An Overview of Multimodal Transport Design and Challenges Underlined by a Carsharing Case Study

Aurélien Carlier, Fabien Tschirhart, Frédéric Da Silva, François Stephan, Olivier Thoni, Alix Munier-Kordon, Manel Abid, Lionel Scremin, and Ludovic Couturier

Abstract. This paper covers some of the main aspects of multimodal transportation design (fundamental elements, topology and some existing approaches) before introducing the numerous and various challenges it poses, as a system of systems: legal and business aspects, demand prediction and multimodal planning and supervision. As an illustration, it then highlights some challenges specific to carsharing such as coping with supply, performance and patterns of the existing multimodal transportation system. Finally, using graph theory and mathematical programming, the paper studies a theoretical model to design and to optimize such a carsharing system.

Keywords: multimodal transport, carsharing, operational research, graph theory, system of systems.

Aurélien Carlier · Fabien Tschirhart · Frédéric Da Silva · François Stephan
Technological Research Institute SystemX, Palaiseau, France
e-mail: {aurelien.carlier,fabien.tschirhart,
frederic.dasilva,francois.stephan}@irt-systemx.fr

Aurélien Carlier
Renault SAS, Technocentre, Guyancourt, France
e-mail: aurelien.carlier@renault.com

Olivier Thoni
Artelys, Paris, France
e-mail: olivier.thoni@artelys.com

Aurélien Carlier · Alix Munier-Kordon
Université Pierre et Marie Curie, Paris, France
e-mail: {aurelien.carlier,alix.munier}@lip6.fr

Manel Abid · Lionel Scremin
Alstom Transport, Saint-Ouen, France
e-mail: {lionel.scremin,manel.abid}@transport.alstom.com

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1 Introduction

In the broadest sense, multimodal transport refers to the transportation of goods or passengers performed via a transition between two different transport modes (*e.g.* rail and road). In light of the growing need for individual mobility, multimodal transportation evolves as a combination of numerous transport modes from collectives' means to individual vehicles. Both conflicting undermined limits in terms of capacity, performance and accessibility. The challenge of multimodal transportation system engineering lies in the optimization and the interoperability of intermodal passenger transport through the appropriate modelling and simulation.
Despite the existence of proper and efficient tools to handle each transport mode, the aggregated behavior of a multimodal system cannot be trivially deduced from the separated behavior of every single component. As such, we may consider multimodal transport as a system of systems, composed by a large amount of different entities, where each one has its own behavior and evolution rules, showing emergent properties.

As there is no coordination either between entities or through a common nexus, theses emergent properties cannot be considered as the result of a huge system's central planning. While its dynamics may be very complicated and include phase transition behavior (*e.g* the different flow regimes of car traffic), as its entities are hierarchically structured in a modular architecture with reproducible and programmable patterns [1][2], a multimodal transport cannot be considered as a random or a chaotic system. Hence, it fully justifies the necessity of new and more adapted models and tools to deal with this complexity of a new kind with a holistic approach. After a short introduction to multimodal transportation we will outline its main challenges: the governance organization, modelling the travel demand, following a sustainable business model, planning and supervising the network. As an illustrative purpose, we shall then discuss the case study of carsharing, which, as an emergent mode, has to consider all the different aspects of a multimodal transportation system.

2 Multimodal Transportation Design

2.1 Definition

In our study, we consider a large transport network that provides to people both public (*i.e* metro, tram, train, carsharing…) and private (*i.e* car, bicycle, walk…) transport modes as well as their corresponding operators and systems. [3] considers transportation systems as a network made out of routes or terminals : routes are simply links between two nodes, which are, as terminals, the contact or exchange points where it is possible for people to either switch to another mode, to enter the system or to leave it. On the basis of those elements, we may identify three main elements of a multimodal transportation system: travelers, transport modes, operators.

A multimodal transportation system is simply a set of transport modes which travelers may use to reach their destination from their origin. Fig. 1 shows an example of a multimodal trip in comparison with two mono-modal trips.

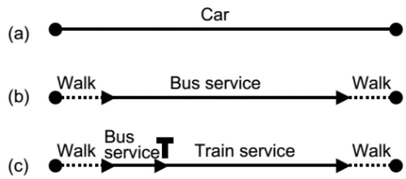

Fig. 1 (a) and (b) are mono-modal trips, and (c) is multimodal trip where T denotes the transfer point from the bus mode to the train mode.

