how to incorporate equity considerations (the welfare function), which existing distortionary taxes to model (e.g., income and consumption taxes), the tax reform to raise revenues (e.g., on exports), and how individuals react to changes in taxes.

This broad range of possibilities has led to various interpretations and confusion about how to approach the MCF estimation. It is outside the scope of this paper to provide a comprehensive framework for estimation; however, we suggest approaches to tackle the problem below.

First, a critical distinction in the application of the MCF is the level of government—central versus local—associated with the financing instrument. Since the degree of distortion varies depending on the type of tax, the relevant marginal excess burden or shadow price of public funds must be matched to the specific jurisdiction levying the tax. When modeling a planner who aims to maximize local welfare, the objective function is restricted strictly to the utility of the local constituency. In this context, the standard national MCF estimates may be misleading, as they aggregate welfare losses across the entire economy rather than isolating the impact on the specific sub-national jurisdiction.

Consequently, a local planner should only consider the distortions and benefits that accrue to local residents. This implies that if a local government can finance a public good using a tax instrument that falls partially on non-residents (tax exporting), the perceived MCF for the local planner will be lower than the national MCF, as the external tax burden is treated as a transfer rather than a social cost. Conversely, if the local tax base is highly mobile due to competition with neighboring jurisdictions, the local elasticity of the tax base may exceed the national elasticity, potentially raising the local MCF. Therefore, accurate project evaluation requires that the MCF be endogenous to the specific tax instrument and the jurisdictional scope of the welfare maximization problem.

Regarding the other decisions, we refer the interested reader to:

- Bastani (2024) for a discussion focused on the MCF estimation possibilities.
- Auriol and Warlters (2012) for the calibration of a simple general equilibrium model that handles five tax classes and can be calibrated with national accounts data.
- Kleven and Kreiner (2006) for a detailed analysis of the MCF with a focus on labor supply changes.

We also provide two approximation rules based on a model of labor taxes and labor supply. The first, which is the simplest, is based on a standard static labor supply model, and the exposition closely follows Bastani (2024).

The model considers an economy of n identical, utility-maximizing individuals operating under perfect competition and linear production. Agents choose their labor supply, h, at a given wage, w. When analyzing a small increase in a proportional tax (dt), the behavioral adjustments in labor supply have a negligible impact on individual welfare; therefore, the welfare loss is approximated strictly by the reduction in disposable income ($-wh \cdot dt$). This direct welfare change is then contrasted with the marginal change in government tax revenue ($-\frac{d(twh)}{dt} \cdot dt$). Dividing and rearranging, the MCF can be written as:

$$MCF = \frac{1}{1 + \epsilon_{h,t}} \tag{1}$$

where $\epsilon_{h,t}$ is the uncompensated elasticity of labor supply with respect to the tax t.

[3] Jacobs (2018) defines the MCF as the ratio of the social marginal value of public income to Diamond's (1975) average measure of the social marginal value of private income.

Under these simplifying assumptions, the MCF can be greater or less than one depending on whether the elasticity is negative or positive. In this simple framework, the labor supply distortion is the key consideration. For example, if $\epsilon_{h,t} = -0.2$, the MCF is equal to 1.25.

A more complex model is proposed by Kleven and Kreiner (2006), which incorporates worker heterogeneity and both intensive and extensive labor supply margins. We focus on the simplest version of their model, for tractability purposes, which focuses on the efficiency aspect, assuming that the social value of an extra unit of consumption is uniform across all individuals. The tax reform considered is a proportional tax change for all groups, and the derivation assumes that uncompensated hours-of-work elasticities are zero; however, it does take into account labor participation elasticities. Under these conditions, the MCF can be written as:

$$MCF = \frac{1}{\sum_{i=1}^{I} \left[1 - \frac{a_i+b_i}{1-m_i}\,\eta_i\right] s_i} \tag{2}$$

where m_i is the marginal tax rate, $a_i + b_i$ is the total participation tax rate, η_i the labor participation elasticity, and s_i is group i's share of aggregate labor income.

This approach requires more information or assumptions about the parameters. The marginal tax rate is usually made publicly available by the tax authority, and the share of aggregate labor income for each group, such as deciles, is typically reported in household surveys or global inequality reports. However, obtaining the total tax participation rate and the extensive margin elasticity is more challenging. The OECD, for example, publishes values for the tax participation rate of some countries.[4] Estimations of the extensive margin elasticity can be found in the specialized academic literature.

To illustrate the methodology, we compute the MCF considering two groups broadly based on the figures in Kleven and Kreiner (2006). Group 1 faces a marginal tax rate of $m_1 = 20\%$, has a total tax participation rate $a_1 + b_1 = 0.8$, and the share of the national labor income is $s_1 = 25\%$. Group 2 earns more, the remaining 75%, faces a higher marginal tax rate $m_2 = 40\%$ and a lower total tax participation rate $a_2 + b_2 = 0.7$. In this example, Group 1 can be considered the low-income group, and Group 2, the high-income group. Assuming the elasticities are $\eta_1 = 0.3$ and $\eta_2 = 0.1$, the resulting MCF is:

$$MCF = \frac{1}{\left[1 - \frac{0.8}{1-0.2}\,0.3\right]0.25 + \left[1 - \frac{0.7}{1-0.4}\,0.1\right]0.75} = 1.19 \tag{3}$$

2.5. Empirical estimations

Unfortunately, empirical evidence provides limited guidance regarding the magnitude of the marginal excess burden and the distributional benefits of non-optimal tax systems. First, while estimating the marginal excess burden of taxation is feasible, uncertainties in deadweight loss estimates can be substantial and heavily dependent on specific assumptions (Kleven and Kreiner, 2003). Second, estimating the distributional benefits of taxation involves defining the social value of income redistribution, as it depends on the government's degree of aversion to inequality. Under certain assumptions and methodologies, the distributional benefits and the marginal excess burden of taxation may be approximately equal, leading to an MCF of one. However, under different assumptions, the distributional benefits may exceed or fall short of the marginal excess burden, resulting in an MCF that is either greater or less than one.[5]

We discuss the empirical results here to provide a range of credible values that can be used for urban transportation pricing. Using the standard approach, Jacobs (2015) estimates the marginal excess burden in the Netherlands to be 0.38, but this figure ranges from 0.25 to 0.51 depending on the labor supply elasticity considered. Moreover, when accounting for the distortionary effects of employers' social security contributions, the Dutch deadweight loss estimates more than double to 1.07 (Bos et al., 2019).

Auriol and Warlters (2012) estimate the MCF using the Atkinson-Stern-Ballard-Fullerton approach in 38 African countries. They calibrate a GE model that can consider five major tax classes: taxes on domestic goods, imports, exports, personal income tax, and corporate income. They find that, on average across countries, the MCF associated with a marginal increase in all five tax instruments is 1.21. The minimum is 1.05, the maximum is 1.72, and the standard deviation is 0.13.[6]

Ensor (2016) extends Auriol and Warlters (2012) and estimates, using a calibrated computable general equilibrium model, the MCF for 105 countries. In Table 1, we present the average, minimum, maximum and standard deviation by subgroup and refer the reader to the thesis for more detailed data:

2.6. Implications for modelling transport

In sum, there are two distinct approaches to defining the MCF. On the one hand, the Atkinson-Stern-Ballard-Fullerton approach defines the MCF as the ratio of the marginal value of income in the public sector to the private marginal utility of income. In this

[4] https://www.oecd.org/en/topics/income-support-redistribution-and-work-incentives.html

[5] Furthermore, as Jacobs notes: Any policy analyst claiming that the marginal cost of public funds is necessarily larger than one is merely revealing their political preferences for income redistribution: apparently, the deadweight losses of taxation are always considered to be larger than their perceived benefits of redistribution. (Jacobs, 2018, 908, footnote 29)

[6] For a more comprehensive analysis and review of the literature on general equilibrium models used to compute the MCF, see Lemelin and Savard (2022)

framework, the MCF may be lower, equal to, or greater than one, depending on the specific characteristics of the markets where the government collects revenue and the public goods financed by the public budget. It also depends on whether inequality considerations are incorporated into the analysis. We use this approach in the GE analysis of Section 3.

On the other hand, the Pigou-Harberger-Browning approach equates the MCF to one plus the marginal excess burden of taxation. This approach is typically applied in PE models, where the MCF is unambiguously greater than one if the government relies on distortionary taxes to finance the public budget. This is the approach adopted in this paper for the PE analysis of Section 4.

The available estimations suggest that the value of the MCF ranges from 0.99 to 1.63, with an average of 1.15. Thus, it would be reasonable to require a rate of return of 15% on the public investment needed to subsidize public transportation if no other tax policy is implemented. This 15% social premium on public funds alters the standard welfare assessment for transport subsidies, which often implicitly assumes this premium is zero. The following sections will formally analyze the consequences of this adjustment.

3. A general equilibrium analysis

The welfare case for subsidizing public transport must be evaluated in a second-best setting where revenues are raised through distortionary taxes. In this context, the relevant question is how fares interact with labor supply, congestion, and fiscal costs. The standard framework builds on Ramsey taxation and optimal corrective taxation (Ramsey, 1927; Diamond and Mirrlees, 1971; Sandmo, 1975), extended to environmental and transport externalities (Ng, 1980; Bovenberg and van der Ploeg, 1994; Parry, 1995).

Most of these early works relied on the simplifying assumption that environmental quality affects consumers' utility separately from the consumption of private and public goods in the consumers' utility function. Under this assumption, the environmental pollution affects individual utility but does not alter consumption choices. In other words, the demand for goods is independent of the level of externalities. While analytically convenient, this assumption is less realistic for transport-related externalities. For example, car use depends on travel time, which is directly influenced by road congestion. In this case, a congestion toll increases the price of car travel and produces two effects on demand: a direct impact that reduces car use and a *feedback effect* that captures the indirect impact of reduced congestion, which leads to a secondary increase in car travel. Thus, the net reduction in car demand is smaller than the initial decrease in demand.

The environmental tax model was first extended to include "congestion-type" externalities with *feedback effects* by Mayeres and Proost (1997) and later adapted specifically to congestion pricing by Mayeres (2000), Mayeres and Proost (2001), Parry and Bento (2001), and van Dender (2003). These studies examine two central questions: (i) how to set the combination of labor taxes and congestion tolls that maximizes social welfare while maintaining a balanced government budget (Mayeres and Proost, 1997; van Dender, 2003; Parry and Small, 2005; De Borger, 2009; De Borger and Wuyts, 2011; Diaz and Proost, 2014; Rizzi, 2014), and (ii) whether a revenue-neutral tax reform that raises the congestion toll and reduces labor taxes can generate net welfare gains (Mayeres, 2000; Mayeres and Proost, 2001; Parry and Bento, 2001; Calthrop et al., 2007; Tikoudis et al., 2015, 2018; Tikoudis, 2020, 2023).

