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# Structural design of a hierarchical urban transit network integrating modal choice and environmental impacts

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## Abstract

The paper develops a structural model and a design methodology for transit system planning in an urban area. Transit “components” are modelled by subarea and by sub-mode in terms of line length, station spacing, and fleet size, in order to determine both quality of service and production costs. Roadway networks are modeled with a Macroscopic Fundamental Diagram that relates speed to network capacity and vehicle demand. Local and global environmental impacts are considered. Travel demand includes both mode-dependent users and mode-choosers able to adopt the mode that offers higher utility.

The design methodology involves a mathematical program of welfare optimization with respect to transit factors and fares. Two definitions of welfare are given, one that takes into account only demand surplus and supply profit, the other including environmental impacts.

An example of application to Greater Paris shows that there is room for system optimization under current subsidy conditions, and that the explicit inclusion of environmental impacts brings about a significant shift in the “optimal” policy package.

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*Keywords:* multimodal transportation; transit network; design model; social welfare; environmental impacts

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## 1. Introduction

**Background.** Passenger travel demand in a metropolitan area involves two kinds of trip, defined by trip length: short trips of less than 1 km, and medium and long trips above that distance. The latter type is better served by motorized modes such as the automobile (private car, cab, car-sharing and ridesharing) or transit modes: bus, tram, metro and train.

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The aim of urban mobility planning is to serve travel demand efficiently: roadway and public transportation infrastructure as well as transit services have to satisfy users' needs with tolerable costs to the public purse and acceptable environmental impacts. The optimal design of a multimodal urban mobility plan is therefore an economic program to maximize a comprehensive welfare function. This incorporates both social welfare and environmental performance under constraints pertaining to quality of service in terms of access time, wait time and on-board time, which on the one hand stem from action levers through the technical process of transit service production and, on the other hand, entail traveler behavior.

**Related work.** Previous research on this topic began at the scale of a single bus line with Mohring (1972), who considered fleet size (hence service frequency) and stop spacing as levers that could be used to maximize social welfare, defined as demand surplus and production profit. While a broad stream of research has focused on the optimization of a metropolitan scale transit network with much spatial detail and discrete variables, Van Nes (2002) placed the emphasis on structural features, including line length, station spacing, and vehicle fleet size. By modeling these as continuous variables to optimize social welfare, he developed a full methodology for the design of roadway networks, transit networks, and also multimodal networks. He addressed multimodality as a weak interaction between modes, on the basis of a logit model of discrete choice by individual users between car and transit modes. Transit networks at the scale of a whole urban area were addressed by Combes and Van Nes (2012), who tackled the case of Greater Paris by introducing the “component” concept, where a component is a pairing of one sub-mode and one subarea. Comprehensive mathematical formulation and in-depth economic analysis were provided by Leurent et al. (2016). This kind of structural analysis relies on the statistical modeling of travel demand, trip-making features, network structure, and traffic conditions.

A second stream of modeling was pioneered by Daganzo for two modes: first to develop an aggregate model of the traffic performance of an urban road network by means of the macro fundamental diagram (MFD) (Daganzo and Geroliminis, 2008), and second to model a grid network of bus lines and optimize its structural parameters (Daganzo, 2010). The two modes were combined by Estrada et al. (2012) to optimize the transit network, taking into account the costs to both car users and transit users, and operator costs. Recently, Badia et al. (2014) adapted Daganzo's transit network design model to a city with a radial street pattern.

**Paper objective.** This paper addresses the structural design of an urban transit network modeled as a set of components, in order to optimize a social welfare function that encompasses both production profit and user surplus not only for the transit network but also for the car mode. Users are either mode-dependent or mode-choosers. Environmental impacts are taken into account for both modes. The model makes it possible to study planning trade-offs between modes based on their respective performance in terms of demand surplus, environmental benefits, and production costs, and to determine the range of relevance of transit sub-modes.

**Paper structure.** The rest of the paper is in four parts. Section 2 introduces the assumptions and structure of the model. Section 3 then defines the planning problem of optimal structural design and provides an optimization algorithm. Section 4 provides a real-world application to Greater Paris. Lastly, Section 5 summarizes the findings and identifies directions for further research.

