Chapter 10
Applications and Future Developments: Future Developments and Research Topics

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Situation A mass transit system is complex, since it combines material resources (vehicles, infrastructures), operational personnel, operational processes, and action protocols. Information plays an essential role in coordinating resources (e.g., allocating routes to stations and drivers to vehicles), in the use of those resources by passengers (prior information on services, real-time information), or in the automation of payments.
By design, therefore, a mass transit system is an intelligent transportation system, founded on the use of a minimum baseline of information, developed during the design of the system.

Let us broaden our perspective by looking both at the day-to-day operation of the system—the usage phase—and at the design phase: Here, the use of a simulation model to plan the network contributes to the intelligence of the transportation system.

In the digital era, information and information processing are becoming increasingly important in the day-to-day operation of mass transit systems, even down to the nature of the services provided. This intelligence has successively penetrated into the control of vehicle traffic on the infrastructure, then into the interaction between operators and passengers (information, payment, reservation), next into the vehicles as subsystems (including into the engines themselves), and finally into the actions and practices of users, thanks to mobile terminals (smartphones), which allow direct and customized informational interaction. Within this

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G. Gentile and K. Noekel (eds.), *Modelling Public Transport Passenger Flows in the Era of Intelligent Transport Systems*, Springer
Tracts on Transportation and Traffic 10, DOI 10.1007/978-3-319-25082-3_10

broad technological—or rather, sociotechnical—process, simulation models are continually finding new applications: in real-time system management; in demand management, in particular directing demand through dynamic information; or for short-term forecasting, which is useful both to operators and users.

Objective This final chapter explores the potential of traffic assignment models for development, beyond traditional or advanced applications. The modeling of public transportation systems is a fertile terrain for research, especially as the digital era is seeing a proliferation of innovations: in the operation of existing systems and above all in the design of original, flexible, demand-responsive mobility services, which rely on different forms of resource pooling.

The principle of pooling, fundamental in mass transit for the sharing of infrastructures by vehicles and the sharing of vehicles by passengers, has now found a very wide range of applications, thanks to the presence of information everywhere in the mobility system, which includes the transportation system and its users.

Chapter content The body of the chapter is structured into three sections. First, we consider the new deal in public urban passenger transport that stems from the new order in the field of information: Ongoing or future innovations pertain to the management of line networks, to the provision of more flexible intermediate services, and to the sharing of vehicles, drivers, and parking spaces, together with the potential associated with autonomous (automated self-driving) vehicles.

Second, we identify a whole range of research topics on traffic assignment models and their inputs to their potential applications for system regulation, passing by (i) passenger behaviors and their statistical structures, (ii) the physics and control of traffic—both passengers and vehicles, (iii) the spatial features and their flow-oriented layout, and (iv) the organization and operations of specific travel modes.

Third and last, we open up a broad perspective onto the relation between mobility systems and simulation models: Models are becoming more and more modular, and they constitute a toolbox that is more and more powerful; a number of tools are implemented to bring augmented reality to the transit systems for all of its stakeholders (users, operators, regulators, general public); arguably, an Urban Mobility Living Lab should be an ideal framework to study system conditions, to design user-oriented innovations, and to test system's responses to them on the field.

10.1 A Forward Analysis of Public Transportation in the Information Era

Fabien Leurent and Ingmar Andreasson

The digital era is characterized by a new order in the field of information: Information has become much more abundant and diverse, very easy to transmit, receive, and use, and very widely available—in fact available virtually everywhere—at an extremely low price. So this is a revolution, in both functional and economic terms.

This revolution affects a wide variety of material products and, to an even greater degree, services: Existing services have been profoundly transformed, whereas innovative services are emerging, in some cases spreading massively.

The technological information ecosystem has progressed in giant steps: miniaturization of electronic components, information superhighways (optical fiber and ADSL), wireless networks (GSM, Wi-Fi), accurate and instantaneous geolocation (GPS), Internet with information, reservation, and purchase services, satellite imagery, and the smartphone as a portable terminal of astonishing functional richness and startling interactive capability. The different technological building blocks reinforce each other, thanks to the multiplicity of possible combinations, which enhance their reciprocal capacities.

This revolution in the technological information ecosystem affects all sectors of the economy, in particular the transportation sector. The notion of an "intelligent transportation system" broadly encompasses the penetration of transportation systems by the information revolution, a process that occurred in large waves, corresponding to the big steps in the development of information technologies.

In this section, we explore the consequences—whether existing or still potential—of the informational revolution for public urban passenger transport. The new technological order has brought technical and commercial renewal in the traditional collective modes of transportation by bus or rail, in the organization and day-to-day operation of the service, which is becoming more interactive, in the mobility practices of users, and also in the interaction between the operator and users (Sect. 10.1.1).

The new technological order is also leading to an industrial transformation in the supply of public transportation through a diversification of modes: The traditional trade-offs between vehicle size, service frequency, and interstation spacing (and therefore the terminal distance travelled to access the service) have been pushed aside and can be eradicated by the development of more flexible intermediate modes than line-haul services (Sect. 10.1.2).

The economic transformation is great enough to prompt transformations of an industrial nature: The roles of the traditional service actors are changing, new players have arrived to perform traditional or innovative functions, since combinations of production methods are facilitated by the availability of information. This industrial transformation is strongly marked by the pooling of resources in all the areas that constitute a public transportation service: vehicles, transportation and parking infrastructures, protocols for usage, information and pricing, with the development of reservation services (Sect. 10.1.3).

An additional major technological transformation is also in progress: automated self-driving vehicles, otherwise known as autonomous vehicles. In public urban passenger transport, this concept is not so new, since automatic subway systems have been developing since the 1990s. However, it is spreading to road vehicles, impelled by a profound economic transformation—economizing the driver's salary, which is the main cost in a taxi system—and increased technical potential (e.g., automatic repositioning or the end of driver rest requirements): We will set out the technical and economic potential of autonomous vehicles for public urban passenger transportation (Sect. 10.1.4).

All these different changes have had the effect of reshuffling the cards between transportation modes. The two traditional pairings, on one side individual means combined with private use, and on the other side collective means combined with shared uses, are now experiencing the lure of different forms of exchange, with a range of hybrids reminiscent of gene recombinations. We explore their impact on transportation supply, on demand, and on the regulation of the mobility system (Sect. 10.1.5).

10.1.1 Line-Haul Public Transportation in the Information Era

Ongoing or upcoming changes relate to the different components of the system: vehicles (Sect. 10.1.1.1), stations (Sect. 10.1.1.2), infrastructures (Sect. 10.1.1.3), and especially operational coordination by centralized management (Sect. 10.1.1.4), as well as user practices (Sect. 10.1.1.5) and the interaction between the service and passengers (10.1.1.6).

10.1.1.1 Vehicle Changes

The new types of vehicles bring improvements of various kinds: Internal layout is optimized to contain more passengers in a given space, with more comfortable but fewer seats, thus leaving more space for standing passengers. Capacity optimization also affects exchange capacity, with more and wider doors, which open and close more quickly.

Driving is assisted by an onboard computer and various sensors, saving energy and giving a smoother ride.

Vehicles are fitted with various systems to provide passengers with information: audio and visual updates on journey progress and upcoming stops.

All these changes make travel more efficient, with better informed passengers.

10.1.1.2 Station Changes

Mass transit stations provide different levels of equipment, depending on their ranking in a hierarchy, from a simple bus stop through to an intermodal platform. The biggest stations are also the busiest; their layout is optimized across multiple levels, and internal passageways are shortened and efficiently signposted to reduce connection times.

For modes with the biggest capacity, BRT or rail, the installation of sliding platform doors improves passenger safety and the transfer of passengers between platform and vehicle, and controls the opening phases, such as green phases in traffic signals at a road intersection.

Whatever the hierarchical level, the generic functions of stations are gradually improving, through a combination of enhanced content and simpler ergonomics:

- Better identified waiting areas with greater protection from the weather, heat differences, and other disturbances;
- Automatic devices for validating tickets or for buying them if the station is big enough;
- Greater information content and increasingly dynamic information: time of arrival of the next vehicle for every service. Also under development is basic information so that passengers can transfer to other services in the event of major disruption.

So stations are better equipped and becoming smarter. The changes are making them more efficient and more comfortable to use, with better information and better oversight by the operator (and even control in the case of sliding platform doors).

10.1.1.3 Infrastructures: Open Sections and Junction Management

On way sections, movement is faster and more reliable in a dedicated corridor, with restricted or even controlled access. The presence of an additional lane, even on restricted sections, makes it possible to overtake and differentiate between express routes and standard bus services. Additional lanes are particularly useful at stations, to allow stationary vehicles to be overtaken. This arrangement makes the service more resilient.

Along the routes, junction management—intersections on roads and branches on railroads—is a major factor. Controlling junctions in order to give priority to mass transit vehicles and keep them moving is crucial to enhancing the efficiency of mass transit relative to individual transportation modes. It requires close and continuous coordination between vehicles and junction controllers by means of the information and line management system.

In the information era, integrated control of vehicle movement and junction traffic is becoming widespread. Real-time coordination of resources is a major technical challenge, a challenge that can be tackled with an efficient information and control system. Coordination remains dependent on spatial arrangements: Smart real-time operation combines with smart forward planning to allow the smooth and efficient movement of vehicles and ultimately of users.

10.1.1.4 Centralized Management to Coordinate Resources

So integrated line control requires the continuous exchange of accurate information on the location of vehicles and the condition of resources, whether controlled or simply monitored. Both the collection and transmission of information have been automated, which frees up operating staff and speeds up processing.

Whether on vehicles or in stations, or remotely by digital tracking, it is now possible to collect information in large quantities, in real time and at very low cost, in particular on the number of passengers on board and even their distribution inside the vehicle. These automatic readings give urban mass transit operators almost the same amount of information as operators of interurban mass transit systems, where seats are reserved in advance: The only differences in knowledge concern the seat the passenger is sitting in and the station where he gets out, and even these factors can be predicted statistically.

So close-grained, real-time information is now available to improve traffic management from a quality of service perspective—in particular by including the number of passengers in vehicles or stations into with management optimization criteria—to make the average service per passenger more efficient.

With an integrated real-time information system, operational management can be adjusted to circumstances and contingencies, making the service more efficient and reliable: It is the cornerstone of the resilience of the system.

In any management application, information obtained in real time is used for short-term forecasting: For example, vehicle trajectories are extrapolated in order to predict the time of arrival in stations or at controlled junctions. Real-time data on passenger numbers provide information on the needs to be met, both for onboard passengers and for those waiting in stations. The state variables of the transportation system are inherent to it: When monitored by the information system, these variables become observable indicators (in the sense of statistical physics), and when simulated in a traffic model, they can be anticipated. That is why the development of a powerful information system comes close to a simulation model: Ultimately, it is natural to include an assignment model in order to exploit real-time observations and thereby contributes to day-to-day operational management.

This convergence between information and management system and a simulation model is a major priority for operational improvement. Assignment models need to be integrated into day-to-day operations, as well as into off-line planning. A crucial step in this convergence is undoubtedly a line model that incorporates passenger numbers into online resource management. The next step is line coordination, which is more complex: This notably includes managing articulating nodes, which are junctions on the infrastructure and connecting stations for passenger flows.

The extrapolation from data collected in real time is useful for the operator, but also for users, whether they are present in the system or planning a trip and seeking remote information on current conditions.

10.1.1.5 The Passenger Side

Information system development benefits passengers, whether while traveling or when planning trips. Information has become dynamic and is also on the way to becoming predictive. The quality of prediction will depend on the capacity of the information system to incorporate both real-time operational adaptations and adaptations by users.

Major progress has already been made, thanks to the customization of information and its adaptation to the particular needs of the user in terms of times and places, and thanks to the selection functions provided by search engines. This informational upgrade costs the user nothing, apart from the cost of going online. In addition, with the smartphone, passengers have a portable terminal through which they can obtain the dynamic real-time information they need, wherever they are.

The effects of innovation are cumulative: The smartphone combines highly varied functions, a vast array of information, telecommunications, and games all in a format that is very easy to use on public transport. It replaces a newspaper and can be used even when standing. It enables people to use the time spent on the move, thereby reducing the inconvenience and masking the discomfort of travel. In other words, it transforms the quality of service, to the benefit of users. This can be expected to change uses and practices as well as, of course, provide feedback on time sensitivity and the trade-off between time spent and price. The possibility to use smartphones and tablets supports the mode shift from driving to transit.

10.1.1.6 Interaction Between Service and Passengers

In these conditions, the interaction between the user and the mass transit service is transformed: The physical presence of the user combines with a sort of mental presence, arising from real-time attention to traffic conditions and the continuous use of telecommunications. As a mobile terminal, the smartphone acts as a supplement to local information media, though without rendering them obsolete (provided that each medium is upgraded. In particular, the boards showing travel times need to become dynamic, shifting from paper to screen: This is a transition that has already happened in some advertising hoardings).

In other words, public transportation as a service is enriched by these informational changes, independently of the improvement in real-time management. In addition, there is a significant fund of synergy between these two respective changes in demand and supply: They make the service much more flexible in the sense that flexibility becomes the rule, rather than being confined to the handling of exceptional circumstances.

The stakes are notably to adapt the supply to the conditions of demand, for example the particular needs of certain days: professional or sporting or tourist events, or dynamic management of multimodal travel in the conurbation in response to a critical episode (bad weather, atmospheric pollution, etc.).

This system will become more flexible with vehicle automation, which relaxes the technical constraints associated with human drivers. It will require cooperation by users, i.e., compliance on their part: The better the ergonomics of travel—in particular with an "all-inclusive" smartphone service—the more spontaneous this cooperation will be.

The aim, therefore, is to change the routines of passengers, by providing an operating network that is sufficiently integrated in both informational and physical terms. These integrations need to go hand in hand with an integrated fare and sanction system.

In fact, the use of the smartphone should facilitate the introduction of positive sanctions: bonuses to stimulate individual cooperation for the smooth running of the system.

10.1.1.7 Summary

The development of traditional mass transit systems, whether bus or rail, has been marked by gradual improvements in their components, i.e., the vehicles, the stations, the infrastructures, the pricing and payment system, and, increasingly, the information system. The latter is becoming more and more powerful thanks to the neural net of local and remote sensors and actuators on the system: It constitutes a kind of nervous system for the line taken as an organized system and more broadly so for an entire transportation network.

This informational apparatus is amplified and boosted by the mobile terminals carried by users: The smartphone is the Swiss Army knife of mobility and also a digital companion that helps people to recycle the time spent in travel.

All that remains is to maximize the power of this nervous system, in order to develop a flexible, responsive, and anticipatory transportation network. The technical ingredients are in place, at least in planning terms, awaiting full deployment, which takes time and demands substantial financial investment. Flexibility will improve not only the system's responses to disruptions and congestion, but also its capacity to handle the diversity of demand situations. The integration of simulation models into the information and management system is necessary in order to make management more dynamic by improving its predictive ability.

User cooperation is equally necessary. This needs to be cultivated by offering services that are simple enough to continue bringing users the benefits of quality of service; by educating passengers; and by making them cooperators in public transportation with the same level of participation as in an individual transportation service.

10.1.2 The Diversification of Public Transportation Modes

Line-haul mass transit will retain certain rigidities, even if it becomes more efficient (Sect. 10.1.2.1). At the other end of the public transportation spectrum, the individual taxi is adapting to the needs of users: This mode too should benefit from the new informational order (Sect. 10.1.2.2).

However, this order should above all stimulate the development of intermediate modes, collective taxis, or microbuses, which combine the flexibility of the taxi with the economies of scale of mass transit (Sect. 10.1.2.3).

10.1.2.1 Line-haul Transit Will Retain Certain Rigidities

We have mentioned the flexibility gains expected for line-haul mass transit, thanks to the increased capacity for response and anticipation afforded by a powerful information and control system.

However, line systems, with their routes and above all their necessary stops, remain restrictive for users in terms of spatial availability. In addition, service timetables impose time constraints that also limit the availability of such systems to users.

These constraints can be attenuated but not eradicated. On the spatial side, intermediate stops along a bus route can be skipped in the absence of stop requests from inside or outside the vehicle. The time constraint becomes softer with increases in frequency: For users, reduced and even headways are more important than strict adherence to timetables.

The traditional economics of mass transit should improve through increased flexibility of production. For users, some conditions will change little: The monetary cost will remain modest, provided that they use travel cards, terminal access will remain their responsibility, waiting time should diminish a little (outside saturation events), and individual reservations will remain unavailable. The use of time spent on board or in stations, by the simultaneous use of the smartphone, will change the conditions of modal choice, probably more than the conditions of route choice within the transit network.

10.1.2.2 The Individual Taxi Will also Benefit from the New Informational Order

The individual taxi, being available to all users, is also a transit mode, but at the other end of the spectrum of capacities compared with mass transit. The individual nature of the service eliminates the spatial rigidities of mass transit: The passenger decides the starting point and destination. On the other hand, the fare is markedly higher than that in mass transit.

With taxi firms, the taxi service is responsible for transportation, billing, and reservation. For the user, reservation entails a transaction cost, along with a waiting time, because the availability of vehicles is limited.

The new informational order offers the taxi mode significant advantages:

- At the level of the firm, centralized information and management system optimize efficiency in the allocation of vehicles to customers, which increases vehicle productivity and helps to reduce passenger waiting times.
- Upfront, integrated management makes it possible to plan the development of the service by adjusting the size of the vehicle fleet, subject to institutional constraints.

So progress in the information sphere provides benefits for the taxi on both the supply and demand sides. The commercial side of the service needs to be centralized in order to grasp this opportunity. This will combine with the advantages specific to a taxi firm, i.e., more integrated and productive management of vehicles and drivers, preferential conditions for the acquisition and maintenance of vehicles, and preferential access to credit.

10.1.2.3 The Consolidation of Intermediate Modes

With the individual taxi, occupancy can only be maximized in the case of small groups traveling together, which considerably restricts the possibility of economies of scale from greater vehicle capacity.

Collective taxi services, whether using vans or minibuses, represent an intermediate mode between the individual taxi and line-haul mass transit. It combines the ability to pick customers up and drop them off where they want, with maximized vehicle occupancy. Pooling the service between passengers reduces the unitary cost and hence the price per passenger, in the same way as for a group in an individual taxi, but with greater earning potential for the service provider.

The new informational order is a windfall for collective taxi modes:

- Firstly, as with an individual taxi, the centralized information management system matches reservation requests to available vehicles. Unlike individual taxi, however, requests that are close to each other in space and time can be grouped by the operator.
- Secondly, additional customers can be picked up in the course of the journey, provided that there is space in the vehicle. This increases the availability of the service, both in space and in time, and every point on a vehicle trajectory becomes an opportunity to recruit a customer.
- In turn, each customer benefits directly from increased availability and lower fares. In addition, if a potential customer receives continuous information on current opportunities, then her confidence in the service is increased: This allows more spontaneous, opportunistic, and unplanned uses, with reduced transaction costs.

Obviously, the need to pick up and drop off other passengers, and the associated route adjustments, reduces the speed of service for each user: The quality of service is halfway between the individual taxi and the traditional bus, although with strong potential in terms of availability.

The enhancement brought about by the information system makes the mode more reliable and more appealing. Linked with the limited size of the vehicle, this can trigger the virtuous circle of the Mohring effect: More demand necessitates more vehicles, which increases the availability of the service (cf. the frequency of a line-haul service) and makes it more attractive, thereby further stimulating demand, etc.

The power of this positive feedback effect will depend on the area. In dense areas, it potentially makes the collective taxi a serious competitor to the bus.

In certain African and Latin American cities, the mass transit system consists entirely of collective taxis, and in other words, they have a bottom-up rather than a planned top-down system.

