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UNIVERSITÉ PARIS EST

Mémoire d'habilitation à diriger des recherches

Design and evaluation of transportation policies: merging economics and engineering

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Acknowledgement

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1. Introduction

Before presenting my published, ongoing, and planned research (Section 1.4 through Section 5), I will first discuss how my current scholarly positioning has been shaped by my academic background (Section 1.1). I will then highlight the important role of teaching and mentoring in my academic career (Section 1.2) and finally discuss my involvement in research management (Section 1.3).

1.1 Academic background and scientific positioning

My research operates at the intersection of transportation economics (and to a lesser extent urban economics) and transportation engineering (which encompasses engineering systems representation and numerical modeling of cities and their mobility systems). By merging these two disciplines, I aim to improve the design and evaluation of mobility services and transport policies. This includes better understanding and assessing the private and external costs of mobility and better accounting for user responses to these costs.

My interest in economics and modeling started in 2001 at Ecole Polytechnique (France), where I chose to major in economics and applied mathematics. After joining the Corps des Ponts et Chaussées in 2003, I became increasingly interested in cities and transportation, so I again chose to major in economics with a minor in urban planning and transportation. Planning to pursue a PhD, I enrolled in the master's program in economic analysis and policy at Paris-Jourdan Sciences Economiques (now PSE-Ecole d'économie de Paris) in 2006. My thesis, written under the supervision of Fabien Leurent (CIRED) and Harris Selod (World Bank & PSE), explored the links between land use - transport interaction models and the canonical model of urban economics, the monocentric model.

After completing my master's degree, I did my PhD at the Laboratoire Ville Mobilité Transport (LVMT), again under the supervision of Fabien Leurent (then also at LVMT, and since 2021 at CIRED). The topic was the analysis of households' residential strategies and the role of transportation costs.

The dissertation allowed me to engage in both theoretical work based on the monocentric model (which eventually led to two publications in 2017, "Prudential measures in housing access: should one include transport costs in the front-end ratio?" in the *Journal of Transport and Land Use*, followed by "Why housing and transport costs should always be considered together: A monocentric analysis of prudential measures in housing access?" in *Transport Policy*), and in empirical work combining survey data with simulation models (which led to a 2013 article co-authored with Fabien Leurent, "Les ménages arbitrent-ils entre coût du logement et coût du transport : une réponse dans le cas francilien" in *Economie et Statistique*).

After defending my dissertation on February 10, 2010, I decided to deepen my knowledge in the field of urban modeling. Therefore, I participated as a post-doc in the European FP7 project SustainCity, led by André de Palma (then ENS Cachan, now CYU). The aim of the SustainCity project was to couple the UrbanSim land use model with dynamic transport models (METROPOLIS and MATSim). This gave me the opportunity to establish contacts with UC Berkeley, with a residency with Paul Waddell, as well as TU Berlin (Kai Nagel), EPFL (Michel Bierlaire), ETHZ (Kay Axhausen) and KU Leuven (Stef Proost). At this time, I also realized the potential of agent-based simulation for policy design and evaluation. In parallel, I started a series of works on reliability assessment together with André de Palma. These led to two companion publications in 2014, "Variability of travel time, congestion, and the cost of travel" in *Mathematical Population Studies* and "The marginal social cost of travel time variability" in *Transportation Research Part C*, followed in 2017 by "The valuation of travel time reliability: does congestion matter?" in *Transportation Research Part B*.

Finally, I joined the LVMT, a position I still hold today. I conduct both theoretical and empirical work, using mobility simulation models in the latter case. Recent papers have all been done in collaboration with co-authors from the Paris Est campus (LVMT, SPLOTT, CIRED, CEREA...), from other research teams in France (CYU, LAET, Paris Dauphine, Védécom, SystemX...) and from abroad (TokyoTech, VTI, Imperial College, University of Chile, HEIG-VD…). As these works are often carried out

in the framework of multidisciplinary projects, they can be published either in general economics journals (*Economie et Statistique, Network and Spatial Economics, Review of Industrial Economics*) or in journals publishing research in the field of transport economics (*Transportation Research Part B and C, Journal of Transport Geography, Transport Policy*...), or in multidisciplinary journals (*Journal of Cleaner Production, Energy Research and Social Science, Mathematical Population Studies*...).

Through my academic training and post-doctoral research activities, I have acquired expertise in both transport modeling (theoretical and numerical) and transport economics. This has allowed me to become a honed expert in the design and evaluation of sustainable mobility strategies, focusing on the one hand on new mobility services (autonomous vehicle-based services, ridesharing, e-scooters…) and on the other hand on more comprehensive (in terms of better addressing environmental and equity aspects) evaluation methods. I believe that my unique dual profile (engineer/economist) will be central in achieving this goal, as I will outline in this manuscript, and have therefore sought to further refine this dual profile through other activities such as teaching, supervision, and science management.

1.2 Teaching and supervision

Since the beginning of my PhD, I have been actively involved in teaching at the Ecole des Ponts ParisTech and more recently at the Paris School of Economics. I started with courses on territorial analysis, combining lectures and seminars with a transport-oriented GIS (TransCAD). From 2008 to 2015, I taught the computer seminars for the "Methods of Analysis of Territorial Systems" course (39h/year) and delivered part of the lectures. Due to the success of this first experience, I was asked to teach the new course "Territorial Analysis" (28h/year) in the Master Engineering and Management of Smart Cities from 2014 to 2020. In addition to these courses on territorial analysis, since 2009 I have contributed to the course "Urban and Regional Planning" (65h/year), which I finally took over in 2015. This course deals with the links between transport and territory, with a multidisciplinary approach that also includes an important economic dimension (urban economics, economic appraisal and cost-

benefit analysis...). Having taught more transport engineering related courses, I recently decided to also teach courses in transport economics to better balance my dual profile. Therefore, in 2018 I developed a new course "Economics of Transportation" (18h/year) for the MSc Sustainable Impact Analysis (SIA) of PSE and Ecole des Ponts. I then also successfully applied to take over the teaching of the "Economics of Transportation" course (20h/year) in 2020, which is shared between the Transport et Développement Durable and Transport Mobilité MSc courses of Ecole des Ponts and Ecole d'Urbanisme de Paris.

My teaching has contributed significantly to my research activities in three ways. First, teaching itself has allowed me to improve my understanding of the topics I teach. Second, several courses involve projects with economic or institutional partners, which has given me the opportunity to explore new research topics (e.g., the economic appraisal of e-scooters through successive projects with Lime, Ville de Paris, and finally Tier), projects that have also allowed students to combine an economic approach with simulation models, as I do in my research. Last but not least, teaching has allowed me to be in contact with a large pool of highly qualified students, which has helped me to develop my supervisory activities, which are also closely connected to my research.

In fact, in addition to teaching, I have chosen to be actively involved in mentoring students for three reasons. The first two are related: It is to expand my network in the socioeconomic world and to keep abreast of the state of the practice in occupational research. Both of these can indeed benefit my research by opening up new avenues of research and making it easier to find partners for research projects. The third reason is simply to find good potential candidates for future PhD or research positions. So, along with the academic supervising of more than 70 dissertations since 2010 (final year project, professional assignment, internship thesis), I have overseen more than ten dissertations (research thesis, final year project). These include papers in the field of transport economics, such as the dissertation by Louis Anderson Joseph (M2 Economie et Management Public, Montpellier Faculty of Economics) entitled "Subjective valuation of access, waiting and transfer times in rail transport",

which I supervised with Philippe Poinsot (LVMT), or Baptiste Bernadac's thesis for the M1 Master in Economics (Ecole Normale Supérieure Paris - Saclay and Ecole Polytechnique) on the economic analysis of carpooling, which I supervised with André de Palma (CYU). I have also supervised papers more concerned with modeling, such as Flora Delhomme's dissertation entitled "Study of the synergies of CO2 emission reduction policies in the transport sector and urban planning" within the M2 Economics of the Environment, Energy and Transport (AgroParisTech - Université Paris Saclay), which I supervised with Vincent Viguié (CIRED). I have also been involved in the supervision of about fifteen student projects (capstone projects at PSE, in-depth projects at ENPC), mainly dealing with transport economics issues (including economic appraisal through cost-benefit analysis, e.g. for self-service electric scooters or comparison of regional services by train or bus). Several of these efforts have resulted in presentations at conferences and working papers that have either been submitted or are in progress. They have also allowed me to establish contacts with students who are now pursuing PhDs either under my supervision (Rayane Alamirdache) or abroad (Mwendwa Kiko at the College of Toronto, Baptiste Bernadac at MIT), paving the way for future possible collaborations.

Finally, I have participated in the supervision of several PhDs, either officially or unofficially. Officially, I co-supervised with Fabien Leurent (CIRED) the PhD dissertation of Vincent Lasserre in housing economics entitled "Housing consumption, residential trajectories and home ownership in Île-de-France: a modeling approach", defended on May 4, 2020. I had the opportunity to supervise part of the PhD dissertation of Xiao Yu (TokyoTech) during a 3-month stay at LVMT to further develop my work on the valuation of reliability, resulting in a publication in *Transportation Research Part B* in 2017. Based on this positive experience, I have sought to develop new work related to rail operations and the economics of rail systems, including the issue of reliability. Therefore, I informally supervised the dissertation of Maria Perez Herrero (LAET), which yielded two presentations at the International Transportation Economics Association conference (ITEA) in 2017. Then I also supervised part of the PhD dissertation of Abderrahman Ait Ali (Linkoeping College & VTI), again during a three-month stay at LVMT in 2019, to develop work on rail capacity allocation based on the social costs of public and

private rail services. I am currently supervising (by dispensation) the dissertation of Félix Carreyre on the economic appraisal of autonomous mobility services, with Laurent Bouillaut (GRETTIA) and Jaâfar Berrada (Védécom) as co-supervisors. I also co-supervise the PhD dissertation of Marjolaine Lannes, directed by Yelva Roustan (CEREA), which analyzes the uncertainties in the mobility - emissions - air quality modeling chains or, more precisely, in the exposure calculations. In addition to PhD students, I have supervised numerous post-doctoral fellows (Julie Prud'homme, Liu Liu, Biao Yin, Cyrille François, Tatiana Seregina...) in the framework of research projects (Lab Recherche Environnement, ANR projects...), leading, among others, to two publications on urban ridesharing in the *Journal of Cleaner Production* and *Transportation Research Part D*.

1.3 Science Management

After starting at LVMT, one of my desires was to participate in leading research in transport economics and mobility modeling.

At the level of my research unit, I have been leading the research axis "Territorial Design" together with Alain L'hostis since 2013. We organize research seminars based on internal contributions or works by invited researchers. For example, we invited Joel Franklin (VTI) in 2019 to talk about congestion pricing, or Toma de la Barra (Universidad Central de Venezuela) in 2016 to collaborate on integrated transport - land use modeling.

Regarding research projects, I have led for Ecole des Ponts the ANR CITiES project on urban modeling and the PREDIT MOBILLETIC project on smart card data analysis in Rennes (France). Since 2018, I have been helming the Lab Research Environment Vinci ParisTech grant chair (€1.2M/year grant to ParisTech, of which I directly manage about €300K per year). The chair funds research and teaching on urban eco-design (from buildings to neighborhoods) and infrastructures (especially highways). I also lead the PRIMEQUAL POLL-EXPO project on prospective modeling of local pollution exposure, and am currently involved in setting up PIA4 projects. I am also implicated in several research projects, such as

the EVRA SAM project (total €110 million, of which about €1 million for LVMT) on the evaluation of autonomous mobility services, where I lead the economic appraisal. In these projects, I seek to further develop the use of agent-based models for the design and evaluation of mobility services and policies, including better consideration of environmental impacts (using life-cycle analysis) and distributional effects of projects, as I will explain in Section 4.

I also participate in the preparation of national/international conferences and scientific events. For example, I was a member of the scientific committees of the TRISTAN conference and the Third Society for Benefit-Cost Analysis European Conference in 2022, and I am vice-chair of the conference board of directors of the Toulouse School of Economics (TSE), which applied to host WCTR 2025.

Regarding scientific networks, I was a member of the Steering Committee and the Scientific Committee of the DIM QI2 network on air quality funded by the Île-de-France Region (Paris) from 2017 to 2021. Building on my network established in the SustainCity project, I organized an international event on agent-based modeling in Paris on September 26, 2019, with the support of the Paris Region Institute, where Kay Axhausen and Kai Nagel gave two keynotes. Following this event, I then sought to consolidate the agent-based community at the national level through the creation of a social network (slack MATSim Francophonie with more than 40 members), complemented by a seminar entitled "Modélisation multi-Agents et tRansporT" (SMART). I also participated in the creation of the new French Association of Transport Economics (AFET), chaired by Marc Ivaldi (TSE), of which I am a member of the steering committee.

Finally, I have been and continue to be involved as an expert in several national and international studies or working groups. For example, I recently conducted two counter-assessments on the economic appraisals of the Grand Paris Express. I am currently co-executive of the inter-ministerial working group on the update of time values in France and a member of the international working group helmed by the International Transport Forum on the financing of public transport networks.

1.4 Organization of the work's synthesis

After presenting my academic background and a brief reminder of my involvement in research, teaching, and mentoring activities, I will now discuss a selection of my research papers that illustrate well my dual profile as an economist and engineer and that are also directly related to my research project (which I will develop in Section 4).

Cities face two competing challenges in the area of transportation. The first is to ensure their economic development and the quality of life of their residents (permanently or temporarily for tourists) through efficient transportation systems. The second is to ensure their environmental transition in order to meet their environmental commitments, particularly with respect to greenhouse gas emissions, biodiversity, and air quality. The issue of mobility-related costs, both private and external, monetary and non-monetary, is therefore at the heart of these two challenges and the associated public policies and trade-offs.

$$GP = p + \mathrm{VTTS} \cdot T$$

The generalized price reflects the tradeoff between price and time that any user would make by adding the monetary cost of the trip p to the non-monetary cost VTTS$\cdot T$, which is the opportunity cost of the time spent traveling. The latter depend on the value of travel time savings VTTS and travel time T. In the French guidelines for the economic appraisal of transport projects, the value of time is uniform in the first editions, reflecting the focus on speed. The consideration of quality of service was introduced in 1964, but was limited to comfort on highways (Meunier, 2019). However, several studies indicate that users increasingly care about dimensions other than speed, including convenience (Haywood et al., 2017; Li and Hensher, 2011; de Palma et al., 2017), reliability (Börjesson et al., 2012; de Palma and Picard, 2005), and safety (Schoeters et al., 2021). This raises the question of how to define and measure the different dimensions of service quality and how to integrate them into economic appraisal.

Regarding the environmental transition, the joint development of models of travel demand and pollutant emissions has led to a better understanding of the external costs of transport. For

example, road transport in the Paris region has an environmental cost of around €6 billion/year, equivalent to about 1% of regional GDP (Coulombel et al., 2018): This includes climate change costs (due to greenhouse gas emissions) and health costs (due to emissions of local pollutants and population exposure). Thus, although the environmental externalities associated with road transport are now relatively well known (see also Leroutier and Quirion, 2022), several gray areas remain, particularly with respect to public transport and, more importantly, freight transport. To consider all environmental issues and impacts (local or global or both), one must go beyond direct emissions and conduct a life-cycle analysis (Nichols and Kockelman, 2015).

In my work, I combine transportation economics and engineering to better understand and evaluate the costs associated with the mobility of people and goods and the implications for public policy design and evaluation. In Section 2, I present a body of work that contributes to a better understanding of travel time reliability costs and easier integration into economic appraisal. Then, in Section 3, I develop contributions aimed at better accounting for travel costs and their impact on user behavior in transportation policy design, focusing first on pricing instruments and then on travel demand management measures. I then discuss my research project in Section 4 before concluding in Section 5.

This synthesis of my work is based on a selection of 8 articles, 6 of which have already been published and 2 of which are still under review. Despite their thematic proximity, some papers are not presented here for the sake of conciseness and clarity. These include publications analyzing the difficulties that travel costs can cause for households by examining the notion of fuel poverty in the transport sector (publication in *Energy Research and Social Sciences*), as well as the risks faced by remote households that do not include travel costs in their housing choices (publication in *Economie & Statistique*) and measures to protect them (publications in *Transport Policy* and the *Journal of Transport and Land Use*).

2. Valuation of travel time reliability

I present in this section a series of theoretical works dealing with the valuation of travel time reliability. These works aim to better define and understand this notion, and to make it more operational for easier integration in the economic appraisal of road or public transportation projects.

2.1 General principles

Travel time variability entails two main forms of cost for users (Bates et al., 2001). The first one stems from scheduling considerations: travel time variability disrupts one's activity schedule through early or late arrivals at destination. In the extreme case, the delay may cause the cancellation of one or several activities, like missing one's plane for a conference or being excessively late at a meeting. A second potential source of cost relates to that some individuals might distaste travel time variability *per se*. The unpredictability of travel times would generate some form of anxiety or would involve additional planning costs (Noland et al., 1998).[1] Although the relative importance of these two phenomena - which prove difficult to disentangle econometrically - remains controversial (Börjesson et al., 2012), several works suggest that the scheduling account prevails in this matter (Noland et al., 1998; Hollander, 2006; Fosgerau et al., 2008). Accordingly, we will focus our analysis on scheduling costs and disregard other potential sources of cost.

Consistent with this assumption, the scheduling model allows to study how and to what extent travel time variability disrupts schedules, thus generating costs for transport users. In this model, an individual wishes to move from A (*e.g.* home) to B (*e.g.* work). Scheduling models assume that the individual derives a utility from each activity that depends on when it is performed, and for how long.

[1] One can then make a link with the financial economics literature dealing with risk aversion (Beaud et al., 2016). Applying this methodological framework, de Palma and Picard (2005) estimate risk aversion for route choice. They find both risk averse and risk seeking behaviors, implying that travel time variability could in some cases be a benefit rather than a cost. This possibility is not considered here, but will be the object of future works.

Moving from A to B allows the individual to switch activities when performing a new activity at B provides him a greater utility than keeping doing the same activity at A. Let t_D be the departure time, T the travel time, and $t_A = t_D + T$ the arrival time. Utility takes the following form:

$$U(t_D, T) = \int_{t_h}^{t_D} h(t)dt + \int_{t_A}^{t_w} w(t)dt = H(t_D) - W(t_D + T) \tag{1.1}$$

The functions $h(t)$ and $w(t)$ represent the instantaneous utility or marginal utility of time (MUT) that the individual derives from being either at home or at work at time *t.* Both functions are expressed in monetary terms and relatively to the marginal utility of travel time, which has been normalized to 0. The constants t_h and t_w represent the beginning and the end of the time period considered, for instance the morning period for the analysis of commuting trips. Alternatively, utility can be written using the functions H, the primitive of h that zeroes at t_h, and W, the primitive of w that zeroes at t_w. It is assumed that the marginal utility at home $h(t)$ decreases with t, while the marginal utility at work $w(t)$ increases with t.