## 2. Model composition

Let us consider an urban area with its population, including workers, and with economic activity that provides job opportunities. To account for territorial heterogeneity, the study area  $Z$  is split into subareas indexed by  $z$ , depending on the densities of the population and the transportation infrastructure. The system of motorized transportation is simplified as two modes  $M \in \{C, T\}$ : car mode  $C$  and a transit network  $T$ .

### 2.1. Travel demand

Motorized transportation demand is classified into three types of users: transit-dependent  $TD$ , car-dependent  $CD$ , and mode-choosers  $F$  – for *Flexible*. Transit-dependent users lack the capacity (i.e. have no license or vehicle) or opportunities to drive a car or carpool with others, so their trips depend totally on public transportation. Car-dependent users have access to at least one car (or motorcycle) but little access to public transportation, or have logistic constraints that require the use of a car, e.g. for some business trips or mass purchases etc. Mode-choosers

have access to both modes and will choose the best option for any given trip. The two dependent types are passively exposed to variations in quality of service, while mode-choosers can respond actively by adjusting their options.

Demand is described in origin-destination (O-D) pairs  $i$  ( $i \in I$ , set of O-D pairs). Trip endpoint zones are smaller than the subarea level. For each O-D pair  $i$ , the total demand  $Q_i^G$  is exogenous:

$$Q_i^G = Q_i^F + Q_i^{CD} + Q_i^{TD} \tag{1}$$

“Mode choosing users”, defined as  $Q_i^F$ , choose their modes with respect to the generalized costs  $g_i^T$  and  $g_i^C$  of the transit and car options respectively. A logit discrete choice model is postulated, in that the respective modal volumes of transit choosers (TF) and car choosers (CF) are as follows:  $\forall i \in I$ ,

$$Q_i^{TF} = Q_i^F \cdot \exp(-\theta g_i^T) / (\exp(-\theta g_i^T) + \exp(-\theta g_i^C)) \text{ and } Q_i^{CF} = Q_i^F - Q_i^{TF} \tag{2, 3}$$

### 2.2. Transit system

The structure of the transit network is modeled as a set of components  $r = (z, m)$  by zone  $z$  and transit sub-modes available in  $z$ :  $m \in T_z$ . The transit services can include bus lines, tram lines, metro lines and / or train lines.

Let  $R$  denote the set of components  $r$ . Each component is characterized by four factors, the decision variables of the model: line length  $L_r$ , number of stations  $\sigma_r$ , rolling stock quantity  $N_r$ , and tariff  $\tau_r$ . Inside the component, the line spacing and stop spacing are considered homogeneous, and the rolling stock operates in ideal conditions with no interruption at the terminus. In a given zone  $z$ , the different  $r$  intersect each other at transit hubs where users can make transfers that incur a penalty. Transit operations and quality of service are modeled as a set of four technical relationships as follows:  $\forall r \in R$ ,

$$S_r = L_r / \sigma_r, \quad 1/v_r = 1/V_r + \omega_r / S_r, \quad \varphi_r = N_r v_r / 2L_r, \quad d_r^{A,D} = \frac{1}{4}(S_r + \chi_z A_z / L_r) \tag{4a,b,c,d}$$

Relation (4a) derives station spacing  $S_r$  from line length  $L_r$  and number of stations  $\sigma_r$ . Relation (4b) derives commercial speed  $v_r$  on the basis of elapsed time per unit of distance traveled, including a running part  $1/V_r$  and a dwelling part  $\omega_r/S_r$  that involves typical dwell time  $\omega_r$  (exogenous) in relation to station density. Relation (4c) derives service frequency  $\varphi_r$  from fleet size  $N_r$  and cycle time  $2L_r/v_r$ . Relation (4d) derives the average access distance  $d_r^{A,D}$  between trip endpoint and service station from station spacing and line spacing  $\chi_z A_z / L_r$  which involves zone area  $A_z$  together with line length  $L_r$  and a shape parameter  $\chi_z$  with a typical value between 1 and 2.