However, the sphere of relevance of the collective taxi is certainly not confined to dense areas. It is a very promising mode for transportation provision in low-density areas where the number of passengers for grouping is small, and there is therefore a significant need for intermediation to organize groups. Here, the opportunity is that the intermediation function can be automated by an information system and by centralized management, at negligible cost!

The infrastructural aspects of such a mode remain to be defined. In principle, it requires no access stations, which is an advantage. For access as for travel, the mode obviously uses the road network: But could it be allowed to use dedicated bus corridors (as is the case in some cities) and even granted priority at intersections?

10.1.3 Toward a Generalized Pooling of Transportation Means?

In the urban environment, mechanized transportation modes will retain their well-established physical composition: a vehicle, a driver, an infrastructure comprising stations and lanes, together with operational protocols: principles of use, highway code, service processes, operating processes, etc. Some of the different components are physical (hard) and others more organizational and informational (soft). The information revolution is expanding the role and functions of the soft components. In particular, it permits highly interactive protocols, offering the possibility of major recombinations in the way the physical components are used. Nonetheless, these recombinations need to maintain certain regularities; they take the form of particular mobility services, which bring considerable diversity to the transportation supply.

Innovative services are an addition to the traditional services; they still employ physical resources, but in a variety of forms of ownership and pooling between users.

All this takes place on the road network, which is the infrastructure for access, parking, and movement, since the general availability of the roads opens up the urban space to mobility needs and services. These therefore share the roads between them and with the pre-existing users.

We have already described the traditional forms of pooling: On the one hand, line-haul mass transit—which vertically integrates a vehicle, a driver, a service route and stations, and a management system—shares these resources between passengers in a single vehicle in real time; on the other hand, the taxi, which vertically integrates a vehicle, a driver, and a management system (in the case of a taxi firm), but where the sharing between passengers takes place by alternation, as does the occupancy of a public parking space.

Service innovations are reshuffling the modal components and offering new forms of organization, based on new ways of sharing physical resources, which of course still have to be amortized over a large number of uses. The scope, durability, and potential spread of an innovative service depend on its information management system. This system is at the heart of the new service, and it dominates the other components not functionally, but in the distribution of commercial power between the central system and the owners of the vehicles and the drivers.

This situation makes it possible for independent companies to form an organizational network, with a micro-franchise system for the basic suppliers of vehicles and driving, in the same way as a company with a network structure.

We will fill out this broad picture with a more detailed description of a series of innovative services—carpooling (Sect. 10.1.3.1), the multipurpose taxi (Sect. 10.1.3.2), car sharing (Sect. 10.1.3.3), shared vehicle systems (Sect. 10.1.3.4), car hire between individuals (Sect. 10.1.3.5), and shared parking (Sect. 10.1.3.6)—culminating in a brief synthesis (Sect. 10.1.3.7).

10.1.3.1 Carpooling: Emergence of the Intermediator

The ancestor of carpooling is hitchhiking, traditionally practiced by non-car owners, in particular young people, often with unpredictable success, long waits, detours, and multiple vehicle transfers. In order to increase the chances of success and reduce waiting time, hitchhikers are well advised to stand by the side of a large, busy road and carry a sign showing their destination in order to match up with a driver going the same way.

A more modern form emerged, which might be described as urban corridor carpooling: Stations are provided along certain big, carefully selected roads, to match up drivers and potential passengers. The advantage for society is to make better use of cars and promote passenger mobility. This kind of system makes particular sense in the case of high-occupancy toll (HOT) lanes reserved for collective vehicles and multioccupancy cars (another modern form: expressway carpool parking).

However, the new informational order offers a much more radical innovation: Over and above possible pickup and drop-off areas, they provide an intermediation service between carpool providers and clients. Information and matching services have been developed by companies for their employees or by local authorities, but with limited success, because the client and provider base is small, the ergonomics is not simple enough (the smartphone had not yet appeared when most of these services were set up), and the service offered no rewards, except perhaps parking priority for the vehicle concerned.

The firm BlaBlaCar provides a similar service, but it is based on a principle of cost sharing and is quite remarkable in terms of ergonomics and commercial functions. Potential clients use a Web app on a computer or smartphone to enter their journey requirements, specifying their starting point and destination and preferred travel window. The application provides a series of appropriate options, each with a price, an indication of whether or not the journey will include toll roads, and feedback on the driver from people who have previously used the services.

On the driver's side, the interface is just as simple. In addition, the driver remains in control of planning the movement and organizing the journey, by accepting customers and negotiating the rendezvous.

Various tactics are possible, in particular reducing the price in order to attract more clients and maximize revenues.

The intermediation service brings together clients and providers. It provides reassurance about the provider, who is duly identified and assessed; for clients, who are personally entrusting themselves to a stranger in a dominant position, it acts as a trusted third party. In addition, the service receives the payment, takes its commission, and transfers the rest of the money to the provider, which facilitates transactions in the vehicle and also relieves the driver provider of the responsibility.

So the intermediator is not a simple intermediary: By centralizing requests, providing information, establishing trust, and taking payment, it creates value both for the client and for the provider. Carpooling thus becomes a three-tier operation, which has achieved considerable success. In the USA, services similar to BlaBlaCar are Lyft and UberPop.

10.1.3.2 The Micro-franchise Taxi

In the three-way relationship of carpooling with an intermediator, the providers are paid by the clients, but this is primarily a sharing of costs. UberPop has been the target of criticism in several countries, because the price exceeds the fuel costs, which brings it close to being a commercial activity.

Other services based on a powerful intermediation system are emerging. In particular, Uber matches clients to drivers for limousine services (Uber Black) and car-and-driver tourist services (UberX).

Compared with a taxi firm with a real-time management system, there is a major organizational difference: the commercial dissociation between intermediation and production. This makes for a particularly flexible combination: Each vehicle holder–driver is a self-employed person who joins a commercial network, but remains the holder of their physical means of production (another important difference is the tax regime, which needs to be harmonized between products belonging to a single family of services).

This difference in distribution allows the intermediator to make profits with modest investment and the individual producer to conduct a paid business with fluid access to a wide client portfolio and to professional services, in particular for billing.

Ultimately, the users benefit from this new service and the efficiency of the intermediation.

10.1.3.3 Car Sharing

A car sharing service provides access to a car for individual use, by pooling the vehicle among different users over time (with alternating use). This service requires vehicles, parking spaces, a reservation and access system, and adherence to protocols of usage, ownership, and maintenance.

Originally, car sharing services grew out of community initiatives. The main organizational techniques developed gradually, and the system became professional, with the emergence of companies that provided protocols—in particular for intermediation—but also vehicles and parking spaces, often in concert with the regional authority in the service locality: cf. firms such as Caisse Commune in Switzerland, ZipCar in the USA, Communauto in Canada, etc.

Car sharing is a service that pools vehicles (in alternation) and parking spaces (permanently); users drive themselves. The pooling aspects relate car sharing to transit systems, while the self-drive aspect is closer to the private car mode.

The advantages to society are that users are less attached to cars and show a predisposition to multimodality—mostly practice alternative modes to the car—as well as more productive use of both parking spaces and vehicles. However, there is no sharing of seats in the car.

The car would seem to be the only vehicle versatile enough for sharing to work. Two-wheeled vehicles, which are much cheaper to buy and run, and much easier to park, tend to be chosen personally by their owners. As far as we know, privately owned bicycles have not been the target of significant community bicycle sharing initiatives.

10.1.3.4 Shared Vehicle Systems

There are now a variety of commercial services for the sharing of two- or four-wheeled vehicles for alternating use over time by different users: Halfway between car sharing and conventional short- to medium-term car rental, shared vehicle services offer very short-term hire within a circumscribed geographical area.

Some modes use stations for shared vehicles, where the vehicles have to be picked up and dropped off. The drop-off station may be different from the pickup station in a one-way system such as Vélib or Autolib, but must be the same in a round-trip system such as Autobleue (in Nice).

Other services do not use stations, notably Car2Go (in Ulm, Austin…). Whatever the specific procedures, however, the system supplies the vehicles, insurance, maintenance and service, as well as the access protocol, perhaps with the possibility of reservation, and of course information system and a payment protocol. The service area needs to be large enough and dense enough for this form of sharing to be attractive and profitable. Cars need to be manually relocated to balance supply and demand.

The no-booking style of access to this mode of travel makes it comparable with transit, as does the sharing of the vehicles and parking. However, the use remains individual. Bicycle-based services (e.g., Vélib, Bixi) capitalize on the societal benefits of this mode—little or no environmental damage, and greater urban integration of both movement and parking. Certain automobile-based services use electric vehicles (e.g., Autolib) to adapt to the urban environment by avoiding local pollutant emissions and reducing noise pollution.

10.1.3.5 Car Hire Between Individuals

Car sharing and shared vehicle services provide a pool of dedicated vehicles, to which no user has privileged access except through the subscription arrangements. A different kind of service that has emerged is car hire between individuals (e.g., Drivy). The vehicle is made available for a period set by its owner, at a cost that undercuts any of the commercial competitors.

The intermediation system plays an essential role as a virtual sales counter between supply and demand, providing information, reservation, and payment.

Here again, pooling benefits both client and provider, as well as the intermediator.

The gains made by all three parties also benefit society, as does more intensive car use, which reduces the technical lifetime of the vehicle and brings forward its replacement by a more modern vehicle, likely to offer better environmental performance.

10.1.3.6 Park Sharing: Sharing of Parking Spaces

Car sharing and vehicle sharing services pool not only vehicles, but also parking between their users.

Shared parking is also developing independently, especially in dense urban areas where parking spaces are relatively scarce and therefore expensive. Intermediation services have developed in this field, targeting both individuals and companies, to encourage people to use each other's resources.

Partway between traditional shared parking systems, either roadside or in public car parks, and long-term renting of parking spaces between individuals, park sharing works with privately held spaces rented for very short periods. In particular, some companies have large, underused car parks, which can be put to good use through services like this.

In France, the ZenPark and MobyPark firms offer to turn parking spaces into connected objects that are made available through a specific Web app: The car user can prospect some places and book one that is vacant. The ParkaDom service is targeted to individuals in order to ease hiring for any duration, from one hour to one month or more.

10.1.3.7 Provisional Synthesis

Powerful systems of intermediation between users and services have emerged in the sphere of urban passenger transport. Such systems centralize information and distribute it continuously to their users, according to the particular needs of the latter. They connect clients with providers and carry out all commercial functions.

The system's material medium is primarily IT, a combination of a central server relaying information by Internet to computers and especially smartphones, using a Web app specific to the service. For the user, the ergonomics are radically simplified: Setting up the service simply requires reading a page or two on a smartphone screen, clicking a few times—i.e., look and touch—according to a principle of immediate access. The transaction time is insignificant, so there is no disincentive to spontaneous use of the service, even if it proves unavailable.

The services provided by the intermediation systems broaden and strengthen the whole transit sphere. The most productive forms are those that optimize vehicle occupancy in real time: collective taxis—especially minibuses—and carpooling. Other forms rely on the alternating use of vehicles or of parking spaces: taxis, shared vehicles, car sharing, and park sharing.

In other words, pooling and sharing are on the move in urban transportation. It affects not just the uses, but also—symmetrically—the ownership of individual resources. Information sharing leads to the functional economy, to less individual attachment to mobility objects.

10.1.4 Autonomous Vehicles

Autonomous or self-driving cars have been demonstrated by several car manufacturers and IT companies. They can legally be used in several US states, the Netherlands, and the UK, albeit with a driver ready to take over, a systems engineer for remote assistance upon request and a bank guarantee. The car industry is investing heavily in autonomous cars, and it is an industry with powerful lobbies and often strong government support. It is expected that laws and regulations will be relaxed to allow driverless vehicles on dedicated lanes, on motorways, and eventually perhaps on all roads. Traffic safety is expected to improve, since over

90 % of traffic accidents are caused by driver error. More efficient car following through the use of "platooning" may improve roadway capacity.

This section discusses the implications of autonomous vehicles in transit, in taxi fleets, and on dedicated or shared guideways.

10.1.4.1 Driverless Transit

More than half of the operating cost for transit is driver wage. This fact has driven development toward ever larger vehicles and trains. In order to fill large vehicles, passengers need to be bunched in space and time by gathering them in stations and serving them at longer time intervals.

Driverless operation has already been introduced on dedicated rights-of-way such as subways, People Movers, and Pesonal Rapid Transit (PRT) or Automated Transit Networks (ATN). Technology developed by the car industry can be applied to trucks and buses as well. Some suppliers already offer conversion kits for standard vehicles.

The implications of driverless transit will be manifold:

- Without drivers, there is less motivation for large vehicles. More and smaller units running with higher service frequencies offer better service with shorter waiting times;
- Smaller buses are more suitable for adjustment to demand, e.g., by route diversions;
- Layover at terminals can be shorter without the need for driver breaks;
- There will be more freedom in scheduling when driver reliefs are not needed;
- Schedule/headway adherence will probably improve when bus runs are centrally monitored;
- Collision avoidance equipment will reduce accidents, repairs, and damage expenses for transit operators;
- Less damage should lead to lower insurance premiums or reduced costs of damage;
- Platoon driving can increase link capacity through bottlenecks such as the overcongested bus lanes in the Lincoln Tunnel between New Jersey and Manhattan New York.

10.1.4.2 Driverless Taxi "aTaxi"

The car industry is targeting the private car market by offering greater driver comfort. Commuters can work, communicate, relax, or be entertained during the ride in their autonomous private car. This in turn may generate further urban sprawl and more traffic.

However, a driverless car is also perfectly suited to taxi fleet applications:

- Taxi fares can be more competitive without the cost of drivers;
- Fares can be known in advance;

- Fleet management can be more efficient with the optimization of dispatching and empty movements, along with the reduction in parking times and parking spaces;
- Ride sharing in taxis can be planned with smartphone apps and central control.

aTaxi can become an alternative to transit at times of low demand and in suburban areas. It will be more attractive than transit by offering door-to-door service on demand, but will still be more expensive than transit because of a lower level of ride sharing.

It is expected that many households will give up their private cars or at least their second car when aTaxi services become available. This would free household capital for other uses. aTaxi would be a public system available to everyone, regardless of driving license, age, and sobriety.

The most visible effect of aTaxi in cities would be the release of parking spaces and car parks for other purposes. By contrast with the private car, which is parked 95 % of the time, an aTaxi simply goes on to pick up the next passenger. Parking spaces today take up more than 50 % of the land area in many cities.

Traffic will not necessarily be reduced with aTaxi replacing private cars. Empty vehicle movements need to be offset by higher degrees of ride sharing (Burghout et al. 2014).

Ride sharing together with empty vehicle movements is key to efficient aTaxi operation. We foresee customers ordering aTaxi with a smartphone app, specifying their destination and a time window for pickup. The pickup point can be given automatically by GPS or entered manually. The ride sharing possibilities will depend on the size of the time window and on the detours accepted to pick up or drop off copassengers. These factors could be set individually and determine the cost of the aTaxi fare.

In comparison with shared cars, aTaxi requires no driver's license and need not be picked up nor be parked.

Security in aTaxi is a factor that needs to be addressed. A taxi with driver is not always very secure, but unmanned taxis may still be a concern. We foresee pre-registration of users, pin codes to identify passengers, cameras in all cars, and emergency call buttons.

From a modeling perspective, aTaxi is equivalent to a conventional taxi except that empty vehicle movements and ride sharing can be optimized with one of the DARP algorithms.

For integrated transit modeling, the aTaxi part of the trip can be represented by average waiting time per zone and OD matrices of average ride time per time of day.

10.1.4.3 Autonomous Vehicles on Guideways and Roads

Autonomous vehicles are already operating on guideways in the form of People Movers, PRT, or Autonomous Transit Networks. Some of them run on rubber wheels and can be developed to leave the guideway under manual control.

The car industry plans to introduce self-driving cars on roads. Elevated guideways for cars may be attractive in areas with heavy congestion. Such guideways may be less costly than adding another paved lane with the dimensions and rigidity needed for heavy vehicles. In many places, there is no space for more lanes.

Elevated guideways can be self-financed by charging a toll. People are willing to pay wherever they can avoid congestion delays. Cars can more easily and safely be made to self-drive on guideways than on roads. Platooning would increase guideway capacity. The journey range of electric cars can be increased by charging systems (using sliding contacts or induction) on the guideway.

The same guideway can be used by guideway-bound transit and by dual-mode cars equipped with the proper communication and control. Transit stations can be elevated or at grade in conjunction with off- and on-ramps for cars.

Private dual-mode cars can be inserted into the transit system when not needed by the owner, instead of being parked, bringing substantial savings in terms of parking space and vehicle fleet sizes.

10.1.5 What Prospects for Urban Mobility and Multimodality?

10.1.5.1 Modes Are Diversifying…

Mobility for people in cities is the object of multiple service innovations. In the era of Web apps, transportation and parking services are being reinvented.

Powerful systems of intermediation provide services that match supply and demand and manage commercial functions. Logistical functions for making resources available, traditionally integrated into the commercial function in mass transit modes and also in the supply of private vehicles to individuals, can now be dissociated.

The result is a wide qualitative diversification in mobility services. Between the two traditional forms of line-haul transit systems and the private car, we are now seeing the insertion of services such as collective taxis, carpooling, micro-franchise taxis, shared vehicles, and park sharing.

Pooling for physical resources is on the agenda, stimulated by information sharing and easy interactions between potential users and providers of resources of all kinds.

10.1.5.2 But also Becoming More Homogeneous

Alongside the general trend toward modal diversification, two movements are underway that are simultaneously driving a degree of homogenization.

On the one hand, for a long time, the urban sphere was long a place of geographical singularity, marked by local customs, influenced by physical, climatic, historical, and cultural factors. True, the private car has spread worldwide, but with local adaptations in vehicles, infrastructures, and conditions of access and movement. Mass transit systems are equally marked by local contexts, in the importance of their role, in their technical and tariff conditions, and in their regulation. Individual or collective taxis show even more local differences. Now, the new mobility services are spreading internationally, some with significant local variants (e.g., shared vehicle systems), but others with adaptations limited to language (in the Web app interface) and the local currency units. If they continue to develop, they will generate a certain convergence between conurbations to a fairly standardized set of multimodal options. Business visitors or tourists will push for this uniformity, which will make it easy for them to transfer their day-to-day routines away from home.

In addition, all the modes and services are becoming smarter. Smart travel, thanks to dynamic information on the physical state of the system and assistance with the choice of route, mode or even schedule. Smart movement, with assisted driving and soon driverless cars. These intelligent functions are incorporated into the objects, which releases the user to carry out other activities at the same time.

As a result, individual transportation is coming to resemble mass transit, collective taxi and carpooling services are approaching the conditions of the private car, and the resemblance will further grow when vehicles become automated.

Alongside this kind of convergence between modes with regard to use, there will be a certain convergence in the technical principles of vehicle movement, for example, automatic travel on a linear infrastructure, or the platooning of driverless vehicles, to form a sort of road train.

10.1.5.3 Personalized Services, but Without People

Automated intermediation offers its users a very wide but at the same time customized range of information, with information that is targeted and dosed, since parsimony is also a factor of efficiency. This customization gives the service a sense of attentiveness.

In addition, intermediation can include community control of service providers (via the scores attributed by users and their feedback comments): This is an effective alternative to hierarchical control, since it stimulates providers to give good quality of service.

Vehicle automation will further promote the customization of mobility services, by bringing the vehicle to the client in the place and time of their choosing. The downside, however, is a profound dehumanization. Operational personnel will concentrate on maintenance and remote complaint handling.