As they are an unavoidable step for travelers to switch from one mode to another, there is no possible multimodal system without transfers. A transfer node may be used to change modes (car to train) or services (tram to train). Since multimodal transport is strongly related to transport services, in the context of public transport the term mode will be usually related to service modes. Finally, the role of walking is essential to almost any trip within a multimodal system as no transfer is possible with no walking, in addition to the necessity to walk to leave or to get into the network.

2.2 Topology and Design

When designing a transport network, two categories are considered:

- the transport service network, such as the bus or the train service network,
- the physical network, such as the road or the railroad network.

If there is a clear evidence that a bus service network is based on a road network, from the traveler's point of view, however, it will only matter whether a bus can be used for his trip. When using a transport service, any constraint that could arise from the physical network are incorporated into the transport service. However, the physical network will often determine whether a private mode is feasible for a specific trip.

The most common approach that is being used to describe a transport network is to define the network as a set of nodes connected with a set of links. Usually, a subset of nodes is used to identify access (entries and exits) and crossing nodes. Representation may include public transport lines that is a set of connected links and their nodes, and associated frequencies. It is especially suited for transportation modelling.

2.3 Some Modelling Approaches

It appears no models or algorithms are available or suitable for large-scale transport systems that simultaneously consider private and public transport networks.

Research in traffic theory encompasses an interesting set of models that can be classified, from a physical point of view, into road and rail, and from a functional point of view, into private and public modes.

Regarding road traffic flow models, there are three different descriptions of the vehicular dynamics: microscopic models, cellular automata and macroscopic models. The major advantages of macroscopic models are their tractable mathematical structure and their low number of parameters, making them faster to compute. Because of this and due to the dimensions of transport networks, macroscopic models are generally preferred over the other two. Among them, one distinguishes first-order models, second-order models, and multi-class models.

One of the most important traffic flow model is the LWR (Lighthill-Whitham-Richards) model [4], built on the analogy between road traffic flow and hydrodynamics. Thus, it does not take into account the driver attributes, while this is the case with second-order models like ARZ (Aw-Rascle-Zhang) [5] or the models of Lebacque et al. [6]. These models comprise number of elements specific to drivers such as destination, type of vehicle and behavioral attributes.

Multi-class models are from the most recent traffic flow macroscopic models. They follow the apparition in the other approaches of multi-class models. One distinguishes different classes regarding the driving behavior (desired velocity, driving style), the vehicle properties (essentially the length) and the route (destination). One can find a significant number of multi-class models [7] using different relations and algorithms.

Due to the considerably smaller number of vehicles on a railroad traffic network (in comparison to road traffic), most of models for railway traffic are microscopic. As the standard, Moving-Block systems [8] divides the railway into multiple areas, each being under the control of a computer. While operating, each train is continuously connected to the latter, so that it knows the location of every train at all time. Then, it transmits to each train the required braking curve to avoid a collision even if the leading train comes to sudden halt. Known as Pure Moving-Block (PMB), this scheme of moving-block gives the best performance and is the basis of all currently implemented systems.

3 Challenges

3.1 Governance

Today, Organizing Authorities of Urban Transports skills for the organization of transport services are, at the request of individuals, limited to regular transport. For the sale of enforcing a consistent and sustainable mobility policy, transport authorities need to extend their skills in areas affecting travel policies such as shared automotive uses and non-motorized transport modes, freight transport in the city, as well as the regulation of traffic and parking. That’s why the French government undertook a reform (Law No. 2014-58 of 27 January 2014) to transform Organizing Authorities of Urban Transports into Organizing Authorities of Urban Mobility.

3.2 Demand Prediction

Travel demand modelling is one of the major building blocks for the study of the transport process. Its core objective is to produce relevant information on the potential impact of new transport infrastructures or policies on travel demand. Such information is pivotal for assessing the benefits of such projects and policy measures and to estimate their possible environmental impacts.

