Chapter

Towards Shared Mobility Services in Ring Shape

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Abstract

A shared mobility service (SMS) under ring shape would combine the principle of service cycle along a fixed route (as in a transit line) and a fairly important territorial coverage, assuming that every user would accept to walk on some length to and from the service. Thus, service availability can be optimised, detours are avoided, vehicles achieve higher productivity. The synergy between the ring-shaped infrastructure and the vehicle fleet enables to optimise the quality of service in terms of access time and ride time, and also to reduce production costs - and therefore the tariff fares, under suitable regulation. The chapter aims to reveal these 'systemic qualities' of ring-shaped SMSs by providing a mathematical model called 'Orbicity'. It has a four-fold architecture: (i) traffic operations, (ii) supply-demand equilibrium under elastic demand, (iii) service management with endogenous fleet size and fare rate, (iv) service policy in terms of technology (vehicle type, number of places, energy vector, driving technology) and also the regulation regime. After outlining the model for ring-shaped shuttle services, we explore a set of scenarios along two axes of technological generation and regulation regime. It appears that ring-shaped shuttle services could be supplied at very affordable prices, while achieving profitability and requiring no public subsidies.

Keywords: ring shape, traffic model, fleet sizing, pricing, service regulation

1. Introduction

Conducting research for the Institute for Sustainable Mobility (a partnership between the Renault Group and ParisTech), we have modelled an array of shared mobility services using different forms of transportation (taxis, shuttles, vehicle hire schemes) arranged in a ring-shaped system [1–3].

For passenger mobility services in urban areas, the ring-shape principle is aimed to combine the axiom of service cycles (like a public transport line) with a broad geographical coverage, assuming that users are willing to walk a certain distance before and after each journey they make on the ring. By keeping the vehicles in service to run along the ring, availability can be optimised and detours avoided, ensuring that every vehicle is genuinely productive. Achieving greater synergy between the ring infrastructure and the vehicle fleet makes it possible to optimise the quality of service in terms of access time and driving time, while also pushing down production costs and thus enabling for affordable fares.

This chapter is aimed to highlight the 'systemic qualities' of shared mobility services adopting a ring format, as well as exploring the conditions required to establish a ring system in urban settlements.

We will first examine recent technological advances in mobility services and mobility-adjacent services, with reference to the fundamental spatial components of transportation: vehicles, stations, lines and networks. We will then demonstrate how a ring system makes it possible to cover a relatively large geographical area while also establishing service cycles for shared vehicles. A simple geographical model will be provided to quantify the geographical potential of demand, with reference to a few examples from France.

Of course, such services still need to be attractive, offering decent quality of service at an affordable price. These factors have been represented in a specific technical and economic model [1–4]. The 'Orbicity' generic model can be tailored to different types of service. The modal models share a four-tier architecture which involves, from bottom up, (i) the physical operations of the service and the laws governing its vehicle flow, (ii) the balance between journey supply and demand, (iii) optimised service management in terms of fleet size and fare price, (iv) the strategic positioning of the service in terms of technologies, conditionally to the applicable regulation regime.

Using this model, we will examine a number of scenarios which incorporate two key analytical dimensions: the generation of technology used and the applicable regulatory framework. We will demonstrate that not only does technological progress considerably expand the scope of possibilities, but also that regulation plays a vital role. It is entirely possible to imagine a shuttle service offering very reasonable fares, and possibly even without public subsidies.

2. Technical and spatial forms of urban mobility

2.1 Sweeping technological change

The 2010s were a decade defined by the confluence of multiple technological advances, with a strong focus on mobility [5]. Various technologies developed over the preceding years were combined with a new sense of synergy: GIS, GPS and smartphones. Geographical Information Systems (GIS) allowing for the processing, mapping and administration of geographical databases, are utilised by Google (Maps, Earth, StreetView) and others. GPS tracking, providing precise geographical location data in real time, became available for each individual mobile entity (individuals as well as vehicles), with relatively inexpensive portable devices. Mobile telephone services mean that individuals are always connected, anywhere and anytime (network coverage). Touch-screen smartphones have become the ideal tool for user interaction with any service. Individual users have the power to organise their travel plans, see their position on a dynamic map, enrich that map with information of interest to them (addresses, traffic conditions, public transport routes and stations), get recommendations for accessing transport and planning routes, and even receive directions in writing or in audio form in the language of their choice. Moreover, these services can be combined with the vast array of multimedia functions offered by modern smartphones.

The rise of individual mobility management has been remarkable. To get an idea of this, we need only consider the task of planning a complex itinerary on a metropolitan public transport network, before and after the advent of online route search services.

Individual users are now masters of their own 'customer experience', designers of their own transport services [6]. Consider the familiar Plan-Book-Ticket steps of the 'customer experience' from a marketing theory perspective:

- Planning to purchase a product: in this case, a travel itinerary;
- Booking: reservations for public transport, where necessary;
- Ticketing: both to provide easy information on the commercial conditions including fares and for payment and invoicing.

These are mobility-adjacent services which add much value to the travel experience as a whole, a value felt more keenly for public transport trips than car trips. The provision of information, the capacity to search massive databases and the customisation features 'make up for' the dissociation between vehicle and user which is an inherent feature of public transport (a dissociation which is necessary at this higher level of organisation, but which represents a fundamental handicap for collective transport solutions in comparison with private vehicles).

The benefits on the demand side are not limited to these mobility-adjacent services. Operators and innovators have seized upon the opportunities offered by advanced technologies to invent (or reinvent) new mobility services and new vehicles:

- Reinventing the bicycle, with more electric options and 'shared' vehicles in the form of short-term cycle-hire services with designated stations (cf. 'Boris bikes' in London or Velib systems in Paris and elsewhere) or without (i.e. free-floating services such as Jump etc). In Paris, the summer of 2018 saw a rapid proliferation of these free-floating cycle-share services, with each new player adopting a different colour for its fleet of bicycles: almost all of them had disappeared by the end of that autumn!
- Scooters have experienced a similar overhaul: modernised, reinforced and equipped with electric motors and batteries, they are also being offered by a variety of free-floating services in big cities. Parisians witnessed a sudden influx of new scooter services in spring 2019, followed by a period of consolidation which left only 3 or 4 companies standing by that autumn.
- Something similar has happened with cars: the renaissance of the electric car in the 2000s was followed in the 2010s by their deployment in urban car-sharing services (short-term rentals where the vehicle must be returned to its point of origin) and free-floating car-sharing services, with stations (Autolib) or without (Car2Go, now ShareNow).
- A similar vehicle sharing system has been developed for electric motorcycles: for example, CityScoot had over 6000 mopeds in circulation in the Greater Paris region at the end of 2019.