GE studies of public transport pricing remain relatively scarce. The few studies addressing this topic rely on four main assumptions (Mayeres, 2000; Mayeres and Proost, 2001; Parry and Bento, 2001; Tirachini and Proost, 2021; Tikoudis, 2023): (i) public transport travel time is either constant or influenced only by congestion arising from interactions with cars or other public transport vehicles (e.g., buses). Thus, the cost faced by public transport users either remains constant or increases with vehicle congestion; (ii) public transport provision operates under constant returns to scale, meaning that operating costs rise proportionally with demand; (iii) crowding externalities within vehicles, stations, and stops are negligible; and (iv) labor productivity is unaffected by public transport provision.

Within this framework, the literature concludes that a revenue-neutral tax reform recycling congestion toll revenues to finance public transport increases welfare only if the benefits from reduced congestion and inequality outweigh the efficiency loss in the labor market caused by the congestion toll. Empirical studies show that this occurs in three cases: (i) when congestion is severe, since a lower public transport fare helps mitigate the externality due to the substitutability between cars and public transport; (ii) when the market share of public transport is high and pre-existing subsidies are low; and (iii) when the government places a strong emphasis on reducing inequality, as public transport users are often low-income individuals. Nevertheless, using congestion toll revenues to subsidize public transport is generally less efficient than allocating them to reduce labor taxes. Moreover, policymakers usually face the problem of setting public transport fares and subsidies, and cannot implement congestion tolls.

A second issue is whether a tax reform that raises labor taxes to lower public transport fares improves welfare. To our knowledge, with the abovementioned limitations, only Mayeres (2000) and Mayeres and Proost (2001) have analyzed this question. Their results show that such a reform does not improve welfare, as the gains from reduced congestion do not offset the welfare losses associated with higher distortionary taxation. While inequality aversion may reduce these losses, it is not enough to make the policy desirable.

Some progress has been made in relaxing these assumptions. Tikoudis et al. (2015) allow for increasing returns to scale, showing that welfare gains from using toll revenues to fund transit depend on whether initial fares are above or below marginal cost. Yet their model still assumes financing through congestion tolls rather than distortionary labor taxes and does not optimize service frequency, thereby excluding the Mohring effect. These omissions leave open the central question summarized in Table 1: how do scale economies and frequency effects interact with fiscal distortions to determine second-best fares?

3.1. Theoretical framework

In this section, we follow Parry and Bento (2001) and van Dender (2003) and propose a GE model to study transport pricing. We begin by presenting the modeling framework, assuming a representative household that chooses between car and public transport for commuting. We then examine two problems: the optimal tax system, including congestion tolls and public transport fares, and whether a revenue-neutral tax reform that increases labor taxes to reduce public transport fares improves welfare. We assume a representative household decides the number of days to work and the mode of transport for commuting. The household's utility function is given by:

$$U = u(H, N) + Q(Y_C, Y_{PT}), \tag{4}$$

where $u(H, N)$ and $Q(Y_C, Y_{PT})$ are quasi-concave and continuous functions. The variable H denotes the aggregate consumption of market goods, and N represents leisure. The variable Y_C refers to the number of days the household commutes to work by car on a congested road, while Y_{PT} denotes the number of days the household commutes by public transport. The function $Q(Y_C, Y_{PT})$ captures the imperfect substitutability between car and public transport commuting.

Households choose the number of fixed-length days to work, denoted by L.[7] We normalize units such that one day of work equals one unit of time. Additionally, since all trips are for labor purposes, commuting is directly complementary to labor supply. Each workday requires one trip, either by car or public transport, hence:

$$L = Y_C + Y_{PT} \tag{5}$$

The household endowment, denoted by $\bar{L}$, represents the total number of days available in a given period (e.g., the number of days in a month). This time is allocated among work, commuting, and leisure activities. Each time the household commutes by car, it incurs a time cost of T_C units. Due to road congestion, travel time T_C increases with car usage. Formally:

$$T_C = T_C(Y_C), \quad T_C'(Y_C) > 0. \tag{6}$$

We assume that public transport congestion and crowding externalities are negligible. Therefore, the public transport travel time $\bar{T}_{PT}$ is assumed to be constant. However, the government optimizes public transport frequency based on the level of demand, Y_{PT}. In particular, we incorporate the *Mohring effect*, which implies that average waiting time T_W decreases with demand (Jara-Díaz and Gschwender, 2003; Jara-Díaz, 2007). Formally,

$$T_W = T_W(Y_{PT}) = T_W(f^*(Y_{PT})), \quad T_W'(Y) = \frac{\partial T_W}{\partial f^*}\frac{\partial f^*}{\partial Y_{PT}} < 0. \tag{7}$$

Cars and public transport operate on separate and independent corridors, implying no interaction between the two modes. As a result, car congestion does not affect public transport travel times, and public transport provision does not influence car congestion. Given the large number of drivers, each household takes car travel time as given and does not internalize its impact on the travel times of others. This generates the standard congestion externality, as car drivers ignore the social costs of car use. Similarly, public transport users do not account for the reduced waiting times their presence generates for others, which is analogous to a positive externality.

Within this framework, the household's time constraint is given by:

$$\bar{L} = N + L + T_C \cdot Y_C + [\bar{T}_{PT} + T_W]Y_{PT}. \tag{8}$$

Firms operate in a competitive market and employ labor to produce consumption goods, denoted by H. We normalize the gross wage and the producer price of consumption goods to one and assume that labor productivity is unaffected by the commuting mode. The government imposes a proportional tax t on labor income and provides a lump-sum transfer, G, to households. It also levies a congestion toll, τ, and a public transport fare, p. Accordingly, the household's budget constraint is:

$$H + \tau \cdot Y_C + p \cdot Y_{PT} = [1 - t]L + G. \tag{9}$$

Households choose leisure, consumption, and the number of days commuting to work by car and public transport to maximize utility, as defined in Eq. (4), subject to the time and budget constraints in Eqs. (8) and (9). The first-order conditions of the household's utility maximization problem yield:

$$1 - t = \frac{\omega}{\sigma}\left[1 + T_C\right] - \frac{\partial Q}{\partial Y_C} \cdot \frac{1}{\sigma} + \tau \tag{10}$$

$$1 - t = \frac{\omega}{\sigma}\left[1 + \bar{T}_{PT} + T_W\right] - \frac{\partial Q}{\partial Y_{PT}} \cdot \frac{1}{\sigma} + p \tag{11}$$

where σ is the marginal utility of income, ω is the marginal utility of time, and ω/σ represents the household's subjective value of time savings. The first-order conditions equate the benefit of working one additional day—the net wage, $[1 - t]$—with its cost. This cost includes the value of time spent commuting and working and the marginal utility and monetary costs associated with commuting by car or public transport.

From the household's first-order conditions, we can derive the Marshallian demand functions for car, $Y_C = Y_C(t, \tau, p, T_C, T_W)$, and public transport, $Y_{PT} = Y_{PT}(t, \tau, p, T_C, T_W)$ and the indirect utility function $V = V(t, \tau, p, T_C, T_W)$. Notice that the transport demand functions depend on travel times, which, in turn, are influenced by the volume of commuting trips in each transport mode. Thus, the model accounts for *feedback effects* in both car and public transport demand.

[7] For simplicity, we do not distinguish the intensive from the extensive margin of labor supply. See Hirte and Tscharaktschiew (2020) for an analysis of how these decisions impact optimal transport pricing.

For example, in the particular case where car and public transport demand are independent, an increase in the congestion toll affects car travel demand as follows:

$$\frac{dY_C}{d\tau} = \frac{\frac{\partial Y_C}{\partial \tau}}{1 - \frac{\partial Y_C}{\partial T_C} T_C'(Y_C)}. \tag{12}$$

The numerator on the right-hand side of Eq. (12) represents the direct effect of the congestion toll on car travel demand. The denominator, on the other hand, captures the positive congestion *feedback effect*, which arises from the reduction in congestion caused by the initial response to the toll. Car travel times decrease as congestion declines, partially offsetting the toll's impact. As a result, the overall reduction in car demand is smaller than what the direct effect alone would imply.

Analogously, an increase in the public transport fare affects public transport demand as follows:

$$\frac{dY_{PT}}{dp} = \frac{\frac{\partial Y_{PT}}{\partial p}}{1 - \frac{\partial Y_{PT}}{\partial T_W} T_W'(Y_{PT})}. \tag{13}$$

The numerator on the right-hand side of Eq. (13) represents the direct effect of the public transport fare on demand. The denominator captures the feedback effect resulting from the Mohring effect. An increase in the fare initially reduces demand through its direct impact. In response, the government lowers the optimal frequency to accommodate the reduced number of users, increasing travel times for all public transport users. This creates a secondary adverse effect that further decreases demand beyond the initial reduction caused by the fare increase.

Finally, the government faces a budget constraint requiring that tax revenues cover the transfer G and the operating cost of public transport, $C(Y_{PT})$:

$$tL + \tau Y_C + pY_{PT} = G + C(Y_{PT}). \tag{14}$$

The function $C(Y_{PT})$ generalizes the concept of operating costs commonly used in the public transport literature (Tirachini and Hensher, 2012; Gómez-Lobo, 2014). It is an increasing function of bus frequency, which rises with demand due to the Mohring effect. Formally:

$$C = C(Y_{PT}) = C(f^*(Y_{PT})), \quad C'(Y_{PT}) = \frac{\partial C}{\partial f^*}\frac{\partial f^*}{\partial Y_{PT}} > 0 \tag{15}$$

The GE framework described above incorporates the main arguments for and against public transport subsidies, as summarized in Table 1, with the exception of equity considerations and negative externalities within public transport. Based on this framework, the following sections address two problems: (i) how to determine the combination of labor taxes, congestion tolls, and public transport fares that maximizes social welfare while maintaining a balanced government budget, and (ii) whether a revenue-neutral tax reform that raises labor taxes to reduce public transport fares improves welfare.