The fundamental approach for modelling the multimodal travel demand is the so called **4-step models** [9] [10] or sequence of models. The steps are: Trip generation, Trip distribution, Mode choice and Route assignment. Travel demand modelling refers to the first 3 steps, the last one being related to the field of traffic modelling.

4-step models are the dominant framework for operational transportation planning and policy analysis, insofar as they perform reasonably well in representing and forecasting aggregate travel demand. However, when the problems under study become more disaggregated, they may be less relevant and this shortcoming has led to the development of activity-based models. As opposed to the 4-step approach, **activity-based models** include a consistent representation of time, a detailed representation of persons and households, time-dependent routing, and micro-simulation of travel demand and traffic. This type of approach allows for a more realistic modelling of travel decisions. It provides an improved capability to model non-work and non-peak travel, to move beyond traditional explanatory zonal variables and to deal with matters like trip chaining, car sharing or links between household members.

3.3 Planning

Planning process can be classified into four steps (see [11] for an example in traffic train context):

- Strategic: crew planning (2-5 years), rolling stock acquisition, etc.
- Tactical: rolling stock scheduling (1 per year), train scheduling (1 per year), etc.
- Operational: crew scheduling (4-6 per year), timetabling (4-6 per year), etc.
- Short-term: crew scheduling (daily), timetabling (4-6 per year), etc.

One of the biggest challenges in transport planning lies in having an overall consistency between each mode. Currently, each mode has its own planning. For example, in case of perturbation, the report from one mode to another can generate heavy problems on this one. So it's really necessary to have predictive modelling capacities to be able to anticipate problems and to test strategies that will be directly exploited in short-term planning.

3.4 Business Model

The ecosystem of urban transports is composed by a lot of public and private actors. A simple enumeration of these different actors is not enough to describe the complexity of a transportation system. Indeed, relations between these actors imply other considerations (for example: juridical or economic aspects).

In fact every business actor optimizes its own business. But for a global optimization of the multimodal transport system, an optimized combination of transport modes is requested. That's why the real challenge lies in having a generic model that describes the complete framework of the urban transports ecosystem. Thanks to this kind of model, it's possible to simulate economic transfers between actors and to optimize and compare different scenarios of a multimodal transport system.

3.5 Multimodal Supervision

Multimodal supervision raises many challenges because it involves the monitoring and the control of several modes that differ in various ways including their availability, density, costs, etc. Indeed, these modes are not perfect substitutes, each one is more appropriate for specific users and uses. Hence, the real-time coordination and synchronization of system as a whole may easily become a very complicated task. From the end users point of view, the challenge is to guarantee mobility with an expected quality of service, whatever the conditions. From the legal point of view, the challenge is to make the stakeholders cooperate on a contractual basis. From a business point of view, the big challenge is to define operational strategies and solutions with global optimization criteria.

4 Carsharing, a New Transportation Mode at the Crossroads of All Challenges

This part will deal with a specific use case of a carsharing system. It's an interesting new emergent transport mode that handles all the previously described challenges.

4.1 Presentation, Urban Impact and Challenges

Since the mid-twentieth century, the greater accessibility to the private car in industrialized countries has significantly improved the people mobility in urban areas. While this new mode of transportation greatly helped societies realize their aspiration for growth and prosperity, it also resulted in serious negative externalities: pollution, excessive consumption of energy and time due to congestions problems, etc. To control, manage and deal with those problems, a lot of efforts are made to found alternative solutions [12]. One of them is carsharing system which involves a small to medium fleet of vehicles, available at several stations distributed over a given geographic area, to be used by a relatively large group of members [13]. Although the first identified carsharing system appeared around the mid-twentieth century, such systems became popular worldwide since the early 1990’s. They represent a real alternative to private car and release the user from constraints related to individual property since the carsharing company is in charge of insurance, maintenance, fuel (or electricity), taxes, depreciation, etc. Different studies (see for example [14, 15]) have evaluated that for a user driving less than 10,000 kilometers per year (as much as 15,000 km/y), it also could be a real alternative to private car, in a financial way, depending on local costs. Since then, we can found over the world two different types of carsharing systems.