Each of these sharing services depends upon a two-sided ***digital platform***: a customer interface which handles the commercial operations, while the production side centralises the management and optimisation of resources.

If operators are capable of mobilising a fleet of vehicles and a team of service and maintenance personnel, they may also offer door-to-door services not dissimilar to a classic taxi service: Uber has emerged as the champion of so-called 'ride hailing' services accessed via mobile phone, combining the Booking, Planning and Ticketing functions into an extremely fluid user experience enshrined in a mobile app.

Other platforms offering car-sharing services (e.g. Drivy) or car-pooling, which are thriving for inter-urban travel (Blablacar), are yet to hit upon the magic formula for urban users.

All of these changes add up to form a new ecosystem, whose components mutually reinforce one another. While in transit, vehicles record information on the urban traffic conditions in real time, and this information is used to adjust the services on offer. The remarkable development of Uber has revolutionised taxi services in major metropolises and beyond (even as far as the distant suburbs of North America, cf. [7]).

2.2 Questions of form

The typical form of the ***vehicle*** as a mechanised, often motorised, form of transportation has been reinforced, with a diversification of models allowing for adaptations to local conditions: small electric vehicles in very dense urban areas where space is at a premium and pollutant emissions need to be kept to a minimum.

The typical form of the ***road network*** as a medium for multiple uses, a circulation infrastructure connecting different places, has also been confirmed. Shared services make use of the road network as their means of circulation and parking, and also recharging for electric vehicles.

Our notion of what constitutes a ***station*** has been diversified. Stations such as railway stations are fixed hubs with large numbers of users which serve as landmarks in the urban landscape. The positioning of bus and coach stops across the road network has become more visible thanks to mobile applications highlighting their location. Cycle hire stations are now being adapted to serve electric mobility options: the concentration achieved by grouping together the available spaces increases the probability of finding a free vehicle when it is needed (yet it puts a parking constraint at the trip destination). Meanwhile, free-floating services are challenging the very notion of stations: in fact, they are making every available parking space on the road network a potential station.

Ultimately, it is the form of the transport ***line*** which has been most affected by these changes. On the one hand, designated itineraries on the public road network are being challenged by automatic route-planning search engines which throw up any number of unlikely variants (such as cutting through a hospital courtyard, or taking a side street between two sections of much busier roads). Put simply, customised itineraries are taking over from established routes. On the other hand, public transport lines such as bus routes are now in competition with shared services, especially those routes where passenger numbers are not sufficient to justify a high-frequency service. The competition is greater still in less dense zones where collective transport services form only a loose network with large blind spots, too much distance between stops and a lack of effective connections to other segments of the network.

Some authors have even questioned the pertinence of rail transportation for long-distance travel from one suburb to another, floating the hypothesis that self-driving taxis could be used to collect passengers travelling from similar starting points to similar destinations, dropping them off at their respective destinations [8, 9].

2.3 Origins of the ring form

Certain public transport lines take the form of a ring: Line 6 of the Madrid metro, the Circle line on the London Underground, the Singapore metro, the systems in place in various Chinese cities, and even the ‘Circulator’ bus route in Washington. The main function assigned to these lines is to fulfil both the transmission and distribution of passenger flows [10].

The principle is similar to that of urban ring roads such as the Paris peripheral boulevard, which are more about distributing traffic flows than circumventing the city altogether.

The key to using a loop transit system to transport products (e.g. water in buckets, to put out a fire) or people (e.g. a cable car) is to effectively combine the form of the circuit with the service cycle of the containers. The result should be a homogenous spread of load between the containers, with regularisation and intensification of the overall rhythm.

Transport lines which are relatively linear in shape are typically used for radial connections, linking dense zones (urban centres) to less densely-packed areas (the suburbs). The flow pressure is high on the dense side, and low on the less dense side. The ring form is more specifically suited to a relatively homogenous spatial milieu: the homogeneity of the milieu contributes to the effectiveness of the ring-shaped service; reciprocally, the effectiveness of the service contributes to the homogenisation of the milieu.

3. Geographical potential and technical advantages of a ring-shaped service

3.1 Geographical principles: potential locations

What is the potential user base for a ring-shaped service operating in a relatively homogenous territory?

To answer, let us build up a simple model. Let A represent the surface area of the territory in question, and P its population. The mean density is P/A people per unit of surface area. Let μ represent the mobility rate per individual and per day, typically somewhere between 3 and 4 trips. In spatial terms, the hypothetical 'outbound density' is μP/A trips per unit of surface area.

Assume further, on a provisional basis, that the ring is a circle of radius R, and that along its whole circumference it attracts passengers from within a band 2ℓ wide – i.e. from a distance of at most ℓ from the pathway of the circular transport service. The total drainage basin for this infrastructure is thus equivalent to a surface area of $4\pi\ell$R (**Figure 1**).

This drainage basin can be represented as a proportion of the total surface area (A) of the territory:

$$\theta = \frac{4\pi\ell \mathrm{R}}{\mathrm{A}} \ (\textit{limited to 1}) \tag{1}$$

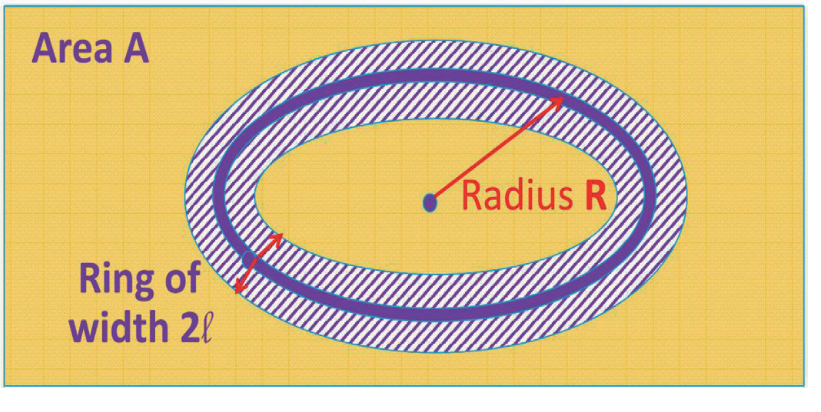

Figure 1.
Area served by a ring-shaped line.