10.1.5.4 Economics of the Services and Potential Demand

Innovative mobility services combine physical resources, which are in principle exploited more intensively than in private use, and a highly automated intermediation system. The unit cost of a service should be lower than traditional modes, in defined conditions of use: the private car for limited annual mileage (up to 10,000 or 15,000 km per year) or the traditional bus with very low average daily occupancy.

The transportation and parking infrastructure does not impose costs on these services: The roads already exist, and local authorities tend to favor parking for shared travel modes.

As a result, innovative services carry few fixed costs, which means that can be easily adapted to the specific local needs of each area. In short, this kind of service is flexible and resilient.

These in principle favorable economic factors will be further enhanced by the confidence of financial investors, who have already put huge capital sums into certain services, even early in their development ($41 billion at the end of 2014 for Uber, set up in 2009). This financial firepower enables them to invest for the long term and to introduce their intermediation service at a very moderate price, or even for nothing in the start-up phase. It seems out of proportion with the investment needs of an intermediation service and hence a striking contrast with line-haul mass transit systems, which traditionally find it hard to finance their large-scale investments.

One reason for this investor confidence in innovative services is the robustness of their business model: because of the specific value of intermediation, but also—more profoundly—because the mobility services provided will be priced in proportion to their use, much more directly than in traditional modes. There is a sort of techno-economic soundness in this, which indeed inspires confidence.

The difference in confidence between innovative services and traditional mass transit should ring bells with public transportation planners, in particular with regard to big projects for orbital lines around cities, like the Grand Paris Express: Would it not be more economical to invest in road corridors, possibly underground, and to encourage collective taxis?

10.1.5.5 Demand and Its Influences on the Multimodal System

Mobility demand is traditionally segmented according to the modes, which their users have become accustomed to and familiar with. Among habitual users of the private car, as among mass transit users, a significant proportion will not change their habits. A fraction will adopt an innovative mode as their preferred travel mode. Yet another fraction will be multimodal in their behavior: Every time they travel, they will first estimate the quality of service on the different modal options. The distribution of all users between the fractions will evolve with time, probably with a gradual development of the multimodal type, stimulated by the availability of comodal trip planners with up-to-date information.

When users compare modes in order to choose one, this establishes conditions of potential substitution and therefore competition between them. By contrast, intermodality is a cooperative relationship between a sequence of modes on a single trip. The functional complementarities between individual modes for access to the mass transit system (walking, bicycle, car) and efficient collective modes for the main journey (railway or BRT) are already well established and widely practiced. One-way shared vehicle services seem to fit harmoniously into this cooperative system, whereas round-trip systems are better suited to the final city stage of interurban journeys. Similarly, carpooling and individual or collective taxis connect easily with efficient mass transit systems.

It is still uncertain, however, how intermodality will work between several innovative services: What can be the link between a carpool service and a collective taxi? Or between two collective taxis, each of which would prefer to remain inside its catchment area? Indeed, for a taxi mode, transfer between vehicles only seems natural to the passengers for access to a higher performance network.

Whatever happens here, demand will benefit from a diversified and globally better quality multimodal service, where prices will be held down by competition.

The advantages are obvious outside the usual mass transit sphere, i.e., outside operating hours or in the periphery of cities, where densities are low. Here, collective taxis and carpooling find a sphere of relevance that has already emerged, in a place where they were traditionally already present.

The diversification of services will be stimulated by the modal choices of clients; by choosing the mode most convenient for them, they will focus each service on its specific sphere of relevance, the expansion of which will depend on the specific location.

This stimulus will be all the more virtuous in that the charges of innovative services are directly proportional to actual use, so the price signal is right, and all the better for the fact that a shared service has a rental aspect, so the price will be geared to the full unit cost rather than a marginal cost.

In these circumstances, the pricing of innovative services should stimulate a tariff revision for mass transit modes, linking them more directly to actual use and harmonizing the unit price more fairly between regular users and occasional passengers.

The pooling of cars will raise questions about individual car ownership: What is the point of owning a car? In fact, a car that is used more intensely should cost less to use. So private car ownership will be justified when individual car use is very intense (annual travelled distance beyond 30,000 km), or in the case of customization that generates usage value: internal arrangements for personal needs (e.g., restricted mobility) or family needs (child seats), value of immediate access for private or professional purposes, and image factors (luxury and show-off).

10.1.5.6 What Future Structural Changes in Demand?

Innovative mobility services will be accessible at a moderate price and therefore to a large majority of the population. Modest but solvent households (e.g., individual returning to employment) should benefit particularly from car sharing, which will provide performances similar to those of a private car but at a much lower overall cost.

Another social advantage: Automated driving will make cars more accessible for people with disabilities and those without a driving license.

Expanding services, combined with falling prices, should stimulate overall demand, especially as payment will be easy and the time spent in travel will cost users less, as they will use it for other activities. However, the clearer pricing structure will make the cost of travel more obvious to users, who may therefore decide to manage their finances better by cutting their spending in transportation. Another factor of change will be the level of congestion on roads and on mass transit modes, which will itself depend on the development of vehicle sharing services, collective taxis, and carpools.

As regards urban forms: The expected benefits of the changes will be greater in the outskirts (unless there is a systemic effect of greater inner-city fluidity). They can be expected to stimulate urbanization and therefore urban sprawl. This is not harmful in itself: The important thing is that the price of transportation should reflect the costs for the user and the community.

10.1.5.7 Regulation: Issues and Strategies

The community regulates the transportation system by carrying out a set of functions:

- It plans the road system as an infrastructure to be shared between travel modes, and it manages traffic.
- It supervises transit, particularly mass transit but also taxis and parking. In cities, the community generally contributes heavily to the funding of mass transit.
- It regulates the multimodal transportation system, in other words the transportation service industry.
- It decides and implements mobility policies, in interaction with other sectorial policies, in order to meet social, environmental, and economic objectives.

Now, the new informational order is ushering in a new order in transit. For line-haul transit, a direct consequence is a—potentially profound—improvement in efficiency. In parallel, innovative services are emerging or spreading, primarily through spontaneous initiatives: They are competing with transit without seeking finance (at least for operations).

The public can gain from this on every front, through better use of mass transit, through the use of innovative services in their sphere of relevance, and even in the use of private cars as increased sharing leads to more fluid traffic conditions. In addition, competition from innovative services is a great opportunity to revitalize line-haul mass transit systems. This competition will help to rationalize pricing, making it more clearly related to the service provided, at a level closer to the full cost, possibly reflecting the degree of pooling entailed (as in the Lyft service which proposes the sharing of costs between users)—all in a simplified form inspired by e-commerce (online payment) and with greater acceptability.

In addition, competition should stimulate improvements in the position of line-haul mass transit systems within their sphere of relevance, probably driven by a reconfiguration of bus lines for a better distribution of their in-route and feeder functions. The feeder function could in many cases be performed by collective taxis and other car sharing systems.

All these potentials constitute a real windfall for urban transit and therefore for the authorities responsible for managing the mobility system. It is up to them to grasp these opportunities boldly: by taking the right support measures and by steering changes in order to reap the benefits and reconcile the respective interests. In particular, the activities of the stakeholders need to be orchestrated so that they contribute to the harmonious development of the whole.

A key point concerns the market potential of innovative services and the refocusing of line-haul mass transit systems on their best sphere of relevance.

We will divide up the opportunities and the regulatory levers into their broad priority areas: first, environmental and urban quality priorities, then infrastructural priorities for traffic and parking, then public transportation service priorities, and finally economic and social priorities.

With regard to *the environment and urban quality*, an efficient multimodal transit system should reduce overall vehicle traffic and therefore reduce local traffic, energy consumption, and pollution emissions. An additional opportunity lies in the renewed appetite of investors for urban transit: This could facilitate the transition from the internal combustion engine to electric or hybrid modes, by mobilizing capital to finance the additional cost of acquiring these vehicles as compared with conventional vehicles. Electric vehicles should fit particularly well into automated driverless systems, since they can carry out their own recharging.

Less traffic, with a growing spread of autonomous and electric vehicles: This should lead to improvements in the urban environment (calmer driving, less noise pollution), health gains (reduce pollution emissions), and road safety gains (as for civil security, steps will need to be taken to prevent the risk of autonomous vehicles being hijacked by ill-intentioned people, by installing local security barriers around sensitive locations, and by fitting these vehicles with automated systems to ensure that these barriers are respected).

With regard to *infrastructure*, better vehicle sharing should reduce parking demand. At the same time, enough free parking spaces must be available for small transit vehicles to be able to pick up or drop off an individual client without disrupting local traffic. Focal points for passenger flows, such as railroad or bus stations, must also be designed to handle minibuses and other collective taxes, through specific forms of design that will reconcile vehicle size, passenger access, and specialization by destination area.

With regard to *traffic*, major arteries will need to be designed so as to avoid local disruptions from individual access needs. There will also have to be agreement about the granting of privileges for pooled vehicles in traffic management: priority at specific junctions, based on a certain vehicle occupancy level and/or deviations from timetables.

With regard to *transit services*, there is a need to think about recentering bus lines on the sphere of relevance specific to the size of the vehicles, both in terms of capacity and dimensions, and particularly by seeking a more efficient service for passengers: on more straight-line journeys, between more widely spaced stations and coordination with local junction control.

With regard to *economic and social priorities*, we would begin by pointing out that the benefits of calm, health, and security—in other words of public order—are key concerns for city dwellers, alongside the benefits to users. So local people, who are both residents and users, have double gain from the new transit order. In addition, on the supply side, recentering on the best spheres of relevance for greater efficiency should also lead to greater profitability.

The subsidiary question concerns the employment of operating personnel, particularly taxi drivers, who will be affected by new services and vehicle automation. Social support needs to be organized to facilitate the transition to related activities: For example, the driver of an individual taxi can become a collective taxi driver, or an urban delivery driver, since more and more people today order goods online for home delivery.

Finally, it is up to the community to orchestrate the overall process, by giving further impetus alongside the spontaneous initiatives of private actors and by setting the pace of change. To achieve this, they need to devise scenarios for gradual transformation, differentiated according to the final scale of transformation and the pace of implementation.

A simulation model will be valuable in seeking to anticipate the practical effects of each scenario, to compare the strategies for change, and to establish a preferential scenario which will support political decision-making.

10.2 Research Topics on Transit Modeling

Fabien Leurent and Ingmar Andreasson

An assignment model of traffic on a mass transit system reflects the encounter and interaction between a system of transportation that provides services and a population of passengers wishing to travel. The fundamental function of such a model is to represent the interaction between supply and demand, by capturing the essential features of that interaction: the flow of passengers at different places and times, the quality of service from point to point, and commercial revenues.

To do this, the scientific method is to *describe* each part, whether supply or demand, in its specific composition and operation (technical and commercial operation for supply, economic and social behaviors for demand) and to *explain* their interaction as the combined set of their respective behaviors. This combined set of behaviors notably produces effects in the local formation of flows and in their influence on the quality of service and the economics of supply.

10.2.1 Background

In a half century of scientific research, assignment models have made significant cumulative advances. The first task was to understand the spatial structure of transit services (in the 1960s) while capturing their time-discrete nature and its impact on passenger route choice (in the 1970s and 1980s). Once these basics were established, it became possible (in the 1990s and 2000s) to model different macroscopic flow and capacity phenomena on the supply side and, on the demand side, to produce better models, more sensitive to the characteristics of passengers and to their particular travel conditions (quality of service, dynamic information). After this (since the 2000s), the focus of research shifted to the time dimension, the quest to capture the dynamics of the system's operation, both within a single day, notably by identifying traffic peaks, and between successive days, with an emphasis on learning phenomena for passengers and stabilization mechanisms for the state of the system. Please, note that our chronology is approximate. Each significant aspect received pioneering contributions, some of them well before the period mentioned, which reflects primarily the abundance of the work published on a given theme and the scientific community's grasp of the complexity inherent to that aspect.

The dynamic operation of the system remains an extremely lively field of study, with macroscopic, microscopic, or hybrid models (macroscopic for travelers, microscopic for vehicles) to capture normal traffic behavior, or disruptions and their consequences, and also the use of flow simulation to contribute to real-time service management (see Chap. 8).

10.2.1.1 Research Problems: Main Research Fields

Over time, therefore, the science of traffic in an urban mass transit system has reached a certain understanding of the spatial and temporal aspects in the operation of such a system. For the present (2015), this understanding remains partial, since the model's explanatory power is essentially focused on traffic flows.

Our understanding of the supply aspect requires further work: a better grasp of the particularities of each mode, from bus to train, not just in terms of vehicles but also infrastructure and the passenger interface; and also, making certain supply characteristics endogenous, in particular service frequency and dynamic traffic management.

On the demand side, the typology of passengers in terms of their needs and behaviors, and the associated statistical structure, is an important research area, as is discerning the route options and decision rules for a given class.

Another major research area is the empirical comparison between simulation results and observational data. Previous work on this subject has produced pioneering contributions: The challenge is to design statistical methods to assign confidence intervals to the different simulation results, as well as to the different observational data, and to make fine-grained estimates of the parameters and functional forms in the model.

In addition, this is a transitional period in the diversification and transformation of mobility systems: diversification in the technical and commercial forms of services, and transformation of uses and users. There is a need to model innovative forms of mobility system, to explore their market potential on a case-by-case basis in a diversity of territorial contexts.

Finally, a transformation is taking place in modeling itself. Computing power continues to grow. More and more observational data are available (big data). The state of the system can be described by variables that are simultaneously simulation results and real-time field "observables," which allow comparisons and reciprocal inputs between simulation and observation.

10.2.1.2 Objective: To Identify Research Paths

In this section, our objective is to identify research topics for the modeling of urban passenger mass transit systems. There are three types of challenges for such research, which cut across the big fields of investigation already mentioned:

- First, a theoretical challenge: to describe and explain generically the composition and operation of components, of subsystems: physical composition and technical operation of the service supply, composition of the demand, and socioeconomic principles of mobility behaviors.
- Second, an empirical challenge: the statistical or econometric capacity to reproduce and to reconstruct, to a given level of accuracy, the observable operation of a real system.
- Third, an operational challenge: to make the simulation model contribute to the real-world management of a system studied by means of the model. The model was originally applied to the planning of a network of lines, in a way that is primarily technical and secondarily economic. From now on, the model may encompass the management of traffic to optimize operational performance: Pioneering applications have already been implemented for road traffic management, but mass transit traffic management is a new frontier for research. Commercial management is another frontier, for the development of pooled mobility services, and a parallel economic rationalization of all transit modes, in particular mass transit.

10.2.1.3 A Systemic Approach

Modeling a sociotechnical system is essentially a form of operations research, in the original sense of the term; a system model enables the analyst to simulate the operation of the system and to adjust different action levers in order to optimize its performance. This is how a simulation model can contribute to the management of the system.

The different facets of modeling—physical and economical theorization, systemic structuring, mathematical formulation, algorithmic specification, econometric formulation, and statistical estimation—are all ingredients in the formation of an applied model. Rather than covering each facet successively, we give priority here to the system's structure, to its organization into two subsystems—supply and demand—and to their interactions.

10.2.1.4 Organization of the Section

The supply–demand structure of a transit system is the reason for the section's organization into seven parts.

Demand is covered in two parts: first, the aspects relating to individual passengers, in terms of situation, practices, behaviors, and decisions (para 1); second, the structural composition of demand into classes of travelers and also in terms of different territorial and temporal circumstances (para 2).

The next part concentrates on micro-local traffic: flow phenomena for travelers and vehicles, their effects on quality of service, and the impact of different management levers, including spatial layout (para 3).

Beyond the micro-local scale, the management of supply is covered in four parts. First, at the level of a transit line, simulating flows and costs, characterizing performances and optimizing management (para 4). Then at the level of a network of lines as a modal system (para 5).

Next, we look at the diversification of transport supply, through intermediate modes that pool vehicles between travelers in different technical and commercial forms (para 6). Finally, we tackle multimodal transit supply in a conurbation, in terms of functional and technical cooperation between modes, but also commercial competition and public regulation (para 7).

10.2.2 Individual Behavior, from Situations to Decisions Passing by Gestures

The individual traveler intervenes in the system and therefore in an assignment model, in several ways: first as a customer, a unit of service delivery; then as a user, exposed to local conditions of traffic and service quality; next as an autonomous decision maker, a decisional unit in route choice and other smaller or larger decisions; and finally as a passenger, a unit within a flow.

Here, we consider three research topics, relating to:

1. The individual's situation within the system, as a user both exposed to ambient conditions and capable of agency.
2. The adaptive behavior of the passenger, who perceives the travel conditions and adjusts by making different kinds of choices.
3. Mobility practices and habit formation, through learning and its application.

10.2.2.1 The Individual User Within the System

As a user, the passenger may be located on a vehicle or in a boarding area or in yet another pedestrian element. He or she will be in a particular physical state, with varying degrees of comfort (notably either sitting or standing). Specific movements will instigate a shift from one physical state to another, either through very basic transitions (e.g., sitting down), or through transitions with greater impact on the journey, such as boarding or leaving a vehicle in a certain station.

In addition, although self-directed, a passenger performs no driving function and is therefore available for additional activities that depend on the particular conditions of the trip.

With a smartphone or tablet, even in congested mass transit conditions, passengers can occupy their minds with a variety of activities. High up on the list of these activities is verbal or written communication, provided that there is wireless access to a telecommunication network. This communication can be general in nature, or can relate to the travel situation in particular, allowing passengers to acquire real-time, customized information and also to produce information relating to their perception of the current situation.

In the latter case, the user becomes an information sensor: This function can be useful for the system, especially as the user is mobile, intelligent, and interactive, but only to a limited degree, since the user is autonomous and will not act as a roving informant who can be controlled remotely.

The research subjects on this topic relate to:

- The disaggregated observation of physical states and basic movements, accessory activities and instantaneous practices, and communication activities relating to the travel situation, throughout the trip and in relation to the traffic conditions experienced.
- The study of feelings and perceptions: sensations of comfort or discomfort? What is the user's particular sensitivity? How are local impressions consolidated or diluted throughout the trip? What conditions would the user prefer, and would he be willing to pay for them? Obviously, this leads to the utility function of a user for a route option.

The primary medium is obviously the user's smartphone, with its GPS functions and even, in certain cases, an internal gyroscope which can record basic movements, and above all with its interface and applications. With the right apps, users could provide information on their specific travel conditions, their basic movements, their perceptions, and their reasons for traveling.

Information could also be acquired about the user's average walking speed, use of staircases and escalators, etc.

10.2.2.2 Route Choice Behavior

Beyond local conditions and basic movements, a traveler makes a choice of itinerary. The core assumption in this respect in an assignment model is that the traveler has extensive and objective information in advance on services, their frequency and journey time, and their spatial configuration. Model variants may include some specified variability affecting certain descriptive attributes or dynamic information, particularly about the arrival time of vehicles in stations. In any case, it is assumed that the user identifies a range of options—a large number in the case of a long journey and highly interconnected network—and can assign a utility to each one, or even combine utilities for bundled options!

This postulate of the traveler as a hyper-informed hyper-planner constitutes a crucial, sensitive, and central point in an assignment model. In this respect, technological developments have brought significant advances:

- Above all, they have made the postulate more realistic, in the case of passengers equipped with a smartphone that provides customized and integrated information. The user's capacities are expanded through information and route advice services. In other words, with regard to information and route advice, the model was ahead of reality.
- In addition, more dynamic information is now available. In particular, information about passenger loads is becoming ever more accurate and can be passed on to users so that they can fine-tune their route choice or their waiting position on a train platform and therefore their position inside the train. The assignment model can contribute to this information. The use of information, the way it is accessed, and the rate of response need to be studied, analyzed in relation to certain factors, and integrated into the simulation model.
- Again for a traveler with a smartphone: Users of route advice services can specify preferences, e.g., the fastest journey, the cheapest, the fewest changes, exclusively by certain modes. The user's preference options correspond precisely to route choice behavior parameters in the assignment model, which is a good reason to investigate them, obviously in relation to the Web app offering the service. Similarly, surveys need to be done on the checking of options and the selection of one in particular, not only in terms of the result but also in terms of the method of use—at what points before or during the journey, etc.

