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The economic cost of subway congestion: Estimates from Paris[☆]

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A B S T R A C T

Related to the increased encouragement of public transport (PT) by policy-makers, over-crowding in PT has become a major issue worldwide. Whilst the impact of in-vehicle crowding on individuals' travel costs has been considered, we focus on aggregate welfare losses. We apply a Pigouvian framework to the case of subways and compute the economic cost of congestion (*ECC*). We combine data of the 14 metro services of the Paris network with survey data from a contingent valuation study of in-vehicle congestion. The gap between current and optimal PT patronage is 9%, and *ECC* is moderate. For the entire Paris subway network our benchmark estimate of 64.6 million euros per year amounts to 0.9% of total users' costs. We also propose marginal congestion costs relevant for socioeconomic appraisals of transport projects.

1. Introduction

Given the various environmental costs generated by automobile traffic in cities, most urban transport policies try to incentivize a modal shift towards public transport (PT) networks, mainly through taxation of automobile usage (Parry and Small (2005)) and/or PT subsidies (Parry and Small (2009)). However, where PT supply cannot adapt to demand (in the case of subways rather than buses in particular), the in-vehicle space available for travelers will decrease. As a consequence, these policies are likely to increase PT crowding externalities (congestion in what follows[1]) thereby imposing welfare losses on existing PT users and mitigating positive economies of density arising from reduced average operational costs and waiting times (Mohring (1972), Proost and Van Dender (2008)).

Researchers have paid growing attention to PT congestion since Kraus (1991). Several studies have highlighted the channels through which PT crowding deteriorates the “travel experience” of users as well as its (indirect) impacts on individuals' health or productivity (Cox et al. (2006), Mohd Mahudin et al. (2012), Haywood et al. (2017)). Valuation studies have recently been made more accessible (Wardman and Whelan (2011), ITF-OECD (2014)), allowing economists to consider crowding costs in a variety of settings: to predict PT demand (Tirachini et al. (2013)); explain individuals' route choices (Raveau et al. (2011), Hörcher et al. (2017)); assess the welfare effects of pricing reforms (Parry and Small (2009), Kilani et al. (2014), de Palma et al. (2017)); contrast competing investment projects (Tirachini et al. (2010)); set timetables (de Palma et al. (2015), de Palma et al. (2017)) or vehicles' design (Tirachini et al. (2014)).

This article investigates the magnitude of welfare losses caused by in-vehicle congestion in Paris subways during peak periods. We take the PT supply (fares, costs of provision, headway, capacities) as given and focus on the effect of in-vehicle crowding on social welfare, estimating the “economic cost of congestion” (*ECC*) on that basis. Our study provides the following contributions to the literature:

First, valuation studies have mostly focused on the influence of PT congestion on individuals' travel costs. By contrast, our analysis puts the emphasis on the divergence between the private and social costs of subway utilization. Whilst *ECC* has often been analyzed with this methodology in the case of road congestion (Newbery and Santos (1999), Lindsey (2006), Small and Verhoef (2007)), we provide some empirical evidence for subways. Given the concerns related to PT crowding shared in many cities around the world, the simple method proposed here could have widespread applications.

Second, we study the Parisian case, particularly interesting in its own

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[1] We recognize that PT crowding may be the product of both objective travel conditions (passenger density notably) and subjective factors (see Cox et al. (2006) or Mohd Mahudin et al. (2012)). For the sake of simplicity, we will use passenger density, crowding, comfort and congestion interchangeably in what follows.

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right: Over the last decade, the municipality implemented a strategy of decreasing the attractiveness of under-priced car use,[2] redesigning roads and investing in PT facilities (buses, streetcars, bike-sharing system). This aim was achieved with a decrease in automobile traffic of over 20% between 2000 and 2010. However, the modal shift towards subsidized PT systems lead to higher congestion, since supply increased less than demand (+13% and +22% respectively). As a result, individual subway congestion costs are found to be considerable by Kroes et al. (2013) and Haywood and Koning (2015). In this second-best setting, it is of particular interest to assess the welfare costs due to over-crowded PT.[3]

This article proceeds as follows: Section (2) sets out the Pigouvian framework used to assess the welfare cost of subway congestion. Section (3) presents the data of the 14 metro services of the Paris network, which is combined with survey data from a contingent valuation study of in-vehicle congestion. Section (4) presents our estimates of *ECC* and contrasts results of various sensitivity analyses. Section (5) concludes.

2. Model

An individual entering a crowded subway faces larger travel costs as compared to a comfortable situation. But his presence also increases travel costs of all users. This section formalizes this congestion problem in a simple framework that can be easily parameterized using available data.

2.1. General setting

The demand of N individuals for subway transport during peaks is assumed to be a linear function of the generalized price p:

$$N(p) = N_{max} + a \times p, \tag{1}$$

a (<0) describes the demand sensitivity to the generalized price.