For each O-D pair  $i$ , the average generalized travel cost of a transit trip is based on the trip stages of access, wait, on-board, and transfer in one or more components  $r$  per stage  $X$ : there is a coefficient  $\gamma_{r,i}^X$  that represents user sensitivity (e.g. value of time depending on comfort state) and the duration of such exposure (e.g. specific time  $t^X$ ):

$$g_i^T = \sum_{r \in R} \gamma_{r,i}^T \tau_r + \sum_{r \in R, X} \gamma_{r,i}^X t_{r,i}^X \tag{5}$$

On the supply side, each component induces production costs that are modeled on the basis of technical factors  $L_r, \sigma_r, N_r$  with respective unit costs of  $c_r^L, c_r^\sigma$  and  $c_r^N$ , which include distance-related costs and investment costs amortized over the technical lifetime. Then, per year of operations:

$$c_r^o = c_r^L \cdot L_r + c_r^\sigma \cdot \sigma_r + c_r^N \cdot N_r \tag{6a}$$

The transit network includes all components, together with general functions (information, ticketing, general safety, management...). The related “general costs” can be attributed to all transit trips on a proportional basis, at unit cost  $c_0^o$ . Let  $Q^T = \sum_{i \in I} Q_i^{TD} + Q_i^{TF}$  denote the daily number of transit trips and  $Y$  the number of operating days in a year. The total cost of transit production, on a daily basis, amounts to:

$$c^o = c_0^o \cdot Q^T + (\sum_{r \in R} c_r^o) / Y \tag{6b}$$

### 2.3. Car mode and roadway system

For the car mode, the generalized cost of a trip on O-D pair  $i$  incorporates three parts: (i) monetized travel time, which depends on distance  $D_{z,i}$  travelled in zone  $z$  at respective car speed  $v_z$ , and on  $\beta_t$  the user’s value of time; (ii) the cost of car possession and usage per unit of distance  $\beta_c$ , which includes purchase depreciation, energy, maintenance, and insurance; (iii) the costs of parking fare and availability  $F_i$ :

$$g_i^c = F_i + \sum_z D_{z,i} \cdot (\beta_t/v_z + \beta_c) \quad (7)$$

For each zone  $z$ , average car speed  $v_z$  is related to the quantity of traffic in two ways. On the demand side, the faster the speed the more demand volume, whereas on the supply side the more traffic, the slower the speed.

To put things precisely, by O-D pair  $i$  let  $Q_i^c = Q_i^{CD} + Q_i^{CF}$  denote the volume of car trips, including dependent as well as flexible users. In zone  $z$ , each car user belonging to  $i$  requests to travel a distance of  $D_{z,i}$  by car, so that the overall car traffic demanded amounts to  $Q_z^+ = \sum_{i \in I} Q_i^c \cdot D_{z,i}/\eta_i$  in which the average car occupancy rate  $\eta_i$  is taken into account.

On the supply side, traffic performance is modeled by a Macroscopic Fundamental Diagram (MFD) that relates  $v_z$  decreasingly to average density  $\rho_z$  per unit distance of roadway lane:  $v_z = V_z(\rho_z)$ , or equivalently  $\rho_z = R_z(v_z)$ . Then, per traffic lane, the exit flow amounts to  $q_z^- = v_z \rho_z = v_z R_z(v_z)$ .

During period  $H_1$ , the total traffic flowed by the zone network of lane length  $l_z$  adds up to  $Q_z^- = l_z q_z^- H_1$ . Let us compare it to the volume demand  $Q_z^+$ . If  $Q_z^+ \leq Q_z^-$  then time  $H_1$  is sufficient to accommodate the volume demand, meaning that the traffic regime is fluid. Conversely, if  $Q_z^+ > Q_z^-$  then the traffic regime is congested. In other words, there is a traffic bottleneck, with a duration  $H_z$  in excess of  $H_1$ . The relation between  $H_z$  and  $H_1$  characterizes the traffic regime: either  $H_z = H_1$  under a fluid regime, or  $H_z > H_1$  at saturation.