Let us first consider the case where the travel time is certain, and therefore deterministic. Departing one minute later/earlier than t_D entails a marginal benefit/loss $h(t_D)$ from staying more at home, but a marginal loss/benefit $w(t_A)$ from spending less time at work. As illustrated in Figure 1, the two are perfectly compensated at the optimal departure time t_D^* (Tseng and Verhoef, 2008):

$$h(t_D^*) = w(t_A^*) \tag{1.2}$$

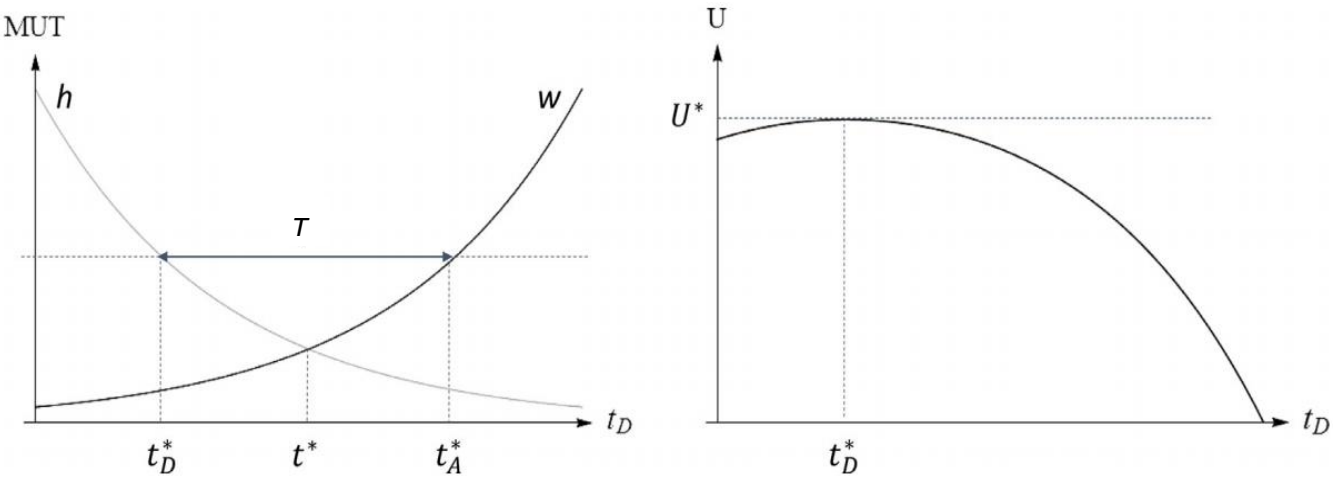
The optimal utility is then given by $U^*(T) = U(t_D^*, T)$.

The scheduling model therefore allows to derive the value of travel time savings (VTTS) as the marginal disutility (expressed in monetary terms) associated with a marginal variation of travel time:

$$\text{VTTS}\ (T) = -\frac{dU^*(T)}{dT} \tag{1.3}$$

From the envelope theorem, the VTTS is then given by: $\text{VTTS}\ (T) = h\big(t_D^*(T)\big)$.

Figure 1 : Optimal choice of departure time in the scheduling model



Source : Xiao et al. (2017)

In order to study the value of reliability, the usual approach is to transform the deterministic travel time T into a random variable $\tilde{T}$ (see e.g. Bates et al., 2001; Fosgerau and Karlström, 2010; Noland and Small, 1995):

$$\tilde{T} = \mu + \sigma\tilde{x} \tag{1.4}$$

μ represents the mean and σ the standard deviation of travel time. The term $\tilde{x}$ is a unit random delay (with mean 0 and variance 1). The probability and cumulative distribution functions of $\tilde{x}$ are noted f and F, respectively.

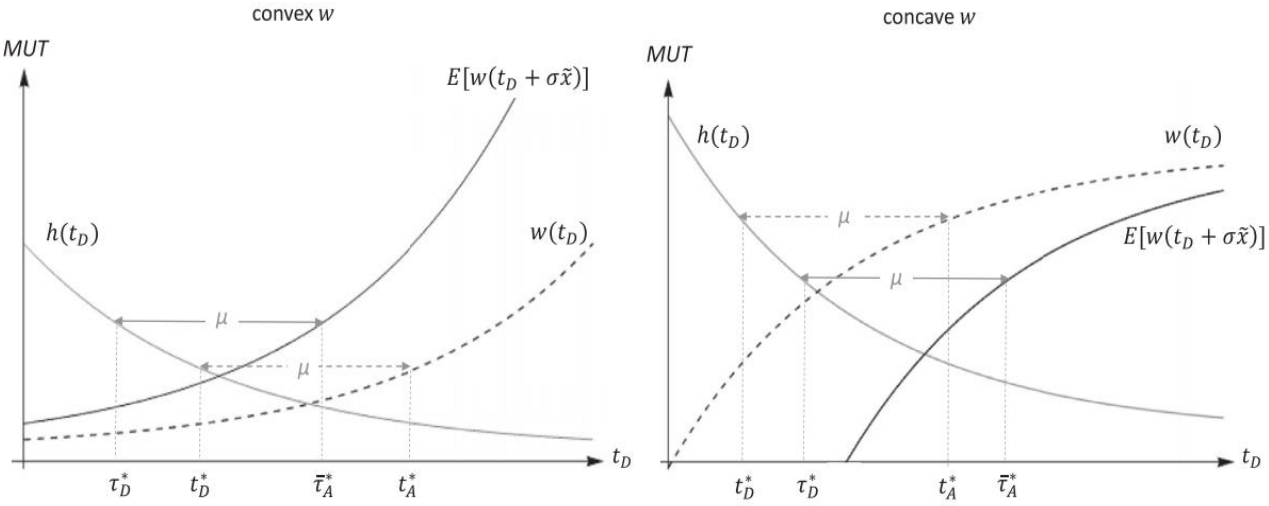
Considering that travel time is now random, the individual chooses his departure time based on his expected utility:

$$u(t_D, \mu, \sigma) = \mathbf{E}\big[u\big(t_D, \tilde{T}\big)\big] = H(t_D) - \mathbf{E}\big[W\big(t_D + \tilde{T}\big)\big] \tag{1.5}$$

Utility at home $H(t_D)$ remains deterministic, while utility at work $-W\big(t_D + \tilde{T}\big)$ becomes stochastic, so that its expected value should now be considered: the user knows when he leaves with certainty, but not when he arrives. The new optimal departure tile τ_D^* is given by (Jenelius, 2012) :

$$h(\tau_D^*) = \mathbf{E}[w(\tau_A^*)] \tag{1.6}$$

Figure 2 : Choice of departure time under deterministic (dashes) or stochastic (plain) travel times



Source : Xiao et al. (2017)

The new condition is similar to the one in the deterministic case, except that due to the random term, the individual now considers the expectation of the marginal utility of time at work $\mathbf{E}[w(\tau_A^*)]$. In the paper co-authored with Yu Xiao and André de Palma (Xiao et al., 2017), we show that the influence of travel time variability on the departure time depends on the convexity of the function *w*. If *w* is convex, the individual leaves earlier than when the travel time is certain, while if *w* is concave, the individual leaves later (Figure 2). The convexity of *w* is indeed related to the relative costs of being early or late. If *w* is convex, being one minute late implies a cost greater than the gain from being one minute early, even more so as time passes. Taking a margin by leaving earlier then reduces the difference between the cost of being late and the gain of being early. On the other hand, if *w* is concave, being one minute late always generates a greater cost than being one minute early, but cost decreases as time passes. In this case it is better to take a negative margin, i.e. to depart a little later.

The Value of Reliability (VoR) - also sometimes called Value of Travel Time Variability (VTTV) - is then defined as the marginal disutility (in monetary terms) associated with a marginal increase in the standard deviation σ of travel time (Carrion and Levinson, 2012):[2]

[2] This corresponds to the case where the indicator chosen to measure the variability of travel times is the standard deviation, which is the standard practice. The definition can be easily generalized to other indicators

$$\mathrm{VTTV}(\mu,\sigma) = -\frac{\partial u^*(\mu,\sigma)}{\partial \sigma} \tag{1.7}$$

where $u^*(\mu,\sigma) = u(\tau_D^*,\mu,\sigma)$ is the maximum expected utility when leaving at the optimal departure time τ_D^*. In the scheduling model, the value of reliability is given by the formula (Jenelius, 2012):

$$\mathrm{VTTV}(\mu,\sigma) = \mathbf{E}\left[w\left(\widetilde{\tau_A^*}\right)\tilde{x}\right] \tag{1.8}$$

In Xiao et al. (2017) we formally show the value of reliability to be positive and to strictly increase with σ if w is C^1. The influence of the mean travel time is more complex: if utility at home h is constant, the VTTV is independent from μ. Otherwise, the VTTV increases/decreases with μ depending on whether utility at work w is convex/concave.

To illustrate these various results, Table 1 summarizes how the optimal departure time and the value of reliability vary according to the scheduling preferences, by considering the 3 most frequent classes in the literature:

- linear MUT, which lead to the mean-variance model for the maximum expected utility (Fosgerau and Engelson, 2011);
- constant-exponential MUT : after the mean-variance model, they lead to the second only other possible form of an additive model over trip legs (Engelson and Fosgerau, 2011);
- constant-step (Heaviside function) MUT, also called (α,β,γ) preferences in reference to their widespread use in the bottleneck model (Arnott et al., 1993; Vickrey, 1969), which lead to a mean-standard deviation model (Fosgerau and Karlström, 2010).

Although each class of preferences uses its own metric for variability -such as variance for linear MUT or standard deviation for the (α,β,γ) case - the VTTVs presented in Table 1 are all calculated using the standard deviation metric to make the comparison easier.

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such as the variance (Fosgerau and Engelson, 2011) or the interquartile range. See de Jong and Bliemer (2015) for a discussion of the value of reliability and the choice of indicators for inclusion in cost-benefit analysis.

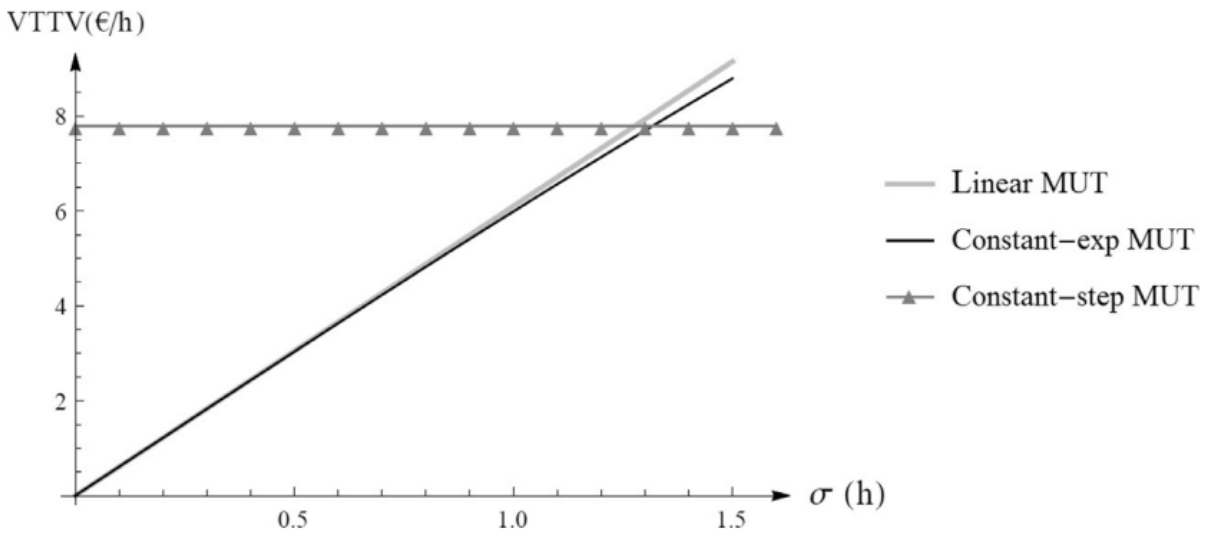
Table 1 : Scheduling preferences, optimal departure time and value of travel time variability

	Linear MUT Fosgerau and Engelson (2011)	Constant-exp MUT Engelson and Fosgerau (2011)	Constant-step MUT Fosgerau and Karlström (2010)
$h(t)$	$\beta_0 + \beta_1 t$	β_0	α
$w(t)$	$\gamma_0 + \gamma_1 t$	$\beta_0 + \eta(e^{\lambda(t-t^*)} - 1)$	$\alpha - \beta + (\beta + \gamma) * \mathbf{1}_{t \geq t^*}(t)$
$\tau_D^*(\mu, \sigma)$	$t^* - \frac{\gamma_1}{\gamma_1 - \beta_1}\mu$	$t^* - \mu - \lambda^{-1} \ln \mathrm{E}[e^{\lambda\sigma\tilde{x}}]$	$t^* - \mu - \sigma F^{-1}(\frac{\gamma}{\beta+\gamma})$
VTTV(μ, σ)	$\gamma_1 \sigma$	$\eta \frac{\mathrm{E}[\tilde{x}e^{\lambda\sigma\tilde{x}}]}{\mathrm{E}[e^{\lambda\sigma\tilde{x}}]}$	$(\beta + \gamma) \int_{\frac{\gamma}{\beta+\gamma}}^{1} F^{-1}(s) ds$

Source : Xiao et al. (2017)

We propose a numerical illustration based on the results from Hjorth et al. (2015), who estimate the three classes of preferences for car drivers from the Stockholm region. The study sample is divided into two subsets, depending on whether the respondent reports having flexible or fixed working hours. In line with intuition, the authors find that the linear and constant-exp specifications perform better for flexible working hours, whereas the (α, β, γ) specification is better suited to fixed working hours. Accordingly, we use in our illustration the parameter estimates from the flexible working time subset for linear and constant-exp MUT, and from the fixed working time subset for (α, β, γ) MUT (Figure 3). As shown in Xiao et al. (2017), the VTTV all strictly increase with σ, except in the constant-step case due to the non-regularity of w (which is only piecewise-C^0 and not C^1). The VTTS adding up to 8.87 €/h for individuals with flexible working hours and to as low as 2.34 €/h in the case of fixed working hours, the VTTV is relatively to the VTTS non negligible over the whole population, and even very high for the

Figure 3 : Influence of scheduling preferences on the value of travel time variability



Source : Xiao et al. (2017), computation based on the results of Hjorth et al. (2015)

users with the most constrained schedules, which is again in line with intuition. This is also consistent with the figures reported by Small and Verhoef (2007), who provide some typical short-run costs for automobile travel in the US. According to these figures, schedule delay and unreliability generate an average social cost of 0.09 $/vehicle.mile, which is around one third the cost of (average) travel time, and a marginal social cost of 0.17 $/vehicle.mile, this time around half the cost of (average) travel time. Considering that travel time costs of road traffic represent around 60-70 M€/day in the Paris region (Coulombel et al., 2018), this suggests that schedule delay and unreliability represent a cost of around 5 B€/year, that is around 1% of the regional GDP.

2.2 The case of road congestion

In the general framework that has just been introduced, travel time is assumed to remain constant. For road passenger transportation, while this assumption seems acceptable for the off-peak periods, it is not valid for peak periods, during which travel times vary rapidly under the effect of congestion. Since congestion is itself the result of departure time choices, which as we have seen are influenced by travel time variability, the question arises of the links between reliability, congestion, and user costs. This point echoes the statement of de Jong and Bliemer (2015) that three elements are needed to include reliability in cost-benefit analysis: 1) being able to estimate a monetary value of reliability, namely the VTTV, 2) incorporating user responses to reliability into travel demand forecasting models, and 3) being able to predict the impact of transportation projects or policies on travel time variability. Point 1) has been developed in 2.1. Point 2) is necessary because the VTTV, like the VTTS, only reflects individual preferences, and not how users collectively respond to travel time variability. However, noting that very few operational models explicitly represent the choice of departure time, the authors propose that the effect of reliability on mobility behavior be considered only in the choices represented in the model (typically mode choice and route choice, possibly destination choice), if at all. A more comprehensive treatment of reliability, including all aspects related to both supply and demand, would only be possible in the very long term.

In a series of works with André de Palma as well as Yu Xiao for the last one (Coulombel and de Palma, 2014a, 2014b; Xiao et al., 2017), we study to what extent the proposal of de Jong and Bliemer (2015) to ignore the effect of travel time variability on users' departure time choices in traffic forecasts - which currently corresponds to the standard practice - can induce biases in the cost-benefit analysis, and to what extent. In the first two works we consider (α, β, γ) scheduling preferences, and start by analytically solving the case of uniform random delays (Coulombel and de Palma, 2014b), then formally treat the case of a general distribution (Coulombel and de Palma, 2014a). In a final work we generalize the previous results to the case of general scheduling preferences. We also discuss the effect of preference heterogeneity on the cost of reliability.

In order to investigate the links between travel time variability, road congestion and user costs, we use the bottleneck model. This model allows to study the dynamics of road congestion during peak periods and the influence of departure time choices (de Palma and Fosgerau, 2011). It corresponds to the combination of the scheduling model, applied to a mass of commuters rather than to a single one, and a congestion technology, taking the form of a bottleneck model and allowing to represent the interactions between users.

Analogously to the case without congestion (or with exogenous congestion) presented in 2.1, we amend the standard bottleneck model by introducing a random delay in travel time:

$$\tilde{T} = \mu + \frac{Q(t_D)}{s} + \sigma\tilde{x}. \tag{1.9}$$

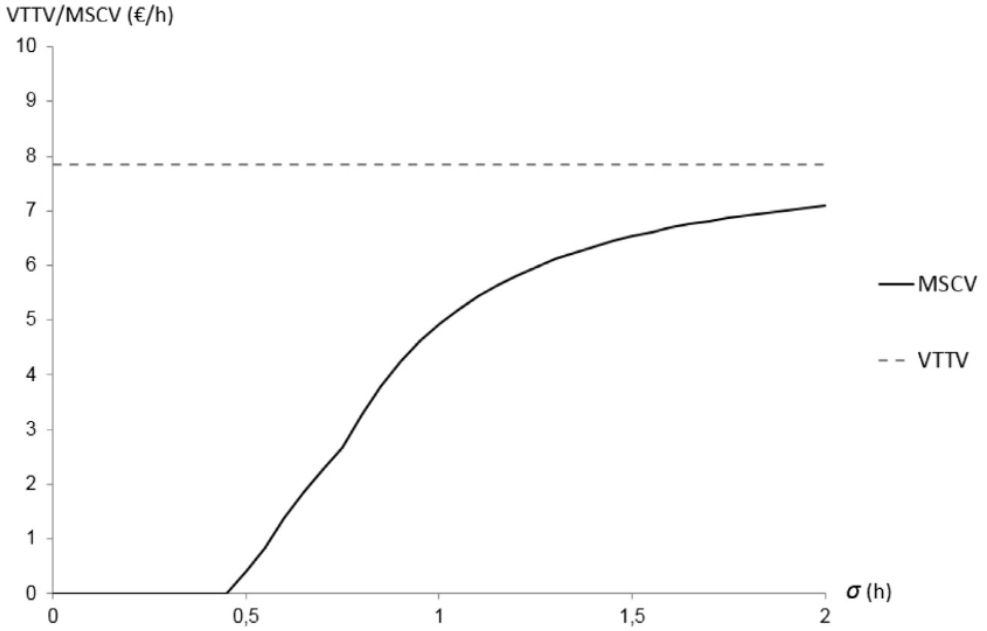
Travel time is thus now the sum of three terms: free-flow travel time μ, congested travel time $Q(t_D)/s$, and a random delay $\sigma\tilde{x}$. The time spent in congestion $Q(t_D)/s$ is the ratio between the queue length $Q(t_D)$ that the individual faces when leaving at time t_D, and the road capacity s that measures the outflow of the road infrastructure in vehicles per unit of time. Relatively to the case with no congestion, the mean travel time is no longer constant and equal to μ, but varies over the rush hour and is equal to $\mu + Q(t_D)/s$.