We do not attempt to model the determinants of subway supply. Taking as given that m subways operate during peaks, the level of in-vehicle congestion Q is equal to $N(p)/m$. It is then possible to express the marginal utility of travelers using an inverse demand curve, $D(Q)$ that depends on the level of congestion in each vehicle,

$$D(Q) = \frac{m \times Q - N_{max}}{a} = b^D + a^D \times Q. \tag{2}$$

The marginal private cost of subway utilization $I(Q)$ is given by

$$I(Q) = t^w \times w^w + t^v \times w^v \times g(Q), \tag{3}$$

where t^w represents the waiting time on platforms (valued by individuals at w^w), and t^v the in-vehicle travel time (valued at w^v when there is no crowding). Importantly for our purpose, equation (3) stipulates that PT crowding raises the utility cost of in-vehicle travel time alongside with $g(Q)$ ($\frac{\partial g(Q)}{\partial Q} > 0$). This function can be seen as equivalent to the travel time-flow relationship used to endogenize time costs in the case of road congestion.[4]

The equilibrium level of subway use arises at the intersection of $D(Q)$ and $I(Q) + f_0$, where f_0 is the fare charged to PT users in the current, effective equilibrium. This equilibrium implies a level of utilization and thus congestion Q_0, at a user generalized price $p_0 = f_0 + I(Q_0) = D(Q_0)$.

This situation may generate welfare losses because travelers do not take into account the congestion externality they impose on other individuals present in the carriages. To see this, consider the aggregate benefits B of subway utilization when m vehicles are operating,

$$B = m \times \int_0^Q D(Q')dQ'. \tag{4}$$

The total resources C engaged by subway users (in terms of time and money) are:

$$C = m \times Q \times (I(Q) + f). \tag{5}$$

With m subways in operation, the PT operator's profit P is:

$$P = m \times (Q \times f - (K + MOC \times Q)), \tag{6}$$

where K represents the fixed cost of subway services (e.g. investments in rolling-stock and tracks) and MOC is the marginal operational cost (e.g. expenditures for vehicles' energy and maintenance).

Social welfare is given by $W = B - C + P$.[5] Maximizing W with respect to Q leads to the following first-order condition:

$$\frac{\partial W}{\partial Q} = m \times \left(D(Q) - \left(I(Q) + Q \times \frac{\partial I(Q)}{\partial Q} + f \right) + (f - MOC) \right) = 0. \tag{7}$$

The marginal social cost of subway utilization, $S(Q)$, consists of three components. First, the marginal private cost of subway utilization $I(Q)$. Second, the marginal external cost of PT congestion ($MEC(Q) = Q \times \frac{\partial I(Q)}{\partial Q}$). Third, the marginal resources engaged by the PT operator to transport an additional user (MOC). As equation (7) shows, the fare f is a transfer and drops from $S(Q)$.[6]

Within this framework, the optimal level of patronage in one vehicle, Q^*, and the associated generalized price, p^*, must satisfy:

$$p^* = D(Q^*) = S(Q^*) = I(Q^*) + MEC(Q^*) + MOC. \tag{8}$$

To reach this optimum, we require individuals to base their choices on $S(Q)$ rather than $I(Q)$. As typically suggested in the case of road congestion (Lindsey (2006)), the simplest way to achieve this is by setting an optimal fare, f^*, that satisfies:

$$f^* = S(Q^*) - I(Q^*) = MEC(Q^*) + MOC. \tag{9}$$

The optimal fare shown in equation (9) follows two objectives: internalizing the marginal external cost of in-vehicle congestion and covering the marginal cost of PT provision.

Contrasting p^* and p_0, the effective equilibrium is characterized by more patronage than at the optimum ($Q_0 > Q^*$) whenever subways are “under-priced” ($f_0 < f^*$). Given the increasing shape of $I(Q)$, a sufficient (but non-necessary) condition is $MOC \geq f_0$. Data for Paris suggest this condition is met (see sub-section (3.3)), suggesting the fare should be increased (by $f^* - f_0$) to reach the optimum. If the condition is not met, policy makers should reduce f_0 to incentivize PT usage.

It is worth noting that this partial equilibrium framework is not well suited to study individuals' trade-offs between crowding costs and scheduling costs, as done by de Palma et al. (2017) who extend the

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[2] As documented in Commissariat Général au Développement Durable (2013), cars' taxation (mainly on gasoline) amounts to 0.040 euro/pkm and hardly covers the marginal external cost of motorized traffic (0.243 euro/pkm) in dense urban areas in France (such as Paris).

[3] The increased usage of central Paris subways was not accompanied by lower reliability, contrary to the situation on the regional train service (RER) where delays have increased over the last decade. Our analysis can thus only focus on crowding costs in central Paris subways. Congestion in Parisian PT has been analyzed in different contexts. Leurent et al. (2014) study the interplay between various capacity constrains (access to platforms, in-vehicle congestion, traffic flow). Kilani et al. (2014) include crowding costs when looking at the welfare effects of transport pricing reforms. de Palma et al. (2017) calibrate a model with crowding and scheduling costs.

[4] Although we do not formalize these effects, waiting times on platforms, access times and reliability could also be affected by an intense PT utilization.

[5] We do not consider potential implications of changed demand for PT and varying externalities of other modes.

[6] This is no longer the case if we take into account that publicly subsidized transport requires distortionary taxation. We would then include a marginal opportunity cost of public funds (α). In that case, the marginal social cost function becomes $S(Q) = I(Q) + Q \times \frac{\partial I(Q)}{\partial Q} + f + \alpha \times (MOC - f)$.