Based on the hypothesis of a homogenous spatial distribution of activities throughout this territory, the ratio θapplies to both the point of origin of trips and their destination. The market potential of the ring service is thus θ^2 multiplied by the city's total mobility, i.e.

$$\begin{aligned}\tilde{Q} &= P.\mu.\left(\frac{4\pi\ell R}{A}\right)^2 \\ &= \frac{P.\mu}{A}.\frac{(4\pi\ell R)^2}{A} \\ &= \frac{P.\mu}{A}.4\pi.(2\ell)^2\left(\frac{R}{R_A}\right)^2\end{aligned} \tag{2}$$

The terms of the formula can thus be rearranged to show:

- Mobility generation density $\mu P/A$,
- An equivalent radius for the urban settlement R_A, such as $\pi.R_A^2 = A$.
- The width of the band 2ℓ, with exponent 2,
- The role of the radii: the ratio R/R_A, squared, determines the potential demand.

For a given territory, the goal is to find the 'natural' proportion between R and R_A. **Figure 2a,b** shows two examples from the cities of Rennes and Saint-Malo, in the Brittany region of France. **Figure 2c,d** shows two examples in the Ile-de-France region: one for the Paris-Saclay area, and another for the Greater Paris conurbation, here labelled Grand Paris.

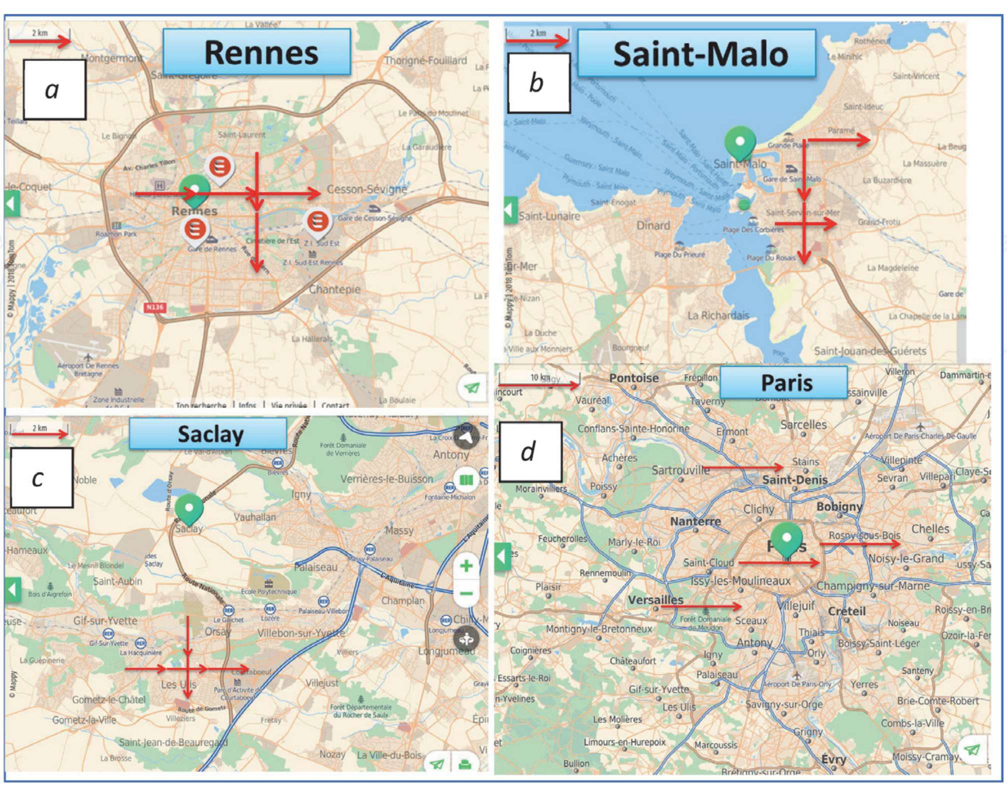

Figure 2.
Examples for (a) Rennes, (b) St Malo, (c) Paris-Saclay, (d) Grand Paris (source: Mappy, modified by the author).

City	St Malo	Rennes	Grand Paris	Ville de Paris
Surface A (km^2)	80	200	2000	100
Eqt radius R_A (km)	5	8	25	6
Population P (thousands)	50	300	11,000	2000
P/A (k people/km^2)	0.63	1.50	5.50	20,0
Ratio $3/R_A$	59%	38%	12%	53%
Ratio θ^2 if R = 3 km	74%	30%	3%	59%
$\tilde{Q}$ (thousands trips/day)	38.9	37.3	13.7	995
Variant if R = 5 km	107.9	103.6	38.0	2763

Table 1.
Quantification of geographical potential.

Table 1 shows a high degree of similarity between the results (Q-tilde) for the two radius values envisaged: between 10,000 and 12,000 journeys per day for a radius of 3 km, or 29,000 to 34,000 journeys per day for a radius of 5 km. To put it another way, the urban conditions found in a variety of French cities all represent interesting levels of potential demand. Nevertheless, the quality of service would need to be attractive to users, in conjunction with attractive prices.

3.2 Quality of service: four components

Whatever the means of transportation - shuttle, taxi, car share, moped, bicycle, scooter etc. – users expect a satisfactory quality of service. While the quality of service has been adequately defined and described for collective transit systems in the Transit Capacity and Quality of Service Manual [11], for shared mobility services that are more diverse a more generic definition is required. To that end, an analysis framework comprising four components was put forward as follows [4]:

1. ***Maintenance and manners***: the vehicle needs to be appropriate for this service, in terms of its mechanical condition and energy supply; it must be clean; if it is to be used collectively (shuttle), each user has a right to expect a minimum level of courtesy from other passengers on board.

2. ***'Pleasure', including Protection and comfort***: four-wheeled vehicles offer shelter from the elements (weather hazards) and potential impacts (shocks), along with more comfortable seating arrangements than mopeds or bicycles. At the other end of the spectrum, scooters require passengers to be standing up (although this does offer a certain degree of excitement).