The mass N of commuters choose their departure time so as to maximize their expected utility, which now writes $u(t_D, \mu + Q(t_D)/s, \sigma)$. We show that there exists a traffic equilibrium in which all commuters have the same ex-ante utility, and that it is unique (Coulombel and de Palma, 2014a, Proposition 1 in the case of constant-step preferences; Xiao et al., 2017, in the case of general scheduling preferences). We then investigate to what the extent travel time variability σ affects the departure pattern and the equilibrium utility level. Regarding the first point, we show that if the function w - the marginal utility of time at work - is regular (C^2), variability shifts the rush hour according to the convexity of w: the rush hour starts earlier if w is convex, later if w is concave. Our findings are therefore similar to those obtained in the case without congestion. In the case of (α, β, γ) preferences, the function w is no longer regular. The impact of variability on the rush hour is then more complex, depending both on the relative values of the parameters β and γ, but also on the distribution of the random term. In the case of an exponential distribution, an increase in variability may for instance shift the rush hour later at first, but then earlier as the standard deviation of travel time keeps increasing (Coulombel and de Palma, 2014a).

While we obtain very similar results overall regarding departure times, the effect of a variation of σ on the equilibrium utility (endogenous congestion) can differ very strongly from the effect on the optimal utility (exogenous congestion). We define the Marginal Social Cost of travel time Variability (MSCV) as the marginal effect of a variation of σ on the equilibrium utility level. Relatively to the VTTV, the MSCV captures the system effect of the reaction of other users to the change in travel conditions. In the case of linear or constant-exponential MUT, the congestion profiles are quasi-independent of σ: σ does not influence the departure rate levels, only the timing of the peak hour, so that the evolution of travel times always follows the same profile. We formally demonstrate in this case the equality $\mathrm{MSCV}(\mu, \sigma) = \mathrm{VTTV}(\mu, \sigma)$. For these two classes of preferences, variability has little to no impact on users' departure time choices, so that including or not their reactions does not change the utility level. In the case of (α, β, γ) preferences, commuters react much more markedly to travel time variability: changes in departure times lead to a smoother departure rate profile and to a decrease in congestion.

In the case of uniform random delays, we thus show $\mathrm{MSCV}(\mu, \sigma)$ to be strictly lower than $\mathrm{VTTV}(\mu, \sigma)$, and to be even equal to zero for small values of σ (Figure 4).

Figure 4 : Comparison of VTTV and MSCV under (α, β, γ) preferences and uniform random delays



Source : Xiao et al. (2017), computations based on the results of Hjorth et al. (2015)

In the presence of preference heterogeneity, our numerical applications suggest that the cost of travel time variability is generally lowered compared to the case with homogeneous preferences, resulting from differentiated impacts on departure time choices across user classes.

In sum, our results show that the cost of variability is not the same with and without congestion, due to the influence of variable travel times on departure time choices. In the presence of congestion, changes in departure times have a feedback effect on travel times, which may change the equilibrium utility and subsequently the cost of variability. This difference between the costs of variability with (MSCV) and without (VTTV) and congestion varies greatly depending on the type of preferences, however, ranging from zero in the case of linear or constant-exponential MUT preferences (typically corresponding to activities with flexible schedules), to very high in the case of (α, β, γ) preferences (typically corresponding to activities with fixed schedules). We discuss the general implications for the evaluation of transportation polices in 2.4.

2.3 The case of public transportation

Theoretical works on the value of reliability mostly focus on road travel. While a few works do address the case of public transit, usually amending their model by making departure time a discrete variable (see for instance Fosgerau and Karlström, 2010), several specificities of public transit remain ignored. This includes the distinction between waiting time and in-vehicle time, which are valued differently by users (Wardman, 2014), or the relationship between headways, waiting time, and in-vehicle crowding. There are additionally two important drawbacks to the use of the VTTV in the case of public transit. The variability of total travel time, to which the VTTV is applied, is both difficult to measure (requiring individual user tracking) and less relevant in terms of public policy. Indeed, the operator has no leverage over the total travel time directly, but rather over the headways and in-vehicle time.

In a work with Vincent Benezech, we seek to overcome these limitations by adapting the scheduling model to the case of public transit (Benezech and Coulombel, 2013). We consider users with (α, β, γ) preferences reformulated as follows:

$$U(t_D, T_W, T_V) = -\alpha_W T_W - \alpha_V T_V - \beta(t^* - t_D - T_W - T_V)^+ - \gamma(t_D + T_W + T_V - t^*)^+. \qquad (1.10)$$

We break down the total travel time into the waiting time T_W, valued at α_W, and in-vehicle time T_V, valued at α_V. We focus the analysis on the case of direct trips, and on the effect of headway variability.[3] We thus assume that the access time (at the origin and destination) is constant, and taken to be zero (or included in T_V) to simplify calculations. Similarly, the in-vehicle time is assumed to be deterministic. Waiting time is a random variable, the distribution φ_W of which can be related to the cumulative

[3] In the paper we focus on the cost of headway variability for users, so that service frequency (headways) is treated as exogenous. The analysis of transit timetables can be carried out with dedicated train operation models in order to study their efficiency and robustness, with a fine consideration of the technical headway constraints (such as a minimum safe headway between two trains to reduce accidents). For a more economic perspective on the optimization of public transit timetables, see Coulombel and Monchambert (2023) presented here in 3.1 in the case of reliable headways, and Perez Herrero and Coulombel (2017) in the case of unreliable headways.

distribution function Φ_H and to the mean μ_H of headways using the renewal theory (Kleinrock, 1975; Osuna and Newell, 1972): [4]

$$\varphi_W(x) = \frac{1 - \Phi_H(x)}{\mu_H} \text{ if } x \in \mathbb{R}^+, \text{ 0 otherwise.} \tag{1.11}$$

As in the standard framework presented in 2.1, we study the effect of variability first on the choice of departure time, then on the optimal utility level. Compared to the optimal departure time $t^* - T_V$ in the absence of waiting time, we show that the presence of variable waiting times leads the user to take a margin equal to:

$$m^* = \Phi_W^{-1}\left(\frac{\gamma}{\beta + \gamma}\right) \tag{1.12}$$

We find an equation similar to that obtained by Fosgerau and Karlström (2010) in the standard case, with the cumulative distribution function corresponding to waiting time instead of the random delay as in Fosgerau and Karlström.

We then study the influence of headways on the optimal utility, considering a marginal variation of either the average headway, giving rise to the notion of value of service headway (VoSH), or the standard deviation of headways, giving rise to the notion of value of service reliability (VoSR). We obtain the following two formulas:

$$\begin{cases} \text{VoSH} = \dfrac{\alpha_W + \gamma}{2}\left(1 - \dfrac{\sigma_H^2}{\mu_H^2}\right) + \dfrac{\beta + \gamma}{\mu_H}\displaystyle\int_0^{m^*} (\Phi_H(x) - \Phi_W(x))dx \\ \text{VoSR} = (\alpha_W + \gamma)\dfrac{\sigma_H}{\mu_H} + \gamma\dfrac{\mu_H - m^*}{\sigma_H} - (\beta + \gamma)\dfrac{m^*}{\sigma_H} + 2\dfrac{\beta + \gamma}{\sigma_H}\displaystyle\int_0^{m^*} \Phi_W(x)dx \end{cases} \tag{1.13}$$

The formulas turn out to be relatively complex in the general case. Nevertheless, assuming that the headways follow a lagged exponential law [5] the formulas simplify, with the existence of two regimes.

[4] We assume that service frequency is high enough so that users do not look at the timetables and instead arrive on the platform with a uniform arrival rate. See Fosgerau (2009) for a justification of this assumption.

[5] This assumption is empirically validated in our case study of the RER A and RER D lines in the Paris region.

In the low variability regime ($\sigma_H/\mu_H \leq \beta/(\beta+\gamma)$), the formulas become:

$$\begin{cases} \text{VoSH} = \left(1 - \frac{\sigma_H^2}{\mu_H^2}\right)\frac{\alpha_W}{2} + \left(\frac{\beta}{\beta+\gamma} - \frac{\sigma_H^2}{\mu_H^2}\right)\frac{\gamma}{2} \\ \text{VoSR} = \frac{\sigma_H}{\mu_H}(\alpha_W + \gamma) \end{cases} \tag{1.14}$$

In the case of strong headway variability ($\sigma_H/\mu_H \geq \beta/(\beta+\gamma)$), we have:

$$\begin{cases} \text{VoSH} = \left(1 - \frac{\sigma_H^2}{\mu_H^2}\right)\frac{\alpha_W}{2} + \left(1 - \frac{\sigma_H}{\mu_H}\right)^2\frac{\beta}{2} \\ \text{VoSR} = \frac{\sigma_H}{\mu_H}\alpha_W + \left(1 - \frac{\sigma_H}{\mu_H} + \ln\left(\frac{\beta}{\beta+\gamma}\frac{\sigma_H}{\mu_H}\right)\right)\beta \end{cases} \tag{1.15}$$

We apply these results to two mass transit lines in the Paris region: the RER A, characterized by a high but irregular frequency ($\mu_H = 2{,}4$ min, $\sigma_H = 0{,}9$ min), and the RER E, having a lower frequency for a similar reliability level ($\mu_H = 7{,}8$ min, $\sigma_H = 1{,}0$ min). We set the scheduling parameters to $\alpha_V = 1$, $\alpha_W = 2$, $\beta = 0.8$ and $\gamma = 3$. This corresponds to normalizing the value of in-vehicle travel time to 1, while setting the value of the other parameters in ratios typical from the literature (Bates et al., 2001; de Palma and Fontan, 2001). We then obtain for the RER A line a VoSH of 1.02 and a VoSR of 1.71, compared to 1.27 and 0.64 respectively for the RER E. The cost of reliability relatively to frequency is therefore relatively higher for the RER A than for the RER E. This result is in line with intuition. For the RER A, the high frequency allows users to arrive as close as possible to their preferred arrival time t^*: any delay therefore causes a large deviation from t^* and induces a high cost. In the case of the RER E, the lower frequency implies that many riders often already arrive earlier or later than t^*. Since the variability of waiting times is already high to begin with, the additional variability caused by the irregularity of headways has a more limited impact.

The paper also considers in an extension the effect of taking into account in-vehicle congestion. We show that congestion does increase the cost of variability if the crowding cost function is convex. With uniform arrival rates, headway variability causes vehicle load to vary from their steady state level, some vehicles having smaller loads while other would have higher loads. If the crowding cost function is convex, the aggregate crowding cost then increases as a result.

2.4 Implications for cost-benefit analysis

The previous works allow to better take into account the specificities of each mode in the economic appraisal of transportation public policies, including the effect of the time of day (peak or off-peak).

For road travel, the peak period is characterized by the presence of congestion by definition. In the absence of a departure time model that includes the effect of reliability, I have shown in the works presented in 2.2 how one can correct the consumer surplus, provided that one can estimate - even roughly - the share of activities with either fixed and flexible schedules. Without such a correction, a "naive" calculation is likely to greatly overestimate the benefits of reliability improvements.

For public transit, we propose to value reliability by using metrics based on service frequency, or more precisely on headways, rather than on travel times. Since headways are easily measurable, our proposal developed in 2.3 aims to facilitate the consideration of reliability in economic appraisal. In particular, it would allow to account for variations in service quality during peak and off-peak hours in a simpler manner.

While our works provide short run solutions to more easily include travel time reliability in economic appraisal, as proposed by de Jong and Bliemer (2015), the ideal solution in the long run remains in my view a comprehensive modelling framework that would be able to model the physical mechanics of travel time variability on the supply side, user behavioral reactions on the demand side, and the interactions between the two. Agent-based mobility models provide a path toward this goal, as I will develop in Section 4.

3. Public policy design: better accounting for travel costs and their impacts through engineering

Cities face the dual challenge of drastically reducing the environmental impact of their transportation system while maintaining or even improving its economic accessibility across the whole metropolitan area (in the sense of ensuring the mobility of people and goods at a reduced cost in money and time). Given the magnitude of the task, cities are leveraging an increasingly wide array of public policies, including regulation (of vehicles with emissions standards, of traffic with low-emission zones, etc.), pricing (positive, as in the case of congestion charging, but also negative, as in the case of subsidizing public transit, ridesharing or active modes), investment (infrastructure projects, green vehicles, etc.), and travel demand management (promoting active modes, peak spreading policies, etc.).

This proliferation of policies aimed at mitigating the private and external costs of travel raises two questions. The first is to confirm the very efficiency of these policies. While infrastructure projects typically undergo an economic appraisal (ex-ante and ex-post), so that their impacts are now relatively well known, this is seldom the case for other public policies. However, by reducing the cost of travel, they can induce changes in behavior, with the risk of a rebound effect that can severely limit the efficiency of the policy (or even cancel it out), as we shall see in the case of urban ridesharing. Similarly, measures can have contrasting effects on the various private (monetary and non-monetary) and external cost items. For instance, I will show that peak spreading policies do reduce crowding costs, but that it may come at the price of very high rescheduling costs: we find for instance in an application to the RER A heavy rail line in the Paris region that to decrease the total time standing by one hour, one should shift fifteen morning peak trips by one hour, which would usually be considered excessive. The design of public policies therefore requires a proper assessment of their direct and indirect effects on the different types of costs, lest giving rise to unwanted effects.

The second issue lies in the extent of interactions between policies when designing (and evaluating) policy packages (Givoni et al., 2013). To reach their environmental transition objectives, especially for decarbonization, cities are implementing sustainable mobility plans that include a wide array of measures which are rarely based on a comprehensive evaluation of the whole mobility plan, but rather on separate evaluations of each measure (Axsen et al., 2020; Sethi et al., 2020). However, by acting on the costs of the various modes, some policies might reinforce each other (positive synergy, i.e. super additivity), or conversely might counteract each other (negative synergy, i.e. sub additivity), thereby significantly altering the overall efficiency of the plan. It is therefore not sufficient to evaluate each measure in isolation; interactions between measures should also be taken into account.

In this section, I present works that carry out ex-ante evaluations of policies relating to either pricing or travel demand management, in the case of public transportation then of road transportation. This summary will illustrate the importance of the various issues mentioned above, namely the need to consider in policy evaluation the various forms of cost, the reactions (changes in mobility choices) of users to these costs, as well as possible interactions between policies. I leverage in these works theoretical and/or simulation models which allow to include the reactions of all users to a policy (and not just the users targeted by the policy) and the evaluation of the resulting private and external costs. The use of models allows to bring to light system equilibrium phenomena, and in the case of simulation models to evaluate the expected effect of the measures with respect to the different types of costs. This leads to unexpected results regarding the efficiency of some policies, such as subsidizing public transit or the development of urban ridesharing. These two forms of modelling can therefore inform the design of public policies, both qualitatively for theoretical models through a better understanding of the economic mechanisms at work, and quantitatively for simulation models by estimating users' reactions and the orders of magnitude of the various impacts for the measure(s) under consideration.

I first present papers focusing on pricing instruments, then on travel demand management, starting each time with public transit, then with road travel.

3.1 Pricing instruments

Public transit: (dis)economies of scale and optimal pricing

Urban public transportation systems are heavily subsidized in many cities across the world (Table 2). The economic literature advances two main rationales for doing so (Parry and Small, 2009). First, public transit systems operate under economies of scale, which may arise from production costs (Farsi et al., 2007; Ripplinger and Bitzan, 2018; Viton, 1992), but also from user costs. Mohring (1972) shows that if an increase in ridership is met with an increase in service frequency, the latter causes waiting time costs to fall and demand to further increase, a phenomenon often referred to as the Mohring effect.

Table 2 : Farebox recovery ratios for public transportation systems

Country	City	Public Transit Authority	Farebox ratio (%)	Year
Hong Kong	Hong Kong	MTR	172	2018
Japan	Tokyo	Tokyo Metro	129	2018
USA	San Francisco	BART	83	2017
Singapore	Singapore	SMRT	75	2016
UK	London	TfL	64	2018-2019
Canada	Toronto	TTC	61	2018
USA	New York City	MTA	52	2018
France	Paris	IdF-M (formerly STIF)	48	2015
Belgium	Brussels	MRBC	47	2018
Australia	Sydney	TfNSW	22	2017-2018
USA	Los Angeles	LACMTA	17	2018

Note: the farebox recovery ratio is here measured as the ratio of fare revenue to operating costs.

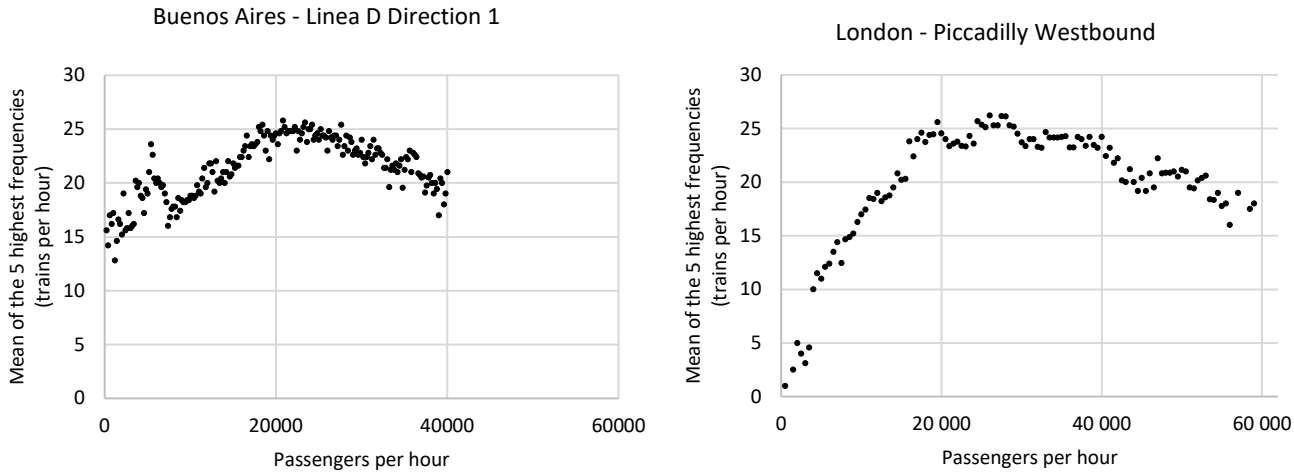
Note: Figures have been computed by the authors or retrieved from the following sources: MTR Annual report 2018, p.211 (Hong Kong), Tokyo Metro Corporate Profile 2019, p.33 (Tokyo), San Francisco Bay Area Rapid Transit District Budget Summary Fiscal year 2018, p.5 (San Francisco), SMRT Corporation Ltd Annual Report 2016, p.34 and 35 (Singapore), TfL Annual Report and Statement of Accounts 2018/19, p.128 and 129 (London), 2018 Annual Report Toronto Transit Commission, p.17 and 43 (Toronto), Metropolitan Transportation Authority Financial Statements for the Years Ended December 31, 2018 and 2017, p.12 (New-York City), Activity Report 2015 STIF, p.7 and 8 (Paris), Statistics 2018 STIB, p.3 (Brussels), Transport 2018, p.10 (Sydney), and Comprehensive Annual Financial Report For the Fiscal Year Ended June 30, 2018, p.160 (Los Angeles).

Second, car travel is typically underpriced relatively to the external costs that it generates, partly due to the political difficulty of introducing road pricing (De Borger and Proost, 2012; Souche-Le Corvec et al., 2016). As such, subsidizing public transit often represents a second-best solution to support modal shift and to limit car use (Adler and van Ommeren, 2016; Anderson, 2014; Glaister and Lewis, 1978; Nelson et al., 2007; Parry, 2002). Other rationales include addressing the special needs for transit of the underprivileged who would be either unable (due to disabilities) or could not afford to drive or access other forms of transportation (Vickrey, 1980), or supporting efficient investment in the transportation system in the long run (Brueckner and Selod, 2006).