3.2. Optimal tax system

The government's optimization problem is to choose the labor tax t, the congestion toll τ, and the public transport fare p that maximize social welfare $V(\cdot)$, subject to the budget constraint in Eq. (14). Three taxes (t, τ, and p) are applied to labor, car travel, and public transport. However, the labor tax becomes redundant since labor and travel are perfect complements (i.e., $L = Y_C + Y_{PT}$). As a result, only the combined effect of the labor tax and each transport price is relevant. Therefore, we can normalize the labor tax to zero ($t = 0$) without losing generality. The first-order conditions of this problem yield the following pricing rules:

$$\tau = \underbrace{\left[1 - \frac{1}{MCF}\right]\Theta_C}_{\text{Revenue-raising}} + \underbrace{\frac{\Psi_C}{MCF}}_{\substack{\text{Pigouvian}\\ \text{(congestion)}}}, \tag{16}$$

$$p = \underbrace{\left[1 - \frac{1}{MCF}\right]\Theta_{PT}}_{\text{Revenue-raising}} + \underbrace{\frac{M_{PT}}{MCF}}_{\text{Mohring effect}} + C'(Y_{PT}), \tag{17}$$

Where MCF denotes the Atkinson-Stern-Ballard-Fullerton marginal cost of public funds, defined as the ratio of the marginal value of income in the public sector, μ (i.e., the Lagrange multiplier of the government's budget constraint), to the private marginal utility of income, σ, $MCF = \frac{\mu}{\sigma}$, and:

$$\Theta_C = \frac{Y_{PT}\frac{dY_{PT}}{d\tau} - Y_C\frac{dY_{PT}}{dp}}{\frac{dY_C}{d\tau}\frac{dY_{PT}}{dp} - \frac{dY_C}{dp}\frac{dY_{PT}}{d\tau}} > 0, \tag{18}$$

$$\Theta_{PT} = \frac{Y_C \frac{dY_C}{dp} - Y_{PT} \frac{dY_C}{d\tau}}{\frac{dY_C}{d\tau}\frac{dY_{PT}}{dp} - \frac{dY_C}{dp}\frac{dY_{PT}}{d\tau}} > 0, \tag{19}$$

$$\Psi_C = \frac{\omega}{\sigma} Y_C\, T_C'(Y_C) > 0, \qquad M_{PT} = \frac{\omega}{\sigma} Y_{PT} T_{PT}'(Y_{PT}) < 0 \tag{20}$$

3.2.1. Second-best congestion toll

The second-best congestion toll in Eq. (16) follows the well-known *additivity property* (Sandmo, 1975; Bovenberg and van der Ploeg, 1994; Bovenberg and Goulder, 1996). This property states that the tax on the good causing the externality is a weighted sum of two components: a *revenue-raising* component, and the *pigouvian*, or *externality-correction* component.

The first component is a *revenue-raising* term that follows a Ramsey pricing logic, which seeks to raise revenue at minimal cost to society, thereby providing the least distortionary way of financing public expenditures (Atkinson and Stiglitz, 2015). In essence, the *revenue-raising* term for the congestion toll captures not only the revenue impact from a change in the road toll on its own demand but also the cross-revenue impact from the induced shift in demand for public transport through Θ_C. It is analogous to the inverse of the elasticity in the simplest pricing problem of a single good, and is weighted by $[1 - 1/MCF]$. The interpretation of the *revenue-raising* component, together with the role of the congestion *feedback effect*, becomes clearer in the case where the transport demand functions are independent ($dY_C/dp = dY_{PT}/d\tau = 0$). In this scenario, the optimal congestion toll simplifies to:

$$\tau = \left[1 - \frac{1}{MCF}\right] \underbrace{\left[\frac{Y_C}{-\partial Y_C/\partial \tau}\right]}_{\text{Direct effect}} \underbrace{\left[1 - \frac{\partial Y_C}{\partial T_C} T_C'(Y_C)\right]}_{\substack{\text{Feedback effect}\\ \text{(congestion)}}} + \underbrace{\frac{\Psi_C}{MCF}}_{\substack{\text{Pigouvian}\\ \text{(congestion)}}} . \tag{21}$$

Notice that Θ_C is decomposed into two factors. The First reflects the direct effect of the congestion toll on car travel demand and follows the well-known inverse elasticity rule, where the tax rate is inversely proportional to the price elasticity of demand. The second term captures the positive congestion *feedback effect*, which arises from the reduction in congestion resulting from the initial toll response. As congestion decreases, the demand reduction experienced by households is less than what would result from the direct effect alone. The government can raise additional revenue by setting a higher congestion toll. Thus, the *feedback effect* increases the optimal toll on congestion (i.e., $1 - [\partial Y_C/\partial T_C]T_C'(Y_C) > 1$).

The other component of the congestion toll in Eq. (21) is the *Pigouvian*, or *externality-correction*, term. It reflects the marginal external congestion cost, Ψ_C, weighted by $[1/MCF]$. This adjustment accounts for the trade-off between the social benefits of reducing road congestion and the adverse effects on the labor market from higher commuting costs, as captured by the MCF (Bovenberg and Goulder, 2002). Hence, when the MCF exceeds one, the *externality-correction* component lies below the Pigouvian level, since the congestion toll both mitigates congestion and exacerbates pre-existing labor tax distortions.

Notice that if the marginal external cost is zero, the road toll simplifies to the standard Ramsey tax rule, represented solely by the *revenue-raising* component. In other words, in the absence of congestion, the road toll serves only to raise revenue at the lowest possible social cost.

Eq. (21) illustrates the two objectives of the congestion toll: to raise revenue with a minimum of distortionary losses and to correct the market failure produced by road congestion. The MCF assigns weights to these two goals. If it equals one, the government can collect revenues through non-distortionary taxes, which is more efficient than raising revenues via congestion tolls. In this case, the weight of the *revenue-raising* component is zero, while the weight of the *Pigouvian* component is one. Thus, the optimal congestion toll equals the marginal external cost, which is the first-best or Pigouvian level. This occurs because, in this case, increasing congestion toll revenues does not yield any additional social benefits or costs beyond reducing the congestion externality.

If the MCF is greater than one, the *revenue-raising* component is added to the toll with a weight that increases with the MCF. At the same time, because the toll raises commuting costs, a higher MCF lowers the weight of the *Pigouvian* component. Thus, when the MCF exceeds one, the toll is shaped by two opposing forces: the *revenue-raising* term pushes it upward, while the congestion-relief term becomes relatively less important. Whether the resulting toll lies above or below the first-best level depends on the severity of congestion, the extent of pre-existing tax distortions, and the sensitivity of labor supply to commuting costs.

The intuition behind the congestion toll in the more general case, where car and public transport are imperfect substitutes, is similar. The key difference lies in Θ_C, which also reflects that raising the congestion toll increases public transport demand and, consequently, public transport revenues. In addition, Θ_C incorporates the *feedback effect* on car demand and a cross-feedback effect on public transport through the Mohring effect, as higher demand increases frequency and shortens travel times.

Whether the optimal congestion toll equals, exceeds, or falls below the Pigouvian level depends on the balance between these objectives. This is an empirical question, as it depends on the complex interactions between road usage, the distortions in the markets where the government collects taxes, and the prevailing level of road congestion.

For example, Mayeres and Proost (1997) compute the second-best tax system using a simple Applied General Equilibrium (AGE) model with heterogeneous households. Their results show that the *externality-correction* component of the optimal congestion toll outweighs the revenue-raising component, resulting in considerable reductions in congestion. However, the second-best congestion toll remains below the Pigouvian level because the MCF exceeds one.

In contrast, van Dender (2003) simplifies the analysis by assuming homogeneous households to examine the second-best congestion toll for commuting and non-commuting trips. In general, the toll on non-commuting trips is higher than that on commuting trips because the Ramsey component of the commuting toll is inversely related to the labor supply elasticity, reflecting the reduction in labor supply caused by an increase in the commuting toll. Consequently, the second-best toll for non-commuting trips exceeds the marginal external cost, while the commuting toll remains below. When a uniform congestion toll is applied to all trip purposes, it seeks to balance three objectives: reducing the congestion externality, recycling revenues to alleviate labor market distortions, and shifting the tax burden toward non-commuting trips.

The seminal works of Mayeres, Proost, and van Dender have been expanded in various directions. De Borger (2009) and De Borger and Wuyts (2011) investigated the effects of wage bargaining on the second-best congestion toll. They find that wage bargaining can lead to substantially different second-best congestion tolls compared to those in a competitive labor market, with values that may exceed the marginal external cost. Diaz and Proost (2014) analyzed the second-best congestion toll within networks that include untolled alternatives. Their findings indicate that the second-best toll accounts for the impact of congestion externalities in untolled alternatives, ultimately reducing the optimal toll.

Parry and Small (2005) examined a closely related issue: the second-best gasoline tax that accounts for congestion, road accidents, and air pollution externalities. They demonstrate that this tax follows the *additivity property* of environmental taxation. Moreover, their numerical analysis indicates that the second-best gasoline tax in the United States is more than twice the actual tax. At the same time, it is less than half in the United Kingdom. Consistent with Mayeres and Proost (1997), they find that the Pigouvian component is the main factor determining the second-best fuel tax.

Rizzi (2014) examines the second-best congestion toll and road infrastructure provision, holding other taxes constant. In this context, the optimal congestion toll equals the marginal external cost and fully covers infrastructure costs, consistent with the Mohring-Harwitz (1962) theorem in a general equilibrium model. Moreover, the MCF for the congestion toll is equal to one in this case, as it does not introduce economic distortions. Rizzi also investigates the optimal gasoline tax as a substitute for the congestion toll to finance road infrastructure investment. In this case, the optimal fuel tax exceeds the marginal external cost because it can be partially avoided by shifting to more fuel-efficient vehicles. Additionally, the MCF is less than one, indicating that each dollar invested in road infrastructure generates more welfare than a dollar allocated to private consumption, thus supporting higher investment in road infrastructure.

In sum, research on the optimal tax system with congestion externalities highlights the dual function of congestion tolls as both corrective instruments and revenue sources. The balance between these roles depends on the interaction with labor taxation, household heterogeneity, wage-setting institutions, and the availability of untolled alternatives. Although the Pigouvian component is often dominant, the revenue-raising component and related labor market effects can substantially alter the second-best toll, leading it to diverge from the marginal external cost.

3.2.2. Second-best public transport pricing

Let us return to the second-best public transport fare in Eq. (17). To better understand the pricing rule, we focus first on the specific case where the transport modes are independent. This yields the following pricing rule:

$$p = \left[1 - \frac{1}{MCF}\right] \underbrace{\left[\frac{Y_{PT}}{-\partial Y_{PT}/\partial p}\right]}_{\text{Direct effect}} \underbrace{\left[1 - \frac{\partial Y_{PT}}{\partial T_W} T'_W(Y)\right]}_{\substack{\text{Feedback effect} \\ \text{(Mohring)}}} + \underbrace{\frac{M_{PT}}{MCF}}_{\substack{\text{Mohring} \\ \text{effect}}} + C'(Y_{PT}). \tag{22}$$

The public transport pricing rule in Eq. (22) has a structure similar to that of the congestion toll, consisting of a *revenue-raising* component and a Mohring effect component, which can be interpreted analogous to the *Pigouvian* term in the congestion toll. The distinction lies in the additional term capturing the marginal operating cost, $C'(Y_{PT})$, and that the Mohring effect can be seen as a positive externality (reduced waiting times), which is subtracted from the optimal fare ($M_{PT} < 0$). In contrast to prior GE literature, the *revenue-raising* component in our model is mitigated by a negative feedback effect driven by the Mohring effect, while a direct Mohring term is incorporated into the fare structure, thereby fundamentally strengthening the case for subsidization within a second-best framework.