- Again for a traveler with a smartphone: Individual itineraries can be recorded to detect repeat journeys and therefore to identify how common a situation is.

Investigating through a Web app with volunteer subjects seems much simpler, although less general, than other methods based on ticketing data or tracking the digital traces left by mobile phones.

Related research subjects concern the way users adapt to variations in travel conditions:

- Characterizing ordinary mobility conditions and detecting the intrinsic variability caused by users themselves in repeat journey patterns, for example, when weather conditions affect the pleasure of walking and therefore the choice of feeder station. Or transporting luggage, or group travel, in a certain proportion of repeat situations.
- Studying the user's perception of disruptions: What traffic situations do they consider normal, or abnormal but tolerable, or abnormal and intolerable, therefore requiring a change in travel plans?
- Studying how users manage disruption. If they have a smartphone and a dedicated mobile app, what information do they look for, how do they handle it, and what decisions do they take? People may assess route options differently in conditions of disruption than in normal travel conditions and give priority to optimizing their travel time in order to prevent delays in their schedules. It is important to know how people behave in situations of disruption in order to simulate them realistically (up to now, disruptions have been simulated with "ordinary" responses on the demand side) and to assess service delivery accurately with the right dynamic information.
- Studying to what extent informed users follow advice or recommendations from the operator, e.g., the recommendation to change route during a service interruption, either short and unexpected, or long, planned, and announced well in advance.

A closely related subject is payment protocols and practices, i.e., the selection and then purchase of a ticket, and its validation during travel. The disutility associated with this is known intuitively, but could be specified by detailed monitoring. In addition, more modern forms of payment—via smartphone, contactless validation—are economical in terms of the actions required and therefore represent a specific use value.

10.2.2.3 Mobility Practices and Habit Formation

Other research subjects concern the incorporation of mass transit travel into the wider framework of the activities and travel patterns involved in a round-trip, a daily activity schedule, or an intermodal travel chain. Users with smartphones could easily be surveyed on this subject, using the time they spend in mass transit systems.

The observation of intermodal practices, or multimodal practices entailing alternation between modes in a repeat travel situation, would be particularly useful in improving the modeling of individual uses. Users could employ a dedicated mobile application to describe their purpose of travel, any time constraints at destination and the impact of those constraints on their choice of departure time, the cost of any delay, etc.

The concepts of reiteration and standard situations lead to the issue of travel patterns. A regular user gradually becomes familiar with the potential and conditions of the transit system and tends to develop routines after a certain learning period. Rather than experimenting personally with route options, and choosing a satisfactory but not necessarily optimal solution, smartphone users have access to information that is in principle comprehensive and reliable, and to good advice (provided that the route search algorithm in the mobile app meets the same standards as the assignment models, which is worth checking).

It would also be good to investigate multimodal practices in relation to the possession of private mobility resources: car ownership, a subscription to a mass transit mode, etc.

Finally, the user's loyalty to his or her information service is also worth exploring and ultimately integrating into the system simulation.

10.2.3 Demand Patterns

Let us now move from the traveler as an individual, to the population of travelers in a mass transit system, in order to describe the structure of that population in relation to space, to time, and also to a typology of behaviors. Assignment modeling has to a large extent concentrated on representing the interaction between supply and demand in space and time: The composition of demand in terms of several types of behavior has been less explored, except in certain research to demonstrate that typological diversity can significantly influence assignment results.

So the modeling of demand patterns in terms of behavior is an important research area. We will begin by looking at behavioral diversity (Sect. 10.2.3.1), then spatial diversity and its link with behavioral diversity, notably in terms of specific generators (Sect. 10.2.3.2), next the time dimension (Sect. 10.2.3.3), and finally the generation of a population of travelers and journeys (Sect. 10.2.3.4). To finish, we will look at how to measure demand patterns (Sect. 10.2.3.5) and the elasticity of demand to traffic and price conditions (Sect. 10.2.3.6).

10.2.3.1 Disaggregating Demand in Terms of Behaviors

Since the 1970s, modal choice modeling has become very sensitive to the particular characteristics of travelers: In the utility function for a mode, the quality of service and price characteristics of a mode are compared with individual traveler characteristics, such as age, gender, socioprofessional category, income, vehicle ownership, and purpose of travel. This disaggregated description of the passenger goes hand in hand with a fairly abstract description of a modal option, reduced to a few broad characteristics such as price, travel time, and number of changes.

Route choice modeling assigns much greater importance to space: Route options are embedded in space, on the network, between decision points, which gives them concreteness. This spatialization of services influences the representation of demand in terms of a primary dimension: the specification of trips with respect to the location of their end points and therefore their distribution in terms of origin–destination pairs, in an OD flow matrix.

In many assignment models, demand disaggregation is limited to this spatial representation, whereas behaviors are represented uniformly, with the same individual utility function for each traveler.

An important research topic for traffic assignment is to disaggregate demand in terms of behavior types, in order to obtain a multiclass model. The model's mathematical formulation is fairly easy to adapt. What is needed in research is a qualitative typology of travelers and therefore of individual journeys:

- In terms of the traveler's particular physical conditions: walking speed, reduced mobility due to disability or luggage, etc.
- In terms of the conditions of access to the transit mode: ticket type and possibility of accessing a particular subset of modes, walking distance at origin and destination, or private feeder mode, etc.
- In terms of access to information: ownership of a smartphone, familiarity with the route options.
- In terms of the route-finding process during the journey: pretrip route choice or dynamic choice at several successive decision points.
- Finally, in terms of economic preferences, trade-offs between quality of service and price factors.

Obviously, to combine all these analytical dimensions is complex and hence the need for research to design specifications, to tackle cases econometrically, and to identify the main descriptive axes within these different dimensions. The result will be an abstract specification (a segmentation of demand), which will need to be given concrete form in each particular application, depending on the territory concerned and the time frame simulated.

10.2.3.2 Spaces and Behaviors: Specific Generators

The structure of demand in terms of behavior types needs to be combined with spatial structure and specified in terms of the OD pair. A first approach is to specify an OD matrix for each behavior type. However, the interactions between spatiality and behavior can be more subtle. For example, some demand segments may be more sensitive to certain quality of service or price characteristics on a short journey than on a long journey.

The specific traffic generators are another topic for research: At certain particular points in space, such as an interurban station or an airport, or a big facility like a stadium or university, and a hospital or shopping center, the purposes and profiles of travelers have marked specificities. Interurban access points or tourist hubs are characterized by a population of travelers who do not live in the conurbation, who have specific reasons for travel and relatively high incomes, who are fairly unfamiliar with the urban transit system and often travel with luggage or in groups. Traditionally, the modeling of specific generators takes into account the particular flows they elicit and adds them to the OD matrix of resident flows. Their specific behaviors need to be modeled, especially for big cities which attract a large number of external visitors.

10.2.3.3 Temporal Variations

Demand, available services, and conditions of use vary over time in interlinked ways. Within a working day, city traffic hits a sharp peak in the morning for mass transit systems, because of commuting and school travel, and a longer and less sharp peak in the evening. Mass transit operators raise their service levels in these periods, which increases capacity but also makes them more attractive compared with immediately pre-peak or post-peak periods, thereby limiting the latter's overflow role as alternatives to peak-period travel.

Each of the typical periods needs to be modeled with its particular conditions of supply and demand: Levels of use depend strongly on these, whether in local flows or in the quality of service of the options and therefore in route choices. Dynamic assignment models capture the dynamics of traffic in the course of a day: Here, we emphasize the need to include time variations in the OD matrix, not only in terms of flows, but also in terms of behavior types, linked with the considerations set out in the previous paragraph. In particular, the distribution of travel purposes varies considerably over the day and hence the distribution of traveler types and the behavior pattern segments.

At a larger timescale, the diversity of days also requires further modeling. Working days and weekends differ, and demand patterns are significantly different between vacation periods (in particular summer in the Northern Hemisphere) and non-vacation periods, tourist seasons, and tourist off-seasons. Supply patterns are often adjusted to some degree, but still in a fairly static way. In the era of information, adjustments should become more dynamic and more could be done on the supply side to anticipate demand patterns. These changes could be preceded by exploratory research into the diversity of demand patterns and their predictability, by supply modeling in order to optimize the system's utility as well as certain operational functions (vehicle maintenance, staff vacations), by the modeling of supply–demand interaction in a more dynamic and interactive way, and by the design of simple information services to facilitate that interaction.

10.2.3.4 Generation of a Population and Its Mobility

Up to now, we have emphasized the diversity of behavior types, especially at the trip level, by means of a macroscopic representation based on demand segments. In the last section, we wrote about the situation of a journey within a daily activity schedule, for an individual in a household taking part in different interactions.

These days, the modeling of individuals and their day-to-day activity schedules can now be addressed on the basis of agent-based models of mobility, a well-known example being MatSim. In this kind of framework, the individual is modeled as a particular agent, with beliefs (perceptions of the environment and subjectivity), desires, and intentions, who makes plans and chooses some to implement. This form of modeling allows us to refine the agent's characteristics, but also his or her interactions with external conditions, which can also be modeled through agents.

The multiagent paradigm offers great potential for the modeling of a mobility system. Its potential for vehicle traffic was discussed in Chap. 6 and demonstrated in Sect. 9.2.2. Its potential with respect to travelers remains to be explored. In this field of research, there are a number of important topics:

- The inclusion of a fine-grained simulation of the conditions of travel by the mass transit mode, resulting from an assignment model, with a fine-grained simulation of passengers and the feedback of quality of service on the organization of their activity and mobility schedule: choice of departure time, choice of mode, and choice of destination.
- In the organization of activity schedules, modeling the interactions between the traveler and the information services in terms of processes and effects. The information service, its route advice function, and its predictive capacity need to be modeled, along with the traveler's use of the service and the adjustments that may arise from it.
- The generation of a population of travelers with mobility needs that are sensitive to mass transit provision and its performance across the territory, from point to point and at different departure times. This kind of model would be situated upstream of a MatSim, running from mobility needs through to types of activity schedules.

10.2.3.5 On-Demand Measurement

The traditional instruments for measuring demand remain useful:

- Generalist socioeconomic surveys such as household travel surveys, to cover the population of residents in a conurbation and its daily mobility.
- Targeted social surveys on a mode of transport or population segment, often by Stated Preferences, increasingly via remote, automated interviews or Internet questionnaires have become standard.
- Counts carried out at certain points on the system.

Technological advances facilitate interview-based surveys, in particular with smartphone versions, as we have already mentioned. Advances have also improved counting instruments, in particular by video with automatic image recognition, to count travelers, measure crowding densities, etc.

Ticketing has become increasingly automated; every passenger interception produces more information, so that a single individual's passage through several successive points can be tracked. These close-grained results are instantaneously or almost instantaneously available. GPS tracking of an individual trajectory produces detailed information that can be exploited off-line or in real time, as Google and other companies do on road systems, using Web apps that capture and automatically transmit location data. Mobile phone operators can also provide counts, individual trajectories, and travel times, by means of GSM tracking.

There are multiple links here with assignment models:

- Synthesizing, inferring an origin–destination matrix from individual tracking field observations.
- Improving the OD matrix from local counts, through pairing with the assignment model which simulates the proportions of use on a segment in terms of the OD relationship.
- Similarly, estimating the parameters of route choice behavior from local observations.

Methodological research is needed to adapt these applications—which have so far been developed primarily for car travel—further to mass transit.

Applied research is needed for each modal network to exploit the data resources in specific ways.

Above all, modern information systems offer extensive time detail, which opens the way for real-time applications (see next paragraph) and also to the establishment of time-varying OD matrices, within a single day or between different types of day.

10.2.3.6 Demand Elasticity and Supply Management

Individual travelers react to the price or quality of service conditions of supply in their choice of route, departure time, mode, and even their choice of destination and journey generation. This is true both for ordinary situations, in relatively stable service conditions, and for conditions of disruption characterized by unplanned real-time variations.

If travelers are aggregated by macroscopic demand segment, a set of individual sensibilities can be summed up by a demand elasticity function which links the volume of the segment to exogenous factors (the supply conditions). Elasticities play an important role in economic models that are more aggregated than assignment models, intended to optimize a supply plan and price levels (ref. Wardmann). That is why determining elasticities from simulations is an issue of research, or exploratory application, in relation to assignment models.

A related issue is to analyze dynamic situations on the basis of a dynamic assignment model:

- In order to estimate the behavioral parameters of the assignment model, through the observation of real-time conditions, including passenger movements.
- In order to anticipate the short-term propagation of travelers on the network and to draw the consequences on the likely upcoming state of supply.
- In order to optimize supply management in real time, by reacting to disruptions.
- In order to draw up service plans that are resilient to disruptions.

Analyses of this kind are a kind of field experiment, although these experiments are passive and not constructed by the analysts who perform them.

Another direction for research is the construction of experiments, either field experiments in situ or simulations in the laboratory. In a conurbation, the establishment of an urban mobility Living Lab would provide a very effective framework, offering significant potential for changes in service management, modes of use, pricing, and commercial revenues (cf. Sect. 10.3.4).

10.2.4 Flow Physics and Traffic Management at the Very Local Scale

Passenger flows play an essential role in a mass transit system, since the essence of such a system is to concentrate travelers in vehicles in order to move them. Filling a vehicle with passenger up or close to its capacity is a key factor of viability in both economic and environmental terms.

The limit of this principle of maximization is the vehicle's capacity, which restricts the flow it can carry; in addition, the denser the flow, the less comfortable the passenger, which mitigates the attraction of the service.

A transit operator manages flows of travelers and of vehicles, which are themselves entities for traffic flows on roads or railroad tracks, with their own traffic phenomena and their own capacity constraints. A mass transit traffic engineer has to work with both types of traffic unit, travelers, and vehicles, in designing and operating a system: The Transit Capacity and Quality of Service Manual (TRB 2013) describes the physical and technical aspects in detail and provides design principles.

A traffic assignment model represents the system and therefore the two types of traffic unit, dealing with their interactions across an entire network. In reality, the interactions occur at several spatial scales:

- The network scale is wide and two-dimensional in space: It includes the local operation of all the elements of the network and the movement of traveler flows between the nodes, along a line and between lines.
- The scale of a route: A route extends in one spatial dimension for the trajectory of a traveler using one or more lines, or for the run of a vehicle serving one line.

- The local scale of a station, which is a subsystem with pedestrian access to and from the outside, pedestrian passageways and waiting areas, and platforms; or the scale of a section of infrastructure between two stations, which is also a subsystem, whether on a road or on a railroad track. A station and an interstation are elements in both a line and a network.
- The micro-local scale of a restricted passenger space, such as the inside of a vehicle, or a boarding area, or a waiting room, or a pedestrian element (corridor, staircase or escalator, etc.). Such spaces can be critical to the system's capacity: In particular, vehicle doors limit the flow of passengers moving between the vehicle and the station.

The research topics relating to traveler and vehicle traffic apply at these different scales. We mark them out in this section and the following two sections, from the most local to the most global. The present section deals with the micro-local scale. The research issues relate to the physical representation of traffic at this scale, in terms of flow, density, and physical time, but also user comfort, as well as the technical or economic management of the flow by different types of measure. We will begin by looking at the physics of traveler flows (Sect. 10.2.4.1) and the management of those flows (Sect. 10.2.4.2); we will then tackle the physics of vehicle flows at local scale and traffic management at the same scale (Sect. 10.2.4.3).

10.2.4.1 The Micro-local Physics of Passenger Flows

A flow of a given type is a quantity of mobile entities (traffic units) at rest or in motion in a given space. The direction and speed of motion are flow characteristics as important as the number of units.

Another important feature is the density of the flow relative to a certain space: its concentration in people per unit of area, or per linear unit along an axis of motion.

The flow dynamic relates to the movement of certain identified entities and also to changes in the traffic at a given point, in particular the variation in local concentration over time. In passenger traffic, and particularly in a mass transit station, the accessible spaces are limited and divided into functions: pedestrian passageway, waiting area, etc. Their physical layout determines their capacity and dynamic performance: What accesses are there between this space and the contiguous spaces, what thresholds or doors or security barriers are between two neighboring spaces, how wide are they, and what opening pattern is employed? Static performance (holding capacity) and dynamic performance (flow capacity) also depend on the composition of the pedestrian flow and its internal behaviors:

- Each pedestrian is a particular individual, varying in height, varying in bulk, and varying in speed depending on physical condition. The speed of which an individual is capable affects the people behind him and governs the movement of a columnar flow.

- Culturally and socially, individuals tolerate interpersonal proximity up to a certain threshold, which depends not only on individuals but also on their collective culture and the heterogeneity of the group. The threshold between homogeneous individuals is relatively lower.
- Each pedestrian has her own intentions and her own direction of motion. If the space is used for several directions of motion, the mobile entities may hinder each other and slow down. Even with a single direction, the available width forces the flow to move by order of precedence.

A model of traffic assignment on a network must represent the physical characteristics that influence the behavior of the traffic or the quality of service (time, comfort) for the passenger.

In this respect, research is needed on the following topics:

- For a passenger in a space, the sensitivity of the physical time at rest or in motion to the micro-local flow conditions: in other words a time flow function per pedestrian element. The element may be the door of a vehicle, a corridor, or a waiting area, etc. The flow is generally vectorial, with several directions of motion and different passenger categories. A microscopic simulation model can be used to establish a macroscopic function, through regression from a set of simulations for different factor values. It should be noted that, for a spatial element such as a boarding area, service frequency influences the rate of exchange between that spatial element and the vehicles and therefore the rate of change in the stock of passengers on the platform. This phenomenon needs to be integrated into the model, for investigation for each type of element and each configuration of vectorial flow.
- The macroscopic laws obtained for each spatial element, to link a physical time to vectorial flow, no doubt depend on the category of passenger exposed: there is a need here for the detection of statistical regularities and for research into a typology of passengers.
- Again for each spatial element, the greater the density of the flow, the more uncomfortable the time spent waiting. Discomfort laws need to be modeled that link the general cost per unit of physical time with the density of the flow and also no doubt with the movements that affect the flow. This will need to identify different passenger states in the spatial element (in particular sitting or standing places both in a vehicle and on the platform), categories of passengers exposed, and local cultural specificities for maximum density. Critical levels of density will also need to be explored, i.e., values beyond which certain movements within the flow become difficult, or even certain gestures, e.g., using a mobile phone, therefore affecting the possibility of accessing customized information.
- Pragmatically, a methodology of application to a transit network: What factors should be tackled as a priority, doubtless depending on the size of the flows concerned and the amplitude of the variations in time and comfort under the influence of the flow.

10.2.4.2 Local Passenger Flow Management

There are four kinds of mechanism for managing a passenger flow locally: spatial layout, use protocols, informational incentives, and pricing.

For a spatial element, layout sets the capacity dimensions, for both stock and flows. Within a space itself, the specific furnishings—notably including seats, benches, information panels, and automatic dispensers—influence the levels of comfort and capacity. Vertical and horizontal signage helps to direct and channel flows.

Use protocols determine certain operational processes, in particular, for access to a vehicle, the priority to alighting passengers onto boarding ones. Channeling flow direction by means of a dedicated lane is a combination of layout and protocol. Controlling vehicle doors in order to adjust opening time and limit dwell time is also a protocol, as is separating passengers between vehicles or between several cars on a single train, by pricing categories or gender.