While the relevance of each rationale may vary depending on the city characteristics, empirical studies typically find substantial economies of scale linked to the Mohring effect (Nash et al., 2001; Nelson et al., 2007; Parry and Small, 2009; Savage, 2010), justifying its central role in the theoretical literature. Yet, a key assumption underlying this effect is that service frequency increases with demand, according to the *square root principle* in the simplest setup or to a modified square root formula if adding features like variable boarding/alighting times or crowding (Jara-Díaz and Gschwender, 2003). In current urban context, public transit ridership has increased to such an extent that this assumption does not hold anymore: there are increasing cases of heavily congested lines for which frequency falls if demand is too strong, as a result of too many users seeking to board and to alight at each station. This point, which is illustrated in Figure 5 for two very busy subway lines in London and Buenos Aires, is similar to the phenomenon of bus bunching (Daganzo, 2009; Schmöcker et al., 2016). Moreover, most studies cited above largely ignore user crowding costs, which are nevertheless a crucial consumption externality characterizing urban public transportation (de Palma et al., 2017).

In a work co-authored with Guillaume Monchambert (LAET), and in the second phase of review in the Journal of Public Economics, we investigate whether a better representation of public transit congestion changes optimal policies in terms of service frequency and pricing (as well as vehicle size). We focus on economies of density, corresponding to economies of scale for a given network structure

Figure 5 : Relationship between demand and frequency for two very busy subway lines



Note: period 2013-2014

Note: period 2013-2014

Source: Coulombel et Monchambert (2022)

and transport technology. We therefore take a medium-term perspective, as opposed to the long term, in which the transit authority could invest in technologies to reduce congestion, either by improving service frequency (e.g., signaling systems to reduce headways, vehicle and/or platform improvements to reduce boarding/alighting times), or by expanding the transit network.[6]

We develop a model capturing the main features of urban public transportation congestion: in-vehicle comfort, and interactions between demand, frequency and waiting times. We amend the theoretical framework initiated by Mohring (1972) and which has since been the subject of numerous extensions (summarized in Jara-Díaz and Gschwender, 2003), by introducing three types of friction. The first type corresponds to friction between users, taking the form of a crowding cost that increases with the vehicle occupancy rate. The second type corresponds to frictions between users and vehicles, modeled by a vehicle dwelling time that varies according to the volumes of boarding and alighting. Finally, the third type, which is the crux of our contribution, is the friction between vehicles on the line, in the form of a minimum safe time between two successive vehicles. This operational constraint (related in particular to safety) imposes a physical limit on the frequency, which was not considered in previous works.

[6] We also disregard costs related to contracting, see for instance Gagnepain et al. (2013) on this issue.

In this model, we show the coexistence of two operating regimes: normal and degraded (illustrated by the two parts of the curves on Figure 5). In the normal regime, the frequency constraint is not active. The operator reacts to an increase in demand by increasing frequency and vehicle size. The system is then characterized by the following economies of scale:

$$N\frac{dASC^*}{dN} = -\frac{C_K}{N}\left(\frac{\eta_K - 1}{\eta_K}\right) - \frac{C_O}{N}\left(\frac{\eta_O - 1}{\eta_O}\right) - \frac{C_W}{\eta_W} \tag{2.1}$$

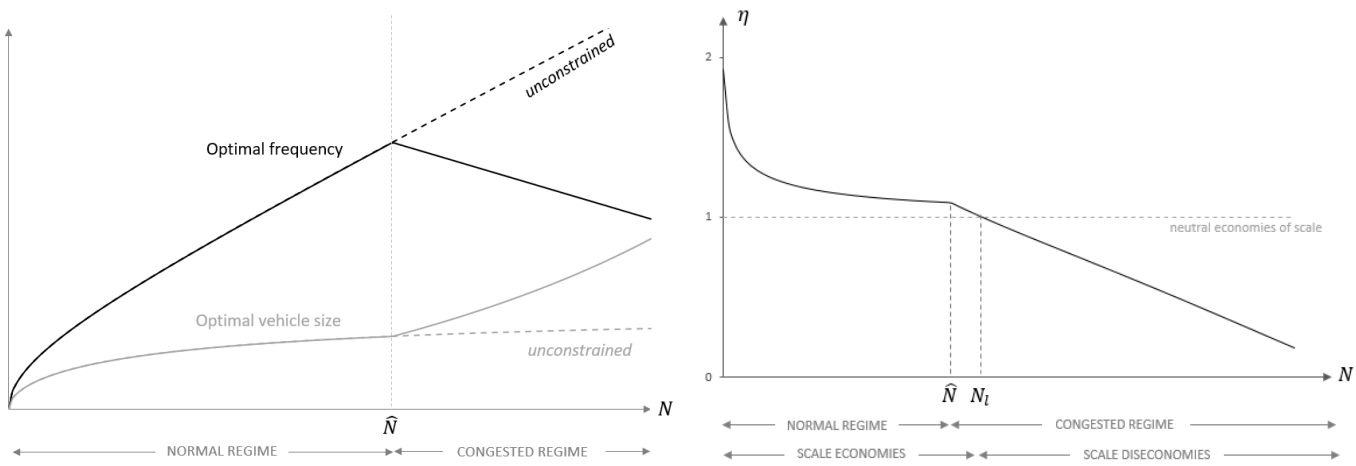
where ASC^* is the optimal average social cost, and C_x and η_x the cost and degree of scale economies (with $\eta \equiv C/yC'$) associated with *x*, i.e. operations (subscript *O*), capital (*K*), or user waiting times (*W*). We show that economies of scale at the system level are related to those at the production level (operating costs and capital costs) and at the user level (waiting costs). In the case of neutral economies of scale at all three levels (case of the linear model), we find again Mohring's result that the externality $N.dASC^*/dN$ equals the average waiting cost $-C_W$. This positive externality implies that the service is subsidized at optimum.

In the degraded regime, the demand is so high that the frequency constraint becomes active. The operator reacts to an increase in demand by increasing vehicle size, but also by decreasing frequency (as illustrated in Figure 6 for the linear model). The economies of scale are then modified according to the prevalence of the constraint through the associated Lagrange multiplier λ :

$$N\frac{dASC^*}{dN} = -\frac{C_K}{N}\left(\frac{\eta_K - 1}{\eta_K}\right) - \frac{C_O}{N}\left(\frac{\eta_O - 1}{\eta_O}\right) - \frac{C_W}{\eta_W} + \lambda\left(\frac{\bar{F}}{N^2} - \frac{\bar{F}'}{N}\right) \tag{2.2}$$

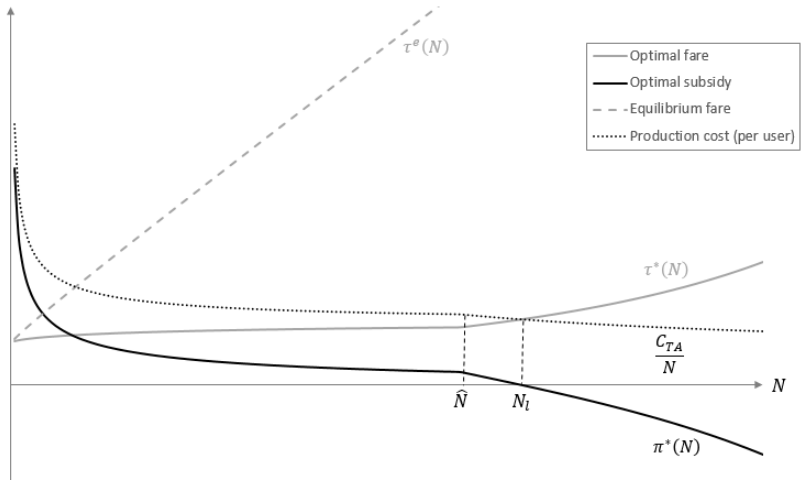
where $\bar{F}(N)$ represents the maximum frequency as a function of the level of demand N. We show that above a certain volume of demand, the system becomes subject to diseconomies of scale (see also Figure 6). Optimal pricing this time involves taxing the transport service, not subsidizing it (Figure 7). We show this result to be robust to the introduction of a modal alternative that would be underpriced and subject to congestion, typically the car.

Figure 6: Optimal frequency and vehicle size (left) and degree of economies of scale (right) in the linear case



Source: Coulombel et Monchambert (2022)

Figure 7: Optimal (and equilibrium) fare and optimal subsidy in the linear case



Source: Coulombel et Monchambert (2022)

In order to test empirically for the existence of diseconomies of scale in public transit networks, we consider the Piccadilly Line, the second-longest tube line of the London Underground network. Consecutive to an ageing rolling stock and insufficient frequency during peak times, the Piccadilly line faces recurrent overcrowding issues which degrade the quality of service. A major capacity upgrade investment program is planned as part of the New Tube for London scheme in order to relieve congestion, which includes investments in signaling systems and new rolling stock (with higher capacity and reduced boarding/alighting times). This makes the Piccadilly line a prime candidate to illustrate the effects of overcrowding and possible ways to address them. After calibrating the linear model,

notably by crossing validation and frequency data (in order to estimate the technological parameters associated with the frequency constraint), we find that the line is subject to significant diseconomies of scale at the morning hyper-peak, both for the observed (-1.49 £/pax) and the optimal (-0.61 £/pax) service level.

The contributions of this work are twofold. On a theoretical level, we specify the degree of economies of scale for a public transportation service, both under normal and degraded conditions. We show these results in a general framework, in contrast to previous work that mainly rely on linear specifications of the cost functions, and that therefore neutral economies of scale for both production and user costs. In terms of public policy, our work shows, through the case study of the Piccadilly line in London, that economies of density disappear when demand is too high, calling then for no more subsidies to public transport but, on the contrary, for taxes in the medium run (as long as the network structure and the transport technology remain constant).

Road transportation: external environmental costs and pricing

Urban freight transport is in a paradoxical situation. Although it plays a key role in the economic functioning of cities (Dablanc, 2009; Macharis and Melo, 2011; OECD, 2003), knowledge of urban road freight remains limited at best due to the lack of sufficient observation in most cities across the world, especially for road transport. However, the imperatives of the ecological transition are causing cities to implement numerous public policies for sustainable urban logistics: pricing, low-emission zones, measures in favor of electric vehicles or of off-peak deliveries (Demir et al., 2014; Ellison et al., 2013; Holguín-Veras et al, 2006; Mirhedayatian and Yan, 2018; Russo and Comi, 2016) ... Despite significant efforts to collect more freight data in recent years (Allen et al., 2013; Holguín-Veras and Jaller, 2014; Toilier et al., 2014), several grey areas remain which hinder the design of the previous policies. Organizing authorities are often unaware of the distances covered by light and heavy goods vehicles, as well as the spatial structure of routes within their territory. This is particularly true of the environmental externalities generated by URF, which are still the subject of much debate.

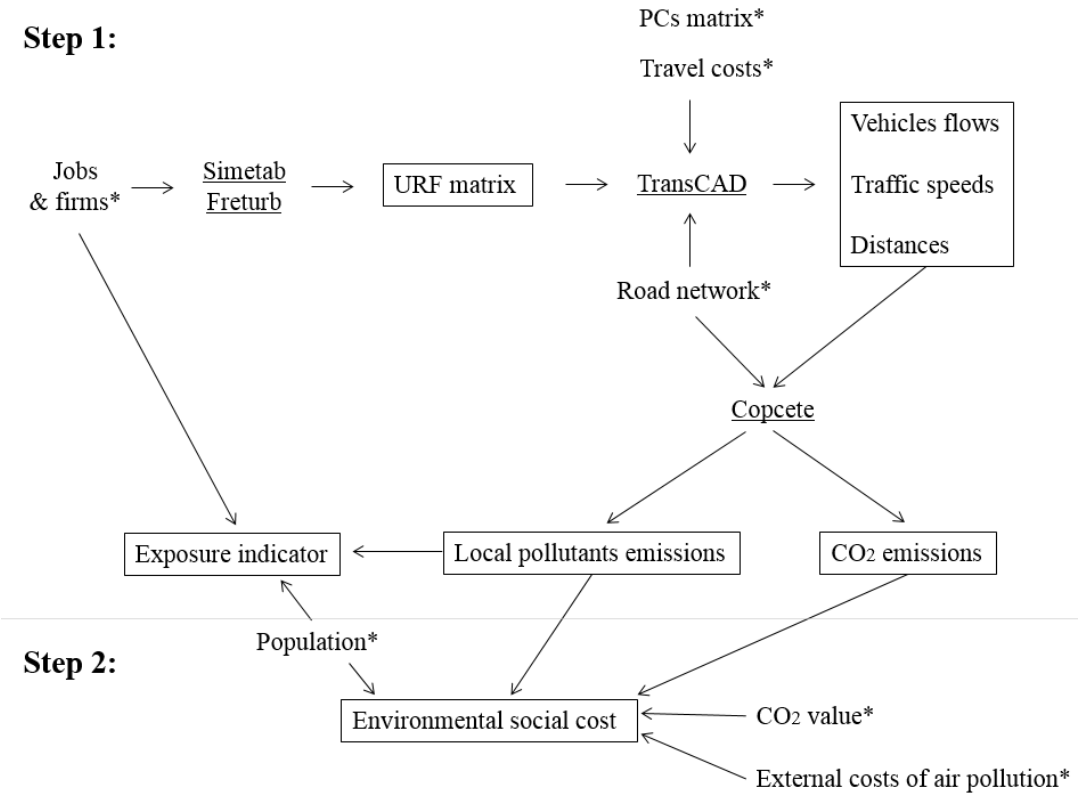
In a paper co-authored with Laetitia Dablanc (LVMT), Mathieu Gardrat (LAET) and Martin Koning (SPLOTT), published in Transportation Research Part D, we seek to fill this knowledge gap regarding urban road freight, in particular regarding the associated environmental external costs. Considering the lack of observed data, we develop a methodology based on a modeling chain which allows to estimate pollutant emissions as well as the environmental social cost of urban road freight.[7] The developed modeling chain also allows us to estimate the costs related to road congestion, for both freight vehicles and private vehicles, and is therefore particularly suited to help design public policies. This is especially true for the consideration of possible pricing instruments in urban areas that would be differentiated according to the vehicle category, as will be discussed at the end of this section.

The methodology consists of two steps (Figure 8): first estimating the pollutant emissions from road traffic, then the associated environmental social cost. We consider four classes of vehicles: passenger cars (PC), light goods vehicles (LGVs), and heavy goods vehicles (HGVs), rigid and articulated. This allows us to single out the contribution of each vehicle class to the environmental social cost.

The first step is to estimate pollutant emissions associated with road traffic, in particular URF. The passenger car demand being considered as an input, we start by estimating the demand for URF. Based on the characteristics (activity sector, size, type of establishment, etc.) and spatial distribution of firms in the Paris area, the Freturb-Simetab models (Gardrat et al., 2014; Routhier and Toilier, 2007) estimate generation coefficients (number of deliveries and pick-ups per week) for all establishments, and the resulting transport demand. The models produce output OD matrices for each class of freight vehicle (LGVs, articulated and rigid HGVs). We combine the freight OD matrices with the PC OD matrix in order to determine the multi-class traffic equilibrium, which is similar to a Nash equilibrium (Correa and Stier-Moses, 2011), and is computed using the TransCAD software. This gives us for each road section the total traffic flow, its decomposition by vehicle type, and the average speed on the section.

[7] In this paper we defined the environmental social cost as the external cost associated with greenhouse gases and local pollutants. We therefore exclude other environmental externalities such as noise or biodiversity.

Figure 8 : Methodology for computing emissions and the environmental social cost of URF



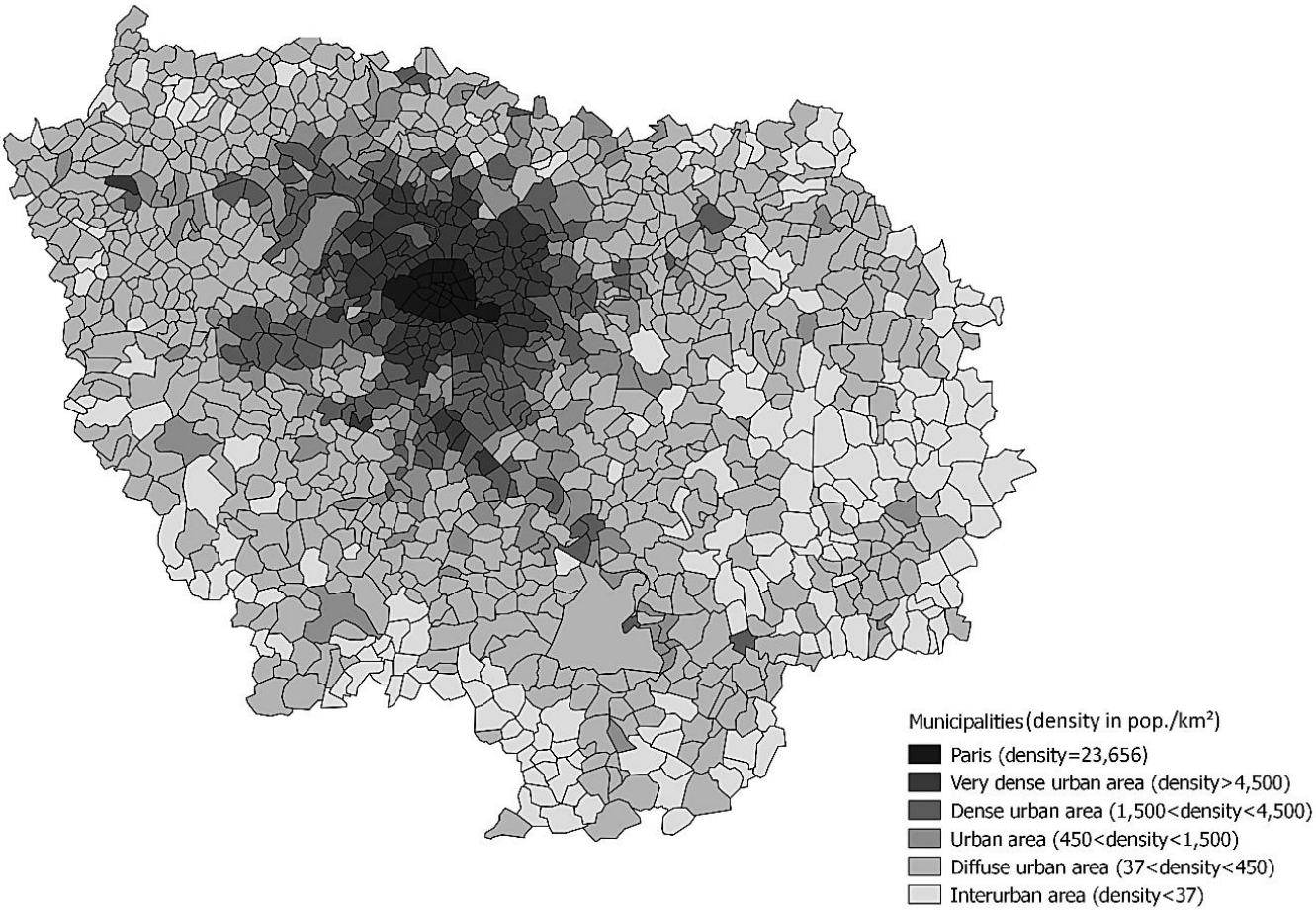
Note: exogenous input data are identified by stars; modeling tools are underlined; estimated outputs are framed.

Source: Coulombel et al. (2018)

These data are then fed to the Copcete emissions model (Demeules and Larose, 2012), which applies emission factor curves that depend on the vehicle type and speed (using the COPERT IV methodology) in order to estimate pollutant emissions for the different sections.

We can then determine the environmental cost associated with the different categories of road traffic, being the second step of our methodological framework. We cross the emissions outputs with the socio-economic input data. The two datasets are spatialized, allowing us to take into account the greater impact of local pollutants in dense areas, as more individuals are exposed to emissions. The Ile-de-France municipalities are thus grouped into six classes of decreasing population density (Figure 9), in accordance with the five categories recommended by the French official guidelines for the computation of external costs (Quinet, 2019), to which we add a sub-category for the very dense zone corresponding to the city of Paris, for analytical purposes.