3. **'*Conductance', including Efficiency, mobility and speed***: 'conductance' is the term we use to describe the aptitude of a vehicle to fulfil its transportation role, from proximity of access to arrival at final destination. A taxi offers maximum conductance. The mobility of a vehicle depends upon its mechanical capacities, and particularly its power source. Speed depends upon the mobility and agility of the vehicle (the latter being greater for two-wheeled vehicles) as well as the fluidity of traffic conditions.

4. ***Ease of use, including Availability***. The less time required to access a service, the more available it is. Shuttles and taxis pick up passengers directly, they

come to them, so the access time depends on the operating speed. For self-service solutions, users must arrive at the vehicle, which implies walking pace. In both cases, the initial distance between the user and the service plays an important role: it will depend on the number of vehicles in service, their level of occupancy and the size of the ring network.

This Availability category might also include the transaction operations between users and the service: information, pricing, payment and invoicing, reserving a vehicle or selecting a destination for taxi and shuttle services. It falls to the operator to simplify the corresponding tasks required of users as far as possible.

3.3 Ring-shaped services and quality of service

Conductance. Running vehicles on a ring-shaped line avoids wasting time on detours, pick-ups and set-downs outside the designated circuit. This allows us to optimise the ***availability*** of each vehicle in service, and thus maximise the availability of the service for potential users.

Avoiding detours helps to increase the ***speed*** of journeys made on the ring. Speed also depends upon infrastructure design on the ground, with certain measures which may be taken to improve the fluidity of travel. Considering the best interests of the circuit as a whole, it is advisable to decide upon a suitable speed of travel, determined with reference to the urban environment and in order to satisfy all users and occupants of the space.

Pleasure. ***Protection and comfort*** depend first and foremost on the vehicles used: when determining which vehicles to acquire for the service, a number of specifications should be outlined in this respect. The design of the infrastructure also plays a role in ensuring the safety of individuals, ensuring that there is sufficient space for vehicles to move, guaranteeing sufficient visibility, smoothing out potential problem points and using appropriate signage to draw attention to them.

Maintenance. This depends on the preventive and curative measures taken by service operators, as well as the behaviour of passengers, other road users and residents. The ring format facilitates the logistics of curative interventions. It also lends itself to CCTV surveillance and on-site surveillance: these functions could well be integrated into the broader system of surveillance for the city's traffic and parking.

Ease of use. It is worth focusing in particular on the ***availability*** of the service: it will depend upon the ratio between the level of demand and the size of the fleet, among other factors including the circumference of the ring, the average distance travelled by passengers and the operating speed. The complex interplay of these factors is rendered more complex still by the fact that quality of service will have an influence on the level of demand. This is why we have developed specific technical and economic models for mobility services in ring form.

3.4 Technical principles

Combining a ring-shaped format with a fleet of vehicles provides significant opportunities for synergy. The ring circuit connects a number of points distributed along its circumference (C), attracting users from a band which is 2ℓ wide, with ℓ the range of attraction either side of the circuit. This ring has the potential to attract a certain amount of demand: let us call it Q number of journeys for each day the service is operational. The ring connects locations on a point to point basis: this function is clear when shown on a map, and must be obvious (legible) on the ground. Along the route, we can distribute logistical functions such as parking bays, recharging stations and cleaning stations, located together or separately as required.

As for the fleet of vehicles, let us assume that it represents modal homogeneity. Each vehicle is capable of travelling at an average speed of v_0. The size of the vehicle will depend on the mode of transportation: let K represent the number of places on board. For two-wheeled vehicles $K = 1$, whereas $K = 4$ or thereabouts for cars and $K = 12$ for shuttle buses. Each vehicle is shared, in that it constitutes a component of a fleet whose total size is N.

Keeping the fleet of vehicles attached to the ring circuit ensures that:

- Each vehicle runs productively, in cyclical fashion, with an average workload of Q/N trips per day.
- Each point receives a guaranteed frequency of service (for shuttles), or else the availability across the whole zone is homogenous (for shared vehicles). This means that any user can access the service at any point.
- Multi-passenger vehicles can be pooled without the need for a detour: the only condition is that the vehicle must stop to let passengers come on and off. These elementary logistical tasks are distributed between the vehicles in circulation.

The average distance of the rides made by passengers, which we can denote as L_R for ride length, is a factor in the rate of occupancy of vehicles, and also of the exposure of passengers to the delays required for other passengers to board and alight the service.

Average operating speed v depends on all of the factors mentioned above:

- In terms of infrastructure, the circumference C and the speed of travel v_0,
- In terms of demand, the volume Q and the average ride length L_R,
- In terms of the vehicles themselves, the passenger capacity K and the time taken for passengers to alight/board the service t_S,
- In terms of the overall service, the size of the fleet N and the number of hours H for which the service runs during the day.

4. Technical and economic modelling

There exists a substantial body of knowledge, theoretical as well as methodological, to design transportation networks and services. The classical textbook [12] provides travel demand models for traffic simulation, therefore enabling for traffic and revenue forecasting. Its domain of application encompasses roadway networks and public transport networks involving lines. The more advanced book [13] also considers more diverse forms of public transport, including on-demand services (chapter 8): on representing service operations, the production costs can be modelled, too, and compared to service revenues in order to assess service profitability.

As the said models of travel demand and transportation supply involve spatial finesse, they are solved numerically. The set of analytical conditions to depict e.g. an optimal system state is typically very large so that little insight might be gained from its inspection. By contrast, the models presented hereafter are analytical, owing to the postulates of ring shape and, more generally, homogeneity in space and time. Then, the models are endowed with circular symmetry, which is crucial to characterise the system state in a simple way and to obtain the few system state variables as easy-to-interpret analytical formulas of the model parameters.

4.1 The Orbicity modelling family

We have developed a family of models called Orbicity, designed to study ring-shaped mobility services in urban environments. As of early 2020 the family comprises three models:

- a ***taxi service***: vehicles take individual clients, picking them up from their start point and dropping them off at their destination [1].
- a ***sharing service for individual vehicles***, typically two-wheeled vehicles or small cars which do not require driving licences: users pick up the vehicle from its parking spot, make their journey and leave the vehicle at their destination [2].
- a ***shuttle service***: vehicles with a capacity of K circulating on a ring-shaped route, with vehicles running in both directions. They stop to pick up and drop off passengers at their requested locations [3].