Informational incentives can be used, to a certain extent, to manage the quantity and quality of a flow, depending on the compliance and specific interests of passengers. On a station platform, information on the waiting time before the next vehicle has the effect of increasing psychological comfort and therefore quality of service. Information on the arrival times and crowding levels of upcoming vehicles would make the option of waiting for a later, less crowded, vehicle more credible and attractive than taking the first, packed vehicle, and would help to manage flow quantities.

In rail transport, giving passengers information on the level of crowding in the different cars along the train would enable them to choose their waiting position on the platform and would doubtless have the effect of evening out the flow inside the train, improving the distribution of passenger movements between the doors and therefore reducing station waiting times.

Finally, pricing is a mechanism that is relatively little used. In air transport, business class passengers have access to dedicated areas in airports and special boarding conditions, as well as privileged conditions on board. In Tokyo's rail transportation, some "premium services" are available only to passengers who pay a relatively high price. At certain peak times, some stations on the London Underground are used only for connections and outside access to the station is prevented: Why not make people pay rather than excluding them?

All these practical forms of flow management have influences on how the system works and the quality of the service. They should therefore be integrated into the system simulation, using specific submodels that can be incorporated into an assignment model. Research is needed to model each practical arrangement, in terms of mechanism, factors, and effects, and to study the magnitude of certain effects at local level, as well as their impact on traffic at network scale. Here are a few examples:

- Using both sides of a train in stations, with one assigned to people leaving the train and the other to people entering.

- Fare discrimination in services.
- Evening out the flows of passengers waiting along a rail platform.

This latter option is particularly worth studying in relation to an assignment model, because a passenger's readiness to reposition herself undoubtedly depends on factors specific to her needs: not only comfort in the vehicle, but also position along the vehicle in relation to the destination station and also in relation to the corridor leading to the boarding platform. The structure of the flow on the platform in relation to the destination station is therefore likely to influence the level of compliance with these positioning recommendations. Walking from one end of a 200-m-long platform to the other takes two minutes for a person capable of walking at 6 km/h and four minutes for a slow walker who moves at 3 km/h: This is not insignificant in the economics of the journey. The passenger makes choices between detours on foot and onboard comfort; one information service about the journey may recommend certain platform positions, while another on local quality of service may suggest a different position. The information age offers a multiplicity of situations and decisions.

10.2.4.3 Vehicle Traffic at the Local Scale

The interactions between travelers in a pedestrian flow resemble those between vehicles in a highway flow. Vehicle traffic is also important in a transit system, with several fundamental interactions: with passengers, between vehicles on the same line, or with other vehicles in different directions. These interactions influence the journey time of the vehicles and therefore of the passengers they carry and indirectly the dwell time in the station. They need to be modeled to describe their effects and if possible to explain those effects by causal mechanisms and factors.

The research topics can be divided into four questions:

- The dwell time of a vehicle in a station. We have already pointed out that while multiple doors increase exchange capacity, they also make the process of passenger exit and entry more elaborate. Physical laws have been proposed to link the length of occupancy of a door with the number of passengers entering and exiting; the physical modeling needs to be extended, notably to take into account the layout of the vehicle, the layout of the platform, and the gap between the platform and the vehicle, and also to account for the distribution of passengers entering and exiting and of people remaining on board along the vehicle and those remaining on the platform. In addition, continuous trains without separation between cars allow passengers to move around inside the train, leading to a certain evening out of the internal load.
- At an infrastructure point, particularly the track on which a train stands in a station, the dwell time of the vehicle, the times for braking and reaccelerating on approach and departure, the safety margins, are successive uses that occupy the point and therefore consume its service capacity. The associated capacity constraint must be expressed in the assignment model. Its physical modeling

requires refinements and adaptations to local conditions. Reciprocally, among the different stages of track occupancy, the approach and departure maneuvers could be adapted to the state of the flows within the vehicle, with sharper braking and acceleration in absolute terms when all the passengers have a seat, which would speed up the interchange of vehicles.

- Headways and capacity. Between successive vehicles on a single route, headway (the time interval between vehicles) influences the number of passengers in the following vehicle and therefore its dwell time in the station and onboard comfort. This phenomenon needs to be investigated with a dynamic model. In addition, headway includes a safety margin between vehicles. On a road, it is easy to adapt the margin to the speed, reducing it at lower speeds. In rail transportation, this tactic is called "restricted speed": It is used to partially restore capacity after a disruption. It is worth modeling in order to assess its feasibility and effectiveness through simulation.
- Run time and delay. Models are needed for other local traffic phenomena relating to the interaction between a vehicle and exogenous factors. In particular, on an ordinary road lane, cars and other individual vehicles can hinder the movement of buses, not only when in motion but also when parked. To give an example, parking spaces situated just before a traffic light intersection can block it during a green phase: At a peak time when all the spaces are occupied, it is enough for a car in search of a parking space to stop behind a space that a car is vacating and in front of a bus; the successive maneuvers of the departing and arriving vehicle can occupy the entire green light phase. These events will further affect a following bus, especially one that stops to allow additional passengers to board… The resulting delays need to be quantified, at least the mean and if possible also the dispersion, to be integrated into the local run time of vehicles. A microscopic traffic model is appropriate for a fine-grained simulation of the phenomenon, in order to derive statistical summaries that can be used in a macroscopic assignment model. However, it would be better to incorporate fine-grained traffic simulation. In this vein, the application of an assignment model is a way of simulating the effects (benefits, costs) of local road layouts—location of the bus stop relative to the intersection and vocational parking spaces—relative to local traffic control.

10.2.5 Line Traffic, Management, and Economics

In a line-haul transit system, each line is a specific subsystem. This subsystem is a vertical composition consisting of a traffic and access infrastructure, a fleet of vehicles, and different technical and commercial protocols, in particular the service protocol, which includes vehicle movements.

Here, we consider an operating line consisting of one or more services in each direction of flow, each with its route made up of vehicle trajectories and stations served. As a traffic system, a line with multiple services possesses horizontal in addition to vertical complexity. In particular, the topology of a rail transit line on a regional network can be complex, with one or more shared trunks and different branches.

In general, a large conurbation possesses both train lines on a regional network and simpler train lines, such as subway lines with a single service in each direction. The particular complexity of a line justifies a reinforced "infostructure," a centralized real-time management system. This dynamic line intelligence system constitutes an additional layer in the vertical composition of the system.

Traditionally, assignment models are used to simulate traffic on a new line on a network, or the effects of a substantial alteration to an existing line. They are particularly necessary with heavily cross-linked networks where passengers can put together more complex itineraries. However, up to now, there has been little modeling of the technical specificities in the operation of a mass transit line in the framework of traffic assignment. A historical reason for this is that in the early mass transit assignment models, all the lines were reduced to a graph of elements, so that the discrete nature of the vehicle runs is represented solely by the set of arcs of boarding from route decision points. Static or dynamic models that treat service frequency macroscopically do not really lend themselves to a fine-grained representation of traffic management. By contrast, run-based analysis makes it possible to model the operational process more closely.

The modeling of operational processes is an important research topic for traffic assignment models (Sect. 10.2.5.1). Reciprocally, the dynamic intelligence systems on existing lines would gain by incorporating a traffic assignment model, in order to relate traffic management to user needs (Sect. 10.2.5.2). Finally, the complexity of a mass transit system seems to have limited economic research, whereas there have been many contributions on marginal costs and pricing in road assignment models: Such research can be undertaken for mass transit on the basis of a single line, taking advantage of the relative simplicity of this subsystem (Sect. 10.2.5.3).

10.2.5.1 Line Traffic Performance and Its Factors

Let us concentrate here on line traffic in terms of vehicles and passengers. It is natural to model the topology of the line and its services by a particular network: Firstly, it is the topology of stations and routes that interest passengers, which justifies a specific graph model, i.e., let us say the passenger network; secondly, stations and routes are part of an infrastructure network, which also includes details of the sections used, the junctions crossed, whether the mode is road or rail (junction points): This justifies a specific graph model, called the vehicle network.

Each graph model can be used to model physical characteristics element by element: The most important are run times taken broadly, including station dwell times. These times depend on ambient traffic conditions and reciprocally determine them: indirectly via passenger route choices, therefore via passenger flows, and directly, because in each trip the downstream service depends on what happened upstream, and because the different trips are managed by the operator in an integrated way.

This operational process needs to be modeled in the traffic assignment, distinguishing each traffic type and operating mode. Up to now, rail traffic has hardly been distinguished from road traffic in the assignment literature. However, it has specific characteristics (cf. TRB 2013; Hansen and Pächl 2014): The track is restricted to trains, whose planned speed can be revised downward or upward to offset upstream delays (e.g., during a stop at a station). This type of catching up is important for users: It can be applied to a significant degree if the stations are sufficiently far apart, i.e., much more for a regional train than for a tramline.

For a given traffic mode, there are several levels of centralized intelligence, as evidenced by fixed or mobile block section signaling systems in rail transport. Another factor is the degree of dynamic responsiveness, which depends on the communication system between the central post and the vehicles.

The different modes need to be modeled with an eye to their specificities. This will make the assignment models more realistic. It should be recalled that in a mega-city (e.g., greater Paris), a very busy train line can carry more traffic than the entire bus network in a mid-sized city (e.g., Besançon, France). Assignment models that are sensitive to operating modes could be used to assess the benefits of modernizing a line's operating system.

While certain operating modes can limit the influence of passenger flows on journey times, the concentration of passengers within the vehicle remains a factor of discomfort.

Centralized management systems are based on an information system and communication between the components of the service. A direct extension is to provide users with dynamic information. On many networks, this information is given for each line, following particular procedures: It therefore needs to be modeled at line scale, before shifting to network scale for higher-order functions (such as advice to shift to an alternative line).

10.2.5.2 User Needs and Traffic Management

The representation of traffic with its management, i.e., of the operational state of the system and quality of service factors, can be used to deduce the utility for each passenger, i.e., each passenger's level of satisfaction. The total utility for all passengers is an important criterion in assessing transportation projects and plans: This applies to the design of a line and could also be applied to real-time management of the traffic on the line, by replacing the current criteria, which are based on the status of service runs relative to the nominal schedule, neglecting the heterogeneity of loads between vehicles.

The use of an assignment model would also make it possible to add a predictive dimension to traffic management. This is because for each vehicle run, the model simulates passenger flows and their changes throughout the trajectory. At a standard point, the model "knows" at what station each passenger on the vehicle will get out.

The decision variables to optimize standard operation are notably:

- The interval between successive runs.
- The ordering between runs on different services which arrive at a confluence point and are in competition to access the shared section.
- Where applicable, for a given vehicle, a variation in the service scheme relative to the planned scheme.

Incorporating an assignment model into centralized traffic management on the line should therefore improve the service the line gives to its users. This is equally true for ordinary operating conditions and for disrupted services.

In order to simulate the system's response to a disruption, the adjustments made by all the actors concerned need to be taken into account, including users with their perception and their decision-making capacity (see Sect. 10.2.1) and of course the operator with its resource management systems.

Probabilistic incident modeling is a topic of research in this respect: Before simulating a particular incident, this involves describing the theoretical structure of the causes of disruption, using a combined physical and probabilistic model. Such a model will be sensitive to the state of wear of the system's components, because this determines their failure rate. It will make it possible to evaluate maintenance policies for the infrastructure and the vehicles, in particular preventative strategies to renew components before they fail.

10.2.5.3 Line Economics: Value Analysis and Yield Management

In transportation economics, there is a well-known effect called the Mohring effect, according to which, for a mass transit service, an increase in frequency improves quality of service (by reducing the wait before boarding) and therefore attracts more customers, which can justify a further increase in frequency and so on. This virtuous cycle is also productive in terms of commercial revenues.

In practice, however, urban mass transit systems are regulated by the authorities primarily in respect of the social utility of the services. Fares do not perfectly and completely reflect production costs, and only a fraction (often small) is covered by commercial revenues.

Improving the rate of cost covering, as well as the match between the service supply and use on the demand side, is an important economic priority for the mass transit system. Since the assignment model simulates the interaction between supply and demand, it could contribute further to economic analyses.

In this respect, it is natural to begin by treating a line as a subsystem, before subsequently tackling the greater complexity of the network. Here are a few research topics relating to this:

- Modeling production value: assigning a shadow price to each journey delivered depending on the route and the period, linked with the general costs for the passenger.

- Analyzing production costs: the cost of using the resources, of the associated wear and tear, and of consumption, particularly energy consumption. The evaluation needs to be done for each run and related to the number of passengers carried, in order to obtain unit costs.
- Looking for a level of frequency that will optimize production value net of costs, in other words the financial balance for the operator. Comparing this financial optimum with the socioeconomic optimum (i.e., the level of frequency that optimizes the service's socioeconomic balance). Analyzing the sensitivity of the results to the length of the service cycle and conjointly optimizing frequency and speed of travel (which influences cycle time but also energy consumption).
- The optimum level of service undoubtedly varies with demand conditions. This should be explored by simulation, with attention to the distribution of fixed costs between the different periods.
- Evaluating the marginal congestion cost of an individual journey: This can be calculated analytically if the model is macroscopic. Compare with the fare level, for different time periods.

These different questions have received much attention in individual transportation, but very little in mass transit, probably not only because of the complexity of the traffic model, but also because of the still somewhat uncompetitive nature of mass transit in many conurbations.

10.2.6 Line-Haul Network

Transit lines tend to become organized into networks in order to cover both dimensions of geographical space. Passengers expect these lines to be interoperable in terms of travel, information, and fares.

For the operator, interoperability applies at two levels:

- At the higher level, the interface with customers is the tip of the iceberg;
- At the lower level, the submerged part of the iceberg includes the functions of basic interconnection between lines, by means of specific technical components, stations for passenger traffic and infrastructure connections for vehicles, and traffic operations through cooperation between lines, here again distinguishing between the passenger perspective and the vehicle perspective.

As we have already covered the micro-local level (in Sect. 10.2.3) and lines as subsystems (in Sect. 10.2.4), we concentrate here on the aspects of a network that contribute specifically to cooperation between lines. We begin by tackling the specific technical components constituted by stations (Sect. 10.2.6.1) and infrastructure connections (Sect. 10.2.6.2), and then, we look at the operational processes that make the lines cooperate (Sect. 10.2.6.3). And then, we come to the informational aspects (Sect. 10.2.6.4) and economic aspects (Sect. 10.2.6.5). As before, our goals are to identify the importance of each item in a real system, to indicate the need for an assignment model to be sensitive to it, and to outline associated research topics.

10.2.6.1 Station Layout and Management

The purpose of a station is to enable passengers to access a service from outside or via a connection from another service, or to leave into the outside world. Here, we concentrate on its traffic functions, ignoring the accessory functions of obtaining information and buying a ticket and ticket inspection. Travelers go through different traffic or waiting areas, as described in the section on the micro-local scale: Each micro-local element imposes a capacity limit on the pedestrian flow. If this constraint has no slack left, it can be critical for the functioning of the station and the lines that serve it. This constitutes a first reason to model the internal layout of a station, i.e., the configuration of the micro-local areas. This includes the "hard" arrangement of spaces by necessary demarcations (partitions, barriers) or the "soft" arrangement by signage and direction systems.

The second reason for explicitly representing the layout of a station relates to passenger access and connection times. The following factors come into play:

- Travelers move around the station, each following a pedestrian route.
- The conditions of movement depend on the passenger flows, because of mutual hindrance, whether physical or visual (masking effect with respect to the information boards). Crowd dynamics are an active research topic, of particular interest for big stations, which concentrate very large flows in restricted spaces.
- Signage resources: The conditions of movement influence route choice and therefore the configuration of the station's internal flows.

All these characteristics are part of a pedestrian assignment model for the station, which we will call the station assignment model (SAM), a complement to the transit assignment model (TAM). The development of such SAMs constitutes an important research goal. Specific topics are as follows:

- Passenger movement in free flow, as affected by the hard and soft arrangement of the movement zones.
- The influence of the crowd on movement.
- On roads, adjacent stops between bus lines are used by passengers for connections. These should be modeled as an "unofficial" station, including the different possible routes between stops and the variability in the travel time between them (especially if this entails crossing streets).
- For any train station, if there are several access points to the platform, there will be a stochastic component in passenger itineraries, to be reflected in a probabilistic model.
- For train stations that combine urban and interurban lines, the allocation of platforms to interurban services can be variable, which means that the access point for the travelers concerned is stochastic.

A SAM is intended to be integrated into the TAM. The mutual relations between a SAM and a TAM are connected to the matrix structure of the origin–destination relations between the station access points, i.e., the platform accesses and the outside accesses:

- The TAM imposes on the SAM an OD matrix of flows between the points, for each demand segment, upon request for each destination on the network and with a travel cost at each access point from that point to the destination.
- The SAM provides the TAM with an OD matrix of the foot travel conditions, in terms of time taken (both mean and dispersion), possibly together with flow distributions from the entry points to the exit points, for each demand segment and destination.

The precise connection between a SAM and a TAM needs to be specified in each model integrated.

A related research topic concerns the actual location of route choice points in the station for the itinerary across the whole network. A traditional postulate is that several competing services are present in a single place, a decision point, where the traveler is considered to find out about the arrival of each vehicle. This postulate works for a boarding zone shared by several bus lines, but less so when the distances between the line stops are greater. For a rail mode, the postulate works for services that use the same platform, or that operate on either side of a shared platform.

The representation of the decision points is critically dependent on the fineness of the topological representation of the network: Modeling an intermodal station with a single node would imply that dynamic information and the possibility of instant access to each platform are available anywhere in the station. In practice, in a complex station, conjoint dynamic information on several services is only available to passengers at a few specific points, where the operator has installed information boards. The spread of smartphones and the development of dynamic information systems make information omnipresent for users, but they cannot move instantaneously to a given platform, and the travel advice service should estimate an access time that is comfortable for the user, allowing for his normal speed and the flow conditions.

Complementary research topics are as follows:

- The modeling of marginal congestion costs for journeys inside a station.
- The design of layout schemes, or information schemes, or even fare schemes, and the assessment of their impact on passenger traffic through simulation.

10.2.6.2 The (Infrastructural) Connections that Affect Vehicles

Chapter 8, Sect. 8.2, pointed out the challenges of synchronizing services that serve a single section, together with the technical operation principles and their modeling in the framework of traffic assignment. The associated techno-economic problem remains a research topic:

- The evaluation of spatial arrangement schemes and their impact on demand through simulation. Greater quality of service requires more optimal—and therefore undoubtedly more expensive—arrangements: What is the socio-economic cost–benefit outcome?

- Including the constraints of coordination between service runs among the operating constraints on each service in a line model.

Another form of connection between lines that concerns vehicles is another synchronization, but this time in order to avoid clashes and to organize the alternation of runs. The aim is to enable vehicles to cross paths safely. One solution is to work on a potential crossover site, by setting lines at different levels. However, the challenges go beyond crossovers alone. They include sharing the infrastructure by having several services traveling on a shared section, in order to make that section profitable. In this case, if the levels at the crossover point are different, access ramps need to be added and the access conditions organized: The "hard" technical solution generates a soft problem of traffic protocols. The "soft" solution for a crossover site is to coordinate the opposing traffic on a principle of alternation, which allows direct crossings and also turning movements.

For the rail mode, the crossover conditions need to be represented in the assignment model. The dynamic status of the junction points combines with block section signals on each section. Each junction point is a potentially critical resource, whose influence on each line must be modeled:

- Directly in a dynamic assignment model, in concert with the line model.
- In a static model, a hindrance function needs to be modeled for each flow current, in relation to all the other flows, similarly to the distribution of capacity between branches on a road intersection.

