Socio-Economic assessment framework for replacing bus lines with DRT services

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Abstract: Recently, new forms of mobility services have emerged (i.e. carsharing, micromobility, TNCs, etc.), having impacts on cities development and particularly on existing travel modes performances. For instance, it has been observed, especially in US and European metropolitan cities, that DRT (inc. Uber, Lyft, Lime) are often associated to the increase of road congestion and the decline of transit ridership. In peri-urban and rural areas, on the other hand, the diffusion of DRT is limited, even if the provided transit modes (i.e. bus) are usually inefficient and expensive for the society.

This paper is devoted to investigating the socioeconomic potential of replacing buses (noted CPT for Conventional Pubic Transport) by DRT (Demand Responsive Transport) in peri-urban areas as complementary services to the existing transit network. It is based on a bi-level modelling approach: (1) at the first level, we propose an agent-based model, which describes movements of on-demand vehicles and assigns them to passengers in order to maximize the vehicle's utility function. The traffic equilibrium is obtained for demand that is function of the generalized cost only. (2) The second model proposes a socio-economic optimization, which determines supply conditions (fleet size and fare) that maximize the gain for the operator, for the users and for the society. An application is then proposed for a real case in Paris metropolitan area by replacing CPT line with DRT service. Results suggest that social welfare is maximized for fleets of 20 to 30 vehicles and fares of 2 to 3€ per trip.

Keywords: socioeconomic optimization, agent-based model, social welfare, DRT, conventional public transport

1. INTRODUCTION

1.1. Context

In a metropolitan area, transit operators are in general providing a panel of mobility solutions to meet needs of diversified territories and to satisfy preferences of different population categories. For instance, mass transit is relevant for large-distance crossing while bus services are technically more relevant as feeders and in low density areas.

However, from an economic perspective, bus lines are often costly for small cities, especially during off-peak periods. In addition, their flexibility is very limited: fixed itineraries and stop stations, predefined schedules, and involve often complex and long transfer times to other bus lines. The emergence of intermediate modes [1] without any authority control, is announcing the decline of bus services, especially in these cities. Hence, the deployment of demand-responsive transport services (DRT) in low density areas would be profitable for passengers (e.g. better flexibility and lower door-to-door time), operators (e.g. no competition with other modes) and public authorities (e.g. higher quality of service and less empty kilometers, then less externalities and less operating costs) as well.

1.2. Related works

Bellini et al. [2] propose four configurations of DRT systems: (1) with fixed itineraries and stops, where users must prebook the service, (2) with fixed itineraries and stops with possible detours, (3) with unspecified itineraries and predefined stops, and (4) with unspecified itineraries and unspecified stops.

The first configuration could be described as a conventional transit service with pre-booking since it is on-demand, while the last configuration mostly corresponds to a conventional taxi service. Finally, the second and third configurations are between these two "classical" forms of mobility services, being based on transfer itineraries towards fixed public interesting points as exchange parking, CPT stations, etc. Recently, several studies have been interested in simulating and assessing the technical and economic performances of these services. They are in majority based on agent-based models [3, 4, 5, 6, 7], which were also used to assess the potential of such DRT configuration if the fleet is autonomous [8].

The majority of these studies have considered that DRT services are provided in addition to the existing transport modes [3, 4, 5, 6, 7, 9, 10]. Very limited studies have investigated the impact of replacing CRT with DRT [11, 12, 13, 14], suggesting that under certain circumstances (i.e. low demand, off-peak periods), DRT could provide a less expensive alternative and higher level of service for passengers. These studies, however, still not developed in terms of economic optimization and socio-economic assessment. For instance, all of them have ignored the service fare and did not assess the impacts of such action on user surplus and social welfare.

1.3. Purpose

This paper proposes a socioeconomic assessment framework for replacing CPT by DRT in a peri-urban area. The developed framework is based on a developed agent-based model [15] that simulates dispatching strategies for on-demand services. A socioeconomic optimization is then implemented in order to determine, for a given traffic equilibrium, the operating conditions (fleet size and service fare) that will maximize the profitability for operators and users as well.