Consider first the benchmark case where public transport travel time is fixed and the system exhibits constant returns to scale, so that marginal and average operating costs coincide. This is the case analyzed by Mayeres (2000), Mayeres and Proost (2001), Parry and Bento (2001) and Tirachini and Proost (2021). It involves no frequency adjustment; hence, both the Mohring component and the feedback effect vanish ($T'_W = M_{PT} = 0$). The optimal fare equals the *revenue-raising* component without feedback, plus the average operating cost.

In this setting, if the MCF equals one, the optimal fare equals the average operating cost, making the system self-financing. However, if the MCF exceeds one, the optimal fare equals the *revenue-raising* component plus the average cost, thus surpassing the self-financing level.

The intuition is straightforward: when congestion is optimally priced, the only efficiency-based justifications for setting the fare below average cost are increasing returns to scale and the Mohring effect. Setting a fare above the self-financing level without these factors improves welfare as revenues are used to offset distortionary taxes.

Relaxing the constant returns to scale assumption and instead assuming increasing returns to scale, as in Tikoudis et al. (2015), changes the outcome. In this case, the optimal fare may lie above, equal to, or below average cost, depending on the relative magnitudes of the MCF and the degree of scale economies. If the MCF equals one, the optimal fare corresponds to the first-best marginal cost pricing $C'(Y_{PT})$, which is below average cost under increasing returns to scale. In this scenario, public transport requires subsidies.

However, if the MCF exceeds one, the *revenue-raising* component pushes the optimal fare above marginal cost, reducing the need for subsidies. The optimal fare can exceed the self-financing level when the MCF is sufficiently high.

By contrast, the Mohring effect reduces the *revenue-raising* component of the optimal fare by generating a negative *feedback effect* (i.e., $1 - [\partial Y_{PT}/\partial T_W] T'_{PT}(Y_{PT}) < 1$). A fare increase directly lowers demand; in response, the government reduces frequency to match the smaller number of users, which raises waiting times. The resulting demand reduction exceeds that caused by the direct effect alone, resulting in a decrease in the revenues collected. Hence, the revenue-raising component is smaller than without the Mohring effect. The Mohring term further reduces the optimal fare, as each additional user lowers waiting times through frequency adjustments. This effect, however, is moderated by the MCF, which reflects the interaction between public transport fares and the labor market. Together, these two mechanisms reduce the optimal fare to below that obtained without the Mohring effect.

The results above also hold for the more general case of imperfect substitution between car and public transport, as shown in Eq. (17). Whether the optimal fare lies above or below the marginal cost pricing rule-and thus whether public transport provision requires subsidies-is ultimately an empirical question, since the three components of the fare act in opposite directions. On the one hand, the *revenue-raising* component increases the fare above marginal cost. But on the other hand, the Mohring component pushes it downward. Additionally, the marginal cost may be above or below the self-financing level, depending on the degree of scale economies in public transport provision.

Moreover, the relative weight of the *revenue-raising* and Mohring effects is determined by the MCF. For example, if the MCF equals one, the *revenue-raising* component disappears and the optimal fare becomes $p^* = M_{PT} + C'(Y_{PT})$, which corresponds to the first-best fare. Conversely, if the MCF is well above one, the *revenue-raising* component dominates, leading to an optimal fare that exceeds the first-best level.

To better understand how these three effects influence public transport subsidies, we derive an expression that indicates the conditions under which the optimal fare requires subsidies. This occurs when $p \cdot Y_{PT} < C(Y_{PT})$, which, after rearranging terms, can be written as:

$$\underbrace{C'(Y_{PT})[1 - S_{PT}]}_{\text{Scale economies}} + \underbrace{\left[1 - \frac{1}{MCF}\right]\Theta_{PT}}_{\text{Revenue-raising }(+)} + \underbrace{\frac{M_{PT}}{MCF}}_{\text{Mohring effect (-)}} < 0, \tag{23}$$

where S_{PT} denotes the degree of scale economies in public transport provision.

The first term can be positive, zero or negative depending on whether there are decreasing, constant or increasing returns to scale ($S \lesseqgtr 1$). The component related to the elasticity of demand is positive ($\Theta_{PT} > 0$), although its magnitude is reduced by the *feedback effects*. The Mohring effect is negative ($M_{PT} < 0$), as we defined it as the benefits on waiting times from an increased number of trips.

Therefore, the Mohring effect and the existence of scale economies are the two forces that can justify subsidization. If they are strong enough, in that their absolute value is larger than the *revenue-raising* component, subsidization is part of the optimum solution. This condition formally represents the trade-off between the subsidy efficiency arguments and the subsidy fiscal costs outlined conceptually in Table 1.

It is worth noting that congestion relief does not affect the optimal subsidy in this setting, since the congestion externality is corrected by the optimal congestion toll. However, congestion relief can justify subsidies when congestion is not optimally priced, as will be discussed in the following sections.

3.3. Revenue-neutral tax reform

A related question concerning the second-best transport pricing is whether a revenue-neutral tax reform—where revenues from transport are used to reduce other distortionary taxes—can improve social welfare. These models build on the literature on the *double dividend* of environmental taxes (see, e.g., Goulder et al., 1999; Bovenberg and Goulder, 2002; Parry and Bento, 2000; Bovenberg and de Mooij, 1994), which examines whether an environmentally motivated tax reform can lower the overall efficiency loss from taxation. Such an outcome arises if the welfare gains from mitigating the externality and reallocating environmental tax revenues to reduce distortionary taxes in other markets exceed the deadweight loss associated with environmental taxation. When this condition holds, the policy yields a *double dividend*, improving environmental quality while lowering the broader economic costs of the tax system.[8]

As discussed above, much of the previous literature on the transport sector has focused on congestion pricing. Mayeres (2000), Mayeres and Proost (2001), and Parry and Bento (2001) investigated whether recycling congestion toll revenues to reduce labor taxes is welfare-improving. In this framework, the welfare impact of the tax reform can be decomposed into three components, as described by Goulder et al. (1997, 1999) and Parry (1995, 1997).[9] The first is the *Pigouvian component*, which reflects the welfare

[8] This is known as the *strong double-dividend* hypothesis, which states that the tax reform can improve both environmental outcomes and non-environmental social welfare. In contrast, the *weak double-dividend* hypothesis holds when the welfare gain from recycling tax revenue through reductions in distortionary taxes is greater than the gain from recycling it via lump-sum transfers.

[9] These seminal works have been extended in several directions. For example, De Borger (2009) and De Borger and Wuyts (2011) analyze the impact of wage bargaining on the second-best congestion toll. Calthrop et al. (2007) study the effects of revenue-neutral tax reforms on freight transport. Rizzi (2014) examines the relationship between the second-best congestion toll and road infrastructure provision while holding other taxes constant. Tikoudis et al. (2015, 2018) introduce a spatial dimension within a monocentric urban framework, and Tikoudis (2020, 2023) extend this approach to a polycentric network with multiple road links, which may be fully or partially tolled.

gains from reducing road congestion—also referred to as the first dividend. The second is the *revenue-recycling effect*, representing the welfare gain from using congestion toll revenues to reduce labor taxes, thereby lowering the tax burden on labor. The third is the *tax-interaction effect*, which reflects the impact of congestion tolls on labor supply. The sum of the *revenue-recycling* and *tax-interaction* effects captures the labor market impact of the tax reform, which constitutes the second dividend.

In contrast, public transport pricing has received less attention in the economic literature. Thus, this section analyzes the welfare effects of a revenue-neutral tax reform in which the government raises labor taxes while reducing public transport fares to keep the budget balanced. Eqs. (16) and (17) describe the second-best optimum but are not an appropriate benchmark for such a reform. Since the tax system is already optimal, any revenue-neutral adjustment would reduce welfare. The analysis must therefore begin from a non-optimal tax system. For example, the initial state could be one where the transit system operates under a self-financing constraint or with a historically determined subsidy level, rather than one derived from a full welfare optimization.

Totally differentiating the government's budget constraint, Eq. (9), with respect to p and t, while keeping G and τ constant, gives the required change in the labor tax when the public transport fare marginally increases:

$$\frac{\Delta t}{\Delta p} = -\frac{Y_{PT} + t\dfrac{dL}{dp} + \tau\dfrac{\Delta Y_C}{\Delta p} + p\dfrac{\Delta Y_{PT}}{\Delta p} - C'(Y_{PT})\dfrac{\Delta Y_{PT}}{\Delta p}}{L + t\dfrac{dL}{dt}}, \tag{24}$$

Here, $\Delta Y_C/\Delta p$ and $\Delta Y_{PT}/\Delta p$ denote the total changes in car and public transport demand due to the combined effect of fares and labor taxes.[10]

Substituting Eq. (24) into the total differential of the welfare function $V(\cdot)$ yields the welfare effect of the reform:

$$\begin{aligned} -\frac{1}{\sigma}\frac{\Delta V}{\Delta p} = \; & \underbrace{\left[p - \left[C'(Y_{PT}) + M_{PT}\right]\right]\left[-\frac{\Delta Y_{PT}}{\Delta p}\right]}_{\substack{\text{Efficiency effect} \\ \text{(Mohring + scale economies)}}} + \underbrace{\left[\Psi_C - \tau\right]\left[\frac{\Delta Y_C}{\Delta p}\right]}_{\substack{\text{Cross-Pigouvian effect} \\ \text{(congestion)}}} \\ & \underbrace{-\lambda\left[Y_{PT} + p\frac{\Delta Y_{PT}}{\Delta p} - C'(Y_{PT})\frac{DY_{PT}}{Dp} + \tau\frac{\Delta Y_C}{\Delta p}\right]}_{\text{Revenue-recycling effect}} + \underbrace{[1+\lambda]\left[-\frac{dL}{dp}\right]t}_{\text{Tax-interaction effect}}. \end{aligned} \tag{25}$$

Here, λ denotes the marginal excess burden, defined as:

$$\lambda = \frac{-t\dfrac{dL}{dt}}{L + t\dfrac{dL}{dt}}. \tag{26}$$

so that $1 + \lambda$ corresponds to the Pigou-Harberger-Browning Marginal Cost of Public Funds.

The welfare effect of the tax reform consists of four components: (i) the *efficiency effect*; (ii) the *cross-Pigouvian effect*; (iii) the *revenue-recycling effect*; and (iv) the *tax-interaction effect*.

