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Marginal congestion costs in the case of multi-class traffic: A macroscopic assessment for the Paris Region

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ABSTRACT

Although road congestion caused by freight activities is often pointed-out by researchers and public deciders as a major issue, few studies model time losses at a macroscopic-regional level within a "multi-class traffic" framework. This research proposes such empirical assessment for the Paris region, using a simple method based on individuals' trip durations. We combine information on passengers and commercial transport (to describe road demand) with a GIS describing the stock of infrastructures (road supply) on that territory.

According to econometric results, the travel times react differently to the flow of similar and dissimilar vehicles: Cars and vans are more impacted than trucks by the volume of "small" vehicles, whereas "large" vehicles are more affected than cars and vans by the presence of other large vehicles. Our methodology thus highlights varying and reciprocal congestion impacts, which is not common in the literature. We then propose various marginal congestion costs, for various origin-destination pairs, various time periods and various types of vehicles. In particular, we decompose external losses incurred to each category of vehicles by each category of vehicles. These results constitute valuable materials for future appraisals of transport policies in the Paris region.

1. Introduction

Because road users rarely pay the whole (social) cost their decisions impose to society (Parry and Small, 2005), congestion and related pollutant emissions are considered as costly "urban externalities", thus justifying the implementation of policies aimed at reducing car traffic in cities (OECD, 1996; ECMT, 2002): urban tolls, road space redesign, parking regulation, investments in/subsidization of mass transit systems… These interventions have been highly effective in European cities where the number of vehicle-kilometers (vkm) travelled by cars has decreased over last decades (EC, 2015; UITP, 2015). However, they hardly reduce the number of vkms travelled by freight vehicles. Commercial transport operators have basic needs in terms of flexibility, reliability and door-to-door trips (Shinghai and Fawkes, 2002; Danielis and Marcucci, 2005), which makes modal-shift very difficult due to the many advantages of vans or trucks to deliver goods in urban areas. As a consequence, freight trips and related congestion remain challenging issues for local authorities (Nemoto et al., 2005).[1]

Whereas road congestion generated by private cars has been studied extensively, research addressing jointly time losses for passenger and freight vehicles over an entire urban area is less common. This article assesses marginal congestion costs in the case of multi-class traffic for the Paris Region, Ile-de-France (IDF). Our contributions to the literature are the followings:

First, academic research has mostly focused on the effects of large vehicles (trucks) on small vehicles' (cars' and vans') travel times. By contrast, few studies deal with the "reciprocal" phenomenon. We here estimate both types of time losses which allows us shedding some light on the relative impacts of large vehicles on cars', vans' or trucks' travel times, and *vice-versa*. Such a result should be useful for further investigations on trucks' tolling strategy (Holguin-Veras and Cetin, 2009; Figliozzi, 2007).

Second, traditional approaches for measuring road congestion mostly rely on simulated traffic data and on sophisticated assignment models (Yun et al., 2010; Ji et al., 2010). We investigate road congestion at a "macro" level, using information available in most urban areas and without looking precisely at the routes chosen by drivers. Since our simple method provides consistent results, it could be transferred to other cities.

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[1] In the Paris region, for instance, the objective of reducing freight vkms has led to the development of projects such as "Low Emission Zones" (Dablanc and Montenon, 2015), the use of existing tramway lines to carry goods (APUR, 2014), or networks of "urban consolidation centers" (Dablanc, 2005), although very few have gone beyond the stage of experimentation.

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Finally, studying the Paris region is interesting in its own right. Accounting for 22% of the national employment and for 18% of the French population in 2012, IDF is one of the most congested areas in Europe.[2] Moreover, the contribution of freight trips to these aggregate time losses has been largely under-researched; the majority of research focusing only on the effects of cars' trips (Leurent et al., 2009; Prud'homme, 1999). Since truck traffic on French local networks is "underpriced" as compared to its social cost (CGDD, 2009), this article could provide parameters useful for policy appraisals.

This research proceeds as follows: In section 2, we present the simple empirical strategy used to assess road congestion in a multi-class framework. Section 3 then details data on roads supply and demand in the Paris region. Econometric results are discussed in section 4. Building on these, we estimate the marginal times losses inflicted by each traffic class to each traffic class whereas section 5 translates these time losses into marginal congestion costs. Concluding remarks and further research are discussed in section 6.

2. Empirical strategy

2.1. BPR functions with large vehicles

We define road congestion as a phenomenon that occurs when a given infrastructure – characterized by fixed capacities – cannot satisfy the demand it faces without decreasing the quality of service proposed to users. Hence we only focus on "recurrent" congestion and we ignore disturbances caused by accidents or civil-works (Skabardonis et al., 2003). Moreover, the service quality is restricted to the travel time spent by individuals on the roads: we neglect the effects of congestion on departure and arrival times (Noland and Small, 1995) or on drivers' productivity and psychological states (Weisbrod et al., 2001).