2. MODEL FRAMEWORK

2.1. Supply side

Consider a reference situation where a bus service (CPT) is provided, characterized by fixed exogeneous technical features: fixed routes and stations, predefined timetables, and predetermined travel times to be respected by drivers. The bus fare is fixed by public authorities in order to protect passengers from high tariffs. On the other hand, subsidies are allowed by public authorities to ensure the service viability and cover its operating costs.

Consider now a DRT service, with vehicles that are homogeneous (i.e. same capacity, same speed, same route choice) and are using the same bus road infrastructure. The service is station based, and stations are the unique access points to the service, enabling passengers boarding/ alighting. A call center receives all passengers' requests and class them based on the origin station, the desired and real departure time, and the destination station. In a common database, passengers' requests are updated at each iteration step time, saved and communicated to all vehicles. Vehicles are then making decisions to board passengers independently based on their own utility function, which aims to maximize vehicle loading while reducing passenger waiting time and extra-times induced by ridesharing. The call center is not a dispatcher; it only changes the state of registered passengers as waiting passengers, reserved, in vehicle or arrived to the destination station.

2.2. Demand side

The substitution of CPT by DRT could have an impact on transit demand volume. We assume that DRT and CPT are interdependent and subject to same competition laws that are enforced by public authorities. Hence, the demand of DRT and CPT are assumed to be elastic and dependent on their respective generalized cost only.

In other terms, for an Origin-Destination (OD) pair ij and for a given CPT demand Q_{CPT}^{ij} associated with a generalized cost C_{CPT}^{ij}, the demand of DRT Q_{DRS}^{ij} is deduced according to its cost C_{DRS}^{ij} according to a fixed elasticity parameter $\varepsilon > 0$:

$$\boldsymbol{Q_{DRS}^{ij} = Q_{CPT}^{ij} \cdot \left(\frac{C_{DRS}^{ij}}{C_{CPT}^{ij}}\right)^{\varepsilon}} \quad \textbf{(1)}$$

Where $\boldsymbol{C_{DRS}^{ij}}$ and $\boldsymbol{C_{CPT}^{ij}}$ are respectively equal to:

$$\boldsymbol{C_{DRS}^{ij} = \mu_{DRS} + \tau_{DRS} + (\alpha_{w_{DRS}} . t_w^{ij} + \alpha_{t_{DRS}} . t_t^{ij})} \quad \textbf{(2)}$$

$$\boldsymbol{C_{CPT}^{ij} = \mu_{CPT} + \tau_{CPT} + (\alpha_{w_{CPT}} . t_w^{ij} + \alpha_{t_{CPT}} . t_t^{ij})} \quad \textbf{(3)}$$

Where $\boldsymbol{\alpha_{t_{DRS}}}$, $\boldsymbol{\alpha_{t_{CPT}}}$, $\boldsymbol{\alpha_{w_{DRS}}}$and $\boldsymbol{\alpha_{w_{CPT}}}$ are positive weights that correspond to the sensitivity components, also called values of time, $\boldsymbol{\mu_{DRS}}$ and $\boldsymbol{\mu_{CPT}}$ positive constants reflecting the mode preference, $\boldsymbol{\tau_{DRS}}$ and $\boldsymbol{\tau_{CPT}}$ the trip fares**,** $\boldsymbol{t_t}$ and $\boldsymbol{t_w}$ respectively the in-vehicle time and the waiting time.

We assume that the extra-time induced by a detour and/or additional stop is included in the travel time. Similarly, comfort is generally considered in travel time and waiting time. Consequently, these two penalties are not mentioned in the utility function in order to avoid the risk of double counting or at least overlapping.

2.3. Traffic equilibrium

The equations above ((Eq.1), (Eq.2) and (Eq.3)) describe the impact of the level of service of available modes on the demand volume. In reality, the level of service is also affected by the demand volume: more users means more waiting time and vice versa. We used here an agent-based model that have been developed by [15, 16] in order to include in fact this reciprocal interaction. In particular, the developed agent-based model enables to simulate the behavior of on-demand vehicles, by considering different operating strategies for loaded and empty vehicles, and by proposing assignment strategies that favorize longer trips, increase vehicle loading ratio and minimize passengers waiting time.