Figure 9 : The Paris region, 2012



Source: Coulombel et al. (2018)

Based on the simulation results of the road assignment model, road traffic added up to 155 million vkm per day for the Paris region in 2012, 33% of which occurring in the peak period (Table 3). Paris concentrates 11% of road traffic while the fringes of the metropolitan area account for 30% of the distances traveled. The share of freight traffic also greatly varies depending on the area: equal to 8% on average in the region, it varies from 16% in Paris to only 2.6% in the interurban area. The average distance covered by URF is slightly greater than that of private cars, since HGVs and LGVs account for only 6% of daily trips in the daily OD matrices (as opposed to the 8% of distances traveled).

Table 3 : Results of the road assignment model (Paris region, 2012)

	Region	Paris	VDUA	DUA	UA	DIUA	IA
Peak periods							
PC (veh/h)	745	1,146	858	664	646	526	404
LGV (veh/h)	33	95	40	23	17	10	3
HGV (veh/h)	28	69	33	22	18	11	3
VOC ratio	0.45	0.62	0.53	0.44	0.37	0.30	0.22
Vehicle speed (km/h)	41.2	20.7	31.8	40.6	49.4	61.4	70.3
Off-peak period							
PC (veh/h)	303	477	350	272	257	209	146
LGV (veh/h)	20	59	25	14	10	6	2
HGV (veh/h)	17	42	20	13	11	6	2
VOC ratio	0.20	0.29	0.24	0.20	0.16	0.13	0.08
Vehicle speed (km/h)	51.3	33.0	44.3	50.8	58.0	67.5	74.5

Note: "VDUA" stands for very dense urban area, "DUA" for dense urban area, "UA" for urban area, "DIUA" for diffuse urban area and "IA" for interurban area.

VOC = Volume-Over-Capacity.

Source: Coulombel et al. (2018)

Regarding pollutant emissions, we find that road traffic emitted in 2012 about 31,300 t of CO_2, 123 t of NO_x and 15 t of PM_{10} every day (Table 4). 40% of these emissions occur in very dense areas (including Paris), which represent 58% of the regional population and 67% of jobs. This difference is the result of two opposite forces: the share of the car is lower in dense areas, but unit emissions are higher due to lower average traffic speeds. URF accounts for about 20% of CO_2 emissions and 30% of NOx and PM_{10} emissions, well above its share (8%) in road traffic. Unit emissions are as a matter of fact higher for LGVs and even more so for HGVs, especially in the case of NO_x and PM_{10}, reflecting both the higher mass of these vehicles and the higher dieselization of the fleet (compared to private cars). While HGVs quite logically emit much more than LGVs per vehicle-km because of their greater mass, we find the opposite result when computing emissions per ton-km of freight transported, thanks to a better filling of the trucks.

Table 4 : Pollutant emissions from road traffic in the Paris region (2012)

	Region	Paris	VDUA	DUA	UA	DIUA	IA
CO_2							
Emissions (tons/day)	31,271	4,256	7,970	6,219	4,485	7,014	1,327
PC	*25,205*	*2,813*	*6,122*	*5,018*	*3,771*	*6,241*	*1,239*
LGV	*1,688*	*421*	*509*	*324*	*190*	*219*	*25*
HGV	*4,378*	*1,022*	*1,339*	*877*	*524*	*554*	*63*
Emissions (%)	100.0%	13.6%	25.5%	19.9%	14.3%	22.4%	4.2%
Share during peaks (%)	34.2%	35.9%	35.0%	34.0%	33.3%	33.2%	33.8%
Share of URF (%)	19.4%	33.9%	23.2%	19.3%	15.9%	11.0%	6.6%
NO_x							
Emissions (tons/day)	122.5	17.5	30.5	23.7	17.5	27.9	5.4
PC	*86.6*	*8.5*	*19.4*	*16.7*	*13.4*	*23.7*	*4.9*
LGV	*5.9*	*1.5*	*1.8*	*1.1*	*0.7*	*0.7*	*0.1*
HGV	*30.0*	*7.5*	*9.3*	*5.9*	*3.4*	*3.5*	*0.4*
Emissions (%)	100.0%	14.3%	24.9%	19.3%	14.3%	22.8%	4.4%
Share during peaks (%)	32.6%	34.9%	33.4%	32.1%	30.9%	31.5%	33.3%
Share of URF (%)	29.3%	51.4%	36.4%	29.5%	23.4%	15.1%	9.3%
PM_{10}							
Emissions (tons/day)	14.8	1.9	3.7	3.0	2.2	3.4	0.6
PC	*10.4*	*1.0*	*2.4*	*2.1*	*1.6*	*2.8*	*0.5*
LGV	*0. 7*	*0.2*	*0.2*	*0.1*	*0.1*	*0.10*	*0.00*
HGV	*3.7*	*0.7*	*1.1*	*0.8*	*0.5*	*0.5*	*0.1*
Emissions (%)	100.0%	13.0%	25.2%	20.0%	14.8%	22.9%	4.2%
Share during peaks (%)	31.8%	31.6%	32.4%	30.0%	31.8%	32.4%	33.3%
Share of URF (%)	29.6%	46.4%	35.1%	30.3%	26.0%	18.9%	11.3%

Source: Coulombel et al. (2018)

Finally, regarding the environmental social cost, we find that the emissions of air pollutants caused by road traffic (PC, LGVs and HGVs) represent an average cost of 23.1 M€ per day (Table 5), that is 1.9 €/inhab/day. This represents about 6 billion € per year, or about 1% of the regional GDP. Considering that the private cost of road transportation averages 90 million € per day, internalizing the external cost of air pollution would result in an additional cost for users which would be around 26%. Urban road freight is responsible for 36% of the regional environmental social cost, compared with 6% of trips, 8% of distances traveled and 20 to 30% of emissions. This "extra cost" is linked to the higher concentration of HGV and LGV traffic in the dense parts of the metropolitan area, thus generating a higher cost due to the greater number of local residents affected.

Table 5 : Environmental social cost of road traffic in the Paris region (2012)

	Region	Paris	VDUA	DUA	UA	DIUA	IA
Total social costs (M€/day)	23.06	6.02	11.64	3.38	1.04	0.88	0.10
PCs	14.80	3.22	7.58	2.37	0.79	0.74	0.09
LGVs	*1.34*	*0.49*	*0.63*	*0.15*	*0.04*	*0.03*	*0.00*
HGVs	*6.91*	*2.31*	*3.43*	*0.85*	*0.21*	*0.11*	*0.01*
Total social costs (%)	100.0	26.1	50.5	14.7	4.5	3.8	0.4
Share of URF (%)	35.8	46.4	34.9	29.7	24.2	15.5	8.0
including CO_2 related costs							
Social costs (M€/day)	1.12	0.15	0.29	0.22	0.16	0.25	0.05
Share of URF (%)	19.4%	33.9%	23.2%	19.3%	15.9%	11.0%	6.6%

Note: "VDUA" stands for very dense urban area, "DUA" for dense urban area, "UA" for urban area, "DIUA" for diffuse urban area and "IA" for interurban area. $PM_{2.5}$ emissions are found by applying a 0.65 factor to PM_{10} emissions (Table 7)

Source: Coulombel et al. (2018).

Quite surprisingly, CO_2 emissions accounted for only 5% of the environmental social cost in 2012. This figure reflects both the low valuation of carbon in 2012 (36 €/t), as well as the very high health cost of air quality, in particular of fine particulate matter.

The results emphasize the magnitude of air pollutant emissions caused by urban freight transport: although weighing for only 6% of road trips in the Paris region, URF causes more than one third of the environmental social cost of road traffic. This results firstly from the heavier mass of goods vehicles, but also from the almost full dieselization of the freight fleet, and finally from the greater concentration of freight traffic within the densest parts of the metropolitan areas (reflecting the tight link between URF and the economic activity of cities). Based on this observation, a companion paper is being written and uses the capabilities of the model chain developed to study the efficiency of pricing instruments targeting road freight, passenger cars, or both.

3.2 Travel demand management

Public transit: what potential to decrease congestion?

As discussed above, cities are facing increasing congestion problems in their public transit networks (see also Yang and Tang, 2018). Although one solution is to invest in network improvements and/or extensions, such as the New Tube for London plan or the Grand Paris Express project, such a choice is often expensive, and may ultimately prove ineffective in curbing congestion because of the traffic induction problem, as brought to light by Duranton and Turner (2011) regarding road travel in the US. Considering the limits of supply-side solutions, the focus has shifted on how to optimize the use of the existing network through Travel Demand Management (TDM). Following the Avoid-Shift-Improve (ASI) typology (Nakamura and Hayashi, 2013), TDM policies can be schematically classified into those that aim A) to reduce distances travelled, S) to shift trips in time or in space in order to make better use of the available transit capacity, and I) to improve the efficiency of the public transit system. Telework (Zhang et al., 2005) is the epitome of the Avoid category. Improve policies include transit operations control (Daganzo, 2009; Schmöcker et al., 2016), passenger flow control (Xu et al., 2016), and combinations of both (Liu et al., 2020). Within the Shift category, congestion pricing has attracted considerable attention since Vickrey's seminal works (Arnott et al., 1993; Vickrey, 1973, 1969), with many applications to road traffic as in Stockholm (Saifuzzaman et al., 2016). As we saw in section 3.1, congestion externalities in public transit imply that one should charge higher fares during rush hour, which may even exceed the average production cost if the public transit line faces severe congestion. Examples of application include peak-fare charging such as in Taipei, Washington D.C and London, and off-peak discounting as in Melbourne (Yang and Tang, 2018). Yet cases of implementation remain rare, because of the technical complexity (for road travel), unpopularity and social inequity of such schemes (De Borger and Proost, 2012; Vanoutrive and Zijlstra, 2018).

Considering the political difficulty of implementing congestion pricing, one possible alternative is to stagger work hours (and school hours). As shown by Henderson (1981), the optimal distribution

of traffic may be achieved by spreading work start times in a coordinated manner, so as to reschedule commuting trips in order to reproduce the optimal distribution of departure times. Staggered work hours (SWH) schemes are relatively easy to implement and inexpensive to boot, resulting in renewed interest and applications in cities over the world (Briand et al., 2017; Zong et al., 2013).[8]

In contrast to a large theoretical literature (reviewed recently in Takayama, 2015), empirical works remain scarce to date, especially regarding how to design SWH schemes. Questions such as how many trips should be shifted, when (before or after the peak), and by how much time, are seldom if at all addressed in the literature. The literature has also largely focused on road travel as yet, with limited attention to public transit.

In a paper co-authored with Emmanuel Munch (LVMT) and Cyril Pivano (PTV Group), under a second round of revision in the journal *Transport Policy*, we develop a framework for the ex-ante evaluation of peak spreading measures for public transport aimed at filling this gap in the literature. This framework takes into account the specifics of urban public transit, for which congestion first manifests itself as in-vehicle discomfort (Haywood et al., 2017). In the case of very high ridership, congestion can also increase waiting times - when users fail to board the first vehicle and/or through a decrease in frequency as seen in section 3.1 - and in-vehicle times, then becoming more similar to road congestion.

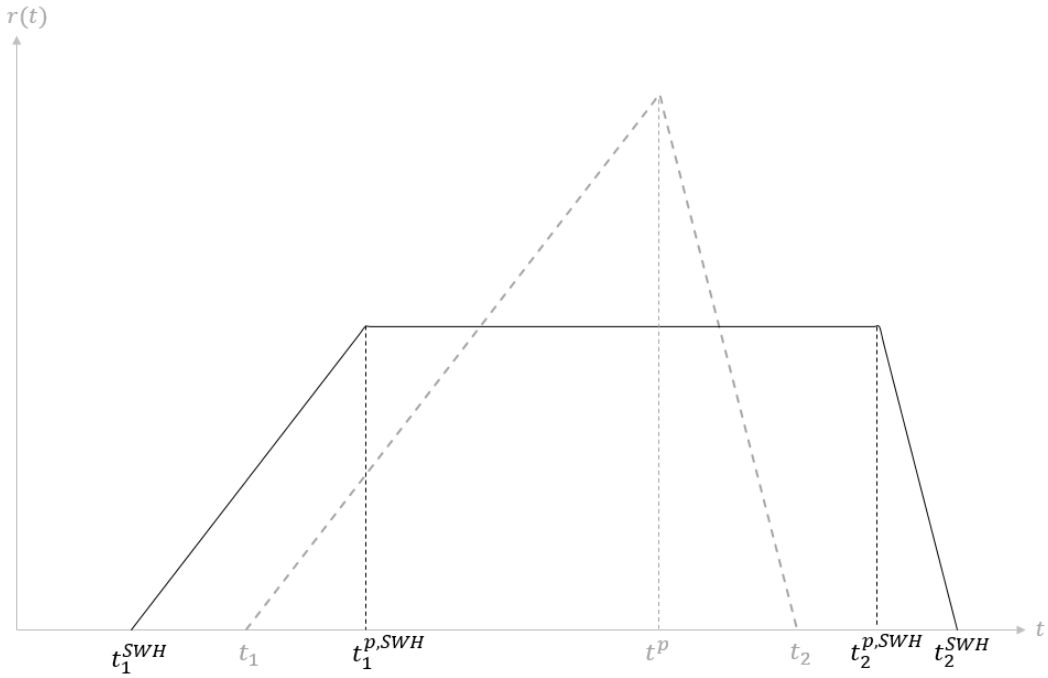
In order to develop this evaluation framework, we first build a theoretical model of public transit congestion. Seeing that we are mainly interested in the choice of departure time, we do not use Mohring's model as in 3.1, but instead use a scheduling model similar to the one presented in section 2.3 for public transit. For a trip departing at time t_D, the utility writes:

$$U(t_D) = -\alpha_W T_W - \alpha_V\big(1 + kl(t)\big)T_V - \beta(t^* - t_D - T_W - T_V)^+ - \gamma(t_D + T_W + T_V - t^*)^+. \quad (2.3)$$

[8] SWH schemes do not present any technical difficulties, mostly coordination within and across firms/schools. Therefore, they require virtually no material investment, only preparation and training meetings.

The parameter k is the time multiplier related to in-vehicle crowding, measured by the load factor $l(t)$ (equal to the ratio between vehicle load and capacity). Users then make a trade-off between departing as close as possible to their preferred arrival time t^*, but facing high congestion, or departing before or after the peak time to avoid congestion, but then incurring a high scheduling cost. At equilibrium, users are indifferent between all departure times used. We show that congestion costs account for two-thirds of the total additional cost (excluding free-flow costs), while scheduling costs for one-third, which is in line with the previous results of de Palma et al. (2017). By staggering work start times t^*, the first effect is to smooth out the departure profile (Figure 10). This leads to a reduction in congestion costs and scheduling costs, with a more pronounced effect on the latter.

Figure 10 : Impact of staggered work hours on departure rates

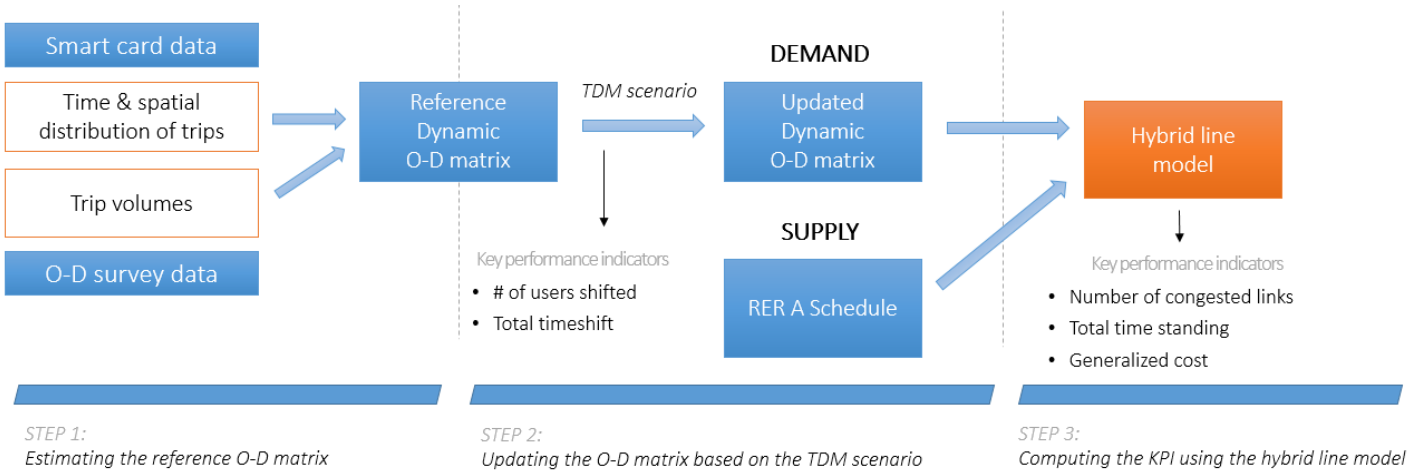


Source: Coulombel et al. (2022)

Following this analysis, we develop an evaluation framework that focuses on crowding costs. Theoretically, this choice is based on the prediction that scheduling costs are likely to remain limited compared to crowding costs, especially so following the implementation of SWH schemes. Empirically, this choice reflects that scheduling costs are often hard to measure empirically, even using surveys.

The evaluation of the various travel demand management scenarios is based on key performance indicators (KPI) that we compute using a 3-step methodology (Figure 11).

Figure 11 : Methodology for computing the key performance indicators



Source: Coulombel et al. (2022)

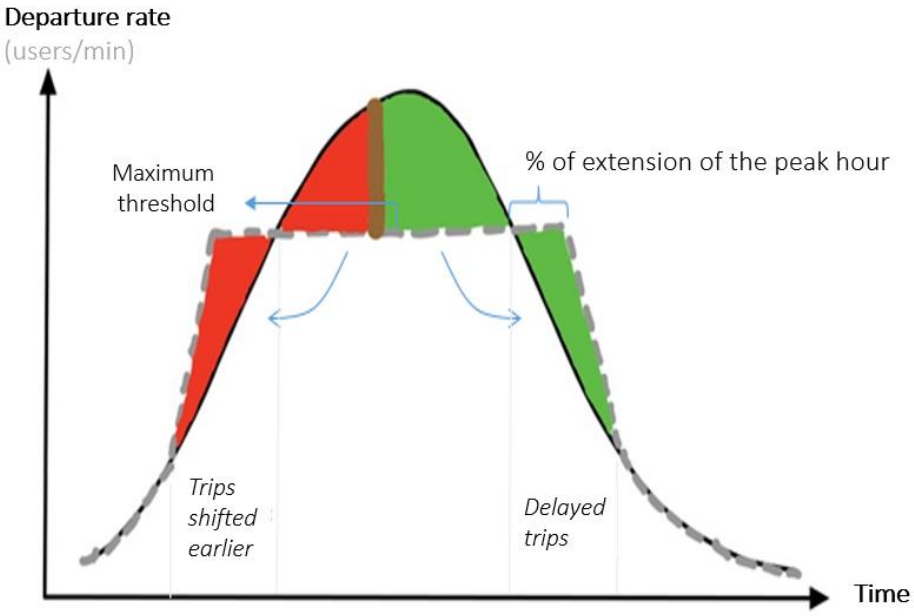
The first step aims to estimate a dynamic O-D matrix for the reference scenario (current situation) by combining two datasets:

- the smart card database provides the initial spatial structure of the matrix;
- the O-D survey is used to rescale the raw AFC O-D matrix to reproduce consistent trip volumes given the incompleteness and the biases of AFC data (paper tickets not taken into account, users who do not tap, destination not always available, etc.).