The first component reflects the efficiency rationale for subsidizing public transport, namely the Mohring effect and increasing returns to scale in the public transport provision. This effect is positive when the fare exceeds the first-best level, defined as the sum of the marginal operating cost and the Mohring term (i.e., $p > C'(Y_{PT}) + M_{PT}$).

To illustrate, consider the case where waiting time is fixed ($M_{PT} = 0$) and public transport provision exhibits constant returns to scale. If the fare is set at the self-financing level, which in this case coincides with both the average and marginal operating cost, the *efficiency effect* is zero. Therefore, the tax reform has no efficiency-based impact on social welfare in this scenario.

This is precisely the setting analyzed by Mayeres (2000), Mayeres and Proost (2001), Parry and Bento (2001) and Tirachini and Proost (2021). The primary benefit of subsidizing public transport in such a framework stems from reduced road congestion from the modal shift. However, this benefit is typically insufficient to outweigh the welfare losses associated with higher labor taxation.

By contrast, if public transport exhibits increasing returns to scale, as in Tikoudis et al. (2015), the self-financing fare exceeds the marginal operating cost, meaning that the fare lies above the first-best level. In this case, reducing the fare narrows the gap between p and the optimal level $C'(Y_{YP})$. Moreover, the stronger the scale economies in provision, the larger the gap between the self-financing fare and marginal cost, and thus the greater the welfare gains from the tax reform.

When the Mohring effect is present (i.e., $M_{PT} < 0$), the first-best fare falls below the marginal operating cost $C'(Y)$, further widening the gap between the self-financing and first-best levels. In this context, the Mohring effect amplifies the magnitude of the *efficiency effect*, thereby increasing the welfare benefit of lowering public transport fares and strengthening the case for subsidization.

The second component on the right-hand side of Eq. (25) represents the *cross-Pigouvian effect*, which captures the impact of the tax reform on the congestion externality. Since cars and public transport are imperfect substitutes, reducing public transport fares induces some drivers to switch modes. This modal shift alleviates road congestion, generating a positive welfare effect when the

[10] For instance:

$$\frac{\Delta Y_{PT}}{\Delta p} = \frac{dY_{PT}}{dp} + \frac{\Delta t}{\Delta p}\frac{dY_{PT}}{dt}$$

congestion toll is below the Pigouvian level, defined by the marginal external cost Ψ_C. For example, if the congestion toll is zero, the *cross-Pigouvian effect* is positive because lowering the public transport fare reduces the untolled congestion externality.

The third component is the *revenue-recycling effect*, which reflects the welfare cost of using labor taxes to finance lower public transport fares. It is given by the marginal excess burden λ multiplied by the change in transport revenues. Since λ is strictly positive, the *revenue-recycling effect* is negative. The intuition is straightforward: funding public transport through higher labor taxes raises the household tax burden, reducing welfare. The fourth component is the *tax-interaction effect*, which reflects the welfare gain in the labor market from lower public transport fares. It is positive because reducing commuting costs increases labor supply.

Overall, the welfare impact of a revenue-neutral tax reform that raises labor taxes while reducing public transport fares depends on the balance between these four effects, which encompasses the main arguments for and against public transport subsidies described in Table 1. Assuming that congestion is unpriced and that the initial public transport fare is set to ensure self-sustainability, three forces favor increasing public transport subsidies: The efficiency-based arguments arising from the Mohring effect and increasing returns to scale, the congestion relief due to model shift, and the increase in labor supply. These forces must be weighed against the welfare costs of raising labor taxation.

While this GE framework provides theoretical consistency, its complexity masks the magnitude of specific transport mechanisms. We therefore turn to a PE model to isolate and quantify these forces.

4. A partial equilibrium unifying framework with costly public funds

We now turn to a Partial Equilibrium model, which allows us to incorporate operational details such as cross-congestion, crowding, and network design.

4.1. Framework

Our unifying framework aims to obtain transparent insights about urban public transport pricing and to have a clear comparison with the GE model. To this end, in our theoretical model, we consider one market, i.e., one origin and one destination and neglect network effects.

Users can travel by car or bus, and the joint demand for these modes is derived from a benefit function, $B(Y_{PT}, Y_C)$, where Y_{PT} and Y_C represent the number of trips by public transport and by car, respectively (see, e.g., Kraus, 2003; Pressman, 1970; Tirachini and Hensher, 2012). The benefit function measures consumers' total willingness to pay for a given number of car and bus trips, analogous to the area under the inverse demand function in the case of a single transport mode (Small and Verhoef, 2007, p. 155-159). It can also be interpreted as the utility of a representative consumer.

Furthermore, this benefit function specification admits typical demand systems such as Random Utility Models (RUM) and Constant Elasticity of Substitution (CES) models (Anderson et al., 1988, 1989). It follows the tradition of modeling horizontal or subjective differentiation between modes in a reduced-form fashion. It also implicitly assumes that commuters are homogeneous regarding their valuation of the transport costs, such as the on-board travel time, waiting time, and crowding discomfort. Therefore, the benefit function $B(Y_{PT}, Y_C)$ captures the perceived modal differentiation.

Finally, this straightforward formulation assumes that the marginal value of income is constant and equal to one (no income effect), which is the typical assumption in PE models and is the case in quasi-linear consumers' utilities (see, e.g., De Borger, 2009).

In equilibrium, the inverse demand functions, denoted by B_{PT} and B_C, must equal the generalized prices perceived by users:

$$B_{PT} = \frac{\partial B(Y_{PT}, Y_C)}{\partial Y_{PT}} = p + T_{PT}(Y_{PT}, Y_C, f) + T_W(f) \tag{27}$$

$$B_C = \frac{\partial B(Y_{PT}, Y_C)}{\partial Y_C} = \tau + T_C(Y_{PT}, Y_C, f) \tag{28}$$

where p is the public transport fare, τ is the congestion toll, and T_m is the travel time cost perceived by users of mode $m \in \{PT, C\}$. $T_W(f)$ represents the waiting time of public transport users, and it is a decreasing function of the frequency of the service. This function allows for capturing the Mohring effect in isolation, as, in the optimum, an increase in public transport users is met with an increase in frequency and a reduction of waiting times for all users. We formally show the mechanism below.

This general formulation nests the main approaches regarding transport externalities and demand substitution patterns. For instance, if $\frac{\partial T_{PT}(Y_{PT}, Y_C)}{\partial Y_C} < 0$, we allow for car trips negatively affecting public transport users and when it is zero we are considering that modes do not share road capacity (e.g., buses on a BRT corridor or a subway). The case of independent demands is obtained by assuming $\frac{\partial B_{PT}}{\partial Y_C} = \frac{\partial B_C}{\partial Y_{PT}} = 0$ and the case of perfect substitution when $\frac{\partial B_{PT}}{\partial Y_{PT}} = \frac{\partial B_C}{\partial Y_C} = \frac{\partial B_{PT}}{\partial Y_C} = d'(Y_{PT} + Y_C)$.

Before defining the public transport operating costs and social welfare, we introduce the following notation for better exposition. The marginal external cost of a car user, due to traffic congestion, is given by:

$$\Psi_C \equiv Y_C \cdot \frac{\partial T_C}{\partial Y_C} + Y_{PT} \cdot \frac{\partial T_{PT}}{\partial Y_C} > 0. \tag{29}$$

The first term on the right-hand side of Eq. (29) is the typical marginal congestion cost of car travel, and the second is the cross-congestion effect.

For public transport, we follow the tradition of assuming that the welfare maximization problem provides an optimal frequency that depends on the number of trips (Jara-Díaz and Gschwender, 2003), which we denote f^*. Therefore, when we consider the marginal external cost of a trip, it includes the direct effect and the effect through changes in the optimal frequency. Consequently, the marginal external cost of a public transport user is:

$$\Psi_{PT} \equiv Y_{PT} \cdot \left[\frac{\partial T_{PT}}{\partial Y_{PT}} + \frac{\partial T_{PT}}{\partial f^*}\frac{\partial f^*}{\partial Y_{PT}}\right] + Y_C \cdot \left[\frac{\partial T_C}{\partial Y_{PT}} + \frac{\partial T_C}{\partial f^*}\frac{\partial f^*}{\partial Y_{PT}}\right] > 0. \tag{30}$$

where the first term in brackets is the marginal impact of a public transport trip on public transport users. This, in turn, captures two effects: (i) passenger congestion ($\partial T_{PT}/\partial Y_{PT} > 0$), which can be due to in-vehicle crowding or boarding congestion; (ii) traffic congestion of public transport vehicles through increased frequency ($\partial T_{PT}/\partial f^* > 0$). The second term in square brackets is the analogous impact on car users.

We have excluded the impact of a public transport user on the waiting time, as this is not strictly an externality. This impact is given by:

$$M_{PT} \equiv \frac{\partial T_W}{\partial f^*}\frac{\partial f^*}{\partial Y_{PT}} Y_{PT} < 0 \tag{31}$$

and captures the Mohring effect.

We define the operating costs, $C(Y_{PT}, f)$, as a function that increases with the fleet size, corresponding to the number of buses required to provide the service. The function $C(Y_{PT}, f)$ generalizes the concept of operating costs commonly used in the public transport literature (Jara-Díaz and Gschwender, 2003). Consequently, it increases with the number of users (i.e., $C'(Y_{PT}) = \frac{\partial C}{\partial Y_{PT}} + \frac{\partial C}{\partial f^*}\frac{\partial f^*}{\partial Y_{PT}} > 0$).

4.2. Social welfare and pricing

We compute social welfare as the sum of the consumers' surplus, given by the difference between the benefit function and the total cost perceived by commuters, and the profit of the transport sector weighted by the Pigou-Harberger-Browning MCF:

$$SW = \underbrace{B - Y_C\left[\tau + T_C\right] - Y_{PT}\left[p + T_{PT} + T_W\right]}_{\text{Consumers' surplus}} + \underbrace{[1+\lambda]}_{MCF}\underbrace{\left[Y_C \cdot \tau + Y_{PT} \cdot p - C\right]}_{\text{Transport sector's profit}}. \tag{32}$$

where we omit the arguments of the functions for the sake of clarity.

The Pigou-Harberger-Browning—or partial equilibrium—MCF is defined as $1+\lambda$, where λ represents the Marginal Excess Burden of taxation, often referred to as the *shadow cost of public funds* or the *deadweight loss from taxation*.

The welfare function in Eq. (32) assumes a revenue-neutral tax reform is implemented to balance the public budget, with transport revenues recycled to reduce distortions in the markets where taxes are collected. Thus, if the transport system generates profits, the government uses these additional revenues to lower taxation. Consequently, an increase in public transport profit by \$1 generates a societal benefit of \$$(1+\lambda)$. Conversely, the government must raise distortionary taxes if the transport system requires subsidies. As a result, for every \$1 spent subsidizing the bus service, society incurs a cost of \$$(1+\lambda)$.