For road-based transit modes, crossover situations and the requirements of turning movement take place on the roadway, in interaction with other vehicle flows and pedestrian flows. The research topics concern:

- On each section, modeling the different "forms of coaxiality" between the different mobility modes—dedicated or ordinary lanes—and the consequences of the layout for the respective journey time of the modes and for the mutual hindrances between flow currents. Microscopic road traffic simulations are particularly suitable: They can be used to establish macroscopic laws for typical sections.
- For the intersections, modeling not only simple forms but also complex forms that connect several local subsystems—sequences of intersections as specific corridors. In a complex form of this kind, the local conditions are linked with particular correlations, which demands specific modeling, the vehicle analogue of a passenger station model.

10.2.6.3 Operating Protocols

We have just referred to the functional coordination between lines, in the organization of connections, and also local forms of technical coordination, through the sharing of a traffic infrastructure and coordination protocols.

Above and beyond local cooperation between lines, network operation is a way for lines to give each other mutual support in response to variations in the state of the system, following a rush of passengers (overflow situation) or a technical failure that affects a particular line, reduces its capacity, and causes transfers that generate rushes on alternative lines. The demand conditions on a line depend not only on the level of demand for the whole network, but also on the current situation on the other lines. Freeway operators now provide information for motorists a long way in advance of the decision points, directing them toward more reliable routes in order to avoid section closures or simply congestion delays in dense traffic.

This adaptive strategy needs to be transposed to line-haul transit and even enhanced in order to exploit the flexibility of such systems: Adjustments to service frequency allow rapid real-time capacity adaptations, whereas the only comparably strong mechanism available to highway operators is the dynamic allocation of road lanes to the directions of flow.

This establishes a few topics of research in traffic assignment:

- making the assignment sensitive to dynamic operating strategies;
- using simulation to explore dynamic operating strategies;
- integrating the assignment model into the centralized traffic management system at network scale, so that it can contribute fully to operational flexibility and responsiveness.

10.2.6.4 Network Information

By design, every mass transit network has static intelligence, for the composition and smooth operation of the service. Thanks to data sensors distributed around the system, to remote communication and centralized information processing, the operator possesses centralized dynamic information that it can use to manage its resources in real time, keep users informed, and encourage them to cooperate.

We have already mentioned the contribution of the centralized information and control system to the operation of a line and the advantage of representing its impact on an assignment model. In this kind of representation, the model must follow the specific dynamics of the chain of information and logistical operations, with their delays, inertia, and errors. In particular, an unexpected and sudden variation in instructions presents a human agent with the difficult task of transition between different operating conditions, requiring a change of routine and mental reprogramming. Such human factors are an integral part of the practical conditions of operation; they also affect users, each of whom is involved in the operation in an elementary capacity by their individual presence. In order to persuade them to cooperate effectively in sudden changes of operating mode, through appropriate adjustments in their route choice or departure times, the information must be presented to them simply and efficiently, as happens with dynamic freeway information signs. In addition, passengers can only be asked to make successive adjustments if the overall sequential logic is sufficiently clear and does not cause excessive disruption to their own journey.

Since the assignment model specifies the service plan and intended routes of passengers, it is particularly well suited to act as a basis for the development of operational variants:

- Off-line, in the design of Traffic Management Schemes in response to particular circumstances (critical demand rush, major weather disruption, accident, etc.).
- In real time, through integration into an operational support system that monitors changes in the network and dynamically develops (or automatically triggers) very short-term action plans.

Such applications undoubtedly have great operational potential, but they are highly complex. Their development requires specific research targeting the following questions:

- Readjusting the simulation almost instantaneously from real-time data, so that the model comes as close as possible to reproducing the actual conditions of the system.
- Developing real-time operational variants that minimize user disruption.
- Formulating criteria for assessing user disruption: An overall indicator is easy to design, but it needs to be combined with indicators of the user's understanding and acceptance of the operational policy (compliance), or of fairness between users in terms of the respective efforts they are asked to make and their monetary contribution.
- Other criteria need to be developed to assess the stress imposed on operational resources, in order to avoid policies that focus solely on immediate effects but would subsequently weaken the system. Since this is a complex system with a very large human component, the operational variants must be robust.

10.2.6.5 Network Economics

In the previous subsections, we tackled several problems of an economic nature:

- The economics of demand, with regard to passenger preferences, their generalized costs, and fares.
- The economics of production at the scale of a line.
- The optimization criteria for traffic management, and the role of user information, employed as a management instrument.

These problems are all the more acute at the scale of a network, which is the primary scale of intervention for the authority that regulates the system and monitors the operators. The assignment model that specifies the operation of the system by incorporating the interests of users and the resources of operators is an excellent medium for informing regulatory decisions, as well as the management decisions specific to an operator, or planning decisions.

At network scale, the economics of production pertain to service lines, traffic infrastructure, and stations. Each station is a subsystem that requires resources and costs to operate, whereas usage produces traffic and therefore shadow revenue. In relation to this, here are economics research topics that can be based on an assignment model:

- The economic analysis of a station, in terms of the functions provided and the components of the supply (including the micro-local spaces) and in terms of their use on the demand side.
- The evaluation of the marginal congestion costs for the movement of pedestrians in the station.
- The allocation of (shadow) commercial revenues to the components of the travel process: runs on lines and movements through stations, taking into account their respective functions—access or transfer for a station, crossing of space for a line—but also access to a crossing line via a feeder line.
- The design of "decomposition and coordination" schemes for the techno-economic management of the parts of the system: line, station, and infrastructure.

With regard to the regulation of the system, an important principle is that the community should be involved through an organizing authority at conurbation scale, in order to tackle global issues and structural links. The relations with the operators are of two types: firstly awarding a service contract and secondly regulating its implementation. A familiarity with the supply–demand system based on an assignment model can be used for research on the following topics:

- Formulating criteria for the remuneration of operators that better represent the services delivered to users. The existing criteria are based on ticketing statistics and operational performance indicators relating to vehicle traffic. The challenge is to establish operational performance indicators that are sensitive to users in terms of their actual exposure to operational conditions.
- Determining the functional conditions (in terms of service quality provided to users) and the technical conditions of coordination schemes for a component-based operation of the system and identifying economies of scale and other externalities that justify unified management of a particular subset of components. This includes the distribution of the lines between one or more operators, but also vertical coordination between infrastructure management and service management and—why not?—the allocation of stations to specific operators, particularly in the case of big intermodal stations (e.g., Madrid). These broad industrial economic topics need to be revisited, with greater attention to the reality of demand as represented in an assignment model.
- Developing fare schemes that do more to follow broad User Pays principles and to cover production costs and Polluter Pays principles with regard to congestion costs.

With regard to fares, urban mass transit has long been limited by old methods of payment: station-based ticketing, with transaction times that are not insignificant relative to total journey time; moderate fare levels that did not cover the substantial costs of collection and payment. Automated ticket purchase and validation are major advances, as are commercial subscription packages, despite their often simplistic nature. Innovative information, payment, user identification, and customized relationship—for technologies—open the way to much more flexible fare schemes. An assignment model can be used to explore the potential demand and commercial revenues for a given fare scheme. Here are some avenues for exploratory research:

- Linking production costs to traffic disaggregated with respect to journeys and modeling an average journey cost for the operator.
- Modeling a marginal congestion cost per journey.
- Comparing the average production cost per journey, on the one hand, and the marginal congestion cost on the other and then the price level in terms of the commercial package with or without subscription, in order to describe the pricing system in terms of User Pays and Polluter Pays principles.
- Assessing the social equity of pricing schemes, between users with and without subscriptions, and also between social classes of users (in particular in terms of income and place of residence), by means of an assignment model that gives a fine-grained picture of demand segments and their respective consumption.
- Designing dynamic fare schemes, linked with average production costs and marginal congestion costs per period.
- Designing incentive fare schemes which reward efforts made by users—e.g., in following a recommended route or timetable—with credits on their next bill.

10.2.7 Pooled Transit Services (PTS)

Here, we define a PTS as a mechanized mode of travel in which vehicles are shared between passengers either simultaneously or successively. This definition covers several modal forms: individual taxi, collective taxi, carpooling, car sharing schemes, and shared vehicle services. The particular features of these options were described in Sect. 10.1.

Each modal form of PTS is a supply subsystem, whose existence and practical performance in an area depend fundamentally on the interaction with demand. The numbers and itineraries of the desired journeys, in other words the clustering of demand, relative to the number and productivity of vehicles on the supply side, determine the availability and speed of service. These performances in turn have a feedback effect on both demand and supply, in terms of levels of service and commercial conditions.

This interaction between supply and demand can be studied using a dedicated PTS assignment model. Here, we present the research requirements to model a PTS, first in relation to demand (Sect. 10.2.7.1), then in relation to supply (Sect. 10.2.7.2), next its use in quantity and quality with the feedback effects on supply and demand (Sect. 10.2.7.3), and finally regulation (Sect. 10.2.7.4).

10.2.7.1 Representing Demand for a PTS

For each modal form of PTS, the demand model must represent (a) the quality of service characteristics, (b) a passenger's sensitivity to quality of service and price, (c) the nature of a travel option, (d) a service user's individual decision-making process, (e) the demand segments, and (f) for each demand segment, the OD flow matrix for every standard period.

Quality of service is described by the following characteristics:

- The length of time spent by the passenger on information and interaction before each journey, i.e., the time cost of the transaction;
- The conditions of access in time and space: the time required by the passenger to access the rendezvous point, vehicle waiting time, and total time to destination;
- The duration and comfort of the trip in the vehicle.

These different characteristics need to be specified for each modal form by a generic description, in other words by a descriptive theory.

An individual traveler's sensitivity to quality of service and price factors is modeled by means of a utility function, which combines those factors with the passenger's characteristics. Here again, a specific theory is required for each modal form of PTS.

The nature of a travel option needs to be modeled in terms of final access and the primary journey between the entry and exit points for the mode: What range of possibilities is open to the passenger for choosing the entry and exit point? Is the itinerary chosen by the traveler or determined by the operator?

The decision-making process depends on the nature of the options. The following features need to be modeled:

- The composition of a range of travel options;
- The user's knowledge of the potential options, notably in relation to the sales information system specific to the modal form;
- The choice of a particular option, depending on the dynamic status conditions of the service—e.g., the presentation of customized attractive options by an intermediator such as Blablacar or Uber.

The submodels so far mentioned together constitute the demand model for an individual customer. In addition, the segmentation of demand between different types of customer needs to be determined and an OD matrix to be modeled for each segment by period type (type of day, depending on the time of day, in particular distinguishing peak periods).

10.2.7.2 Representing Supply in a PTS

For each modal form of PTS, the supply model must represent (a) the infrastructure conditions, (b) the vehicle, (c) the usage protocols, and (d) the techno-economic model of the service.

The infrastructure conditions relate to (i) the road network available to the service, including any semi-dedicated lanes and (ii) the area served for entry and exit, whether or not it is focused around physical stations.

The service is based around a vehicle type: Its passenger capacity must be specified, along with the driving protocol, i.e., whether driven by the passenger or by the operator, manually or automatically.

The usage protocols relate to the physical use of the service, as well as the informational aspects: media and interfaces for giving information to potential users, the degree of customization, and ergonomics of those media, as well as:

- their impact on transaction time for a particular use;
- subscription packages in terms of price levels and service levels (e.g., separate premium packages).

The techno-economic supply model consists of the following components:

- The journey time function and the access time function for a boarding customer, in terms of the infrastructure conditions, the infostructure conditions, and the vehicle pooling mode;
- The transit operator's production function, whether integrated across a whole fleet for a company such as a taxi firm, or individually for a sole trader under a micro-franchise;
- The construction of the price in terms of demand level and production conditions;
- The intermediator's production function, in terms of the technical and commercial functions it performs between customers and providers: identification, information, reservation, payment, and price setting.

10.2.7.3 Modeling the Interaction Between Supply and Demand

The technical and economic conditions of the relationship between supply and demand have been anticipated in their respective models: Their characteristics are described by quantitative variables, the values of which are endogenous to the combined supply and demand model.

These are the actual conditions of the usage of supply by demand:

- Journey time, access time, and price: with respect to service type (premium or other), OD pair, and period;
- With their feedback on demand, which influences the volume of traffic;

- With their feedback on supply, which influences fare levels and service availability, in particular through the rate of use of each vehicle and the size of the fleet.

Here, the modeling requirement is to relate the demand model to the supply model: the connection between them and in particular:

- The total number of individual trips across all the demand segments;
- The total commercial revenues across all the service periods;
- The overall coordination of supply: depending on the type of company, either through integration or through concentration around an intermediator.

In addition to technical and economic modeling, mathematical, algorithmic, and IT processing needs to be developed in order to solve the model numerically.

10.2.7.4 Regulation

Mass transit modes are often subject to strong regulation: restricted access to the profession, vehicle quota systems, price controls, specific taxation, as well as the allocation of public spaces and access rights to certain dedicated transit routes.

In a particular conurbation, knowledge of the specific arrangements can facilitate the modeling of supply. However, for local authorities, the main priority is to maximize the population's well-being: An assignment model can and should help to integrate PTS into transit planning and to design regulatory arrangements not for restrictive purposes but for purposes of optimization and openness, taking advantage of the specific potentials of these services.

10.2.8 Multimodal Transit System

The different public transportation modes, whether mass transit or demand-responsive, need to cooperate for the benefit of travelers (see Sect. 10.1). That is why their integrated modeling is an important topic of research in traffic assignment (Sect. 10.2.8.1), together with the economic analysis and regulation of the system (Sect. 10.2.8.2), and the integrated design of such a system (Sect. 10.2.8.3).

10.2.8.1 Integrated Supply–Demand Modeling

Traffic assignment models on a mass transit network are necessarily multimodal, since they include walking and road or rail transit lines. The addition of demand-responsive modes involves a hard and a soft aspect, respectively, the physical conditions (hard) and the commercial conditions (soft).

With regard to the physical conditions, there are two research themes:

- Modeling intermodal transitions at a given point, in physical terms that include in particular the question of the availability of the second mode, and parking constraints for shared vehicle or car sharing services. Another factor to model and explore is the inconvenience of shifting between a demand-responsive mode and a mass transit mode, in terms of the traveler's preferences, as well as his or her propensity to follow a number of trip sequences in a certain subset of modes within a single urban trip.
- Modeling the local choice between a range of demand-responsive or mass transit modes. At what point(s) is the passenger in a position to make a decision, using what dynamic information, and what are the physical conditions for accessing each of the available modes?

The commercial conditions of the multimodal system encompass information, pricing and payment, and the associated subscription packages:

- Since multimodal systems are highly complex, static and dynamic information will be very useful in helping the passenger identify potentially convenient route options. So the information services available to passengers will need to be modeled, together with their particular conditions of use in a multimodal system with varying degrees of integration.
- To facilitate transitions between modes, the passenger needs not only local guidance, but also the minimum possible number of transactions to buy and validate a ticket. The more complex the network and the larger the number of modes that can be encompassed in passenger journeys, the more acute is this requirement. An integrated assignment model must explicitly include transactions and their effect on journey cost. In addition, the model should represent the fare conditions specific to each mode and the diversity of price levels between demand-responsive and mass modes: In principle, the more individualized the service, the higher the price. The price sensitivity of passengers, and their segmentation with respect to their respective sensitivity, is an important component in an integrated assignment model. However, this component has long been treated as a minor factor in line-haul transit assignment models.
- Subscription options for all or part of the available transit modes in a multimodal system are a related research topic. Subscription packages are more varied for shared vehicle modes than for mass transit, with a varying mix between a fixed component that provides access and is linked to the length of subscription and a variable component that is based on effective use. Combined subscriptions are therefore likely to be even more commercially optimized: their effects on demand and use need to be modeled. Furthermore, the ability to use a single physical medium (smart card, smartphone) for several modes is an important factor in integrating and reducing transactions, one that needs to be represented in a combined model.

10.2.8.2 Economic Analysis and Regulation

An integrated assignment model should represent the diversity of prices, price sensitivity on the demand side, and the effects of price on commercial revenues. It should also represent the economics of supply and the profitability of each mode or each operator, stating the costs of production and deducting them from commercial revenues in order to establish net profit.

Different impacts, and their economic valuation, also constitute modeling issues:

- The latent demand generated by multimodal supply: This needs to be broken down into segments and time frames;
- The specific contribution of each service to territorial access: For example, carpooling may have a significant effect on non-car owning individuals with poor mass transit provision and therefore contribute to social inclusion;
- The surface area occupied by the different modes in public space allocated to traffic and parking, notably on the streets: firstly, in physical terms of space occupied; then, interference between the modes and their flows, as well as with other traffic streams such as pedestrians, cars, and bicycles; and finally, the economic costs of this interference for those experiencing it;
- Environmental impacts: noise and atmospheric pollution, energy consumption, relative to vehicle routes, and the number of local people exposed to negative environmental impacts.

The evaluation of these different factors can be used to establish the overall value of the multimodal system for the community, in order to optimize the technical and commercial configuration and the operating modes for the community. Because of the different externalities, an ideal system optimum state necessarily differs from a user equilibrium, or rather an actor equilibrium when supply is endogenous.

The concept of a system optimum should play a fundamental role in regulation and planning.

An additional topic for economic research based on a multimodal assignment model is the distribution of added value (e.g., commercial revenues, social benefits minus costs) between the system's components:

- Between the different modes, particularly in terms of their functional combinations in journeys made by their joint users and further in terms of fare packages and their scope in space and time;
- Between mobility services, intermodal stations, and also the traffic infrastructure.

10.2.8.3 Multimodal Design

If sufficiently sensitive, assignment models can be used for exploratory applications intended for the design of transit systems that are efficient in all respects, in terms of demand, in terms of the environment, and in terms of the economic viability of the service.

Certain design topics relate to the technical aspects of supply (hard factors):

- Designing intermodal platforms that are optimized for demand, which minimize transfer and waiting times while offering associated services (information, payment, shops);
- Determining the specific added value of a certain level of development and facilities on a particular modal platform, for the overall operation of the services that use it;
- Drawing up "planning and coaxial operation schemes" for several transit modes along an urban artery: distribution of access rights to traffic and parking lanes and positioning of respective stopping points, all in relation to junctions and their specific distribution along the artery and also in relation to incoming and outgoing flows and to the requirements for connections between modes.

Other design topics relate to supply management, particularly on the commercial side (soft factors):

- Designing operating modes that are sensitive to the multimodal system's load conditions: for example, at peak times, directing demand-responsive modes in dense areas toward a premium service, but democratizing their use outside peak times and particularly at night, during periods when line-haul mass transit systems are closed;
- Dynamically allocating traffic lanes to different transportation modes;
- Designing multimodal Traffic Management Schemes, notably in order to compensate for the failure of a mass transit mode by an exceptional shift to demand-responsive modes: emergency use of carpooling, optimized use of self-service bicycle repositioning trucks, etc.;
- Ensuring that the assignment model contributes to multimodal information services;
- Designing combined fare packages for multimodal and intermodal uses.

These design topics are particularly innovative. A model could be used to explore their potential. It would also be desirable to test and optimize innovative approaches interactively with potential providers and users. An Urban Mobility Living Lab (Sect. 10.3.4) would be a particularly good framework for experiments of this kind.

10.3 System Simulation and Augmented Reality

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In this final section, we explore the relation between mobility systems and simulation models. In Chap. 8, as in Sect. 9.2, it was observed that assignment models are becoming more and more modular, with subsystems being identified and separately represented by a submodel.

In other words, modeling is becoming increasingly systemic, through assemblages of elementary models. However, elementary models themselves are continuously developing, forming an ever larger asset base as they accumulate. We will run through this asset base—a toolbox of models—and discuss the feasibility of a scale 1 assignment model (Sect. 10.3.1).