4.2 Architecture of an Orbicity model

Each model has a four-tiered structure which covers, from bottom up, [i] Traffic conditions and service operations, [ii] Demand in equilibrium to supply, [iii] Service management, [iv] Technology and regulation.

i. ***The technical performance of the service***, with a fixed fleet size N, in order to serve a fixed level of demand Q which is compatible with N. This model gives us the mean journey time t_R and access time t_A for each journey, along with indicators useful for designing the service offered.

ii. ***The balance of supply and demand***: with a fixed offer in terms of fleet size and pricing, the volume of demand Q can be modelled as a function of the fares charged and the waiting t_A and journey t_R times. But these times are themselves dependent on Q, as per the traffic model. These two causal systems are interlinked, and together they determine the state of equilibrium between supply and demand in terms of volume Q and time t_A and t_R.

iii. ***Service management***. Production of this service aims to optimise a certain objective function, which is determined by the regime of regulation. In cases involving an unregulated monopoly, the objective function will be the net profit accrued by the operator, equal to the difference between commercial revenue and production costs. The producer determines the fleet size and pricing policy with a view to maximising this objective function. Maximisation is realised by taking into account both the technical requirements of the service and elasticity in demand.

iv. ***Service policy depending on regulation regime***. It is at this upper level that the structuring characteristics of the service are decided:

    a. The regulatory regime corresponds to one of several available options – unregulated monopoly (MO), optimal system with no budget constraints (SO), optimal system with the constraint that the producer must balance their budget (S2) or return on public funds (S1).

b. The technology corresponding to the mode of transportation: vehicle capacity (factor K), type of motor (combustion engine or electric), driving technology (human or robotic).

c. Territorial conditions: size of the ring (circumference C or radius R), average speed of travel (parameter v_0), demand function.

This upper level thus determines the strategic conditions of the service. For the service operator, this is a matter of strategic marketing. For a public authority responsible for coordinating sustainable mobility, it is a matter of strategic planning.

Figure 3 offers a schematic representation of this four-tier architecture.

4.3 Indications regarding the traffic model

Figure 4 shows the chain of causation which determines the traffic conditions. The traffic model establishes a 'stochastic equilibrium' for the availability of

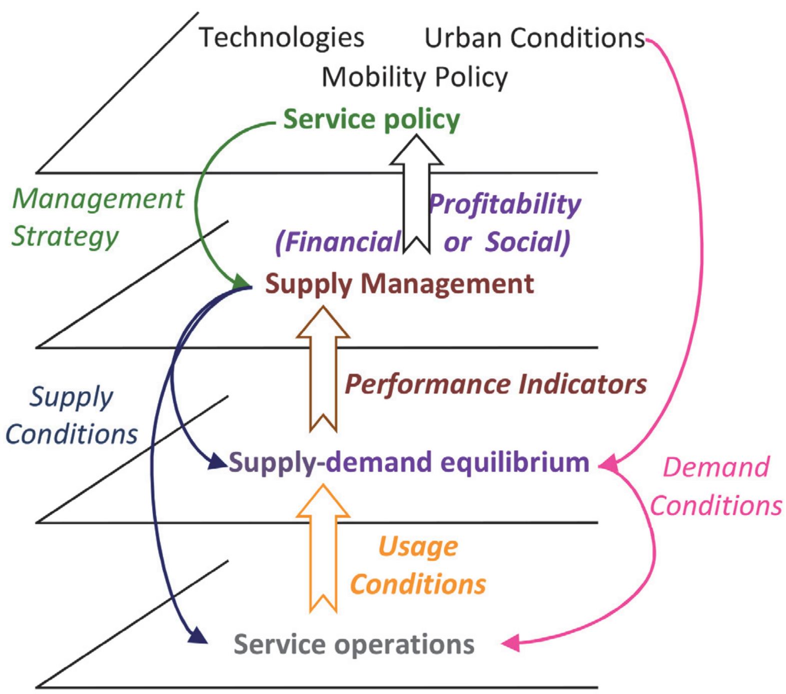

Figure 3.
Four-tier architecture.

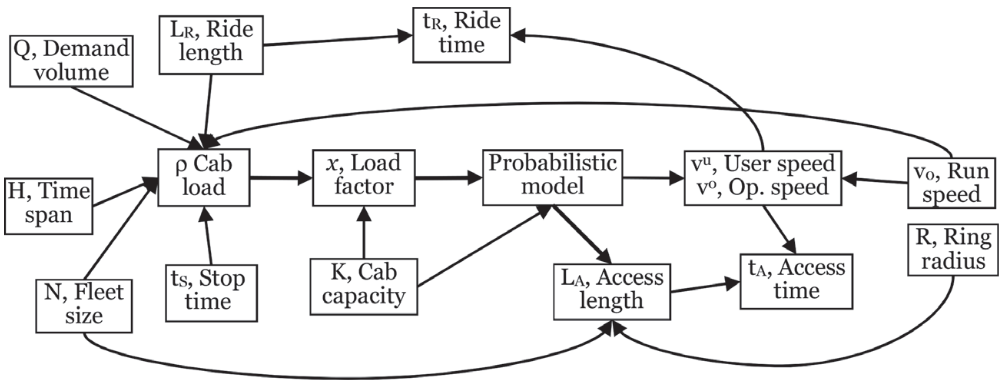

Figure 4.
Systemic diagram of the traffic model for a ring-format shuttle service.