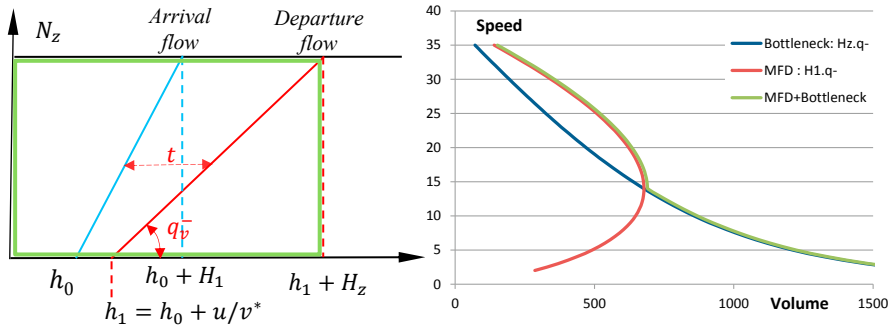


Fig. 1. (a) Cumulative flows in bottleneck; (b) Speed-volume function.

To deal with saturation, let us consider a bottleneck model with entry flow rate of  $q_z^+ = Q_z^+/(l_z H_1)$  during  $[h_0, h_0 + H_1]$  and exit flow rate of  $q_z^-$ , for a notional road of length defined as the average distance travelled by car users in zone  $z$ :  $u_z = (\sum_{i \in I} Q_i^c \cdot D_{z,i}) / (\sum_{i \in I} Q_i^c \cdot 1_{\{D_{z,i} > 0\}})$ . The number of cars,  $N_z = Q_z^+/l_z$ , are flowed out from instant  $h_0 + u_z/v_z^*$  with  $v_z^* = \arg \max_v q_{zv}^-$  the flow speed at capacity flow  $q_z^*$ , up to instant  $h_0 + u_z/v_z^* + H_z$ .

The rectangle area  $N_z \cdot (u_z/v_z^* + H_z)$  (green box in Fig. 1a) is related to the average time per user,  $t = u_z/v$ , by

$$N_z \cdot (u_z/v_z^* + H_z) = t \cdot N_z + \frac{1}{2} N_z H_1 + \frac{1}{2} N_z H_z$$

So that  $t = u_z/v_z^* + \frac{1}{2}(H_z - H_1)$ , hence  $H_z = H_1 + 2u_z(1/v - 1/v_z^*)$ .

Then, from flow conservation and the MFD, we have  $H_1 q_z^+ = H_z q_z^- = H_z v R(v)$ , yielding a fixed-point problem:

$$v = (q_z^+ H_1 / R(v) - 2u_z) / (H_1 - 2u_z/v_z^*)$$

Postulating a Daganzo and Geroliminis (2008) type MFD,  $R(v) = \omega_z \ln(v_0/v)$ , which decreases from  $+\infty$  to 0 as  $v$  varies from 0 to  $v_0$ , then the right-hand-side function in the fixed-point problem is a monotonic increasing function that varies from  $-2u_z/(H_1 - 2u_z/v_z^*)$  to  $+\infty$  on  $]0, v_0[$ . As the slope on its positive part is greater than 1, it crosses the identity function once only, meaning that the FPP has one solution which is unique. Furthermore, an increase in  $q_z^+$  increases the RHS function and makes the solution smaller:  $\tilde{v}$  decreases with  $q_z^+$ , hence  $H_z$  increases with  $q_z^+$ . As the solution is positive, necessarily  $q_z^+ H_1 > 2u_z R(\tilde{v})$ , hence  $\tilde{v} > V_z(q_z^+ H_1 / 2u_z)$ .

Figure 1b depicts the relationship that links car speed  $v_z$  to demand volume  $Q_z^+$ . It is a decreasing function in two parts, first the fluid part for  $Q_z^+$  varying from 0 to capacity volume  $Q_z^* = H_1 q_z^*$ , then the saturated part. Denote it as:

$$v_z = V_z^c(Q_z^+) \quad (8)$$

#### 2.4. Environmental impacts

The environmental impacts of a transportation system occur along its life cycle from the development of mobility equipment/services to operational transportation processes. The sources of pollution are multiple: infrastructure

construction and maintenance, energy distribution for vehicles, and vehicle operation. In this article, we consider only the impacts of the operational period.