Considering again (Eq.1), (Eq.2) and (Eq.3), and by observing that $\boldsymbol{t_w^{ij} = t_w^{ij}(Q_{DRS}^{ij})}$, the traffic equilibrium is then obtained through solving a fixed-point problem in $\boldsymbol{Q_{DRS}^{ij}}$. The traffic equilibrium exists a priori by definition and leads to the existence of a fixed-point solution:
Assume the continuity of the cost function on a compact set. The Method of Successive Average [17] approaches the solution point through updating in each iteration the cost function using an auxiliary state function defined by $C' = C + \xi_i(\tilde{C} - C)$, wherein $\xi_i, i \geq 0$ is a decreasing convex suit of numbers converging to zero. The demand is then also updated using (Eq.2). The convergence is obtained by the value of the duality gap $Q.(C' - \tilde{C})$. **Figure 1** presents the overview of the procedure to obtain the traffic equilibrium.

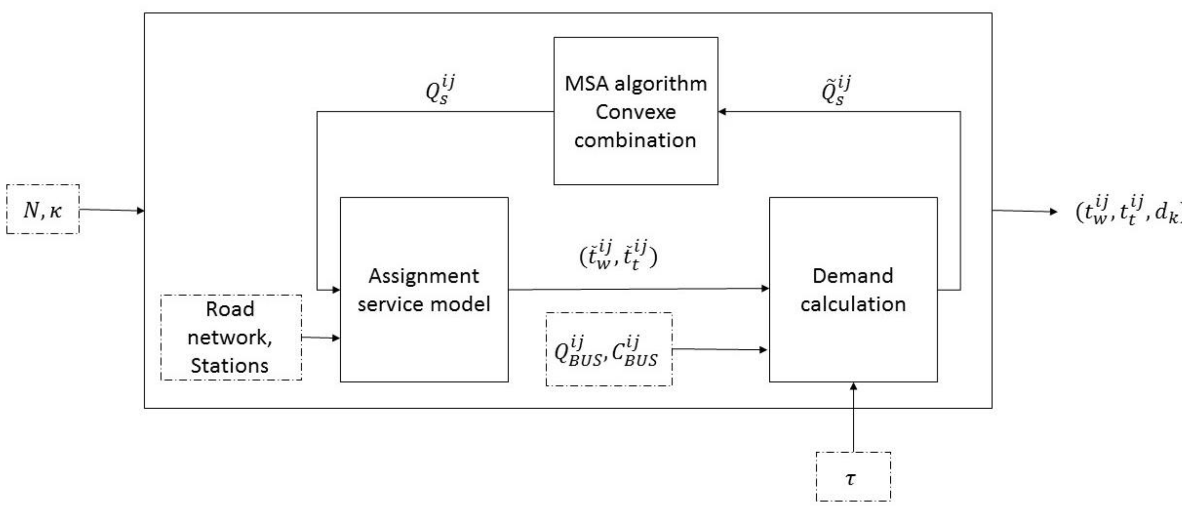

Figure 1 Scheme of the traffic equilibrium calculation

2.4. Socioeconomic optimization

The socioeconomic optimization problem is formulated in order to maximize the gain for society, by considering users' surplus, operators' profit and environmental impacts. The gain for society, called also the social welfare or the total surplus, is then defined as:

$$\boldsymbol{P_S = P_O + P_u + P_e} \quad \textbf{(4)}$$

Where $\boldsymbol{P_O}$, $\boldsymbol{P_u}$ and $\boldsymbol{P_e}$ are resp. operator profit, user surplus and environmental surplus.

Operator profit ($\boldsymbol{P_O}$) is the difference between revenues $\boldsymbol{R}$ and costs $\boldsymbol{C_p}$:

$$\boldsymbol{P_O = R(\tau, Q) - C_p(N, Q, t_t, t_w)} \quad \textbf{(5)}$$

Where:
- $\boldsymbol{C_p}$: are production costs, as a combination of daily and running costs. Daily costs include vehicle depreciation, dispatching costs, drivers' wages, maintenance of vehicles and infrastructure, etc. Running costs concern specifically energy costs.
Hence, production costs could be written as:

$$\boldsymbol{C_p = \chi N + v c_u (t_L + t_E)} \quad \textbf{(6)}$$

Where C_p the total production cost, χ daily costs, relative to number of vehicles N, c_u mileage costs, v the average speed, t_L and t_E the total loaded and empty kilometers respectively.