In the second step, we generate the dynamic O-D matrices for the TDM scenarios by altering the reference matrix according to the corresponding measures. Two types of scenarios are considered for the staggered work hours:

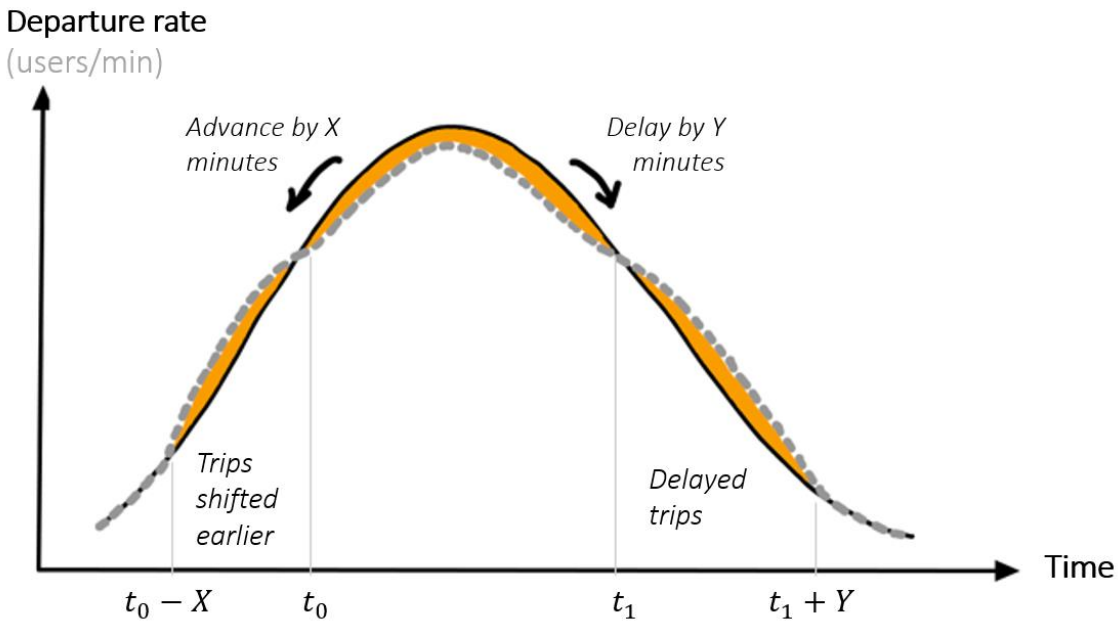
- centralized scenarios in which trips are shifted before and after the peak hour to cap the departure rate, as predicted by theory (Figure 12);
- decentralized scenarios corresponding to simpler rules in which a portion of the trips would be shifted either X minutes earlier or Y minutes later, or a combination of both (Figure 13).

Figure 12 : Schematic representation of the centralized TDM scenarios



Source: Coulombel et al. (2022)

Figure 13 : Schematic representation of the decentralized TDM scenarios



Source: Coulombel et al. (2022)

We also consider telecommuting scenarios, in which a given fraction of users no longer travels, for comparative purposes.

Scenarios may be applied either to all the users of the transit line considered, or only to users who travel to a specific destination (by targeting only schools, universities and firms near the corresponding transit station).

In the third and final step, the usage of the transit line and the KPI for the TDM scenarios are computed using the hybrid line model, which combines a macroscopic representation of passenger flows with a microscopic simulation of vehicles (Poulhès et al., 2017). The hybrid line model considers vehicle capacity and several forms of congestion: in-vehicle crowding, denied boarding, and on-platform congestion (longer dwelling times as the number users seeking to board and alight increases). This allows us to estimate the benefits of travel demand management measures in terms of comfort, but also in terms of reduced waiting times and travel times (by shortening dwelling times and limiting instances where users cannot board the first vehicle).

Two sets of indicators are used to assess the performance of the TDM measures being considered. The first set appraises the congestion relief benefits using a combination of vehicle-based and user-oriented indicators:

- number of congested links (in veh.interstations);
- total time standing (h);
- aggregate user generalized cost (€) and crowding cost (€).

The second set of indicators evaluates the rescheduling cost for users and for firms by measuring:

- the number of trips shifted;
- the mean timeshift (min), conditional to the trip being shifted.

It is important to stress that the peak spreading measures do not seek to reduce the total ridership, but rather to spread it more evenly over the entire period. A performance indicator such as the average load per vehicle would therefore be inappropriate, since it would not vary in the various scenarios (save for the telecommuting scenarios). In contrast, indicators that capture the convexity of congestion

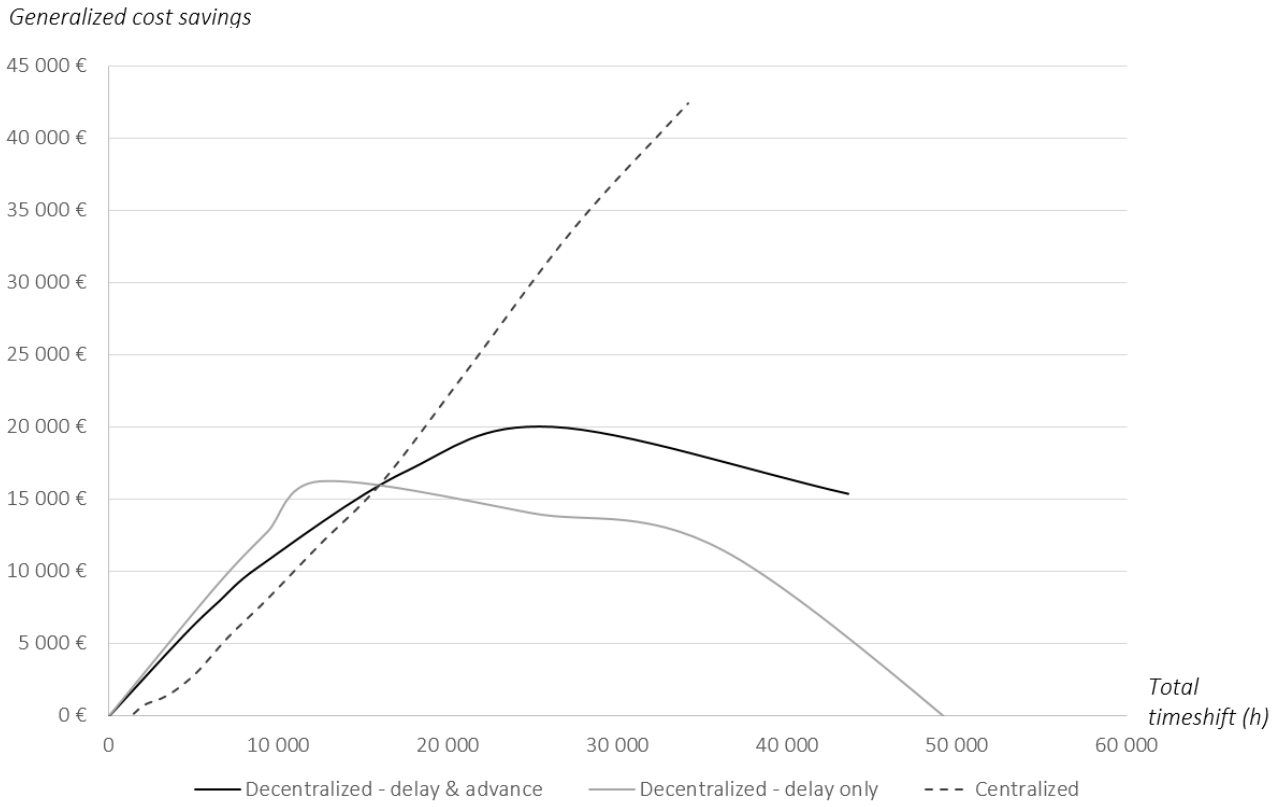
costs, such as the three proposed indicators, can be used to assess the extent to which the tested policies do lead to smoother loads across vehicles.

The methodology is applied to the RER A heavy rail line in Paris.[9] With more than 1.2 million passengers per day, it is the most used urban transit line in Europe, facing recurrent crowding issues. Frequency and vehicle capacity having been raised to the maximum - with 27 trains/h at peak hour, each with a carriage capacity of 2,600 users – the RER A is a prime candidate for SWH schemes. In fact, the transit authority and the two operators of the RER A have initiated in 2019 on these exact grounds a small-scale SWH experiment with the firms of the CBD La Défense, also including telework incentives (Région Île-de-France, 2018). We seek to determine what effect upscaling this experiment would have, either by targeting more users at La Défense or by deploying it on the entire line.

We find that large-scale peak spreading measures do smooth the peak load, as expected, by better distributing users across vehicles, thus improving on-board comfort. More surprisingly, we find that for a similar total timeshift (in number of shifted trips x average shift in h), decentralized measures often perform better than centralized measures (Figure 14). This suggests that it is generally more efficient to shift few users but more strongly, than to shift many users but by a small amount of time. Nevertheless, for very large-scale applications, centralized measures are robust by design, while decentralized measures tend to produce counterproductive results by merely shifting the peak to another time in the morning. Regarding the spatial implementation of peak spreading measures, we find that targeting only the RER A station of La Défense (the primary trip attractor in the morning) yields - for a given total timeshift - effects similar to a deployment over the whole line (implying a much stronger measure for a targeting on La Défense given the lower number of users involved).

[9] In this paper we only consider changes in departure time, and not other travel decisions such as changes in route choice or mode choice, by assuming that the impact of SWH policies on these choices remains limited. Validation this working assumption will be the object of future works.

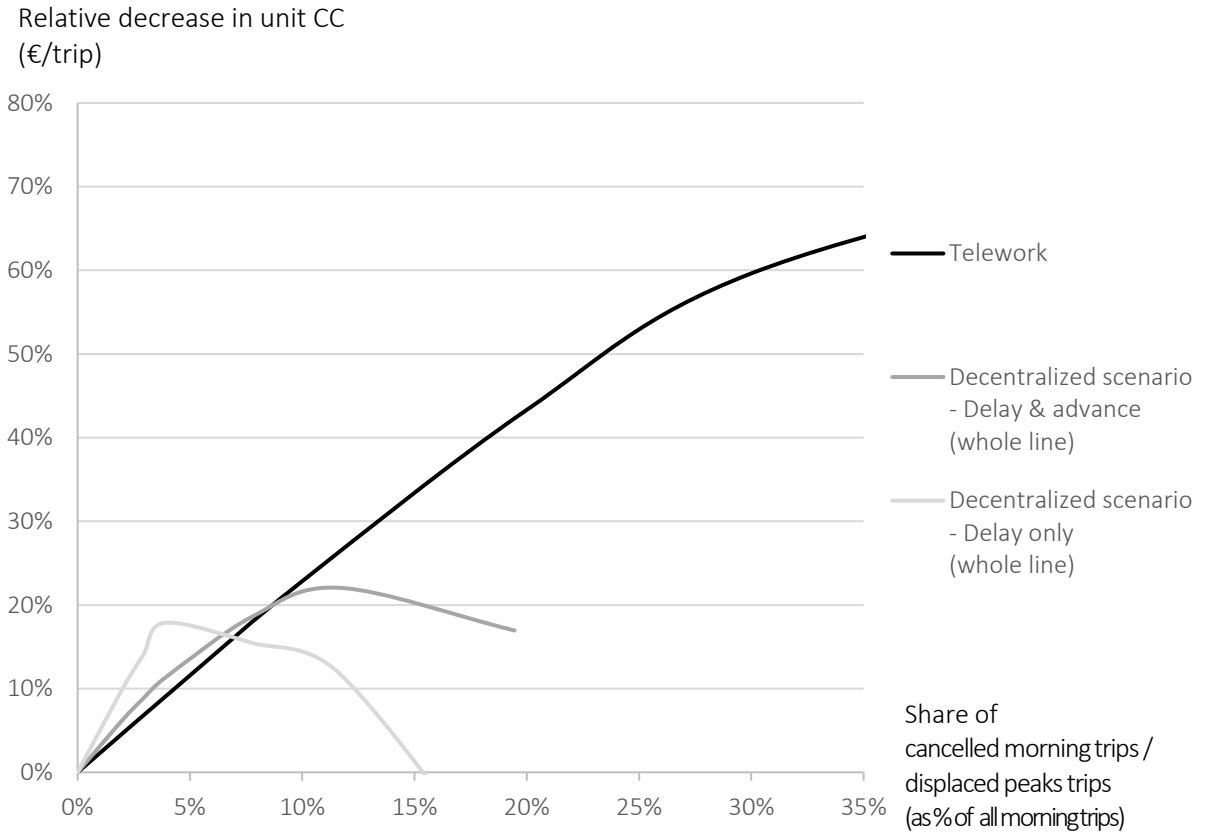
Figure 14 : Congestion relief benefits (in €) as a function of total timeshift



Source : Coulombel et al. (2022)

We find mixed results when it comes to the overall performance of staggered work hours schemes in the case of the RER A line. On the one hand, SWH policies have a commendable efficiency compared to telecommuting: shifting a trip during the peak hour (arrival between 8:30 and 9:30) produces an effect similar to cancelling a trip in the morning (between 6:00 and 11:00) regarding congestion costs (Figure 15). On the other hand, the decentralized scenarios tested only succeed in reducing congestion costs by a maximum of 20%, while leading to very substantial rescheduling costs. To reduce the standing time by one hour, fifteen trips must be shifted by the same amount of time. Alternatively, we find that for sprawl measures to produce an economic benefit, the long-run rescheduling cost (associated with the change in t*) must be less than one-tenth the value of the VTTS, which seems unrealistic.

Figure 15: Congestion relief benefits (in €/trip) as a function of the share of trips targeted



Source: Coulombel et al. (2022)

SWH measures also have redistributive effects, with winners and losers. By shifting some of the peak users to the edges of the rush hour, peak users who stay benefit the most from the measure, since they face less congestion without incurring rescheduling costs. Conversely, off-peak transit users now face more congestion due to the shift of some users to that time period.

If staggered work hours schemes can therefore contribute to improving the performance of transit systems, they require careful design of their deployment in space (which stations) and in time (by how much one should shift trips). Otherwise, these measures may have either a limited or even counterproductive effect. Moreover, our results suggest that for very busy lines such as the RER A, staggered work hours must be complemented by other travel demand management instruments (pricing, telecommuting) in order to significantly reduce congestion.

Road travel: can we reduce its externalities through urban ridesharing?

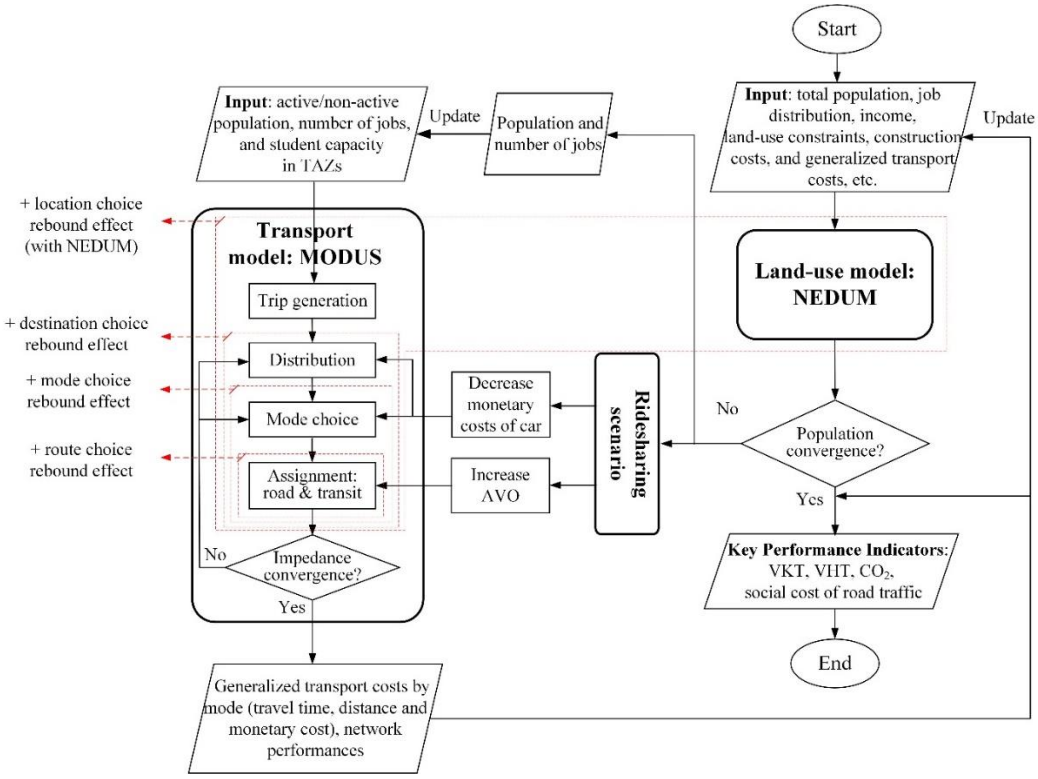
In France, only 3% of commuting trips on average are made by ridesharing (ADEME, 2016), and this mobility practice has been in almost continuous decline since the 1970s. This low use of ridesharing can be explained, in part, by the organizational constraints that it implies on a daily basis for schedules, and by the additional time related to detours to pick up teammates. Nevertheless, the environmental imperatives, particularly relating to the improvement of air quality or the fight against climate change, combined with the recent soar in energy prices, have renewed interest in this transportation mode. Among the new mobility solutions, urban (or short-distance) ridesharing has thus been the subject of particular attention in the context of the debates on the French law on the orientation of mobility.

By reducing solo driving, ridesharing should reduce the number of vehicles on the road and, consequently, contribute to reducing congestion and pollution. According to AirParif, road traffic currently accounts for 32% of greenhouse gas emissions in the Paris region. Limiting the number of cars on the road would therefore mechanically reduce them. Ridesharing would also lighten the travel budget of households, especially in a context of high energy prices. Finally, it would be a new mobility option for non-motorized individuals. While on paper ridesharing is the ideal solution for reducing road traffic externalities, its actual efficiency is debated because of the behavioral changes it could cause. Given the improved road travel conditions, in time for all users due to congestion relief, and in money for carpoolers due to cost splitting, individuals might shift from other less polluting modes to the car (RIDES, 1999; Shaheen et al., 2016), or travel longer distances by car, especially for those who would use this opportunity to relocate further from the city center (Salomon and Mokhtarian, 1997). These rebound effects are similar to those observed following improvements in the thermal insulation of buildings, where the initial gains are often reduced by the overconsumption response of users (Greening et al., 2000; Berkhout et al., 2000). Although mentioned in the literature, the various rebound effects of urban ridesharing have not been considered as a whole, so that their magnitude, the interactions that may take place between the various rebound effects, and the means of limiting them, remain not well known.

In a series of two papers carried out with Liu Liu, Biao Yin, and Vincent Viguié, and Virginie Boutueil for the second one, and published in the *Journal of Cleaner Production* and then in *Transportation Research Part D*, we study to what extent user (and non-user) behaviors can amplify or, on the contrary, mitigate the expected benefits of ridesharing. We focus on urban ridesharing, circumscribed within a given metropolitan area, as opposed to long-distance carpooling, which is rarely part of daily mobility. We seek to evaluate the overall rebound effect for this form of mobility, as well as the contribution of each elementary rebound effect, in order to propose solutions to limit them. Although we focus on greenhouse gas emissions, as ridesharing policies are usually associated with the fight against climate change, we also investigate the effects on the short-term social cost and its main components (private monetary and non-monetary cost, and external environmental cost).