These impacts may be local (e.g. noise, air pollution) or global (e.g. carbon emissions). The level of local impacts depends not only on the quantities of emissions but also on the local populations exposed to them: this means that population density must be taken into account in monetization (CGSP, 2013). Here we restrict the scope to two kinds of impact, namely (i) air and noise pollution from roadway vehicles including automobiles based on traffic  $Q_z^+$  and also from transit vehicles which run daily for a fixed duration  $H_r$ , and (ii) GHG emissions from energy consumption based on  $Q_z^+$  and also on average speed  $v_z$ . The environmental cost per day of operations, where parameters  $\alpha_{1r}$ ,  $\alpha_{2z}$ ,  $\alpha_3$  are cost coefficients per distance unit, and  $\delta_1$ ,  $\delta_2$ ,  $\delta_3$  describe the sensitivity to roadway speed, is as follows:

$$-P^e = \sum_{z \in Z} \alpha_{2z} \cdot Q_z^+ + \sum_{r \in R} \alpha_{1r} \cdot H_r v_r N_r + \sum_{z \in Z} \alpha_3 \cdot Q_z^+ \cdot (\delta_1 v_z^2 + \delta_2 v_z + \delta_3) \quad (9)$$

### 3. Planning problem

#### 3.1. Social welfare functions

Mobility stakeholders in the territory include the users, the operators, and also the environment in which residents are exposed to local impacts. The users' surplus consists of the surplus of mode-choosers (log sum formula for a logit discrete choice model formulated by Small et al. in 1981) and of dependent users:

$$P^u = \sum_{i \in I} (P_i^{uF} + P_i^{uD}) = \sum_{i \in I} \left[ Q_i^F \cdot \frac{1}{\theta} \ln(\exp(-\theta g_i^T) + \exp(-\theta g_i^C)) - Q_i^{TD} \cdot g_i^T - Q_i^{CD} \cdot g_i^C \right] \quad (10)$$

The operators' surplus, restricted to transit production, consists of commercial revenues minus production costs:

$$P^o = \sum_{i \in I} \tau_i (Q_i^{TC} + Q_i^{TD}) - c^o \quad (11)$$

The environmental profit is as stated previously. Two definitions of social welfare are considered:

$W_0 = P^u + P^o + P^e$  or  $W_1 = P^u + P^o$  only, where the environmental impacts are neglected.

#### 3.2. Transportation planning as a policy-making problem

In the territory under study, mobility policy is aimed to foster social welfare. To do so, transit modes are subsidized at level say  $S$  in order to make their production profitable to their operators.

Given  $S$ , the policy-making problem is modeled as the maximization of social welfare subject to requirements of production profitability along with technical constraints (1)-(11):

$$\max_{L, \sigma, N, \tau, v} W \quad \text{s.t.} \quad P^o + S \geq 0 \quad \text{and constraints (1)-(11)}. \quad (12)$$

The state vector includes components' state variables ( $L_r, \sigma_r, N_r, \tau_r: r \in R$ ) together with endogenous car speeds ( $v_z: z \in Z$ ). We used the ad-hoc function in Python library to solve this program of constrained optimization.

## 4. Case study of mobility planning in greater Paris

#### 4.1. Reference situation and its modeling as a system state

In 2010, Greater Paris had a population of about 12 million in an urbanized area of about 1,250 km<sup>2</sup> within the Île-de-France region, an area of 12,100 km<sup>2</sup>. The regional area is split into three subareas, namely Paris city, inner suburbs, and outer suburbs (Fig. 2a).

Our synthetic description of the motorized transportation networks is based on the National Regional Planning Agency's (DRIEA) 4-step Travel Demand Model MODUS, yielding the respective lengths and number of lanes of the subarea roadway networks (Fig. 2b,c). The transit system consists of four sub-modes ( $m$ ): RER (green line in Fig. 2d), Transilien (purple line in Fig. 2d), metro (red line in Fig. 2e), and bus (Fig. 2f).

According to the regional Household Travel Survey "EGT 2010", motorized travel demand in 2010 consisted of 15.5 million car trips and 8.3 million transit trips. These were converted into an equivalent peak demand concentrated on period  $H_1 = 10$  h.

According to the Mobility Authority’s 2010 activity report (Ile-de-France Mobilités, or STIF), transit costs excluding new investment amounted to €8.1 billion, versus fare revenues of €2.4 billion and subsidy of €5.7 billion.