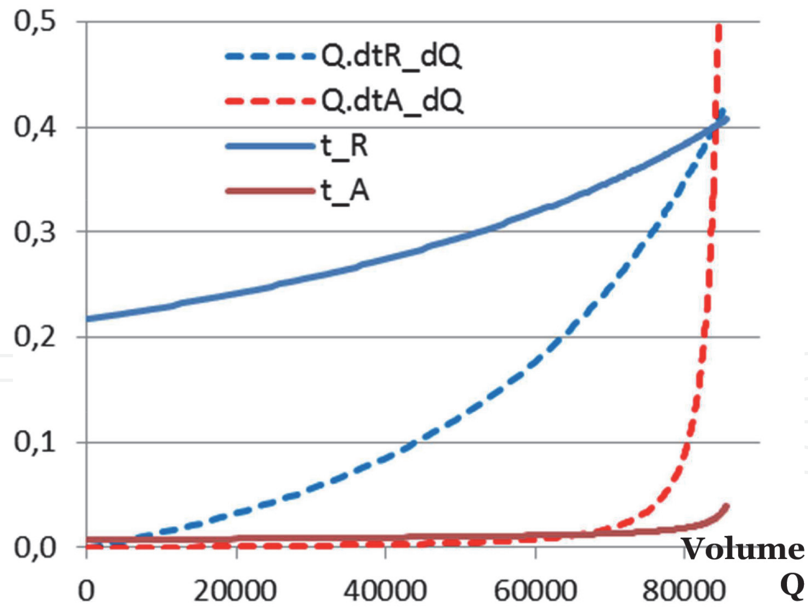

Figure 5.
Traffic laws for a ring-format shuttle service (under N = 200).

vehicles, taking into account the components of demand and their fluctuation along the ring route, over time and in terms of ride length. This gives us the average speed of the service, with the operating speed per vehicle, which is of interest to the operator, as well as the average usage speed, of interest to users. These speeds will also determine the average ride time and access time.

Figure 5 shows the variations in average access time t_A and ride time t_R in response to the volume of demand, for a fixed-size shuttle fleet.

4.4 Indications regarding the supply-demand equilibrium

Figure 6 shows the variations in the volume of demand in response to price, or rather the generalised cost (the sum of the ticket price plus access and ride times, weighted by their respective 'values of time'), for a fleet of fixed size and for a demand function with constant elasticity of -2 with respect to generalised cost. The blue curve shows the 'original' demand function for exogenous traffic conditions, while the red curve illustrates the 'adjusted' demand function which takes into account the interaction between the volume of demand and the traffic conditions (simulated in the preceding tier of the model).

4.5 Indications regarding optimised service management

Table 2 shows the objective function assigned to the production of the service, for each of the different operating regimes available as options in the strategic phase. Demand function $Q(\tau, N)$ represents the volume of demand in response to trip price τ and fleet size N: it summarises both the demand model and the traffic model. Cost function $C(N, Q)$ represents the cost of producing the service, on a daily basis: this depends on the number of vehicles and number of trips required. The underlying parameters, for example the capacity of the shuttles or the energy costs involved, are to be determined at the strategic level.

Figure 7 provides a graphic representation of the solution to the production optimisation problem, in this case for a shuttle service. The primary unknown is price per ride τ, on the y axis. The variable x is a load factor: this is the key factor to resolving the traffic model. The pink function models the behaviour of demand: demanded price

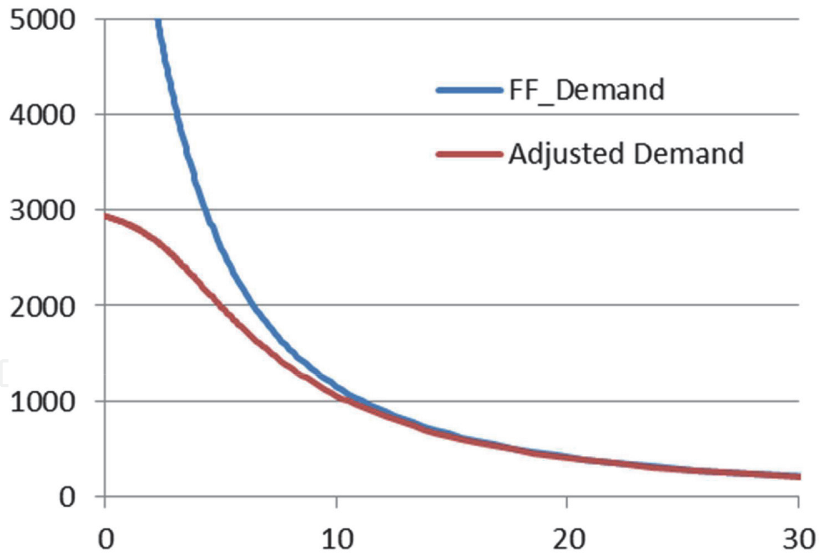

Figure 6.
Volume of demand with respect to generalised cost.

Pattern	Objective function and side constraint	Pricing rule	Notation
MO, monopoly	$P^o(\tau, N) \equiv \tau.Q(\tau, N) - C(N, Q(\tau, N))$	$\tau = \frac{\varepsilon\left(\dot{C}_Q + Q\dot{g}_Q\right)}{\varepsilon+1}$	$\tau = \hat{\tau}^o_{MO}$
SO, system optimum	$P^{ou} \equiv P^o + P^u$ with $P^u \equiv \int_0^Q D^{(-1)}(q).dq - Q.g$	$\tau = \dot{C}_Q + Q\dot{g}_Q$	$\tau = \hat{\tau}^o_{SO}$
S1 = SO under min return	P^{ou} under $P^u/(1+b) + P^o \geq 0$ Min benefit per € of public funds, b	$\frac{C}{Q} - \frac{g_T + C/Q}{1-(1+\varepsilon)(1+b)}$	$\tau = \hat{\tau}^o_{S1}$
S2 = SO under budget balance	Min P^{ou} subject to $P^o \geq 0$	$\tau \geq C(N, Q)/Q$	$\tau = \hat{\tau}^o_{S2}$

Table 2.
Objective function and pricing rule depending on regulation pattern.

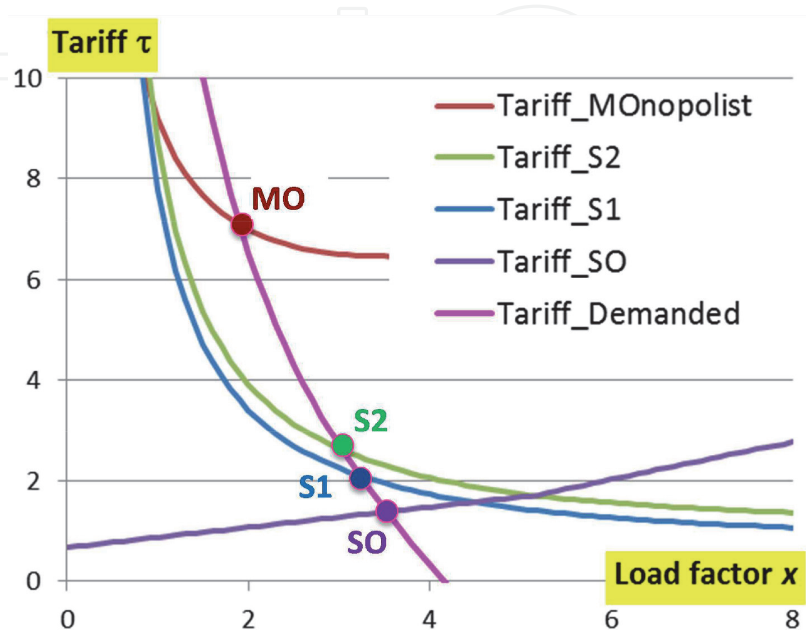

Figure 7.
Supply-demand state is the solution to a fixed-point problem.