- $\boldsymbol{R}$: are revenues that are generated from using the service, but also possibly from other funding mechanisms. In Paris region, for instance, transit modes are subsidized by public authorities (departmental, regional and state allocations) and by companies (the so-called "the mobility tax") [18]. Consequently, if we note subsidies $\boldsymbol{S_{DRS}}$ and fare revenues $\boldsymbol{R_\tau}$**,** the total revenues $\boldsymbol{R}$ for the operator would be expressed as:

$$\boldsymbol{R = S_{DRS} + R_\tau} \quad \textbf{(7)}$$

We assume in addition that the fare is flat and fixed per trip, then revenues are:

$$\boldsymbol{R_\tau = \tau Q} \quad \textbf{(8)}$$

User surplus ($\boldsymbol{P_u}$) is measured as the difference between the utility of the provided service and the minimal utility that is desired by passengers. If the desired utility is higher than the current utility, then passengers are getting more benefit from using the service. Mathematically, it corresponds to the definite integral of the demand function with respect to the generalized cost, from the actual generalized cost to any larger cost value:

$$\boldsymbol{P_u = \int_{C_{DRT}}^{+\infty} D(g')dg'} \quad \textbf{(9)}$$

Environmental surplus ($\boldsymbol{P_e}$) is expressed in terms of avoided / additional emissions of CO_2 as a result of replacing CPT with an DRT.

$$\boldsymbol{P_e = \tau_{CO_2} * (CO_2^{(CPT)} - CO_2^{(DRS)} + \beta(Q_{DRS} - Q_{CPT}).CO_2^{(PC)})} \quad \textbf{(10)}$$

Where τ_{CO_2} is the carbon price, $CO_2^{(CPT)}$, $CO_2^{(DRS)}$ and $CO_2^{(PC)}$ respectively CO_2 emissions of CPT, DRT and private cars, $\boldsymbol{Q_{CPT}}$ the total demand of CPT and β the proportion of passengers preferring private cars over the DRT service.

We assume that replacing CPT with DRT is possible only if DRT subsidies are lower than or equal to those of CPT. In addition, the service is sustainable only if the provider has a positive net profit. Hence, the socioeconomic maximization problem with respect to N and τ is written as:

$$\begin{aligned} \max \boldsymbol{P_S(N,\tau)} &= \max_{\mathrm{N},\kappa,\tau}\left(\int_{C_{DRT}}^{+\infty} \boldsymbol{D(g')dg'} + \boldsymbol{P_o(N,\tau)} + \boldsymbol{P_e(N,\tau)}\right) \\ \boldsymbol{u.c.} \qquad & \boldsymbol{S_{DRS}} \le \boldsymbol{S_{CPT}} \\ & \boldsymbol{P_O(N,\tau)} > \mathbf{0} \end{aligned} \quad \textbf{(11)}$$

By injecting (Eq.4) in (Eq. 11), the problem:

$$\begin{aligned} \max \boldsymbol{P_S(N,\tau)} &= \max_{\mathrm{N},\kappa,\tau}\left(\int_{C_{DRT}}^{+\infty} \boldsymbol{D(g')dg'} + \boldsymbol{P_o(N,\tau)} + \boldsymbol{P_e(N,\tau)}\right) \\ \boldsymbol{u.c.} \qquad & \boldsymbol{P_O(N,\tau)} \le \boldsymbol{S_{CPT}} + \boldsymbol{\tau Q} - \boldsymbol{\chi N} - \boldsymbol{v c_u (t_L + t_E)} \\ & \boldsymbol{P_O(N,\tau)} > \mathbf{0} \end{aligned} \quad \textbf{(12)}$$

3. SIMULATION CASE STUDY

3.1. Study case presentation

3.1.1. Territory issues

The model is applied on Palaiseau, a city located in Paris metropolitan area, in southwest at 17km from the center of Paris. Palaiseau is home of about 32.000 inhabitants 22.000 jobs. Urban development plan expects rapid urbanization of the territory during next ten years. Being in addition at the center of the French scientific cluster, Palaiseau is becoming a point of interest for research studies in France. During 2020, several experiments studies will offer services based on autonomous vehicles to serve universities, graduate schools and research labs and institutes.