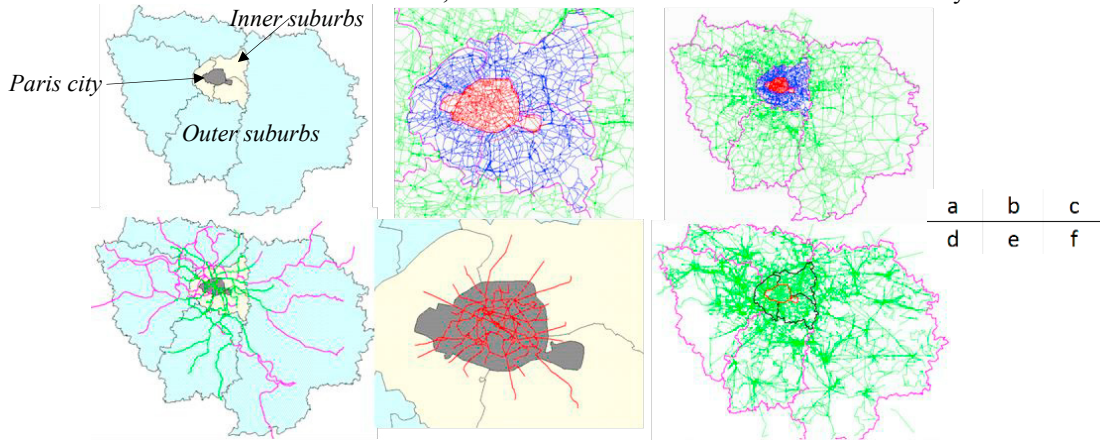


Fig. 2. Subarea division, road network division and four transit systems.

Tab 1. Road network characteristics.

subarea	$l_z$ km	$\omega_z$	$v_{0z}$ km/h	$F_z$ €	Car flow M veh/day	Car traffic M veh*km/day
Paris city	1670	48.5	38.0	2.0	2.35	13.3
inner suburbs	4417	53	48.0	0.5	6.59	39.2
outer suburbs	19097	40	59.0	0.0	10.67	84.3

Tab 2. Parameter set-up.

$\theta$	0.61	$\alpha_{10}$	4.5€/km*bus in Paris City	$\delta_1$	1.60E-05	$\gamma_{A,D}$	2.0
$\beta_t$	10€/h	$\alpha_{20}$	0.163€/km*veh in Paris City	$\delta_2$	-0.00234	$\gamma_W$	1.5
$\beta_c$	0.4€/km*veh	$\alpha_3$	0.1€/l	$\delta_3$	0.1381	$\gamma_R$	1.0

Tab 3. Transit network components and demand statistics.

Subarea	Paris					Inner suburbs			Outer suburbs		
	# Component	1	2	3	4	5	6	7	8	9	10
Transit network	Bus	Metro	RER	Transilien	Bus	Metro	RER	Transilien	Bus	RER	Transilien
Passenger flow (M pax/day)	1.25	3.97	1.91	0.62	2.03	1.35	2.06	0.77	1.24	1.13	0.65
Crow-fly distance between stations	2.06	4.01	5.02	3.15	2.27	1.85	6.94	6.61	3.46	7.72	12.68
Travel time in vehicle (min)	14.7	19.4	15.0	10.9	15.3	5.9	15.9	13.0	10.1	13.6	13.5
Access distance (km)	0.29	0.41	0.54	1.74	0.28	0.52	0.65	0.57	0.31	0.91	0.98
Generalized cost (€/travel)	6.84	9.24	5.64	4.23	7.36	5.84	7.72	6.19	7.70	12.59	13.38

Table 1 and Table 2 set out respectively the major indicators and the model parameters for the roadway network, together with the parameters of user behaviors and socio-economic appraisal (right side). Table 3 gives the demand and service indicators per transit component in the reference state.

#### 4.2. Simulation outcomes and discussion

Two planning policy scenarios were simulated: S0 to optimize welfare function  $W_0 = P^u + P^o + P^e$  and S1 for  $W_1 = P^u + P^o$ . The optimization of zone fares and component service frequencies (via fleet size) for all transit components, and that of line length and stop numbers for bus components, is more realistic in the short and medium term than that of line length and station numbers for rail components. The overall level of transit subsidy,  $S$ , is imposed, as are the O-D trip flows according to user types.