At present, models of this kind are still on the drawing board, although it is now conceivable that the location of all mobile entities could be determined on the move in real time. More concrete developments are already underway in two areas. Firstly, using IT techniques, elementary models are helping to bring augmented reality to the transit system for stakeholders in all categories: users, operators, regulators, and general public (Sect. 10.3.2). Secondly, the applications of assignment models are changing: Real-time applications are emerging, whereas new off-line applications are being developed (Sect. 10.3.3).

Finally, both model and application developments need to be related to the dynamic of transformation in the urban mobility system, as described in Sect. 10.1, and to the scientific dynamic described in Sect. 10.2. An urban mobility Living Lab should be an ideal framework for relating an actual system—operating in a territory and covered by a whole range of observations—to its operators and regulator, to industrial partners who design hard or soft innovations for such a system, and to academic partners who develop knowledge with potential operational outcomes, as well as users of the system (Sect. 10.3.4).

10.3.1 The Modeling Toolbox

An assignment model for traffic on a network reflects a transport system in a way that is simplified, but also broad, since it includes the main entities—vehicles, passengers, and infrastructure components—together with their interactions in traffic as a physical process. Yet there are now specific models for every type of entity, with potentially extensive detail that allows for very fine-grained simulation. We run briefly through these detailed models of entities (Sect. 10.3.1.1) before discussing the simulation of their interactions (Sect. 10.3.1.2). In addition, the diversification and spread of sensors now make it possible to observe entities and subsystems in detail: The collation of information relating to a single entity from different sensors also constitutes a computer model of that entity. There are natural convergences between a simulation-oriented model and an observation-based model. In addition, sensors and their observations can be simulated, and in other words, observations can be synthesized: The field of simulation and observation is wide open (Sect. 10.3.1.3).

In these conditions, simulation becomes an art of composition. A scale 1 empirical model of the transit system, giving real-time estimates of the status of disaggregated entities, now seems possible (Sect. 10.3.1.4).

10.3.1.1 A Review of Model Entities

A mass transit vehicle is a mechanical system that includes a cabin, a driving system, an engine, and wheels. It can be modeled with different levels of detail:

- In car production, each mechanical part is modeled as a subsystem with its own physical and technical behavior, by reference to its interactions with other parts in the vehicle's operation. In particular, engine operation is modeled in detail, in order to optimize energy efficiency;
- It is also possible to model the driving seat inside the vehicle, to simulate the position and working conditions of the driver, who interacts with traffic and controls the movement of the vehicle and interaction with passengers;
- There are simple mechanical models for the vehicle's motion dynamics and its energy balance: The vehicle is described as a material body with certain dimensions;
- And there are geometrical models for cabin layout and passenger comfort.

Each of these models is a considerable expansion on the basic representation of the vehicle included in an assignment model. A much more detailed simulation could be substituted, although it would be costly in IT resources.

The same is true for the modeling of a passenger as an entity. What exists now are as follows:

- Fine-grained biomechanical models, used to study road traffic accidents;
- Dynamic models of the passenger as a material body in a spatial configuration, in interaction with the limits of that space, street furniture, and other travelers;
- Psychological models of mental load, elementary physical actions, and the cognitive processes that determine them;
- Agent models to represent the beliefs, desires, and decisions of the traveler in motion.

Agent models are beginning to spread to assignment models, giving a more accurate representation of the travel situation in terms of all the needs and mobility conditions of the passenger as an individual.

Numerous models have also been developed for infrastructure "elements":

- Wear and tear models for each material component with respect to utilization processes, as input into asset management and predictive maintenance;
- Mechanical performance models for each track section, for vehicle movement;
- Still for each track section, technical traffic process models for controlling flows;
- For each element of pedestrian movement, geometrical layout models to simulate the conditions of use and the dynamic interactions between travelers.

The latter two model types tackle factors and processes that are important for traffic assignment. They can be used jointly with an assignment model, in order to specify the operation of the system for certain elements that seem sensitive—especially if the simulated flows coming out from the assignment model reach or surpass macroscopic physical capacities.

10.3.1.2 The Modeling of Situations, Behaviors, and Interactions

In Sect. 10.2.1, we took a detailed snapshot of the passenger situation and the passenger's behaviors in terms of elementary acts or decisions, in interaction with traffic conditions (local or remote) with regard to available information and individual perception.

The associated models capture physical and informational aspects of the situation. The psychological and behavioral aspects are much less deterministic and vary much more between individuals or even, for a single individual, between repeated situations. So, for example, the modeling of a passenger's secondary activities in a vehicle is necessarily stochastic.

Similarly, in Sect. 8.3, we wrote about the stochastic aspects of the passenger and vehicle movements. Computers can now tackle very detailed simulations of very specific and highly disaggregated interactions.

As far as possible, the structural relations between the elements need to be captured, in particular the topology of the infrastructure elements, of the vehicle runs and of passenger journeys. We also need to capture the two-way physical conditions between infrastructure and mobile entities, between vehicles and travelers, as well as the informational conditions.

Stochastic factors limit the ability of a particular simulation to mirror the operation of the physical system: There is no direct correspondence, and we can only interpret the specific enactment relative to a set of simulations that sample the stochastic process through which the system was modeled.

10.3.1.3 Collecting and Synthesizing Information

More and more sensors are now incorporated into the elements of a transit system: on the infrastructure, in the vehicles, and on travelers themselves through the smartphone. These sensors gather information that can be collected and centralized. Information about a particular entity can be used to backtrack its activity, and in fact, for an entity that is being observed by a variety of sensors, the collection of this information constitutes an empirical computer model of that entity.

A lot of information is produced in this way—we call it Big Data—especially as information generates information:

- Travelers react to a situation they have learned about, by themselves producing information for the operator or for other travelers with whom they interconnect in different ways (social networks);
- The messages sent by a telecommunication network can be analyzed by dedicated software, which will in turn generate further information.

The information can be processed in a multiplicity of different ways, potentially resulting in an infinite proliferation of information that reflects reality to varying degrees. In addition to information that draws on real observations, there is synthetic (in the sense of virtual) information.

In particular, the results produced by a model constitute synthetic information. A traffic assignment model generates such synthetic information in massive quantities. It is also possible to model sensors, to simulate situations that the sensor would perceive, and to synthesize information comparable to what a real sensor would capture.

10.3.1.4 Virtual Reorganization of the Transit System

The quantity of information and the power of the resources for generating and processing it widen the possibilities for simulation. For an urban mass transit network, it is technically possible to have a network of sensors on the infrastructure, a set of sensors in the vehicles, and, conceivably, a sensor for each traveler. The total information on the real-time status of each entity, in particular the location of mobile entities, would constitute an empirical computer model of the system, with the same level of detail as an assignment micro-simulation of vehicles and travelers. An instantaneous disaggregated status model of this kind would, in itself, only have very limited predictive capacity, achieved by extrapolating the motion of each mobile entity on the basis of its previous positions.

The transit service schedule is a much more predictive model: The two models can be combined and joined with an assignment model that will include predictions of passenger movements and adjust the prediction of vehicle movements and infrastructure-related operations.

By adding other sensors, in particular for vehicle operation, or equivalent models to simulate vehicle energetics, the system could be represented in depth. As regards passengers, an empirical model of all the entities would ideally also represent their respective situations: In practice, however, not all real-time positions will be captured, and the state of the system in this respect can only be assessed by simulation, except in specially prepared and instrumented experiments.

10.3.2 Augmenting Reality

In the era of information, therefore, progress in observation and simulation has made it possible to substantially increase our knowledge of a real transit system. This enhanced knowledge can be of practical benefit to the different stakeholders in the system: (1) users, (2) operators, (3) regulators, (4) analysts, and (5) the general public. This is about augmenting reality, increasing its informational component and converting its physical component.

10.3.2.1 Augmented Reality for Users

For users, the information, pricing, and payment functions are simplified physically, through automation, while their informational aspect is amplified. Dynamic information, route advice, the delivery of different alerts from the operator, but also from other providers and users, augment the reality of the service delivered. Reciprocally, users themselves become information providers, even disseminating messages themselves.

In addition, physical reality is augmented by the emergence of new mobility services (see Sect. 10.1).

Service augmentation is further facilitated by the fact that the physical time spent in a vehicle or on the platform is available for informational interactions, in a way that can be compared with the availability of certain station areas for use as advertising media.

10.3.2.2 Augmented Reality for Operators

Different actors want to be involved in the design, organization, and shaping of the augmented reality offered to users: not only operators of new services, but also operators of traditional services seeking to encourage users to cooperate in the smooth operation of the system, or else information service providers (e.g., the Moovit service). All this is because the time available to the user is also a window of commercial interaction for the use of augmented services.

For a transit operator, the increased real-time complexity of the system is primarily an opportunity to improve operational monitoring and responsiveness. It also helps to strengthen the capacity for anticipation at several timescales, from real-time through to long-term planning, passing by very short-term scheduling adjustments and also by the medium-term planning of adaptations to demand levels.

As a result, the managerial capacity of operators should be substantially increased. This impacts on the management of production resources, from the automation of elementary functions (local vehicle management, traffic actuators on the infrastructure) through to the optimization of high-level functions for line and network management. It also impacts on commercial management, both for the elementary functions that benefit from automation (payment, pricing information, customized advice) and for high-level yield management functions: This offers a whole area of progress for urban passenger transit, with the potential for the development of specific functions and professional expertise.

Overall, the development of technical functions and commercial functions brings augmented operational reality by reinforcing the role of soft inputs. Hard inputs also develop in support, through the installation of sensors, transmitters, and telecommunication networks in vehicles and on infrastructure. These new commercial—or simply informational—services have the effect of augmenting the overall reality of operations.

The proliferation of information in this wider transit system, in particular between users through social media, constitutes for the operator a big opportunity with regard to traffic management but also a challenge, in that external recommendations may replace its own advice and prove counterproductive for the performance of the system. To pre-empt this, the operator needs to take on a further role: community management, obviously with an emphasis on incentives rather than coercion.

10.3.2.3 Augmented Reality for Regulators

Augmented realities on, respectively, the demand and supply side also apply to transit system regulators:

- More functions provided: mobility services and information services;
- Traditional operators and also providers of innovative services;
- More information available for knowledge and therefore for regulation of the system.

All this increases the scope, the needs, and also the resources of regulation:

- There needs to be informational interoperability between the different operators' information systems (this problem also arises for a network operator between the separate information systems on its lines);
- Cooperation needs to be maintained between operators in the dynamic management of services and flows, not only through mutual exchange of information, but also in the organization of the respective modal infrastructures, in particular for the introduction of new physical mobility services;
- Information needs to be regulated: its availability to users not only in terms of physical infrastructure and software capacity, but also in terms of authorized providers, as well as exchanges between users;
- Regulation can now be based on a more fine-grained description of system performance.

On the latter point, it is now technically possible to track the detailed operation of the system in real time. This should encourage the establishment of a Territorial Traffic Information and Management Center, as exists for road traffic, which channels information messages to the general public through traditional media (radio, television, Web services).

10.3.2.4 Augmented Reality for Analysts

The augmentation of reality through the increase in soft inputs to the physical system is particularly helpful to the development of knowledge, in action research and other studies, both through the emergence of new research topics and through the enabling of investigation methods. The research topics were set out in detail in

Sect. 10.2. Here, we will concentrate on the facilitation and reinforcement of investigation methods, which contribute to augmented reality for analysts, helping them to develop their understanding of demand and supply.

On the demand side, interaction with users is made easier through hardware (smartphones) and software (Web apps, automatic information processing). This transforms possibilities for surveys based on directive or more open questionnaires, while reducing survey costs and enlarging samples. Time spent in vehicles or on platforms offers a good opportunity for interaction. The information ecosystem also lends itself well to off-line surveys, owing to the availability of data and media for interactions, and also techniques for preparing, conducting, and processing interviews. This process can go as far as immersing volunteer users in virtual reality environments.

On the supply side, for the design of systems—in particular services and operating modes—the development of models and information systems facilitates and reinforces simulation-based experiments. The applications reported in Sect. 9.2 relate to this. Increased computing power also makes it possible to add optimization functions, in order to improve real-time operation or off-line design. Immersion in a virtual reality environment would also enable analysts to identify different potential real-world improvements in many areas—such as the design of services and spaces, vehicles, and infrastructures—aided by an understanding of the system in its real complexity.

10.3.2.5 Augmented Reality for the General Public

Mass transit services are available to everyone living in a territory. In general, their users constitute a significant proportion of the general public. As for mass transit information services, they are addressed both to users and to potential customers.

With information and simulation resources, it is now possible for people to prerun a journey in virtual reality, which would offer the general public the experience of augmented reality travel. Route advice services already offer a significant degree of customization. Nonetheless, the outline of an itinerary on a map, with details of timetables, travel time, and fares, still remains a fairly abstract description.

For motorists, some information services provide local 2D and even 3D views to illustrate the travel conditions encountered on a route: Remote access offers an experience of augmented reality for any individual. Equivalent services will undoubtedly emerge for mass transit, in order to reproduce the sensory experience of travelers at successive stages in a journey, in a vehicle, on the platform, and in the station. In particular, it will be important to convey the ambient traffic conditions.

10.3.3 Toward What Typical Applications for Assignment Models?

Assignment models have long been used for planning transit systems. In this role, they help to augment reality for users, operators, and regulators alike.

In the course of the sections in this chapter, we have pointed out the trends in the direction of systems and avenues of research for the improvement or application of assignment models. We will now recapitulate the types of application that appear both useful to stakeholders in the system and technically feasible. Before discussing the applications for long-term planning (Sect. 10.3.3.3), we will cover the real-time applications for traffic management and user information (Sect. 10.3.3.1) and then the medium-term applications for making supply and demand more flexible and reciprocally better matched (Sect. 10.3.3.2).

10.3.3.1 Toward Real-Time Applications

Real-time traffic management on a transit system can employ a centralized information platform. Centralized traffic management has a long history on interurban master networks, or for train management on an interurban rail network. Today, in 2015, however, such systems are still to be applied to urban mass transit passenger networks. It would seem just as technically feasible and equally socially useful in a big city as on an interurban system, since the traffic scales in terms of passenger kilometers per day or passenger hours per day are comparable.

At the end of Sect. 9.5.1, we highlighted the idea of using a scale 1 assignment model to make a real-time estimate of the state of the system, broken down into individual mobile entities and technical infrastructure elements. Establishing such a model through the pooling of different sources of observed or synthetic information is a first step.

The second step is to give this model predictive capacity by incorporating scheduled operations on the supply side and journey progress on the demand side. In this way, demand forecasts can be incorporated into the real-time adaptation of supply, alongside forecasts of the system's state in the dynamic traffic information communicated to users.

The third step will be to integrate the dynamic reactions of operators and users consistently into ongoing and anticipated situations. This is where the real scientific challenge lies, because there will be mutual cross-referencing between model and system, and in other words, the model will be self-referential. In particular, it will need to include the role of dynamic information vectors, i.e., the flow of information within the real system via the operators and other information services.

10.3.3.2 Toward Medium-Term Applications

While transaction costs (information, pricing, payment) remained high in urban mass transit systems, the service schedules were set statically, with few regime differences: peak and off-peak on working days, working days or weekends, and seasonal periods. With the general reduction in transaction costs, much more dynamic service schedule programs can be envisaged, as is already done by interurban transit operators, whether in rail or in air transportation.

Although the traffic constraints remain high—in particular peak hours on working days are determined by commuting trips which are very rigid—there are two obvious fields of application for yield management in urban mass transit:

- Journeys taken by passengers without subscriptions. It would be good to introduce a targeted customer management system for them, with a specific type of subscription and incentives for flexibility, in particular price adjustments for certain timetables and types of day, like travel cards for the elderly in interurban rail transportation. This customer segment should become the foundation of a new kind of commercial management in urban mass transit. The techno-economic principles of the commercial conditions can be established via an assignment model that will show the direct and indirect costs and benefits for the system.
- More generally, customized pricing has become as technically possible as customized information. Of course, people will need to be convinced and users will have to accept the changes.

An assignment model could be used not only to establish pricing principles, but also to inform negotiations between the regulator and representatives of the population and users, who could work together to explore future pricing and service scenarios.

Apart from (though not unconnected with) yield management, the medium-term applications include the preparation of Traffic Management Schemes in order to anticipate critical conditions, for example, a massive influx of additional passengers or a serious service breakdown. By analogy with interurban road systems, the priority would be to draw up such schemes for each major artery or, even better, each major corridor around a large artery, by incorporating alternative routes. Every large capacity line should have a Traffic Management Scheme, based on the use of an assignment model for simulation purposes, which anticipates passenger shifts within the network.

10.3.3.3 Long-Term Planning of the Transit System

The planning of a transit system is fundamental, whether in the development phase or at the more stable stage, during which both renovation and maintenance in good operational condition need to be managed. Assignment models are traditionally used as tools to guide planning decisions. This role will undoubtedly develop as a result of two major factors: first the transformation of the system in the information era (see Sect. 10.1) and secondly scientific development of models, in both theoretical and algorithmic terms.

The applications to planning are likely to develop in four major directions: (1) refining and enhancing representation, (2) extending the scope of planning, (3) reinforcing techno-economic and commercial optimization, and (4) interacting with stakeholders and supporting consultative forms of planning.

(1) Refining and enhancing representation:

- Differentiating periods and capturing intra- then interday dynamics;
- On the demand side, differentiating between types of user on the basis of physical travel situations and economic trade-offs, in particular by describing the actual uses, the benefits obtained, and the costs experienced by each category of user;
- On the supply side, endogenizing the techno-economic management of services;
- Modeling a diversity of information services, as well as the receptiveness and sensitivity of travelers to information in its different forms and according to their usage practices.

(2) Extending the scope of planning to reflect the expansion of the urban domain for transit systems:

- Extending the assignment model to multimodality and taking account of the different service modes and user navigation on a multimodal network;
- Capturing the organization of individual mobility over a single day and also over the week, or even more;
- Incorporating a range of pricing scales, as well as the corresponding price sensitivities of users;
- Through the model, capturing the diffuse nature of services based on the pooling of small vehicles, analyzing their sphere of relevance, and synthesizing their overall contribution to mobility.

(3) Greater techno-economic and commercial optimization: Once techno-economic behavior on the supply side has become endogenous to the assignment model, the model can be reinforced by optimization functions that will automate (at least partially) the quest for a more efficient service schedule, for pricing conditions that generate higher revenues and greater fairness between the different categories of user, etc.;

(4) Interacting with stakeholders and supporting consultative forms of planning:

- Sharing and publishing the theoretical foundations and other scientific hypotheses implicated in the establishment of an applied model;
- Sharing the results of different scenarios, including details of local traffic conditions;

- Making the model's computational capacity available to volunteer or selected groups, whether to construct and process a scenario, or simply to customize the results of a certain scenario;
- Above all, developing planning scenarios in concert with the stakeholders concerned, with the oversight of regulators, involving the operators, user representatives, taxpayer representatives, and environmental groups.

10.3.4 Toward Urban Mobility Living Labs?

Assignment models should therefore find increasingly varied applications for the stakeholders in the transit system, whether users, operators, or regulators. Each category of stakeholder has a specific role to play in the operation of the system, in interaction with the others through relations of cooperation, complementarity, and, indeed competition, in providing services or infrastructure. Beyond the interplay of particular interests, the common objective is that the system should supply users with a good quality service combined with acceptable financial, social, and environmental performance.

All the different stakeholders can benefit from an overall understanding of the real system and its development prospects, in order to target their own activities and gradually adjust their own strategy. It is a good thing to share technical and economic understanding based on scientific theories. It is also a good thing to work together to anticipate the future and share potential scenarios for change: This is a fundamental priority of regional transportation master plans.