3.1.2. Network design

The DRT service is implemented to replace an existing bus line service. The network is composed of 13 links, with a total length of 9 km, and serving 11 stations including a train line station. Vehicles have a capacity of 5 seats and have a constant speed of 30 km/h. The network is presented in **Figure 2**.

Figure 2 Map of the studied territory including the service network frame

3.1.3. Demand generation

The simulation is carried out for one morning peak hour and for home-to-work trips. Trips are estimated using a four-step model for the Paris area and then disaggregated by taxi stations by analyzing the distribution of homes and jobs [10]. The total number of CPT trips is found to be equal to 600 passengers. The DRT demand matrix is then deduced for a given generalized cost using (Eq.1). Finally, trips are generated in time using a Poisson distribution per one-minute time step for one hour of simulation.

3.2. Simulation design

The agent-based model is written in Matlab, which allows solving complex mathematical programs and visualizing simulation results. The model imports the network infrastructure, (i.e. links and stations), the demand matrix and CPT impedance matrices. It enables to set parameters of supply (e.g. speed, fleet size, vehicle capacity, fare, etc.) and demand (e.g. value of time, elasticity, etc.). Indicators are calculated and saved on a reference period of one hour.
The traffic equilibrium is obtained after 15 iterations or when the value of the duality gap is inferior to 50 (§1.3).

3.3. Simulation parameters

Simulation parameters are presented in **Table 1.** These parameters are estimated based on literature references that are presented in the third column below. DRT fixed costs are based on depreciation costs for medium-size vehicles and consider the average French values of taxi drivers wages. Subsidies per trip correspond to 2018 values for Paris region. Finally, time values and generalized cost elasticity are estimated in [9, 10] for taxi services.

Table 1 Parameters

	DRT (car)	*CPT (bus)*	*References*
Production costs			
Fixed costs	16€/veh.h	24€/veh.h	[19, 20, 21, 22]
Running costs	0.5€/km	3€/km	[23]
Revenues			
Ticket price per trip	(*To optimize*)	0.2€/trip	[24]
Subsidies per trip	≤ 0.52€/trip	0.52€/trip	[24]
Revenues per trip	(*To optimize*)	0.72€/trip	
Environmental costs			
Emissions of CO2	0.25kg/km	1.3kg/km	[25]
Demand inputs			
Total number of passengers	(*To optimize*)	600	
Travel time penalty (€/min)	0.3	0.4	[10]
Waiting time penalty (€/min)	0.4	0.4	[10]
Elasticity to generalized cost	-2.3		[9]

3.4. Simulation results

Solutions of the socioeconomic optimization (e.g. fleet size and fare) belong to a 2D-space. **Figure 3** depicts the evolution of socioeconomic gains from different perspective (environment, user, operator and society). As expected, the user surplus is maximized for greater fleet sizes (i.e. lower waiting times) and lower fares. The operator, on the other hand, has interest in increasing the fare level (i.e. fare revenues) and reducing the fleet size (i.e. fixed costs). The green spectrum reflects the supply conditions that enable to reach the bus profitability. Beyond this spectrum, DRT is profitable for the operator but costly to passengers, corresponding more to conventional taxi services (high fares and fleet sizes). Finally, we observe that the environmental gain, while being less sensitive to fleet and fare, is maximal for higher fares (i.e. less demand).
As a result, the total surplus, as a combination of the three other graphs, is optimal for fleets of 20 to 30 vehicles and a fare of 2 to 3€.