A number of salient features are common to both scenarios (Table 4). Firstly, network optimization would yield many benefits to transit users (about +8% on average) and also to roadway users (about +3% on average and +7% in the central area), because of better quality of service on transit modes. This improved quality results in a modal shift from car to transit, relieving roadway congestion and bringing benefits to the remaining automobile users.

Secondly, improving transit service quality entails significant development of transit services: the associated costs would increase by +27% for S0 and +34% for S1. With subsidy remaining constant, this is funded by large increases in transit fares, by 90% under S0 or 115% under S1, amounts that are very significant yet appear tolerable since the base level is quite low and the time saving is considerable.

Thirdly, transit improvements involve also a reorganization of transit services. The changes in service plans are indicated in Table 5: for instance, bus line length and station numbers would be much reduced, combined with a small reduction or stability in fleet size, which would improve service frequency, thereby modifying the trade-off between access times and wait times.

Tab 4. Characterization of system states by surplus indicators, unit: bn€/year.

Scenario	Subarea	p <sup>o</sup>	p <sup>u</sup>	p <sup>e</sup>	Transit operator		Users			Environment		
					Production cost	Fare revenue	Car dependent	Transit dependent	Flexible	local pollution	GHG	Transit all
Current situation	Paris city		-15.2	-2.4	2.7		-0.86	-7.98	-6.36	-1.96	-0.04	-0.43
	Inner suburbs	-5.68	-17.7	-2.4	2.6	2.4	-2.05	-7.17	-8.51	-1.92	-0.10	-0.34
	Outer Suburbs		-23.2	-0.7	2.8		-4.60	-6.34	-12.2	-0.41	-0.16	-0.09
	sub-total	-5.68	-56.1	-5.4	8.1	2.4	-7.51	-21.5	-27.1	-4.29	-0.30	-0.85
W0	Paris	-1.58	-13.7	-1.9	3.5	1.9	-0.80	-7.63	-5.29	-1.44	-0.03	-0.38
	Inner suburbs	-3.18	-15.8	-1.8	3.4	0.2	-1.93	-6.87	-7.02	-1.50	-0.07	-0.24
	Outer Suburbs	-0.91	-20.6	-0.5	3.3	2.4	-4.51	-5.35	-10.7	-0.35	-0.13	-0.07
	sub-total	-5.68	-50.1	-4.2	10.2	4.5	-7.25	-19.9	-23.0	-3.29	-0.22	-0.70
W1	Paris	-0.96	-14.0	-2.1	3.7	2.8	-0.80	-7.79	-5.37	-1.52	-0.03	-0.51
	Inner suburbs	-3.22	-15.9	-1.9	3.5	0.3	-1.93	-6.93	-7.03	-1.49	-0.07	-0.29
	Outer Suburbs	-1.50	-20.1	-0.5	3.5	2.0	-4.50	-5.18	-10.4	-0.33	-0.12	-0.08
	sub-total	-5.68	-50.0	-4.4	10.8	5.1	-7.24	-19.9	-22.8	-3.34	-0.22	-0.88

Tab 5. Redesigning transit services.

component information	subarea	Paris				Inner suburb				Outer suburb		
		Service mode	Bus	Metro	RER	Train	Bus	Metro	RER	Train	Bus	RER
	Transit component	1	2	3	4	5	6	7	8	9	10	11
Current state	Line length (km)	598	171	57	13	2894	39	181	123	20032	355	761
	station number	1795	248	29	6	7575	52	85	40	25173	128	187
	rolling stock	1295	549	106	15	3078	104	180	108	4271	266	455
	station spacing (km)	0.33	0.69	1.97	2.17	0.38	0.75	2.13	3.08	0.80	2.77	4.07
S0 : Max Po+Pu+Pe	Line length (km)	456	350	99	16	1161	93	391	191	4005	544	532
	station number	1271	485	43	3	3191	172	272	115	9620	386	312
	rolling stock	891	736	138	28	2029	158	250	95	4402	250	174
	station spacing (km)	0.36	0.72	2.30	5.33	0.36	0.54	1.44	1.66	0.42	1.41	1.71
S1 : Max Po+Pu	tarrif (€/pass.)	0.73	1.12	0.88	1.28	0.18	0.27	0.00	0.00	1.78	2.83	1.98
	Line length (km)	557	356	101	17	1283	93	395	193	4265	563	552
	station number	1445	487	44	3	3390	173	274	115	10150	406	328
	rolling stock	1334	797	154	34	2476	164	263	102	4987	268	188
	station spacing (km)	0.39	0.73	2.30	5.67	0.38	0.54	1.44	1.68	0.42	1.39	1.68
	tarrif (€/pass.)	1.53	1.57	1.17	1.48	0.39	0.26	0.00	0.00	1.49	2.25	1.36