An additional form of cooperation between stakeholders with different interests-recently emerged (originally in the 1990s, rising to a few dozen and then hundreds of implementations between 2000 and 2015): the Living Lab (LL), a form of cooperation that stresses knowledge and innovation:

- Cooperation between complementary actors, working together in a collective project that generates a strong group dynamic;
- Around a real-world site where each carries out their respective activities;
- This site is handled as a study field where the system is observed and its operation theorized and also as a test site for innovations. The combination of observation and experiment provides a way of observing the effects of each experiment.

In this final subsection, our goal is to present the principles and potential benefits of an urban mobility Living Lab, and also to situate the role and contribution of an assignment model in the activities of such a laboratory.

After setting out the general principles of a LL (Sect. 10.3.4.1), we explore its advantages for each stakeholder category in the particular case of urban mobility: for users (Sect. 10.3.4.2), regulators (Sect. 10.3.4.3), operators (Sect. 10.3.4.4), and designers and innovators (Sect. 10.3.4.5) and for researchers (Sect. 10.3.4.6). We shall finish by recapitulating the findings (Sect. 10.3.4.7).

10.3.4.1 Key Living Lab Principles and Methodology

According to Umvelt (2014), a LL is a framework for the design, development, and in situ experimentation of innovative services or products in which different stakeholders (public bodies, private partners including industrial companies and operators as well as start-ups, research bodies, and in particular users) cooperate closely in an open innovation process.

So an "Urban Mobility LL" would be an integrative platform based around an experimental site used for the creation and development of multimodal and mobility-oriented services.

The term first appeared in the 1990s in the work of Professor William J. Mitchell, from the MIT Media Lab and School of Architecture, in reference to the development of innovations through user-centered research methods applied in real-world environments. However, the concept received further impetus from the European Union, which employed the term to promote and finance a new kind of innovation. The developing power of ICT and the opportunities provided by such technologies suggested the possibility of user-centered development. The foundation of the ENoLL (European Network of Living Lab, "international federation of benchmarked Living Labs in Europe and worldwide") in CoreLabs (2007) marked the expansion of a movement which has since grown steadily. As of 2010, there were 370 certified Living Labs, in addition to structures that are Living Labs according to the definition, without being aware of or presenting themselves as such (Picard et al. 2011).

The ENoLL specified LL methodologies on the basis of five characteristic principles, namely (i) spontaneity and value creation, (ii) user empowerment, (iii) realism, (iv) openness, and (v) continuity.

Spontaneity and value creation: For new products and services to succeed, they have to offer not only more and objectively better functions but also subjective functions that inspire use, fulfill personal desires, and fit in with and contribute to the fulfillment of social and societal needs. For innovations to satisfy such clusters of needs and desires, it is not enough to explore and address the initial needs expressed by users. They must also have the capacity to detect, aggregate, and analyze spontaneous reactions and ideas over time, throughout the full life cycle of a product or service.

User empowerment: The role of users (primarily end users of the product, but also people who indirectly benefit) is fundamental: LL methodologies are user-centric, by contrast with traditional R&D approaches that are techno-centric.

Moreover, users are invited to co-create the product or service, with the result that innovations are user-driven. Product design in a LL focuses on the understanding of emerging customer needs and aims to use this knowledge to develop products that yield additional value for customers.

Realism In order to generate valid results, the Living Lab has to provide a “natural environment” where users and stakeholders behave realistically. In this way, innovative products or services can be tested in real-world conditions. This principle differentiates the way Living Labs work from other types of open co-design environments.

Openness The innovation processes must be as open as possible. This is essential to ensure that multiple perspectives are included and to attract sufficient input to achieve rapid progress. Openness enhances the appeal of Living Labs. It is a principle that also includes concepts such as open data or open innovation. Open innovation can be defined as “the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and to expand the markets for external use of innovation, respectively” (Van de Vrande et al. 2009). Open innovation in a Living Lab methodology is about facilitating the flow of knowledge and accepting ideas from multiple stakeholders or citizens. It also raises the question of how the Living Lab deals with the profusion of ideas, how relevant knowledge is selected, etc.

Continuity Since cross-category collaboration is based on trust, which takes time to develop, a Living Lab has to be a structure that remains stable over a certain period of time. The continuity principle enables stakeholders to develop collaboration and to plan and run experiments in a durable environment.

Along with the five key methodological principles that characterize LLs, a LL is a framework that comprises five main components: users, partners, application environment, technology and infrastructure, and organization and methods (cf. Bergvall-Kareborn et al. 2009):

- The *application environment* is the context in which users interact with products and services. It includes the real-world conditions as well as the particular conditions of use, the product’s user interface, and the usage protocol for the service.
- *Technology and infrastructure* refers to the LL’s stock of sensors, telecommunication facilities, and software for analysis or design, or for interaction with users.
- *Organization and methods*. A LL is a platform where different partners join forces to increase the efficacy of their innovation process. Different organizational and management methods can be developed in order to achieve the objective of global collaboration. The LL’s structure should also have the capacity to evolve in response to the changing needs and desires of both partners and users. In fact, a LL needs to have a governance system that focuses on the production process inside the structure and that also handles economic issues or other support functions, such as the communication and exploitation of results.

Ideally, there should be close partnership between private companies, the public sector, industries, research centers, associations, citizens, etc. The goal is that the different stakeholders should share their skills and take maximum advantage of their mutual capacities to drive innovation. The stakeholders may have different interests in the Living Lab (Umvelt 2014), which are set out in Table 10.1 (Fig. 10.1).

Table 10.1 Benefits of a Living Lab

Stakeholder	Benefits of a Living Lab
Private sector: industries, start-ups, SMEs, etc.	• Being able to test new products or services directly on users and to obtain feedback based on real use; • Reducing costs and enhancing development processes; • Sharing knowledge with other partners and feeding their experience into the innovation process: Better knowledge of existing practices stimulates creativity and inventiveness
Public sector: public authorities and public services	• Providing the best living conditions for the population; • Keeping abreast of innovations; • Improving the dialogue between public and private, and public and citizens; • Allowing companies to test innovations in their territory to foster its attractiveness
Research centers, R&D clusters, and universities	• Observation and analysis of phenomena; • Real-world experimentation; • Developing new educational tools
Users and citizens	• Expressing needs and desires; • Contributing to a process of innovation in which their interests are central

Fig. 10.1 Key components of a Living Lab (from Ståhlbröst 2008)

10.3.4.2 Importance of Users

In a LL, attention is focused on the users of products and services, with the aim of satisfying needs and desires. Over time, this attention goes into the design of products, while in real time, the focus is on observing uses. In addition, users are invited to express their impressions and suggestions, which feeds back into the design process over time and then into the real-time interaction with the product/service.

The user-centered approach is entirely suited to urban mobility, which is a basic individual need in which each individual has his or her own particular goals. Usage entails physical presence, which is relatively easy to observe, while allowing time for interaction on the informational side. Moreover, smartphones are a powerful and efficient medium for interaction with the designers of products/services, as well as fulfilling the functions of information, payment, etc.

The physical description of uses can be effected by different sensors, traffic measurement systems, cameras, ticketing apparatus, digital tracking of mobile phones, and GPS tracking for smartphones. The smartphone can also feed data into informational activities.

The choice of the experiment site is very important: The geographical position determines the user population, and the site should be big enough to observe large parts of every trip that takes place in the site. Individual user sensors are a way to extend the spatial range of observation and experiment. Another important thing is to specify a set of individual and mass transit modes, with potential for multi-modality and intermodality.

As regards the products/services to be designed and tested, let us summarize the ideas highlighted in the previous sections:

- innovative mobility services, collective taxis, etc.;
- innovative management methods: flexible options, dynamic pricing, customized pricing based on use, etc.;
- journey facilitation: physical facilitation of movement through the layout of station areas, traffic management, travel assistance through information and signage, simplified information and payment transactions, etc.;
- Not forgetting mobility practices, repeat journeys by individuals, travel choices, usage routines, and messages about travel that users exchange with others through various channels (including social media).

The introduction of a traffic assignment model, if possible at the heart of a multimodal mobility model, constitutes a major advantage for an urban mobility LL:

- Describing a transit system is a way to manage its technical complexity (construction of a service from infrastructures, vehicles, and commercial protocols) as well as demand patterns;

- The model enables one to design a service on first principles, to test it virtually, and to pre-test its commercial targets and conditions of use. It also enables to analyze the value of the service by comparison with alternative services;
- Through experimentation, a model offers a way to qualify uses retrospectively, to describe them relative to all the different journeys and the user population, and therefore to derive a typical customer profile.

Reciprocally, a LL system provides a whole ensemble of information that can be fed into the model, in order to improve its empirical accuracy and to develop theories (see para 6).

10.3.4.3 Public Stakeholders

Mobility has significant social implications, as a service for the population, with an important contribution to quality of life, and also as a physical phenomenon that presents an accident risk as well as health and environmental impacts. That is why the experimental aspect, as much as the territorialized aspect of a LL, is relevant to local authorities, who are responsible for quality of life, safety, health, and public security, and also for regulating the technical and economic performances of the transit system.

In principle, the mobility products and services designed within the framework of a LL should make a positive contribution to the public interest as fostered by public authorities, by improving the service delivered to users, reducing environmental damage, creating value, and subsequently generating economic activity and jobs.

On this principle, the public authorities should encourage an urban mobility LL, support, and even contribute to it:

- By facilitating the formation of partnerships between stakeholders, by supporting its establishment and operation, and by assisting with administrative formalities;
- By encouraging design and experiment initiatives from private actors;
- By giving innovation projects the benefit of their knowledge of local conditions and users, and also of the legal conditions applicable to the service scheme;
- By promoting cooperation or at least harmonious co-existence with existing services and their operators;
- By making technical and financial resources available: contributions "in kind" regarding the use of public spaces (access, parking and travel conditions for vehicles, meeting points for travelers, installation of specific street furniture, signage), or else the use of private telecommunication networks, and also the dissemination of information to local populations and sponsorship of initiatives.

In addition to these support functions, local authorities should apply and manage a multicriterion assessment system for the proposed services, in line with their oversight prerogatives (in addition, the observational system implemented on the experimental site should also be used to assess the general state of the system on a period-by-period basis in order to monitor trends):

- impacts on traffic behavior: contribution to efficacy, reliability, and the reduction of incidents and other disruptions;
- effects on the quality of life of users and local people;
- environmental balance;
- financial balance and socioeconomic balance.

This oversight role would benefit greatly from a multimodal assignment model and environmental impact models, so that simulation could be used to evaluate effects not covered by the LL's observation system and also to carry out forward assessments of all impacts on the service and on its broader environment.

Local authorities could also use the LL to promote innovations in pricing, taxation, and subsidies in mobility services, in order to improve the economics of public transportation, while maintaining social equity.

For local government, and also at a larger scale, a LL is another way to channel innovation: rather than being a passive observer to the anarchic emergence of disparate innovations, encouraging their testing in optimum conditions both for themselves and for the community. This latter reason should be enough to recruit the local authorities who together hold the different sectorial responsibilities relating to the LL.

10.3.4.4 Transit Operators

Transportation in a territory is a well-established economic activity, carried out by operators who are linked to local authorities either by direct affiliation or through an operating license. The operators are fully engaged in the technical aspects of transportation:

- Highway operators, for infrastructure and traffic management;
- Mass transit operators manage their services and the resources they put into them.

Operators are involved in an urban mobility LL in several respects:

- For the establishment of in situ observation methods, on highways, on railroads, or in transit vehicles;
- By every innovation in mobility products or services, because of the technical and social interactions: technical interactions in the operation of the service, its use of a mobility infrastructure but also an access infrastructure (intermodality), its coordination with existing services, its influences on passenger practices in terms of modal combinations or shifts, or indeed in changes of practice, etc.;
- And of course, they can themselves be the drivers and beneficiaries of innovations, in their operational resources (including infrastructure and vehicle

resources, and operational processes) and in their interactions with users, in particular with regard to information, sales, or pricing.

Some may be tempted to see innovation as a threat, in its ability to bring change and therefore to undermine the status quo. In a globalized world, local opposition would be counterproductive: At worst, a stance of alert neutrality is advisable and at best, a position of welcoming cooperation, in order to anticipate the potential of innovation as quickly as possible and consider how to adapt to it: in other words, to co-construct one's environment.

The integration of a multimodal assignment model would seem crucial in this respect, in order to accurately interpret the scope of a local experiment, by relating it to the structure of the client base and also to the composition and operation of the multimodal service.

10.3.4.5 Industrial Firms, Designers, and Innovators

In a Living Lab, the private partners may be industrial companies (manufacturers of products with a life cycle much shorter than the longevity of a system), SMEs with a particular product line, and start-ups built around an innovation.

Centering on users, and therefore on customers, as well as on value creation, is entirely consonant with the aims of a private company. Regardless of the parent body, however, be it private partner, public partner, or research center, our focus here is the designers of innovative products or services.

For them, a LL is a framework for cooperation both in design and in experiment. With regard to design, the participation of users, operators, and a public regulatory body ensures a comparison of viewpoints and perceptions, and strategic positions and respective interests, within a constructive dynamic that helps to bring concepts to fruition more quickly. With multiple partners involved, design becomes co-design.

The positive involvement of partners who in practice represent complementary functions relating to the service being designed is a major advantage for the designer.

With regard to experimentation, user participation is crucial to the development of the concept: validating functions, adapting the ergonomics to patterns of use, through the observation of usage patterns, impressions, and habit formation, and specifying commercial and pricing structures.

Embeddedness in a given territory makes it possible to test not only the concept, but also its spread through the population, customer volumes, and therefore its market share and sales revenues.

The site's specialization generates economies of scale in the design and implementation of experiments; the observational resources in place facilitate the collection of information on uses and the conditions of use.

Overall, a LL framework shapes innovation through three specific processes: first, an analysis of value, by the designer from a user-centered perspective; then exposure to the partners; and finally field testing.

With a multimodal assignment model, a further process is possible: virtualization of the service and testing through simulation, which allows a large number of variants to be explored at relatively modest cost.

The availability of “immersive” virtualization facilities would obviously increase simulation capacity, both in the preliminary design phase and in the preparation of field experiments.

10.3.4.6 Researchers

The involvement of researchers in the LL brings scientific capacity and knowledge focus to the partnership, along with certain neutrality toward the economic interests at stake. In terms of content, scientific capacity includes expert knowledge in the domain concerned, including theories, stylized facts, and state-of-the-art international knowledge, combined with scientific curiosity (challenging) and investigative capacity. In terms of form, research methods prioritize objectivity, logic and rigor, critical doubt, and relativization.

This standpoint and approach are valuable to both design and experiment. Since theories and methodologies are organized into disciplinary segments, an urban mobility LL would benefit from the involvement of an interdisciplinary research pool:

Human and social sciences: for human factors regarding users or operational staff: psychology of perception, of attention, of mental load and emotion; sociology of needs, motivations and ways of life; sociology of organizations; microeconomics and econometrics of behavior and decision-making…

In engineering sciences: physical theory of flows, control techniques, mathematical and algorithmic modeling, computer science and computer engineering, statistical theory, massive data processing, etc.

Planning and development is an intermediate discipline, focusing on spatial organization and functions, and on the arrangement of spaces for the presence and movement of individuals.

Interdisciplinary cooperation fosters a holistic understanding of the system concerned, since mobility is a sociotechnical phenomenon. The advantage of a systemic understanding is obvious in the design of an innovative product or service:

Anthropologists and sociologists can identify the targets of a product/service in advance and its capacity to fulfill needs, its qualities (in particular congruencies with other services), and also its weaknesses;

Engineering and urban planning specialists can discern the technical and spatial characteristics of a product, and in the case of a service, its respective functional, applicative, and technical architectures, as well as its modes of functioning and interactions with the transit infrastructures and services already in place in the territory.

In other words, an interdisciplinary research center provides knowledge that is essential to innovation in the system concerned. Innovation also requires a desire, an aspiration, that some researchers may individually possess, so that they join the ranks of designers-innovators. Another favorable condition is cooperation between research and education: The student body may include learners with a vocation for innovation and entrepreneurship.

Since experimentation is a fundamental component of knowledge development, researchers are also competent and well equipped to contribute to experiments:

- For the design of an experimental protocol, its embeddedness in the territory and in the sphere of information: what information to collect, from what sources and under what practical conditions, while ensuring that observation does not disrupt the performance of the system;
- For the analysis of results: eliminating noisy observations, exploiting the remaining observations using statistical methods, and identifying essential features, factors of success or failure, qualification in terms of particular conditions.

Reciprocally, a LL offers researchers an extremely stimulating opportunity: as a big localized structure for observation and experiment, with both scientific and service components. For urban mobility, this is a truly unique opportunity, since concentration on a site makes it possible to grasp the relations between mobility and its urban context.

The observation of mobility as a phenomenon is an opportunity to identify regularities and stylized facts, which lays the groundwork for the development of theories.

Intensive observation also lends itself to the development of methods of analysis. One priority application is the calibration of simulation models—particularly economic and technical submodels—within a traffic assignment model.

The innovations to be designed may relate to the end users of mobility, which is of interest to the human sciences, or the intermediate stages, i.e., technical subsystems, which is of interest to engineering sciences. Management sciences have an interest in every stage.

Interdisciplinary cooperation leads to cross-fertilization, the effects of which develop over time to the benefit of all parties.

Finally, the cooperation between partners is enriching: The in-depth knowledge of the terrain and users held by local authorities, the specialist expertise of operators, and the creative spirit of designers stimulate the emergence of topics for research projects.

10.3.4.7 Recapitulation

To sum up, we have set out the general principles of a LL: fruitful cooperation between partners with complementary skills and roles, around a location site chosen as a place of observation and experimentation, for the analysis and design of innovative products or services.

We have concentrated on the case of urban mobility, identifying the specific interests of each category of stakeholder: The framework of a LL offers opportunities for each category, and reciprocally, the involvement of those stakeholders is a key factor for the success of the LL.

Mobility as a sociotechnical phenomenon is a valid focus for an urban transit LL, rather than a single particular mode of transportation. This is because, with regard to their mobility needs, end users see travel options as a multimodal package. In addition, transit modes run in technical interaction, and the more massive the respective exchanges and flows, the stronger the connection.

Reciprocally, the territorial embeddedness of a LL is particularly fruitful in relation to urban mobility, allowing it to be understood in context.

We have also pinpointed the benefits of partnership: complementarities and synergies between the respective competences of local authorities, including transit regulation, road and mobility service operators, designers-innovators, and researchers.

For the public authorities and private operational partners, a LL is useful at any time, if for nothing else than as a snapshot of the current status of the system that they contribute to manage. The same is true for researchers, for purposes of empirical observation and theorization.

Innovation and its dynamics constitute further motives, both because existing systems can undoubtedly be improved and because the digital era is rich in potential for change. Changes will include the renewal of existing technical forms, the emergence of new technical forms, also the renewal of the social forms of mobility, and the composition of new logistical lifestyle patterns (e.g., online shopping and delivery, instead of buying and carrying).

Finally, we highlighted the potential of a multimodal assignment model and more broadly of an arsenal of simulation models:

- To provide qualitative and quantitative knowledge about the operational status of the system in question, assessing it, and identifying the sequence of cause and effect, and structure, composition, and system effects;
- To conduct virtual experiments on products/services in terms of potential customers and consumption, and impact on the overall operation of the system. And therefore, to contribute to the forward development of the product/service;
- To complete the experiment in situ, deduce its impact on the rest of the system, and contribute to its retrospective assessment against a set of criteria;
- Reciprocally, the availability of an instrumented site is an ideal opportunity to improve the empirical validity of models. A comparison of real observations and simulation results is one obvious application. Going further, a LL is a way to observe reality in individual components or subsystems, i.e., at a more fine-grained level.

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