$\tau^{u}(x)$. Each of the other curves represents a specific pricing policy adopted by the producer: proposed price $\tau^{o}(x)$. Optimising production consists of levelling up demanded price and proposed price: for each producer behaviour, the corresponding solution is the point of intersection (x^*, τ^*) which ensures that $\tau^{o}(x) = \tau^{u}(x)$.

5. Exploratory study

Using a systems model allows us to simulate different scenarios, varying the values assigned to exogenous parameters. In this section, we will explore in greater detail the potential parameters of a shuttle service operating on a ring basis, focusing on two major investigative variables: technology and regulation.

5.1 The strategic domain

These two investigative variables represent the two dimensions of our strategic domain. We will now cross-compare four different levels of technology and three potential regulatory regimes, giving 12 possible scenarios.

These levels of technology in fact represent successive technological generations which succeed one another in a process of progressive accumulation. Level zero, the 'pre-platform' generation, corresponds to the situation which prevailed before the emergence of platform-based services. For each trip, we take into account a user transaction time of 2 minutes as an additional ride time in the generalised cost. The first level corresponds to the platform era, defined by the advent of platform technologies and the radical simplification of transaction operations for customers. We use the abbreviation PF to represent this level. The 2nd generation of the platform uses electric vehicles, better suited to the urban environment and more economical when used intensively. We can abbreviate this as PF + EV, where EV stands for Electric Vehicles. The 3rd generation of the platform might incorporate self-driving shuttles, drastically reducing the primary cost of production. We can abbreviate this to PF + EV + AD, where AD stands for Autonomous Driving.

The regulatory axis comprises three possible regimes: monopoly (MO), first-best system optimum (SO), second-best system optimum (S2). Abbreviation MO stands for an unregulated monopoly, with a single operator dedicated to maximising profit. Abbreviation SO stands for a socio-economic system optimum of both supply and demand; then the objective function includes the net profit to the operator and the net surplus for users (the total reserve price less the generalised cost). Abbreviation S2 stands for an optimised system subject to the constraint of balancing the production budget. The objective function is the same as for SO, but optimisation is restricted to all values of the paired parameters (fleet size and price) which ensure a non-negative return for the service provider. As such, S2 is an intermediate solution between SO and MO.

5.2 The projected service

We have chosen to focus on a collective service running shuttles whose capacity $K = 12$ places. The ring format is consistent with the service cycle principle, and the vehicle capacity corresponds to the shared occupancy associated with public transport.

The limited capacity of the vehicles offers several advantages. First, as for the physical form of the vehicles, limiting their size should allow for a certain degree of agility on the road network, and reduce the disruption of other traffic caused by the shuttles stopping to pick up/drop off passengers. Second, per user ride, limiting capacity enables us to reduce the number of stops required to pick up/drop off other passengers, thus increasing the usage speed. Third, in order to satisfy a given volume of ridership, the fleet size will need to be bigger than it would if using vehicles with a larger capacity (e.g. around fifty passengers in a standard city bus); this makes it possible to increase the frequency of the service, and thus to reduce the time users wait to access it. Fourth, on an industrial level, the manufacturing of larger fleets of vehicles allows for greater economies of scale and drives down the cost price per vehicle. We might also expect to see greater flexibility in the internal logistics of the service: recharging, cleaning, maintenance and repairs. Fifth, regarding the environment, the impact of the fleet of vehicles over its whole life cycle may be reduced: this applies to the construction phase, due to the industrial efficiency gained, and the usage phase, thanks to the increased operating speed.

Nevertheless, using collective vehicles of a smaller size presents at least two disadvantages. The first is that the cost of driving the vehicles is increased proportionally to $1/K$. The second is the sacrifice of potential economies of scale for vehicles powered by combustion engines. However, these disadvantages could feasibly be swept away by the advent of self-driving vehicles and the rise of electric motors.

For all of the simulation scenarios envisaged here, the common parameters are as follows. The territorial aspects involve:

- A ring route with a radius of R = 2.3 km.
- Driving speed $v_0 = 20$ km/h.

For demand:

- An average journey distance of $L_R = 3.7$ km.
- Benchmark volume of $Q_0 = 26{,}000$ journeys per day at a generalised cost of €2 per trip. The elasticity of the volume of demand to this generalised cost is set at -2.
- Values of time are set at €12/h for running time and €8/h for access time.

Production parameters:

- For each day of activity, service in operation for H = 14 hours.
- For each shuttle, a daily cost price of €600 (resp. 500) for electric (resp. combustion) vehicles with drivers and €100 for self-driving electric vehicles.
- Energy cost: €0.05/km for an electric motor, or €0.15/km for a combustion engine.

5.3 Results and discussion

Table 3 presents the main results for each of the 12 scenarios simulated, with one scenario per column. The scenarios are grouped by technological generation, in ascending order of technological progress. For each generation, the three regulatory regimes are presented in the order MO – S2 – SO.