Proost and van Dender (2001, 2008) were the first to use this Kaldor-Hicks type of social welfare measure to evaluate transport policies, which has become the standard approach to account for tax distortions in transport models (Ramos and Silva, 2023; Horcher and Graham, 2022; Asplund and Pyddoke, 2020; Börjesson et al., 2019; Batarce and Galilea, 2018; Palma et al., 2017; Sun et al., 2016).

It is important to mention that they made some assumptions that are sometimes overlooked by the transport literature: Firstly, tax revenues are recycled to reduce labor taxes. Secondly, the tax reform does not produce efficiency losses in the labor market. In the GE notation of Section 3 and using the *double-dividend* framework outlined in Section 3.3: the *tax interaction effect* balances with the *congestion feedback* and the *revenue-recycling effect*, so transport fares charged to commuters have a neutral effect on labor supply. Thirdly, the welfare benefits of the tax reform emerge from what Proost and van Dender (2001) denote as the *tax shifting effect*.

The *tax-shifting* effect comes from the fact that public transport fares affect labor and non-labor trips. Transport fares do not create distortions in the labor market; therefore, increasing the price for commuters to reduce labor taxation has no welfare effect. In contrast, raising the fare for non-commuters to reduce labor taxation yields a positive welfare effect, shifting the tax burden from labor to other non-labor incomes. Thus, the value of the MCF used by Proost and van Dender (2001, 2008) accounts only for the welfare benefit of recycling revenues from non-commuting trips.[11]

Maximizing social welfare in Eq. (32), subject to equilibrium conditions Eqs. (27) and (28), yields the following pricing rules:

$$p = \underbrace{C'(Y_{PT})}_{\substack{\text{Marginal}\\ \text{cost}}} + \underbrace{\Psi_{Y_{PT}}}_{\substack{\text{Marginal}\\ \text{external cost}}} + \underbrace{M_{PT}}_{\substack{\text{Mohring}\\ \text{effect}}} + \underbrace{\frac{\lambda}{1+\lambda}\Theta_{Y_{PT}}}_{\text{Revenue-raising}}, \tag{33}$$

[11] Following these assumptions, Proost and van Dender (2001, 2008) employ a value of λ equal to 0.066 for Brussels and 0.035 for London, while Börjesson et al. (2019) obtain 0.2 for Stockholm. Other authors, such as Basso and Silva (2014), use a value of 0.15 recommended by Parry and Small (2009).

$$\tau = \underbrace{\Psi_{Y_C}}_{\substack{\text{Marginal}\\ \text{external cost}}} + \underbrace{\frac{\lambda}{1+\lambda}\Theta_{Y_C}}_{\text{Revenue-raising}} \tag{34}$$

where: $$\Theta_{Y_{PT}} = -\frac{\partial B_{PT}}{\partial Y_{PT}} Y_{PT} - \frac{\partial B_C}{\partial Y_{PT}} Y_C > 0, \qquad \Theta_{Y_C} = -\frac{\partial B_C}{\partial Y_C} Y_C - \frac{\partial B_{PT}}{\partial Y_C} Y_{PT} > 0. \tag{35}$$

The pricing rule in Eq. (33) summarizes the main forces at play in setting the welfare-maximizing public transport fare, as summarized in Table 1. We discuss each term and the evidence on its size in the following section and leave the comparison of PE vs GE welfare-maximizing pricing to Section 5.

4.3. Welfare-maximizing subsidization

It is not straightforward to state whether the welfare maximizing fare of Eq. (33) is high enough to cover operating costs. To answer this question, we look at empirical estimations available in the literature and try to determine the likelihood of public transport subsidization being welfare optimizing.

First, the need for subsidization occurs when $p \cdot Y_{PT} < C(Y_{PT}, f)$, which, rearranging terms can be written as:

$$[1 - S_{Y_{PT}}]C'(Y_{PT}) + M_{Y_{PT}} + \Psi_{Y_{PT}} + \frac{\lambda}{1+\lambda}\Theta_{Y_{PT}} < 0 \tag{36}$$

where $S_{Y_{PT}}$ is the degree of scale economies in the production of public transport trips.

The first term can be positive, zero or negative depending on whether there are decreasing, constant or increasing returns to scale ($S \lesseqgtr 1$). The Mohring effect is negative ($M_{Y_{PT}} < 0$), as we defined it as the benefits on waiting times from increased number of trips, and both the marginal external cost ($\Psi_{Y_{PT}} > 0$) and the revenue-raising component are positive ($\Theta_{Y_{PT}} > 0$).

Therefore, the Mohring effect and the existence of scale economies are the two forces that can justify subsidization. We confirm the intuition provided by the GE model: if the two forces are strong enough, in the sense that their absolute value is larger than the marginal external cost and the revenue-raising component, subsidization is part of the optimum solution. Once again, this formal condition directly reflects the balance between the competing arguments for and against subsidies presented in Table 1. We now turn to discuss these forces and provide a review of the available quantification for each.

The body of literature examining returns to scale in public transport production has expanded considerably in recent decades. This review focuses on recent contributions, which typically leverage more granular data to analyze how average costs evolve with aggregate outputs, such as passenger-kilometers or vehicle-kilometers.

Evidence from urban bus systems suggests that the average cost has a U-shaped form, meaning that economies of scale are often exhausted as operators grow, eventually leading to diseconomies (De Borger and Kerstens, 2007).

For instance, using cost data from the Italian local bus sector, Avenali et al. (2016) find that initial economies of scale transform into diseconomies of scale once a service threshold of 4 million bus-kilometers is surpassed. Similarly, de Grange et al. (2018) identify diseconomies of scale for bus firms in Santiago, Chile, with an annual ridership equal to or greater than 87.5 million passengers.

In contrast, the context of rural transit may yield different results. Ripplinger and Bitzan (2018), examining 42 rural transit agencies in North Dakota, find evidence of increasing returns to density and size at all output levels, although these returns diminish as agency size increases. This finding suggests that consolidating smaller rural systems could generate cost savings and provides an economic rationale for government subsidies to help providers reach socially optimal service levels.

Shifting the focus to urban rail, Graham et al. (2020) analyze an unbalanced panel dataset of 24 systems over 14 years. Their research identifies significant increasing returns to density (RTD), with an estimated elasticity of 1.56, which they attribute to the industry's prevalence of substantial fixed and semi-fixed costs.

Notably, their study also finds evidence of increasing returns to scale (RTS), with an elasticity of 1.22. This result challenges the conventional finding in the literature, which often points towards constant returns to scale in urban rail. The authors argue that their divergent conclusion stems from an empirical approach that explicitly controls for endogeneity and the dynamics of firm-level productivity, which better reflects observed industry behavior where large firms are common.

The empirical evidence of the Mohring effect is scarce; the main reason is that it is challenging to measure, as changes in waiting times due to changes in demand are often difficult to isolate from other impacts or changes (Silva, 2021). Nevertheless, the theoretical foundation is clear. As vehicles are an essential input in transport production, an increase in output is served by an increase in vehicles and thus frequency. A higher frequency implies decreased waiting times. Just as clear is that the effect may become negligible as demand increases because waiting time reductions decrease strongly with frequency. For example, Rizzi et al. (2025) calibrate a model with data from Paraguay and find that the benefit of an additional passenger in diminishing waiting times at off-peak periods is US$5 cents.

Deepening the discussion, Coulombel and Monchambert (2023) argue that a transit service can reach an upper limit of service frequency, beyond which further reductions in waiting time are no longer possible, and the Mohring effect dissipates. They also argue that even when higher frequencies are technically feasible, procuring new trains and upgrading signaling systems takes several years.

Table 2
Estimations of the marginal cost of public funds. Source: Ensor (2016).

Subgroup	Average	Maximum	Minimum	Std. Dev.	Number of Countries
Developed economies	1.14	1.32	0.99	0.09	14
Emerging Europe	1.12	1.20	1.00	0.06	12
Latin America	1.12	1.27	1.00	0.09	10
Developing Asia	1.14	1.23	1.00	0.08	11
Islands	1.16	1.63	1.00	0.13	18
MENA	1.11	1.23	1.02	0.08	10
Sub-Saharan Africa	1.19	1.56	1.00	0.13	31
Overall	1.15	1.63	0.99	0.11	106

Mature urban rail systems in developed countries commonly face this issue, and the Mohring effect there does not play a supporting role for subsidization. An empirical application to London's Piccadilly line shows that the Mohring effect dissipates in peak-periods.

Other sources of scale economies are beyond our single-line model. We briefly overview the effects here and refer the reader to Jara-Díaz et al. (2023) for a more detailed discussion. A key insight in the literature is that higher passenger volumes enable significant network effects that lead to scale economies. Greater demand allows an operator to design a more efficient network with more direct routes, reducing the need for transfers and minimizing overall travel times for passengers (see, e.g., Fielbaum et al., 2020). Similarly, density economies emerge as higher demand in a given area permits better network coverage, reducing the walking distance for users to access the service.

Finally, a larger scale of operation can justify the high fixed costs of technological economies. These technologies can range from implementing more efficient fare collection systems (Jara-Díaz and Tirachini, 2013) to undertaking a complete modal shift to higher-capacity and more efficient technologies such as bus rapid transit (BRT) or urban rail, which would be financially unviable at lower demand levels (Tirachini et al., 2010). However, when the technology is fixed, very crowded systems face operational constraints regarding service frequency that lead to diseconomies of scale (Coulombel and Monchambert, 2023).

Regarding crowding costs, a recent review of the literature by Fedujwar and Agarwal (2024) finds that most of the papers model these costs as a value of time multiplier. The review shows many studies reported a sitting multiplier close to 1.5, with a range between 0.95 and 2.15 for different levels of crowding. When looking at standing multipliers, the maximum estimated values of the multiplier using a standee density range up to 3.82. The average, though, is not substantially larger than the sitting multiplier.

Regarding the cost per additional passenger, as it would enter our formulation in Eq. (36), the study reveals a wide range across different urban contexts. For instance, passengers in Santiago exhibit a particularly high willingness to pay, valuing the avoidance of high-density crowding (5–6 pass/m^2) at US \$11.54/h, which suggests a strong incentive to switch modes for less crowded conditions (Batarce et al., 2016). In comparison, the value in Sydney was estimated at US \$2.09/h for securing a seat (Hensher et al., 2011). Valuations in other cities tend to be lower; transit users in Sweden are willing to pay US \$0.816 \$0.953/h to eliminate crowding entirely (Björklund and Swärdh, 2017), while passengers in Istanbul would pay the equivalent of US \$1.08/h to move from the highest crowding level to the lowest (Çelebi and Şükrü, 2020). Similarly, travelers in Bogotá and Shanghai show comparable willingness to trade for less crowding (Márquez et al., 2019; Shao et al., 2022). While the common inference is that willingness to pay increases with the level of crowding, these varied estimates underscore that the specific value is highly case-specific. The valuation ultimately depends on various factors, including passenger sociodemographics, transit mode, region, trip purpose, and less crowded alternatives.