Environmental impacts were assessed in relation to local population densities. A factor 3 was taken to adapt the recommended unit cost of air pollution in high density areas (CGSP, 2013) to the extreme value of 23,000 people per km<sup>2</sup> in the central area – the highest urban density among European cities. This yields a considerable cost of about €5.4 billion a year, 95% attributable to local pollution and almost half pertaining to the central area i.e. Paris city. This is consistent with the high level of political attention paid to this issue in the 2010s; on average, a person living in central Paris bears 3.5 times the local environmental cost as a suburbanite.

As the scale of environmental costs is roughly equivalent to total transit subsidies, their inclusion in welfare function W0, but not in W1, leads to some differences between Scenarios S0 and S1, beyond their common features. On the one hand, both policies would improve environmental performance: relieving roadway congestion would benefit not only the remaining car users but also the local environment (cf. air pollution impacts) and hence residents, so that all stakeholders would gain from this policy. On the other hand, being environment-myopic, policy S1 would bring less environmental benefits than S0. Taking the environment into account in S0 would lead to less development of transit networks than in S1, with increases of transit fares in outer suburbs and decreases in Paris city, and different kinds of development: rail-based modes would be preferred to the bus mode in the central area.

To sum up, there seems to be plenty of room to optimize the planning of the mobility system in the Paris agglomeration, with potential benefits to all stakeholders.

## 5. Conclusion

The paper provides a comprehensive methodology for mobility system modeling and planning design that unifies the two lines of research pioneered by Van Nes and Daganzo. Our model combines:

- a division of the urban area into subareas with specific characteristics, in particular demand density;
- travel demand between the subareas made up of three categories of users: car-dependent, transit-dependent, and mode-choosers;



- a transit network made up of several components with structural parameters as levers for change and with related service production costs;
- a roadway network with fixed capacity and production cost yet with endogenous quality of service based on an aggregate speed-flow relationship;
- environmental impacts of vehicle traffic in terms of local pollutions and carbon emissions.

The segmentation of travel demand, the consideration of modal choice, the hierarchical transit network, and the inclusion of environmental aspects, constitute improvements on the existing models. Furthermore, the economic analysis of the optimization program is novel and sheds light onto the balancing of the diverse priorities of urban mobility planning.

The wide range of real-world issues addressed in the model, together with appropriate simplification of spatial details, make it particularly valuable in providing high-level insight into the sustainability performance of urban mobility systems. In the application case, it was shown that the explicit inclusion of environmental impacts leads to a noticeable shift in policy packages.

Of course the model is incomplete, not only because of the simplification of spatial detail but also because of the restricted set of action levers considered. For instance, we did not consider parking fees or roadway pricing as levers. Nor did we contemplate planning options such as segregated bus lanes or bus prioritization at roadway junctions, or electric buses which, in the application example, could yield greater environmental benefits than the transition from the baseline situation to the S0 state.

The model could be further developed along the following directions of research:

- more detailed description of the relations between transit sub-modes (contribution vs. competition);
- transit operation incorporating vehicle capacity and line congestion;
- more precise costing of transit system production, particularly in relation to passenger traffic;
- better representation of roadway networks, with explicit hierarchy between motorways and arterial streets in each subarea, and explicit representation of roadway production costs;
- modeling of parking conditions with explicit consideration of local capacity and demand, of the impact of parking service quality in the utility functions of automobile mode;
- calculation with temporal and spatial distribution for both demand and supply;
- more flexibility of demand, notably for trip-timing and destination choice;
- welfare optimization with respect to the levers pertaining to all modes and also to demand management.

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