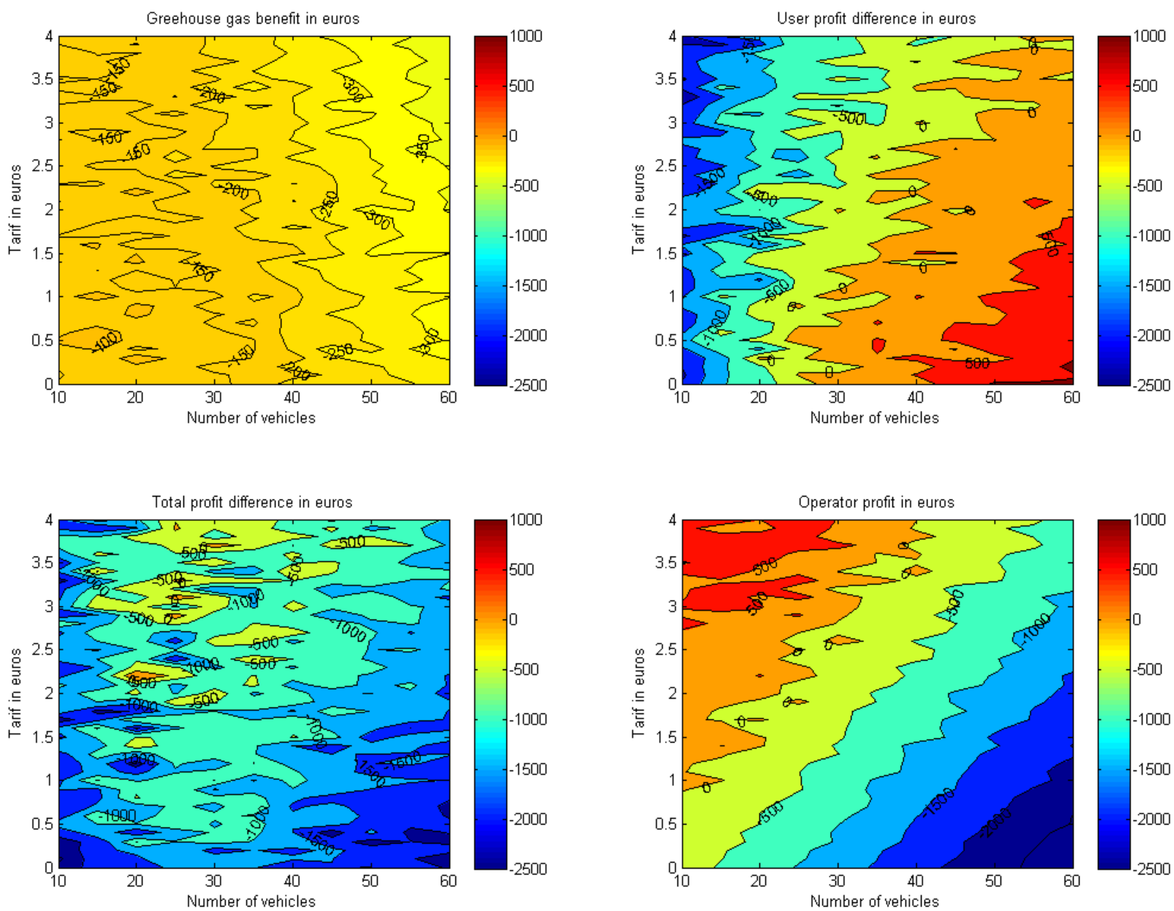

Figure 3 Results of socioeconomic maximization problem for GHG emissions, user surplus, operator profit and social welfare with respect to fleet size and fare

4. CONCLUSION

This paper proposes a socioeconomic framework that assesses economic and social benefits of replacing a scheduled transit by an on-demand ridesharing service. This framework is based on an agent-based model.

The optimization is performed from the society perspective with respect to the number of vehicles and the fare level. Results show that the operator would aim to propose a sort of taxi-service in order to increase their profitability. Public authorities, on the other hand, have interest to regulate fares (2 to3€) and the fleet size (20 to 30 vehicles).

The demand is assumed in this paper as elastic with the generalized cost. The elasticity for DRT is assumed equal to that of CPT and the mode split is calculated consequently. The impact of the elasticity value is critical, and sensitivity analysis are required in order to conduct more complete economic discussion.

There are also other some limitations of this study. The infrastructure-related costs, including upgrading roads and stations, are ignored. More elaborated estimation of fixed costs for CPT and DRT should be proposed. Secondly, the estimation of OD trips is estimated based on old surveys and should be validated using more recent data. Thirdly, the assignment strategies assume that

each vehicle makes its route and passengers choices independently while a centralized coordination of vehicles could lead to other interesting results.
Future work should address these issues with including centralized dispatcher, consider different vehicle capacities, and propose sensitivity analysis of elasticities and production costs. The interaction between CPT and DRT could be more elaborated, by considering a competitive/ cooperative context where both modes are available.

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