Coulombel and Monchambert (2023) provide a different perspective on the congestion and crowding effects. Their study develops a model incorporating three types of congestion: in-vehicle crowding, increased station dwell times due to passenger flows, and a minimum safe headway between vehicles that imposes a physical limit on service frequency. Their analysis reveals that while public transit exhibits economies of density at lower demand levels, it transitions to diseconomies of density under highly congested conditions. In the short term, this is driven by crowding and dwell times. In the long term, the primary constraint becomes the physical limit on train frequency. Their empirical application to London's Piccadilly line confirms these findings, showing substantial diseconomies of scale during the morning peak but economies of scale during off-peak periods.

Finally, the revenue-raising term in the pricing equation and subsidization condition in Eq. (36) is not measured directly by any study. Nevertheless, we can shed light on its magnitude by using the average value for the marginal cost of public funds reported in Table 2 of 1.15, which implies $\lambda = 0.15$. This value means that the term multiplying the term $\Theta_{Y_{PT}}$ is 0.13.

In Section 4.5, we deepen the interpretation of the relative weight of these terms by looking at studies that have estimated them together.

4.4. Unpriced car externalities

To focus on public transport pricing alone, we now look at cases where car trips are not priced according to the externality they impose on society. For simplicity, we assume no cross-congestion between modes. As a result, we get the following pricing rule:

$$p = \underbrace{C'(Y_{PT})}_{\substack{\text{Marginal}\\ \text{cost}}} + \underbrace{\Psi_{Y_{PT}}}_{\substack{\text{Marginal}\\ \text{external cost}}} + \underbrace{M_{PT}}_{\substack{\text{Mohring}\\ \text{effect}}}$$

$$\underbrace{-\frac{\Psi_{Y_C}}{1+\lambda}\cdot\left[\frac{\frac{-\partial B_C}{\partial Y_{PT}}}{\frac{\partial T_C}{\partial Y_C}-\frac{\partial B_C}{\partial Y_C}}\right]}_{\text{Unpriced car externalities}} + \underbrace{\frac{\lambda}{1+\lambda}Y_{PT}\cdot\left[-\frac{\partial B_{PT}}{\partial Y_{PT}}-\frac{\frac{\partial B_{PT}}{\partial Y_C}\cdot\frac{\partial B_C}{\partial Y_{PT}}}{\frac{\partial T_C}{\partial Y_C}-\frac{\partial B_C}{\partial Y_C}}\right]}_{\text{Revenue-raising term}}, \tag{37}$$

Compared to the pricing rule in Eq. (34), this equation incorporates a crucial new term to capture the welfare benefits derived from correcting unpriced car externalities. A lower public transport fare, p, attracts riders from automobiles, reducing Y_C and its associated marginal external cost, Ψ_{Y_C}. This new "Unpriced car externalities" term formalizes the role of public transport fares as a second-best instrument to correct the market failure in road use. It can be understood as the marginal social benefit of using the transit subsidy to reduce car travel, adjusted by the cost of the public funds required to do so. The term is composed of several key parts:

First, Ψ_{Y_C} represents the marginal external cost of a car trip (e.g., the congestion imposed on other drivers and buses). This is the damage the policy aims to mitigate. Second, the fraction within the brackets, $\left[\frac{\frac{-\partial B_C}{\partial Y_{PT}}}{\frac{\partial T_C}{\partial Y_C}-\frac{\partial B_C}{\partial Y_C}}\right]$ quantifies the effectiveness of the modal shift. The numerator reflects how much car demand decreases when public transport use increases. At the same time, the denominator adjusts for the fact that this reduction in congestion also makes driving slightly more attractive (a feedback effect). This fraction measures the net reduction in external damage for each new passenger attracted to public transport. Finally, this entire benefit is divided by the MCF $(1+\lambda)$ because the welfare gain from reducing the externality must be weighed against the social cost of the subsidy used to achieve it.

The empirical literature has focused mainly on quantifying the components of this equation to determine whether the combined effects justify a fare below marginal cost, thus requiring a subsidy. Two main analytical frameworks have emerged in the last decades.

A seminal stream of research, initiated by Parry and Small (2009), utilizes a PE model to quantify these effects for London, Los Angeles, and Washington, D.C. Their principal finding is that, starting from a 50% subsidy, further increases are almost always welfare-improving. The analysis provides a powerful argument for subsidization by decomposing the marginal welfare gain of a fare reduction. It demonstrates that the benefits—primarily from reduced road congestion (especially at peak periods) and network economies of scale via the Mohring effect (particularly for bus services and off-peak travel)—typically outweigh the direct financial loss of the subsidy. Importantly, their original analysis assumes costless public funds ($\lambda = 0$) and that the public transport supply responds with a constant elasticity, i.e., when demand increases by one percent, the vehicle kilometers increase by 0.67 percent.

Subsequent applications of this influential model to Mexico City (Parry and Timilsina, 2010) and Bogotá (Gómez-Gélvez and Mojica, 2022) have corroborated the case for high subsidies, with optimal levels found to be sensitive to local parameters such as demand elasticities and modal substitution patterns. For example, Gómez-Gélvez and Mojica (2022) show that for TransMilenio (the BRT system), subsidies are justified only when the vehicle kilometers elasticity is above 0.65, and that they grow rapidly with the elasticity, reaching more than 90% of the operating costs when the elasticity is between 0.8 and 0.85. Similar to Parry and Small (2009), they find that congestion is the main externality, especially during the peak period. The contribution of TransMilenio users to externalities is relatively low because the use of dedicated lanes limits their impact on congestion. As a result, the net externality benefit is positive for TransMilenio, even considering that only 10% of its additional demand comes from private vehicles.

It is worth noting that these models do not simultaneously consider price changes across different modes, which prevents a combined analysis of subsidies and congestion pricing. Furthermore, they do not incorporate long-term structural changes to the bus system, as they have the abovementioned constant supply elasticity rule.

A second, complementary line of inquiry, exemplified by Basso and Silva (2014), employs a more general approach to analyze the interaction between subsidies and other transport policies. The public transport supply responds optimally to changes in demand, and the marginal cost of public funds is set to 1.15. By modeling a stylized urban corridor for Santiago and London, they demonstrate that the case for subsidies is strongest when more direct, first-best instruments are absent. While their findings support subsidies of 55% to over 90% when implemented in isolation, they show that these same subsidies yield minimal or even negative welfare gains if enacted alongside policies like congestion pricing or dedicated bus lanes. This highlights the role of subsidies as a corrective measure that becomes less necessary as more efficient policies are adopted.

Extensions of this framework have reinforced this core insight. Börjesson et al. (2017) derived an optimal subsidy of 44% for a corridor in Stockholm, with differentiation between peak and off-peak fares. Börjesson et al. (2019) found that the Mohring effect is more dominant in smaller cities, making subsidies more effective there. Most recently, Basso and Silva (2023) extended the model to include metro systems and different spatial distributions for Santiago and São Paulo, finding that optimal subsidies can reach 90%

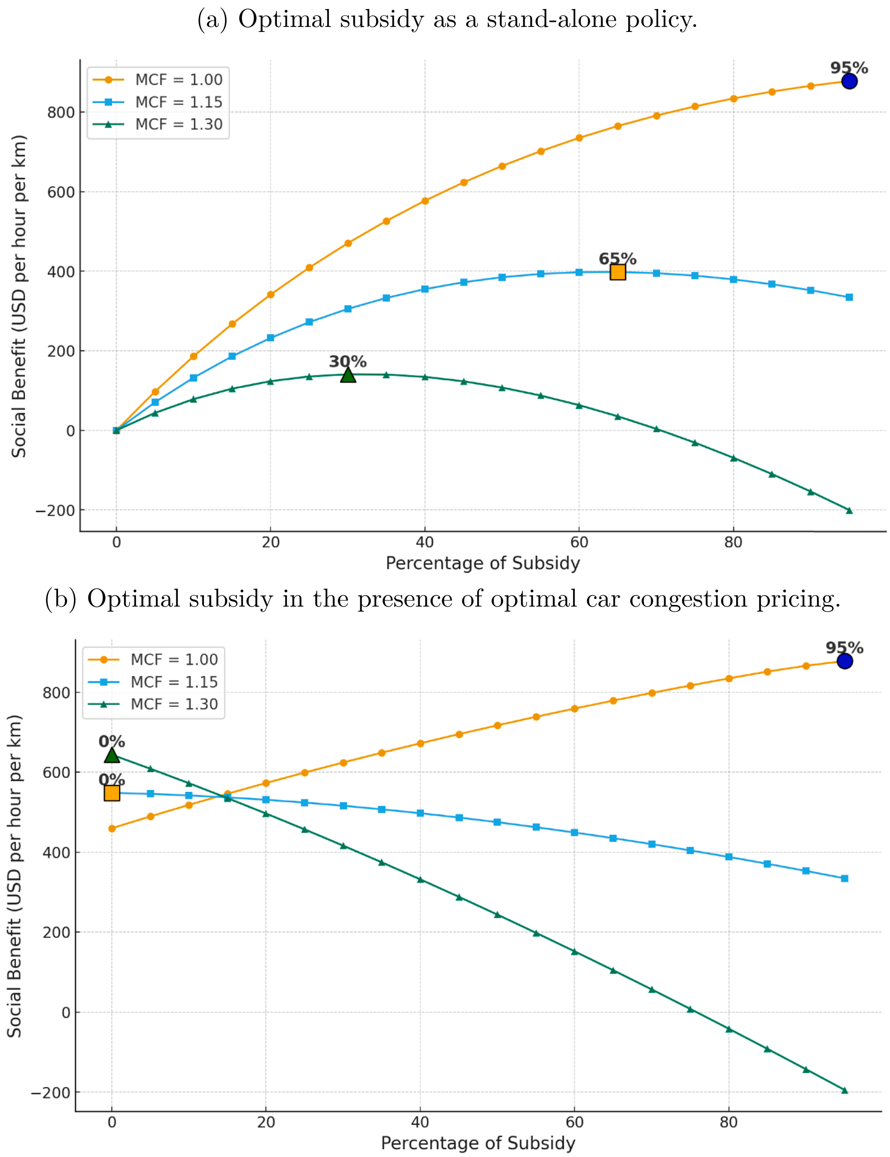

Fig. 1. Optimal subsidy and MCF. Extension of Basso and Silva (2014).

when fares cannot be significantly differentiated between metro and buses and first-best policies are not in use. In sum, this literature demonstrates that while subsidies are a powerful second-best tool, their optimal level is highly contingent on the broader policy package in place.