Taking all of these scenarios into consideration, the following indicators emerge. The number of trips per day varies from 455 to 8000 depending on the scenario. The size of the fleet varies from 4 vehicles, for an MO regime in the pre-platform

Technology	**0: preplatform**			**1: platform**			**2: PF + EV**			**3: PF + EV + AD**		
Regulation	**MO**	**S2**	**SO**	**MO**	**S2**	**SO**	**MO**	**S2**	**SO**	**MO**	**S2**	**SO**
Load factor x	1.72	2.82	3.5	1.9	3.08	3.8	1.85	3.1	4.0	1.4	2.0	2.05
Ride price τ	8.75	3.45	1.59	8.02	3.2	1.55	9.0	3.8	1.7	4.4	1.1	0.7
Gen. cost g	14.6	8.3	5.93	13.7	7.5	5.45	15	8.5	5.8	7.4	4.0	2.6
Demand Q	455	1510	2913	554	1858	3500	450	1500	3100	1900	6800	8000
Fleet size N	4.0	8.9	14.4	4.5	10.1	16.4	4	8	14	20	50	60
Costs C	2600	5210	8280	2855	5860	9300	2800	5500	9400	3000	7100	8200
Revenues R	3980	5210	4640	4450	5860	5200	3400	5500	5060	8000	7100	6000
System profit	8270	12550	13760	9193	13900	15040	8100	12200	13500	19000	26400	29000

Table 3.
Principal results for the simulated scenarios.

era, to 60 for an SO system running PF + EV + AD: this fifteen-fold increase needs to be seen in light of the respective passenger numbers. The number of trips provided by vehicle and by day varies from 95 for self-driving technologies to 220 for the generation PF + EV. In the simulated range of traffic conditions, the 'Load factor' is almost equivalent to the average number of passengers per shuttle. The values range from 1.4 to 4.0, suggesting that the capacity of 12 seats per shuttle is excessive and a 6 or 8-seater alternative would be sufficient.

Average access time varies from one hundredth of an hour to one tenth of an hour. It is systematically lower in SO and S2 regimes than in MO systems using the same technology. Average journey time does not vary so substantially, ranging from 0.22 to 0.28 hours. For each technology, this time is systematically lower in MO systems than it is in SO regimes. Fare per trip varies from €0.7 to €9. For each generation of technology, it is systematically much higher in MO than in SO and S2, from the platform generation onwards. Furthermore, the pre-platform fares in S2 systems are lower than those charged in the MO regime with the most advanced technology PF + EV + AD, which goes to show that offering an efficiently-organised service, combining a ring format with a suitable regulatory regime, is more important than the generation of technology deployed. The generalised cost per trip ranges from €2.6 to €15, obtained by adding the fare and the average ride and access times (weighted by their specific time values).

The commercial revenue is large, varying from €3400 to €8000 per day. Both of these extremes are found in the most advanced technological generation. Daily production costs are also substantial, ranging from €2600 to €9400 and depending on the generation of technology used and the operating system (via fleet size). Daily operating profit is nil for S2 regimes, highly positive for MO (increasingly so as technology advances) and negative for SO, with lower profits for the most advanced technologies compared with intermediate technologies. The daily surplus of demand is very large: double the total generalised cost to passengers, due to the specific elasticity of the demand function. For each generation of technology, the SO and S2 operating regimes are much more beneficial to demand than the MO system, while the difference between SO and S2 is relatively slight. The socio-economic benefits of the service ('system profit Puo') are massive: these benefits increase with each technological generation, and within each generation of technology the profit is greater for system optimal regimes than for the unregulated monopoly (in keeping with the definition of the system optimum).

In summary, the configuration of the service requires a large fleet of vehicles, indeed a very large fleet to make the system 'optimal'. Optimising operations gives us a number of trips per shuttle and per day ranging from one to two hundred. This gives us an idea of scale. A vehicle capacity of 6 or 8 places should be sufficient.

Generally speaking, technological progress leads to quantitative and qualitative improvement of the service. However, switching to fully self-driving technology alters the economics of production and reconfigures certain parameters: for some indicators, the variation in performance as technology advances is a U-shaped curve rather than a steady increase. The regulatory regime has a major influence, which becomes increasingly important with each successive generation of technology. S2 systems are most compatible with achieving financial equilibrium in the production of the service, while also getting as close as possible to the system's first-best socio-economic optimum. They allow for relatively moderate tariffs compared with monopoly scenarios (which operate at the same rate as pre-platform era taxis).

The target value for the most advanced generation of technology is €0.7 per trip, for an average length of 3.7 km. For intermediate technological generations, S2 prices are around €3.5 per trip. These values provide points of reference which can help us to gauge the current economics of public transport services.

6. Conclusion

When designing shared mobility services, ring-shaped configurations allow us to cover a relatively large territory with a cyclical service provided by shared vehicles. These advantages mean that we may expect a relatively high level of demand, as well as a service which is economically attractive. By combining them we can hope to achieve a symbiosis between these two qualities, forming a virtuous circle: increased demand, more profitable production, expansion of the service allowing for greater quality of service and reduced fares, and so on and so forth.

We have also considered a number of potential geographical configurations, and the technical and economic conditions required to make them profitable. A ring-shaped system, combined with platform management and the use of electric vehicles, allows for prices in the order of €3.2/veh.km while maintaining the budgetary equilibrium of the service provider. By switching to fully self-driving vehicles, this equilibrium price could fall to as little as €0.6/veh.km.

These simulations are based upon the 'Orbicity' technical and economic model, focusing on a ring-shaped shuttle service. The model holds that demand is elastic to the trip generalised cost, including the fare and the access time weighted by their respective values of time. In practical terms, this elasticity means that the service must provide a competitive alternative to travelling by car, in terms not just of price but also of user comfort: comfort on board the vehicle, ease of access, quality of information, and the smoothness of transactions.

This exploratory study will need to be followed up with further research focusing on urban integration. This research should take several geographical levels into consideration, from local to district and up to metropolitan. The specific local level involves the layout of the ring roadway, as well as the adaptation to junctions to avoid traffic hindrance. At the district level, the ring can be targeted to a specific function within the city, for example protecting the epicentre by providing a system for passenger flow distribution and access. Finally, at the metropolitan level, the issue is to embed ring-shaped on-demand shuttle services in a coherent transport strategy. Various schematic solutions could be envisaged: for example, a star-shaped network with a central ring connecting to radial routes, or else multiple rings forming a patchwork across the whole urban area (with or without points of intersection).

Acknowledgements

To Jean Grébert (expert leader on mobility systems for Renault) for his suggestion of the loop transit system, and to Jaafar Berrada (Védécom) for our stimulating discussions during his doctoral thesis, which I had the pleasure to supervise on related issues.

Conflict of interest

The author declares no conflict of interest.

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