In order to analyze the main rebound effects associated with urban ridesharing, we develop an integrated transport-land-use model based on the coupling of a 4-step transport model, MODUS (as for the work presented in 3.1), with a land use model, NEDUM. By representing the main choices in terms of daily and residential mobility, this modeling chain allows us to capture four elementary rebound effects associated with: 1) route choice, 2) modal shift, 3) travel distance (destination choice), and 4) residential relocation. The MODUS model corresponds to a standard 4-step transport model, while the NEDUM model follows the principles of the monocentric model of urban economics and extends them to a polycentric context to provide realistic numerical simulations (Viguié et al., 2014). As is usual for integrated transport-land-use models (often called LUTI models for Land Use Transport Interaction), the MODUS travel demand model provides the NEDUM land-use model with area-to-area levels of service (namely travel times and network distances for the various transportation modes), while NEDUM in turn provides MODUS with the volumes of population and jobs by area (Figure 16). As opposed to other LUTI models such as UrbanSim (Waddell et al., 2007), NEDUM only models the location choices of households, however, and not that of firms, so that the number of jobs per zone actually remains the same in all scenarios

Figure 16: Model flowchart and integration of urban ridesharing



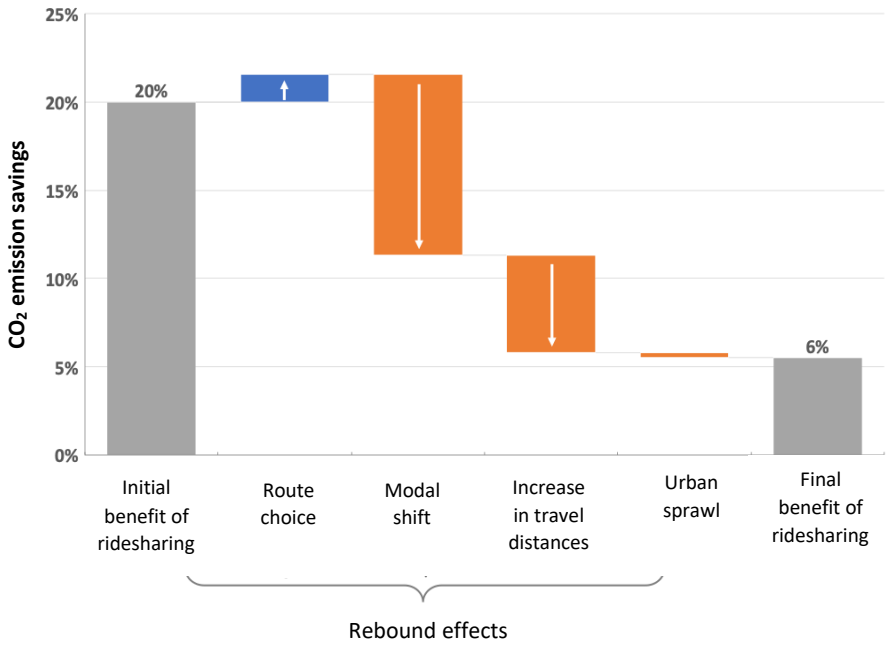
Source: Coulombel et al., 2018

Consistent with the structure of MODUS, ridesharing is represented as an increase in vehicle occupancy (AVO), and a decrease in monetary cost proportional to the increase in vehicle occupancy. For example, in a scenario where the development of ridesharing increases AVO by 50%, the monetary cost of a car trip is reduced by 33% (= 100% / (100% +50%)). Rebound effects are measured relatively to the initial direct effect of ridesharing, which in this same example is to reduce road traffic by 33%, and thus emissions also by 33%. Considering our focus on the environmental impact of ridesharing and on the rebound effects, as well as the limitations of MODUS, we do not model explicitly the matching technology (as in e.g. de Palma et al., 2022b, 2022a), and instead assume that matching is frictionless.

We apply our modeling chain to evaluate various ridesharing scenarios for the Paris region. The simulation results confirm that the development of ridesharing, by making car use both cheaper (cost splitting) and faster (reduced road congestion), leads to rebound effects that strongly mitigate the expected reductions in CO_2 emissions. In a scenario where ridesharing would increase the average vehicle occupancy by 25%, CO_2 emissions would not decrease by 20% as expected, but by only 6%

(Figure 17). This is the result of a positive rebound effect (amplifying the decrease in CO_2 emissions), corresponding to more direct routes following the initial reduction in congestion (as drivers make less detours to avoid traffic jams), and of three negative rebound effects related 1) to the modal shift from public transit and active modes to the car, 2) to an increase in travel distances made by road users, and 3) to a smaller extent to the relocation of households to peripheral areas (i.e. to urban sprawl). We find that the rebound effects result approximately for half from the decrease in monetary costs, and for half from the decrease in road congestion (travel time effect).[10] Because the rebound effects are partly related to congestion, they are stronger the higher the level of road congestion, but diminish as the development of ridesharing reduces congestion more and more. Similarly, the substantial modal shift rebound effect stems in our case from the high modal share of public transport in the Paris region. Our results therefore suggest that the rebound effects associated with urban ridesharing will be stronger in cities with high levels of road congestion and/or of public transit modal share.

Figure 17 : Reduction of CO_2 emissions and rebound effects in a +25% AVO scenario

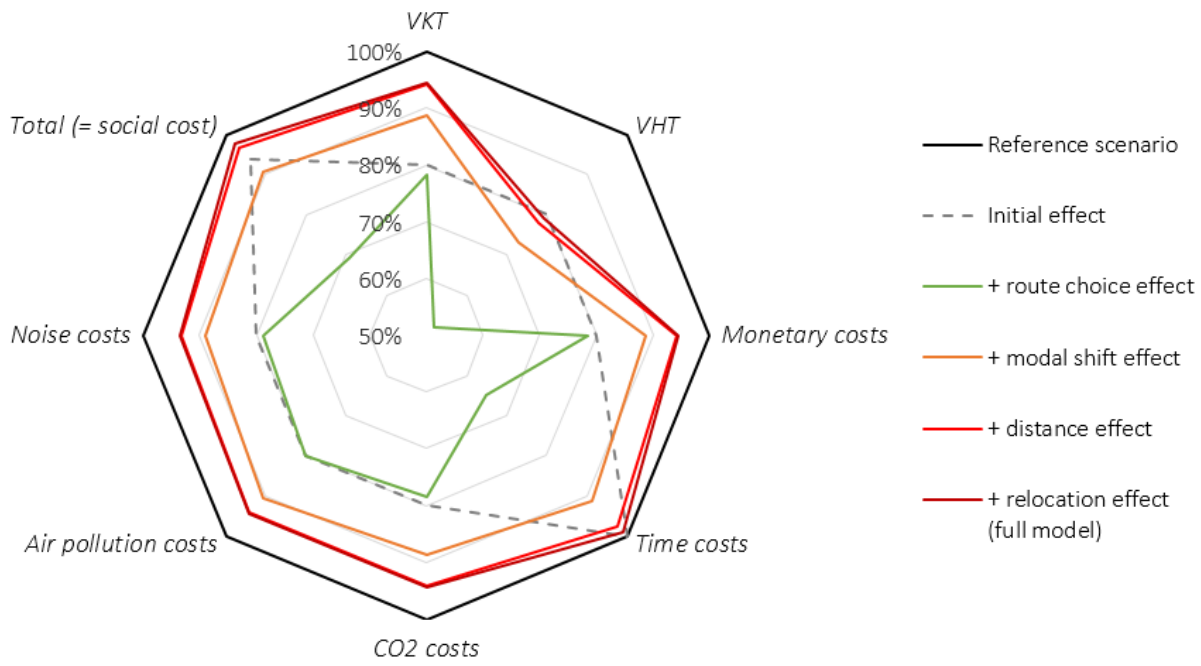


Source: Coulombel et al., 2019

[10] Focusing on the impact of the decrease in monetary costs, this implies a rebound effect that is around 30%, with 20% resulting from modal shift and 10% from an increase in travel distances. This last figure of 10% is in line with the empirical literature on fuel efficiency and rebound effects, such as the study of de Borger et al. (2016) which provides a 7.5-10% estimate for the rebound effect on travel distances.

Regarding the other private and external costs, we find rebound effects comparable to those observed for CO_2 emissions, apart from non-monetary time costs which are ultimately little impacted by ridesharing (Figure 18). Indeed, ridesharing does not directly decrease the time spent in the car (two people in one car spend as much time in it as each one in his own car). It does reduce it by reducing congestion, but because the reduction is offset by the rebound effects, the final effect is almost zero. Considering the prevalence of the opportunity costs of time over other private and external car costs, the total social cost is only slightly reduced in the end (with only a 2.3% decrease in a scenario with a 25% change in average vehicle occupancy).

Figure 18 : Effects of a +25% AVO scenario on the social cost and other KPI



Source: Coulombel et al., 2019

Given the magnitude of the rebound effects, we investigate various accompanying measures aimed at increasing the efficiency of urban ridesharing policies. We consider three types of measures: 1) increasing the public transit supply through the implementation of the Grand Paris Express network, 2) a reduction in road capacity, and 3) raising the cost of car use. These measures aim at limiting the various rebound effects, especially the one related to modal shift which is the most significant in size. While one might expect that increasing public transport supply would be effective in countering the

rebound effects, we actually find a negative synergy between this measure and ridesharing (Table 6). The two measures compete with each other to attract users, so that combining them reduces their respective efficiency.[11] Conversely, decreasing road capacity allows synergies with ridesharing as it manages to limit the rebound effects consecutive to lower road congestion. This involves, for example, converting motorway lanes into lanes reserved for ridesharing (and most often for public transport), following the example of the high-occupancy vehicle (HOV) lanes that have been in place for many years in North America. This concept is being transposed in several French cities such as Lyon and Paris, through the concept of reserved lanes (VR 2+). Finally, we find that increasing the cost of car travel in order to limit the price (and income) effect related to cost splitting presents negative synergies with ridesharing for CO_2 emissions, and no particular synergy regarding the social cost.

Table 6 : Effects of ridesharing (+25% AVO scenarios) and on various complementary measures on greenhouse gas emissions and the social cost (relatively to the reference scenario)

	CO_2 emissions	Social cost
AVO + 25%	-5,5%	-2,3%
Grand Paris Express	-4,1%	-10,3%
Grand Paris Express & AVO +25%	**-8,8%**	**-10,5%**
Theoretical impact without interaction [a]	*-9,4%*	*-12,3%*
Road capacity -20%	-7,4%	+16%
Road capacity -20% & AVO +25%	**-13,1%**	**+8,7%**
Theoretical impact without interaction [a]	*-12,5%*	*+13,4%*
Car cost +25%	-9,6%	-10,6%
Car cost +25% & AVO +25%	**-13,1%**	**-12,8%**
Theoretical impact without interaction [a]	*-14,6%*	*-12,6%*

[a] Effect computed by cumulating the individual effects in a multiplicative (and not additive) manner

Source: Coulombel et al. (2019)

[11] Note that intermodality (ridesharing then public transit) is not considered in our model, which might increase the efficiency of combining the two measures.

Our works show that developing urban ridesharing will trigger a series of rebound effects, including modal shift toward the car, increases in travel distances and urban sprawl, which result from the improved road travel conditions (both in time and money). These rebound effects are likely to be stronger in cities with high levels of road congestion and/or modal shares of public transportation. Considering the magnitude of the rebound effects, complementary measures are needed to maximize the benefits of ridesharing schemes. Based on our simulation results, reducing road capacity seems the most promising on paper. To limit the unpopularity of capacity reductions, these could be achieved by converting road lanes into dedicated bus lanes, bike lanes, or even HOV lanes to provide an additional incentive to rideshare. Still, because the decongestion effect only arises after ridesharing has reached a certain level of development, the question is whether decreasing road capacity will actually encourage users to rideshare, or whether it will trigger other reactions, such as using public transportation, teleworking, or even quitting work were travel conditions to become excessively bad. Though not involving synergetic effects like for road capacity measures, increasing the cost of car travel (*e.g.* by road pricing) might be more promising in that regard. Unlike for time costs, a simple way to cope with increases in monetary costs is to engage in ridesharing. Road pricing could therefore be an efficient way to simultaneously encourage ridesharing while limiting the associated rebound effects. While these could not be investigated due to the limitations of our aggregate modeling chain, ridesharing subsidies that would differ between drivers and riders as investigated by de Palma et al. (2022a) could further improve the efficiency of such schemes. Last, public transit improvements seem less promising: while they do address the modal shift effect, they amplify the other rebound effects (increased trip distance and urban sprawl).

All in all, the findings corroborate the idea that to achieve their low-carbon transitions, cities should not rely solely on one type of solution (technological, infrastructural, or behavioral), but rather on a combination of these. Given the complex effects related to the combination of public policies, which may result in counterintuitive positive or negative synergies, this underlines the usefulness of modelling for designing programs of measures in the context of sustainable mobility plans.

4. Research perspectives

4.1 Limitations of static and aggregate simulation models

My research works aim at supporting the design of sustainable mobility policies, by working on issues related to their economic appraisal. To this end, I have developed models either theoretical in order to better understand the economic forces at work (as for reliability or congestion of public transport), or numerical when the objective was to quantitatively assess the magnitude of the economic impacts (as for the environmental social costs of urban road freight and of urban ridesharing). In both cases, the modeling approach aims to represent the decisions of the various agents and to analyze the result of their interactions, allowing to capture complex system effects and to evaluate their magnitude: rebound effects, interactions between public policies, etc. Crossing modeling and economic appraisal is in my opinion all the more necessary in view of the current challenges in terms of public policy design. On the one hand, the increase in constraints, whether economic (increasing scarcity of public money following the various recent economic crises), environmental (taking into account the planetary limits), or social (with more important focus on equity issues and the impacts on the least well-off households) calls for multi-criterion approaches. On the other hand, it also becomes increasingly important to be able to evaluate public policy packages to ensure that the objectives set are achieved, particularly in the case of decarbonization strategies, and thus to be able to analyze interactions between policies. For example, the French National Low Carbon Strategy involves the implementation of 45 guidelines, including 6 for transport, as well as a monitoring with a dashboard of 184 key performance indicators.[12] Only modeling approaches are in my view able to meet these two challenges; I will therefore continue my research in this direction. Regarding simulation works, however, the transport models I used in my first studies were 4-step models, used either alone or in combination with a land-use model in order to integrate the effects related to households' relocation choices. The 4-step models are static models

[12] https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc

- focusing on a given time of day assumed to be in steady state - and aggregated, operating at the scale of passenger flows and not of individuals. Although they have the dual advantage of being widespread, especially among public authorities and consulting firms, and of a long user history that has provided proof of their operationality (via numerous calibration and validation studies for their instantiation), these models have several limitations in relation to the issues mentioned above.

First, their static nature prevents analyzing the daily dynamics of the phenomena represented. Yet, at least three phenomena of major interest to cities are characterized by significant dynamics, questioning the relevance of the steady state assumption. This is first of all the case of congestion, especially road congestion. In many cities, the high level of road traffic leads to hypercongestion, the decrease in traffic flow in the basic traffic diagram that can be observed first at the infrastructure level, but also at the macroscopic level (Geroliminis and Daganzo, 2008). This can be aggravated by spillback congestion phenomena, causing significant impacts on speeds (as for example in Krug et al., 2021). This is the case in the Paris region, so that the static MODUS model does not manage to correctly reproduce flows and travel times under these conditions, leading the DRIEAT-IF (which develops and uses the MODUS model) to seek to replace the road traffic static assignment with dynamic assignment. Like congestion, environmental externalities also have marked dynamics. Air quality for instance highly depends on the intraday dynamics of local pollutant emissions and weather, limiting the relevance of static approaches. In a different manner, noise is a phenomenon that is very localized in time and is characterized by non-linear impacts, so that dynamic models - which can capture exposure peaks, including at night – are better suited for the computation of exposure indicators than static models (on the topics of exposure to local pollutants and noise, see the state of the art by Yameogo, 2021). Finally, new mobility solutions are often characterized by a quality of service or even a pricing that can vary greatly within a day. This is the case of shared mobility systems - self-service bicycles and scooters, car-sharing, dynamic ridesharing, etc. - for which the availability of the service fluctuates significantly according to the spatio-temporal dynamics of supply and demand.

Second, the aggregate nature of the 4-step models precludes tracking the mobility of individuals throughout the day. Four-step models do not allow for the representation of the phenomenon of trip chains and their increasing complexity in recent decades, with the recent increase in telecommuting, for example, which can lead to short tours near home or to longer tours with an anchor point at the workplace depending on the day.[13] As far as evaluation is concerned, the aggregate nature of 4-step models does not allow for the calculation of indicators at the individual level. This makes it difficult to study exposure to environmental externalities, or the distributional effects of mobility policies and equity issues.

4.2 Agent-based modeling and economic appraisal

Acknowledging the limitations of static and aggregate simulation models, I am developing a research project that seeks to develop the use of agent-based modeling for the evaluation of public policies, both for passenger and freight transportation. By proposing a dynamic and disaggregated framework, agent-based modeling allows to overcome the main limitations of 4-step models (Ziemke, 2022). Indeed, the more detailed representation of the 3 dimensions - agents, time, space - opens up new perspectives in terms of both modeling and evaluation.

At the modeling level, the fine representation of space and time allows to better represent physical phenomena. It allows to take into account their dynamics such as chemistry-dispersion in the case of air quality modeling (Elessa Etuman et al., 2021; Vosough et al., 2022), or the characteristics of the natural and built (street width, height...) environment in the case of noise propagation (Garg and Maji, 2014; Kaddoura and Nagel, 2018; Le Bescond et al., 2021). The micro-simulation of agents allows the implementation of disaggregate choice models, which can include both the characteristics of the individual and of her household, as well as their constraints (having to drop children at school,

[13] Regarding activity schedules, and the resulting mobility chains (or non-mobility), see for example the recent work of Motte-Beaumvol et al (2022).

availability of the household vehicles, work or study schedules...) as explanatory variables. It also opens the way to a finer estimation of the environmental impacts of mobility, based on the detailed characteristics of the household vehicles instead of using an average vehicle fleet (Lannes et al., 2022). Due to their capabilities, agent-based models are being overwhelmingly used to analyze new mobility services - in particular autonomous mobility service as we have shown in a state of the art with Félix Carreyre, Jaâfar Berrada and Laurent Bouillaut (Carreyre et al., 2022) – or new mobility policies such as the implementation of Mobility as a Service (see for instance the recent study of Becker et al., 2020) or low emission zones (Börjesson et al., 2021).

Similarly, agent-based models also open many perspectives in terms of evaluation, since they allow economic indicators to be estimated at the most disaggregated level in the three dimensions (agents, time, space), and then reaggregated as needed. This is especially useful for investigating redistributive effects of transportation policies (as in e.g. Tirachini and Proost, 2021) and equity issues (e.g. Meyer de Freitas et al., 2017; Souche-Le Corvec et al., 2019). The disaggregated nature of ABMs also allows to modulate the impacts according to the individual characteristics and sensitivities: heterogeneity in values of time, in health effects (for active modes, air pollution), etc.

The much more detailed level of modeling nevertheless implies major challenges in terms of calibration and validation, as discussed during the agent-based modeling seminar that I co-organized in 2019 with the help of Liu Liu (LVMT) and in partnership with the Paris Region Institute, and as we are studying in a work in progress on calibration with Tatiana Seregina (LVMT) and Mustafa Ameli (GRETTIA), presented at the TRISTAN 2022 conference, with a paper being written.

In order to successfully carry out this research project, I have sought to first establish a solid and sustainable foundation both on a scientific level and in terms of human and financial resources. On the scientific level, the international research seminar that I organized in 2019 allowed me to launch the project and to invite Kay Axhausen (ETHZ) and Kai Nagel (TU Berlin), two world specialists on the subject, and to draw up a state of the art of the work in the field (with a focus on the MATSim platform,

www.matsim.org, being currently the most used agent-based mobility model worldwide). Since then, I take part every year to the MATSim User Meeting with the team that I supervise in order to keep us informed of the recent works on the platform. I also collaborate with André de Palma (CYU), world expert in transportation economics and urban modeling, and at the origin of the METROPOLIS model. This platform, which is more focused on the microeconomic representation of user behavior and the resulting equilibrium, represents a relevant alternative to MATSim depending on the research topic. Both platforms are open, an important element in the choice to select them.