4.5. An empirical application

In this section, we use the model and application of Basso and Silva (2014) to understand the sensitivity of the results to different values of the MCPF. Fig. 1 presents a summary of results for $\lambda = \{0; 0.15; 0.30\}$. It shows the benefit of subsidizing the bus system between 0 and 95% of operating costs. It does so when considered as a stand-alone policy in mixed traffic (Panel (a)) and when it is set together with a welfare-maximizing car congestion toll (Panel (b)). Considering the case of MCF = 1 and MCF > 1 also allows for isolating the impact of the marginal cost of public funds on the optimal subsidy.

This distinction allows for studying and quantifying in our general framework each of the components of the optimal subsidy condition in Eq. (37). The setting closest to our case in Section 4.4 is in Panel (a), where buses and cars congest each other, car externalities are not priced, and funds are costly. The five terms, marginal-cost pricing, marginal external costs, Mohring effect, unpriced car externalities, and revenue-raising, determine the optimal fare and subsidy. We discuss them in detail in what follows.

First, Panel (a) of Fig. 1 sheds light on the impact of the revenue-raising term in shaping the optimal subsidy. Without costly funds (MCF = 1), the welfare-maximizing subsidy reached 95% of the operating costs. This implies that in the Santiago setting, the efficiency and car substitution effects outweigh the marginal external cost of an additional bus passenger, and it is always welfare maximizing to raise subsidies.

When considering the cases of MCF = 1.15 and MCF = 1.3, the revenue-raising term comes into play as funding public transport subsidies implies raising distortionary taxes that cause a deadweight loss of US $ 0.15 and 0.3 per dollar. In the first case, the optimal subsidy decreases to 65% and in the second, to 30%. Therefore, costly public funds significantly impact public transport fares and subsidies. In this application, within the values of MCF reported in the literature, it increases the fare but not enough to cover operating costs.

Panel (b) reports the results of the same exercise, but pricing cars optimally. It is analogous to the scenario of Section 4.3, where the so-called second-best argument to subsidize public transport is absent. Additionally, in this case, the optimal subsidy reaches 95% when public funds are not costly, i.e., MCF = 1, indicating that the efficiency arguments alone are sufficient to justify subsidization.

The most salient result in Panel (b) is that in the presence of first-best congestion pricing, the efficiency case for subsidies is weakened by the cost of public funds. An MCF of 1.15—the average value found in the empirical literature—is sufficient to eliminate the rationale for subsidization in this simple model, with the optimal subsidy falling from 95% to 0%. This illustrates that when more direct instruments are available to correct car externalities, the justification for subsidies (the Mohring effect and scale economies) may not be strong enough to overcome the social cost of distortionary taxation.

An important qualification to the results above is that the model abstracts from several sources of scale economies. As Table 1 summarizes, scale economies may also arise from denser networks, technological advancement, and agglomeration benefits, among other factors. Therefore, the question of whether these forces outweigh the impact of costly funds needs to be analyzed in a more detailed model.

5. Conclusion

5.1. Comparing the partial and general equilibrium frameworks

A central goal of this paper is to compare the results derived from partial equilibrium (PE) and general equilibrium (GE) models when analyzing public transport pricing with costly public funds. While both frameworks incorporate the social cost of taxation, their underlying assumptions about the economy lead to differences in the structure of the optimal pricing rules and, consequently, in their policy implications. On the one hand, the GE framework optimizes transport prices jointly with the labor tax. In contrast, the PE model assumes a revenue-neutral tax reform in which revenues are recycled to reduce non-optimal taxes.

The main distinction between the two approaches lies in the treatment of the marginal cost of public funds (MCF). In the GE framework presented in Section 3, the MCF is endogenous and derived within the model as the ratio of the marginal utility of income for the government to that of the representative household. This approach explicitly captures the link between transport markets and the labor market, showing how changes in commuting costs affect labor and leisure choices and, in turn, labor tax revenues. By contrast, the PE framework presented in Section 4 treats the MCF as an exogenous parameter, computed as one plus the Marginal Excess Burden λ. The value of λ is drawn from empirical studies and used to weight the financial results of the transport sector, representing distortions in other, unmodeled markets.

A second difference concerns the relationship between transport prices and the market where the government collects taxes. In GE models, the government relies on labor taxation, and transport and labor supply are usually assumed to be complements, following Parry and Bento (2001) and van Dender (2003). Therefore, raising public transport fares directly affects labor by increasing commuting costs, amplifying efficiency losses in the labor market. Conversely, the PE model, following Proost and van Dender (2001, 2008), assumes that transport fares do not directly affect labor supply. In this case, raising the public transport fare shifts the tax burden from labor to other income sources unrelated to transport. As a result, changes in fares do not directly affect the pre-existing tax distortions in the markets where the government collects revenues.

These assumptions are reflected in the structure of the optimal fare equations. The key difference lies in the weight of the Mohring effect. In the GE pricing rule (Eq. (17)), it is multiplied by the inverse of the MCF, since fares directly affect the labor market. In the PE rule (Eq. (33)), the Mohring term enters without this weight, because fares are assumed to have a neutral effect on labor. The only tax-related impact of transport fares arises from recycling revenues to reduce taxation, and this effect is already captured in the revenue-raising component of the optimal fare.

The differences between the GE and PE approaches can also be understood by examining the welfare effects of a revenue-neutral tax reform, as explained in Section 3.3. While the GE pricing rule is shaped by the four forces described in Section 3.3 (efficiency, congestion relief, revenue recycling, and tax interaction), the PE rule depends only on the Efficiency and revenue-recycling effects. The tax-interaction effect is absent because fares are assumed not to affect labor supply, while the cross-Pigouvian effect arises only if congestion is not optimally priced, as discussed in Section 4.4.

Beyond these theoretical differences, the choice between the two frameworks involves a trade-off. The GE model offers greater theoretical consistency but at the cost of complexity, as it requires stronger assumptions and is less transparent, making it harder to isolate individual mechanisms. By contrast, the PE model is more transparent and tractable. Its simpler structure allows a clear decomposition of the forces driving subsidization, as in Eq. (36), and is easier to calibrate for applied policy analysis. Despite its more restrictive assumptions, it remains helpful in highlighting the mechanisms that justify subsidies.

5.2. Quantitative implications and policy takeaways

While the GE and PE frameworks differ in their theoretical structure, their quantitative implications point toward consistent policy conclusions.

The GE literature generally finds a weaker case for public transport subsidies by focusing on the interaction between transport and distorted labor markets. Prior studies that exclude the Mohring effect and scale economies conclude that a tax reform raising labor taxes to finance transit subsidies is typically not welfare-improving. The gains from congestion relief are insufficient to offset the efficiency losses from higher labor taxation. While our theoretical GE model incorporates pro-subsidy forces, such as the Mohring effect, the broader implication remains that the negative interaction with the labor market, captured by an endogenous MCF, provides a powerful argument against high levels of subsidization.

The PE framework allows for a more direct quantification of the competing forces at play. The literature provides strong evidence for the two primary efficiency arguments favoring subsidies: The Mohring effect is a significant driver, explaining up to 60% of the optimal subsidy for off-peak services as Parry and Small (2009) note. Unpriced car externalities, especially congestion, provide a powerful second-best rationale, with models showing that optimal subsidies can exceed 85% when public funds are assumed to be costless.

However, a key policy takeaway emerges from quantifying the impact of the MCF. Our empirical application based on Santiago, Chile, clearly illustrates these trade-offs. When car travel is unpriced, as is often the case in real-world scenarios, and an MCF of 1.0 (costless funds) is assumed, the optimal subsidy is approximately 95%, driven by both efficiency arguments and the need to correct car externalities. With an empirically-founded MCF of 1.15, as Table 2 shows, the optimal subsidy is reduced to 65%. With a higher MCF of 1.30, the optimal subsidy is further cut to 30%.

On the other hand, when car travel is optimally priced with a congestion toll, the picture is quite different. With an MCF of 1.0, the optimal subsidy remains high at 95%, justified by the Mohring effect and scale economies alone. However, with an MCF of 1.15, the social cost of taxation is sufficient to eliminate the efficiency case for subsidies, with the optimal level falling to zero.

The conclusion is stark: the optimal level of public transport subsidization is highly contingent on the balance between the competing forces summarized in Table 1, namely the magnitude of the MCF and, critically, on the presence of other transport policies. In the absence of congestion pricing, subsidies are a powerful second-best tool. However, once cars are priced efficiently, the case for subsidization is weakened once the real cost of raising public funds is considered. A more detailed model that considers all forces in Table 1 is required to obtain definitive answers.

5.3. Qualifications and avenues for future research

Finally, we must acknowledge the qualifications of our analysis. For tractability, our framework necessarily simplifies several important dimensions of the urban transport problem. A notable drawback of the GE approach, for example, is that it typically does not allow for the detailed, micro-founded modeling of transport externalities, such as crowding, reliability, and complex network interactions, which are a strength of PE models. Furthermore, while central to the analysis, our treatment of the labor market simplifies the labor supply decision by not distinguishing between the intensive margin (hours worked per worker) and the extensive margin (the decision to participate in the labor force). Recent work has shown that these distinct margins can have different implications for optimal transport pricing (see, e.g., Hirte and Tscharaktschiew, 2020). These simplifications represent necessary trade-offs, but they also highlight important areas for future refinement.

This review also points toward several promising avenues for future research. A primary challenge is to combine the strengths of both modeling traditions by integrating the detailed transport features from PE models into a GE framework, utilizing costly public funds. Such an approach could, for instance, explore the optimal provision of service quality (frequency, crowding) in a setting with endogenous labor supply.

A second avenue is to embed the analysis within a richer spatial context. Some advances have been made. For instance, Fielbaum et al. (2017) propose a parametric description of cities for the normative analysis of transit systems that helps capture different yet fixed spatial patterns. Basso et al. (2021) extends the monocentric city model to capture more realistic aspects of public transport and patterns of income locations, yet employment remains concentrated in a single point. Hörcher and Graham (2024) build upon the principles of quantitative spatial economics to design an empirically relevant transport appraisal method in spatial general equilibrium (SGE), extending the work of Ahlfeldt et al. (2015), among others.

Finally, while our paper focuses on the efficiency rationale for subsidies, a crucial extension is to incorporate the equity dimension more consistently. This would require transitioning from representative household models to models with heterogeneous agents to rigorously analyze the distributional consequences of different subsidy and fare policies, a topic of intense contemporary policy debate.

CRediT authorship contribution statement

Raúl Ramos: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization; **Hugo E. Silva:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis.

Data availability

No data was used for the research described in the article.

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