Engineers have developed various methods to assess road congestion (Spiess, 1990; TRB, 2010; Small and Verhoef, 2007), either from the vehicles' perspective ("cars-following" models) or from that of the infrastructures ("link-based" models). Even if the mathematical specification chosen to characterize the "supply function" strongly impacts the outcome (Stopher and Stanley, 2014), later family of studies generally relies on the relationship between the travel time and the flow of vehicles using the infrastructure, as designed by the American Bureau of Public Roads (the so-called "BPR function"):

$$D = D^0\left(1 + \alpha\left(\frac{F}{K}\right)^{\beta}\right) \tag{1}$$

where D represents the travel time necessary to perform 1 km on the considered road, D^0 is the "empty road" travel time (derived from the maximal authorized speed), F is the hourly vehicles flow (per kilometer of road) and K is the theoretical capacity (in vehicle/hour/kilometer, a function of the road's width and number of lanes).

In this framework, road congestion is characterized by $\alpha\ (>0)$ and $\beta\ (>0)$ parameters that express the increase in travel time as compared to the empty road travel time when the "flow-to-capacity ratio" ($\text{FCR} = {F}/{K}$) grows. Obviously, these parameters differ across the types of roads and the geographical areas (Webster and Elefteriadou, 1999).

Equation (1) does not take into consideration multi-class traffic: F is thus viewed as a flow of homogeneous vehicles, while large vehicles (trucks, buses) may impact differently the travel times as compared to small vehicles (cars, vans). To bypass this shortcoming, one can differentiate the total flow across traffic classes S (for "small vehicles") and L (for "large vehicles") and re-write equation (1) as proposed by Setra (2001) or Moridpour and al. (2015):

$$D = D^0\left[1 + \alpha\left(\frac{F_S}{K} + \phi\frac{F_L}{K}\right)^{\beta}\right] \tag{2}$$

where F_S represents the hourly flow of small vehicles, F_L the one of large vehicles, and F_T the total traffic flow ($F_T = F_S + F_L$).

The congestion impact of large vehicles is playing here through the ∅ parameter which describes the "passenger car equivalency factor" (PCEF). The Highway Capacity Manual (TRB, 2010) defines it as the "number of passenger cars that are displaced by a single heavy vehicle of a particular type under prevailing roadway, traffic and control conditions". Estimated values for PCEF vary greatly, from 1.5 to 5.[3]

Alternatively, Yun and al. (2010) suggest adapting equation (1) so that:

$$D = D^0\left[1 + \alpha\left(\frac{F_S}{K}\right)^{\beta}\left(1 + \frac{F_L}{F_T}\right)^{\delta}\right] \tag{3}$$

As compared to equation (2), no PCEF is displayed here. The parameter δ (>0) rather describes the increase in the travel time when the share of large vehicles within the total traffic (${F_L}/{F_T}$) is higher. It is worth noting that both equations (2) and (3) collapse to equation (1) if there is no single truck on the considered road ($F_L = 0$).[4]

Equations (1)–(3) present some limitations. First, they are not reliable if the FCR is close to the unity, i.e. the so-called "hyper-congestion regime" (Verhoef, 2001; Small and Chu, 2003). When roads capacities are saturated, the marginal vehicle reduces both the travel time and the traffic flow due to the formation of one bottleneck at road's entrance. Put differently, the BPR relationship is in reality non-monotonic for high levels of road demand. This explains why many researchers have proposed alternative specifications, for urban arterials in particular (Akçelik, 1991; Spiess, 1990).

The second drawback is data requirements. In order to calculate time losses for an entire agglomeration, one needs extensive traffic datasets. Yet, road counts and captors do sometimes exist, but they are scarce and not always reliable. Therefore, most studies rely on simulated data (Yun et al., 2010; Ji et al., 2010), making it difficult to generalize results from a specific infrastructure to the adjacent roads.

Last, but not least, these equations focus on the average travel time. However, it may be the case that the incremental journey time due to a marginal vehicle is heterogeneous: for example, the marginal truck is likely to affect differently the travel time of small vehicles and the one of large vehicles. The empirical strategy proposed below aims at solving some of these problems.

2.2. Reduced forms

In this research, we do not attempt to estimate the structural parameters of the congestion functions shown in equations (2)–(3), as done by Yun et al. (2010) for instance. Our reduced form approach rather approximates the respective influence of the different explanatory variables, in isolation to others. Actually, our empirical analysis focuses on individual trips performed over some large geographical areas rather than traffic speeds recorded over specific road segments. Looking at macro congestion functions is standard for passenger trips (Prud'homme, 1999; Mayeres et al., 1996; Geroliminis and Daganzo, 2008; Couture et al., 2016), less so in a multi-class framework.

We illustrate our empirical strategy with equation (3), where the flow of trucks is expressed as the share of large vehicles within total traffic. In

[2] More than 62% of kilometers of delays registered in France are located in IDF (URF, 2013), where motorists spent in 2013 an average of 55.1 h per year in traffic jams, only behind London and Stuttgart (INRIX, 2014).

[3] The effect of several variables on PCEF has been studied (Webster and Elefteriadou, 1999): roadway grades, length of grades, percentage of truck in the traffic stream, trucks' weight-to-power ratio, truck length, number of lanes, free-flow speed of the traffic, traffic flow rates ….

[4] Interested readers may refer to Müller and Schiller (2015) who propose additional specifications of travel time-flow functions accounting for truck traffic.