Regarding human resources, I have hired a team of researchers, PhD students and interns thanks to the funding I have obtained (Lab Recherche Environnement, thesis funding with ENPC, Védécom, and DIM QI2, SAM project on autonomous mobility...). This allows us to reach the critical mass needed to work on agent-based modeling, which requires skills in programming, optimization, and mobility analysis. Currently, the team consists of Tatiana Seregina and Biao Yin as post-doctoral research fellows, and Félix Carreyre, Marjolaine Lannes and Rayane Alamirdache as PhD students. Considering the entry cost of MATSim (which is not a commercial software, involving a less complete documentation and less effort on the ergonomics despite the pros of being open source), a major stake relates to the loss of competences in case of leave - a fortiori unforeseen - of members of the team. This risk is particularly high given the increasing difficulties to secure employment for non-permanent members, leading to (far too) many departures. To overcome (to some limited extent) this difficulty, we have developed with Sebastian Hörl (SystemX) a Slack network for the MATSim community in France, in order to support exchanges and cooperation between research teams on a national level. The idea is that by sharing know-how and developments on the widest possible scale, all the teams can move forward more quickly and have the insurance that if the unexpected departure of a member prevents the transfer of the know-how accumulated internally, the community can then take over from the team to train the new members when they are recruited.

Finally, at the strategic level of financial resources, and as mentioned in 1.3, I am involved in several projects in order to both support my research and collaborations, and to ensure enough funds to support the whole team. The Lab Recherche Environnement with Vinci plays a key role in this part, which I nevertheless make sure to diversify with other sources of funding in order to limit dependence on a single funder.

4.3 Ongoing and future projects

In order to go forward with my research project aiming at crossing agent-based modeling with economic appraisal, I have already initiated several works that are still in progress.

On methodological issues, I am currently supervising the thesis of Félix Carreyre - with Laurent Bouillaut (GRETTIA) as co-director and Jaâfar Berrada (Védécom) as co-supervisor - on the economic appraisal of autonomous mobility services. Following a state of the art of the topic, published in the *Review of Industrial Economics*, we have chosen the MATSim model to perform mobility simulations. MATSim is as mentioned previously especially appropriate for this purpose considering its capabilities, and in fact the most used in the literature. We are therefore working on how to implement cost-benefit analysis in the MATSim framework and adapt it to the case of autonomous mobility services, with their specificities in terms of cost and investment structure, impacts in terms of externalities (environment, safety, congestion) or user behaviors (with issues related to the value of time). In parallel to this thesis, Rayane Alamirdache has started in October 2022 a thesis on the integration of equity in the evaluation of transport projects, which will take advantage of the capacities of multi-agent models to calculate indicators at the individual level.

On thematic issues, we are working with Biao Yin and Tatiana Seregina on the evaluation of innovative public policies, such as driving restrictions that are being considered in the center of Paris, or the development of e-scooters services to promote intermodality and the use of public transport (or on the contrary to compete with them, a point which we are trying to clarify). I also co-supervise

the thesis of Marjolaine Lannes, directed by Yelva Roustan (CEREA). This thesis studies uncertainties related to the calculation of exposure to air pollution using agent-based models for the mobility part (coupled with the HBEFA emissions model and an air quality model). Finally, the thesis of Félix Carreyre, beyond its methodological issues, also aims to determine what could be the contribution of autonomous mobility services for territories, by trying to establish what type of service is the most adapted according to their characteristics (density, existing public transport supply...).

Regarding future works, I would like to extend my previous works on urban ridesharing by leveraging the capacities of agent-based models to study various types of incentive measures, including subsidies and managed lanes which are a hot topic in the Paris region with the upcoming Olympic games (for which several managed lanes will be implemented, with the question of whether these should be temporary or permanent). More generally I would like to work on how to transform urban motorways to achieve a more sustainable mobility. Considering the environmental emergency, this topic is in my opinion a key issue to strongly curb solo-driving and its strong environmental impact, and is in line with the roadmap of cities as well as highway infrastructure managers (including Vinci) who are looking for solutions to decarbonize highway transport and to reduce emissions associated with their Scope 3.

5. Conclusion

My research relies on two forms of modeling, theoretical and numerical, to evaluate public policy on transport and mobility, with increasing concern of necessary environmental transition and equity. Although transportation microeconomics remains my theoretical frame of reference, as evidenced by my work on public transit reliability and congestion, my simulation work has evolved from a traditional approach based on the 4-step model to a more innovative approach based on agent-based models. While this framework provides great flexibility for evaluating mobility measures on the supply side (traffic restrictions, low emission zones, shared mobility services) as well as on the demand side (staggered work hours, tradable mobility permits, telecommuting), it also poses three challenges that I will pay attention to in my future projects.

The first challenge is related to the microeconomic foundation of agent-based mobility models. When most models base agents' decisions on the notion of utility (in a more or less direct form, where utility in MATSim is called score, for example), both the individual optimum (utility maximization program) and the system equilibrium are not always well defined. This results from the disaggregated and dynamic approach combined with a typically very large universe of choices (mode of transport, departure time, route...), which lead these models to tend to focus on the notion of convergence rather than on an equilibrium solution (if it exists at all). This raises questions about the stability of the solution at the individual level (the model could oscillate between two states that are close in terms of total utility but imply significant variations in individual choices) and about the uniqueness of the equilibrium at the aggregate level.

The second challenge lies in the calibration and validation of agent-based mobility models. As mentioned earlier, the complexity of these models, both in terms of model structure and data requirements, makes these two issues important. It will therefore be necessary to collaborate with the scientific community in the area of applied mathematics and complex systems modeling, as I have

already had the opportunity to do in the ANR Cities project on calibration and validation of land use-transportation interaction models. In other areas (e.g., weather or air quality models), there is a large literature using, for example, sensitivity analysis methods (Sobol indices), metamodeling, or uncertainty propagation to work on these issues.

A third challenge relates to the limitations of mobility models, which represent only a portion of the urban system and must be coupled with other models depending on the needs of the research topic. Multidisciplinary work with specialists in air pollutant emissions, atmospheric physiochemistry for air quality, life cycle analysis for broader environmental impacts, or urban economics to integrate urban development and real estate strategies of businesses and households is increasingly necessary given current research challenges. To this end, I can draw on the multidisciplinary nature of the “Villes, Transports, et Territoires” PhD School and, more broadly, the Cité Descartes campus and the collaboration with the Institut Polytechnique Paris that is currently being established.

6. List of papers presented in the manuscript

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Invited speaker

"La valeur du temps, de quoi parle-t-on?", Groupe de Travail "Valeur du Temps" du Ministère de la Transition Ecologique, 8 juin 2022, Paris, France.

"Decarbonation strategies in the transportation sector and rebound effects: the case of ridesharing and telework ", PSE Annual Conference on Global Issues: « For a Systemic and Humanist Environmental Transition », 2022, May 11-13, Paris, France.

"Congestion, diseconomies of scale and subsidies in urban public transportation", 5th Winter Workshop on Urban Economics: « Managing Urban Congestion », 2020, January 24, Copenhagen, Denmark

"Modélisation des transports à l'échelle nationale: enjeux et perspectives", Séminaire international CGDD Modèles de transport interurbain : le cas français et des exemples à l'international, 2019, 19 Juin, Paris La Défense, France.

"The value of service reliability", TSU International Seminar « Challenging Issues on Transport Studies », 28th February 2012, Tokyo, Japan

"What tools to analyze land-use transport interactions?", Task Force "Energy Efficiency and Urban Development", 2010, Séminaire AFD Formes Urbaines et Transports Urbains, Paris, France

"Tackling the Urban Sprawl Issue: A Monocentric Analysis of Housing Budget Restrictions, Including and Without Transportation", 2009, Task Force AFD "Energy Efficiency and Urban Development", Paris, France

International conference with proceedings

LIU L, BIAO Y, COULOMBEL N, 2019, "Developing ridesharing, but for which trip category? A comparative analysis for the Paris region", *Proceedings of the 19th COTA International Conference of Transportation Professionals*, July 6–8, 2019, Nanjing, China

COMBES F, COULOMBEL N, KONING M, 2018, "An Empirical Analysis of External Marginal Costs for Passengers and Freight Transport: The Paris Case Study", *Proceedings of 7th Transport Research Arena TRA 2018*, 13-16 May, Vienna, Austria.

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International conference (no proceedings)

CARREYRE F, BERRADA J, BOUILLAUT L, COULOMBEL N, 2022, "What are autonomous vehicles worth? A Cost Benefit Analysis", 4th Bridging Transport Researchers (BRT) Conference, 4-5 August, Online low-carbon conference

CARREYRE F, BERRADA J, BOUILLAUT L, COULOMBEL N, 2022, "What are autonomous vehicles worth? A Cost Benefit Analysis", ITEA Annual Conference, 15-17 June, Toulouse, France

KIKO M, COULOMBEL N, SEREGINA T, POULHES A, TREMBLIN G, 2022, "Intégration du télétravail dans un modèle de demande de transport et évaluation socio-économique de ses effets : premiers résultats", 4èmes Rencontres Francophones Tansport Mobilité (RFTM), 8-10 June, Esch-sur-Alzette, Luxembourg

YIN B, DIALLO A O, SEREGINA T, COULOMBEL N, 2022, "Evaluation of low traffic neighborhoods: the Paris case study", MATSim User Meeting, 31 May, Leuven, Belgium

LANNES M, COULOMBEL N, ROUSTAN Y, 2022, "Car fleet synthesis model based on households characteristics: machine learning vs. discrete choice modelling", MATSim User Meeting, 31 May, Leuven, Belgium

OLAVE I, COULOMBEL N, BROUSSEAU E, COME E, 2022, "Parking Regulations to Harmonize Dock-less E-scooters: An Empirical Analysis from Paris", Heart Conference, 1-3 June, Leuven, Belgium

KIKO M, COULOMBEL N, SEREGINA T, POULHES A, TREMBLIN G, 2022, "Extent of the effectiveness of telework at a metropolitan scale: Lessons of a Travel Demand Model", Nectar Conference, 17-18 March, Marne-la-Vallée, France

COULOMBEL N, POINSOT P, 2022, "Quelle zone de pertinence du train dans les lignes de desserte fine du territoire", Séminaire du LAET, 10 March, Lyon, France

BERNADAC B, COULOMBEL N, DE PALMA A, "Last mile commuting in von Thünen’s city", ITEA Annual Conference, June 24-26, Rome, Italy

KONING M, ELESSA A, GARDRAT M, COULOMBEL N, "The external environmental cost of road freight transport: New evidence from the Paris region using the Olympus multiagents model ", ITEA Annual Conference, June 24-26, Rome, Italy

FRANCOIS C, COULOMBEL N, 2021, "Écoconception de la mobilité à l’échelle d’un quartier", Rencontres Francophones Tansport Mobilité (RFTM), 2-4 Juin, Marne-la-Vallée, France

LIU L, COULOMBEL N, YIN B, 2021, "Simuler l’impact environnemental de la mobilité douce au sein d’un quartier", Rencontres Francophones Tansport Mobilité (RFTM), 2-4 Juin, Marne-la-Vallée, France

MONCHAMBERT G, COULOMBEL N, 2021, "Congestion, diseconomies of scale and subsidies in urban public transportation", 10th European Meeting of the Urban Economics Association, 29 April - 1 May, Online.

KONING M, COMBES F, COULOMBEL N, GARDRAT M, 2020, "Welfare losses caused by under-priced and heterogeneous road transport: The Paris region case study", LEM seminar, 17 novembre, Lille, France.

CARREYRE F, BERRADA J, BOUILLAUT L, COULOMBEL N, 2020, "Autonomous Vehicles Simulations: Indicators use in the Literature", 2020 EWGT conferece, 16-18 September, Paphos, Cyprus.

LIU L, COULOMBEL N, 2019, "A la recherche d'une mobilité durable à l'échelle d'un quartier", Séminaire « Modélisation » du département AME, 19 septembre, Champs-sur-Marne, France.

COMBES F, COULOMBEL N, KONING M, 2019, "Des modèles numériques aux modèles théoriques : Le cas de la tarification des routes en Ile-de-France", Séminaire « Modélisation » du département AME, 19 septembre, Champs-sur-Marne, France.

COULOMBEL N, MONCHAMBERT G, 2019, "Diseconomies of scale in public transit: When the Mohring effect ends", 2019 ITEA Annual Conference, 12-14 June, Paris, France.

COMBES F, COULOMBEL N, GARDRAT M, KONING M, 2019, "Welfare losses caused by under-priced and heterogeneous road transport: The Paris region case study", 2019 ITEA Annual Conference, 12-14 June, Paris, France.

VIGUIE V, COULOMBEL N, BIAO Y, LIU L, LEPETIT Q, 2019, "Can land value capture finance a large public transport project in Paris? A prospective analysis using a land-use model", 2019 ITEA Annual Conference, 12-14 June, Paris, France.

COULOMBEL N, KONING M, HEITZ A, ANDRE M, FORET G, 2019, "Transport legacies of Paris 2024 Olympic and Paralympic Games: from analysis to prospects", ORME conference « Legacy of Olympic and Paralympic Games », June 17-18, Champs-sur-Marne, France.

COULOMBEL N, 2019, "La modélisation intégrée transport-usage du sol: principes et exemples d'application", Séminaire Habitat du Lab'Urba, 10 janvier, Champs-sur-Marne, France.

COMBES F, COULOMBEL N, GARDRAT M, KONING M, 2018, "Welfare Losses Caused by Under-priced and Heterogeneous Road Traffic: The Paris Region Case Study", Conférence Evaluation des Politiques Publiques (AFSE-DG Trésor), 13 December, Paris, France.

COULOMBEL N, BOUTUEIL V, LIU L, VIGUIE V, YIN B, 2018, "Covoiturage urbain et effets rebonds : le cas francilien", Atelier Thématique de Recherche "Ville, Transports et Mobilité Durable", 2ème édition, 29-30 novembre 2018, Guyancourt, France.

COULOMBEL N, DE PALMA A, 2018, "Optimal timetable for unreliable transit services", 2018 ITEA Annual Conference, 27-29 June, Hong Kong, China.

COULOMBEL N, MONCHAMBERT G, 2018, "Congestion et déséconomies d'échelle dans les transports en commun: Jusqu'où tient l'effet Mohring ?", 1ères Rencontres Francophones Transport-Mobilité, 6-8 juin 2018, Lyon, France.

COULOMBEL N, DABLANC L, GARDRAT M, KONING M, 2018, "L'étalement logistique en Ile-de-France : Quels effets environnementaux ?", 1ères Rencontres Francophones Transport-Mobilité, 6-8 juin 2018, Lyon, France.

COULOMBEL N, 2018, "Budgets de transport et vulnérabilité des ménages", Séminaire SELEST du DEST, 5 avril, Champs-sur-Marne, France.

COMBES F, COULOMBEL N, GARDRAT M, KONING M, 2018, "Welfare Losses Caused by Passengers and Freight Road Transport: The Paris Case Study", Seminar of CESAER, 5 March, Dijon, France.

COULOMBEL N, YIN B, LIU L, VIGUIE V, 2017, "Covoiturage en Ile-de-France et prospection: impacts environnementaux à l'horizon 2030", Soirée Conférence de la Chaire Éco-conception des Ensembles Bâtis et des Infrastructures, 20 septembre 2017, Rueil-Malmaison, France.

ELESSA A, COLL I, VIGUIE V, COULOMBEL N, PRUD'HOMME J, 2017, "Urban compaction vs city sprawl: impact of road traffic on air quality in the greater Paris", The international conference on Atmospheric Sciences and Application to Air Quality (ASAAQ) 2017, 29-31 May, Strasbourg, France.

COULOMBEL N, DABLANC L, GARDRAT M, KONING M, 2017, "Impact environnemental du transport routier de marchandises en Ile-de-France", 16ème séminaire francophone de socio-économie des transports, 18-19 mai, Marne-la-Vallée, France.

MONCHAMBERT G, COULOMBEL N, 2017, "Diseconomies of scale in public transport: When the Mohring effect ends", 2017 ITEA Annual Conference, 21-23 June, Barcelona, Spain.

COULOMBEL N, PEREZ HERRERO M, 2017, "Delay propagation and marginal social cost of headway: the case of planned transport services", 2017 ITEA Annual Conference, 21-23 June, Barcelona, Spain.

PEREZ HERRERO M, COULOMBEL N, 2017, "Rail capacity constraints: a supply-demand equilibrium approach", 2017 ITEA Annual Conference, 21-23 June, Barcelona, Spain.

COMBES F, COULOMBEL N, KONING M, 2017, "External marginal costs and optimal taxation of passenger and freight transport in large urban areas: the case of Paris, France", 2017 ITEA Annual Conference, 21-23 June, Barcelona, Spain.

COULOMBEL N, YU X, DE PALMA A, 2015, “The valuation of travel time reliability: does congestion matter?”, ITEA Conference 2015, Oslo, Norway

COULOMBEL N, DE PALMA A, 2013, “The marginal social cost of travel time variability”, 13th WCTR 2013, Rio de Janeiro, Brazil

COULOMBEL N, 2012, “The determinants of housing demand: An analysis for French households”, 59th North American Meetings of the RSAI, Ottawa, Canada

COULOMBEL N, LEURENT F, POULHES A, 2012, “A land-use transport interaction model for the Greater Paris Region: The Land Use Price Time model (LUPT)”, 59th North American Meetings of the RSAI, Ottawa, Canada

CHRISTOFOROU Z, COULOMBEL N, 2012, “Challenges and questions about the A4 highway project in Ile-de-France”, BUFTOD 2012 conference, Marne-la-Vallée, France

COULOMBEL N, DE PALMA A, ZERGUINI S, 2010, “The impact of the variability of travel time on travel behaviors”, 5th Kuhmo-Nectar Conference, Valencia, Spain

COULOMBEL N, 2009, “Tackling the Urban Sprawl Issue: A Monocentric Analysis of Housing Budget Restrictions, Including and Without Transportation”, 4th Kuhmo-Nectar Conference, Copenhagen, Denmark

COULOMBEL N, 2009, “Tackling the Urban Sprawl Issue: A Monocentric Analysis of Housing Budget Restrictions, Including and Without Transportation”, 56th RSAI North American Meetings, San Francisco, USA

National conferences, international/national seminars

COULOMBEL N, LEURENT F, 2012, « Evaluation ex-ante du projet d’aménagement du cœur de cluster Descartes : une approche d’ingénieur », Actes du Congrès ATEC-ITS France 2012 : Intelligence dans les déplacements : de la recherche aux pratiques, Versailles, France

COULOMBEL N, BOUTUEIL V, LIU L, VIGUIE V, YIN B, 2019, "Substantial rebound effects in urban ridesharing: Simulating travel decisions in Paris, France", Séminaire de recherche Polytechnique - Ecole des Ponts, 19 mars, Paris, France.

BERRY A, COULOMBEL N, GUIVARCH C, JOUFFE Y, 2015, “Building fuel poverty measurement for the transport sector”, Young Energy Engineers and Economists Seminar (YEEES) 2015, La Défense, France

LEURENT F, COULOMBEL N, POULHES A, 2013, “A land-use transport interaction model for the Greater Paris Region - The Land Use Price Time model (LUPT)”, Land Use Transport Interaction seminar, 23 May 2013, Marne-la-Vallée, France.

COULOMBEL N, 2008, « Faut-il restreindre l’effort logement ou l’effort combiné logement + transport? Une analyse monocentrique », Séminaire du LET, Lyon, France