Historically, the first one requires users to return vehicles to the station they were picked up. These are called “round-trip” carsharing systems and are the most common. They are simple to manage since the demand for each station is enough to dimensioning the station. The user behavior in such systems is mainly oriented to leisure and household shopping purpose ([16, 17]). The second one, called “one-way” carsharing system, is much more flexible for the user since it allows the latter to pick up a vehicle from a station and return it in a different one, which can be different from the origin. Unfortunately, this greater flexibility comes with hard operational problems due to the uneven nature of the trip pattern in urban areas. However, it is worth mentioning that despite these difficulties for the operator, one-way system captures more trips than the alternative system thanks to this flexibility which is, as showed in [18], a critical factor to joining a carsharing scheme. In the last decade, several authors have showed that these systems have a positive impact on urban mobility, mainly because of higher utilization rate than private vehicle ([14, 19]). Indeed, shared vehicles spend more time on the road and less time parked (which represent for a private car almost 95% of its total use time, as mentioned in [20]), thereby decreasing parking requirements in dense areas [12] and reducing the average number of vehicles per household ([21, 22]). It also decreases the total number of vehicles on the road, since one vehicle can be driven by several users and thus improving the traffic fluidity. Furthermore, it’s now recognized that carsharing systems have positive environmental effects. It reduces greenhouse gas (GHG), CO_2 emissions ([23, 24]) and provides noise reduction since electric cars are quitter than thermal ones. The reduction of parking demand can also be used to reallocate the land for additional green spaces, new mixed-use development, or other community needs [25].

Thus, carsharing systems seems to be a very attractive and profitable solution for transportation issues, improving on the one hand the global transportation system efficiency in dense areas and bringing on the other hand a significantly ecological impact in the urban environment. As mentioned in [26] and because of their relatively recent emergence, they must be devised taking into account the specificities of the whole multi-modal transportation system: the existing supply, its operational performance, the inter-relations between existing modes, the economic associated models, the travel patterns and behaviors of the travelers, etc. This is a real challenge, not only because of the modelling complexity of such systems, but also due to the collect and the estimation of realistic data concerning a lot of different aspects, from the most strategic to the operational. It's now known that a lot of travels through the transportation system are using more than one mode and any user of a given mode can almost come from any other existing mode. Then it turns out that in order to tackle the dimensioning of a carsharing system, it's crucial to be able to describe and capture the amount of demand that switches over modes, taking into account departures/destinations, existing multi-modal infrastructure and time.

4.2 Case-Study: Dimensioning Carsharing Fleet within a Multimodal Transportation System

The problem discussed here consists in finding the optimal configuration, in terms of stations size and fleet size, of a set of possible carsharing stations when demand and travel times are given over time. As several studies (see for instance [27–29]), we will use graph theory and mathematical programming to tackle this problem, attempting to integrate their results and recommendations. A lot of them integrate relocation operations between stations that, as showed in [30, 31], allow the operational system to reach an efficiency level that cannot be achieved otherwise. This characteristic seems then necessary since we are interesting in the best system performance although it comes with many challenges, especially in terms of complexity and computing time.

However, we want to introduce here some differences with previous research. Most of them tried to maximize the carsharing operator revenue, whereas we will focus on the system efficiency in terms of number of demand it can handle. In our view, it could also be very interesting to design the carsharing system taking into account multiple objective optimization. We selected three criteria: number of satisfied demand, number of relocation operations and number of vehicles.

The main idea is to consider a Time Expanded Graph (TEG), introduced in [32], where the nodes represent the stations over a given set of discrete time-steps $\mathcal{H} = \{0, \dots, T\}$ and arcs symbolize the "movements" of vehicles. These are defined through three distinct sets. A first one called E_1 represents the vehicles parked in stations between two consecutive time-steps. In that case, arcs could be viewed as a stock rather than a movement. The capacity on these arcs are fixed to the maximum station size (number of parking slots). Then, a second set E_2 will capture the demand of vehicles from a station to another at a given time-step. This time, the capacity is set to the number of vehicles required to that specific demand. Finally, a third set E_3 will represent the possible relocation operations of vehicles between each pairs of stations for every time-step. This last set admits infinite capacities on its arcs. Arcs of E_2 and E_3 are defined such that the time step of each destination node correspond to the departure time-step from origin station plus the time that a passenger would make to do the trip, including penalties depending on the travel context, as congestion for instance. Fig. 2 gives an example of these sets.

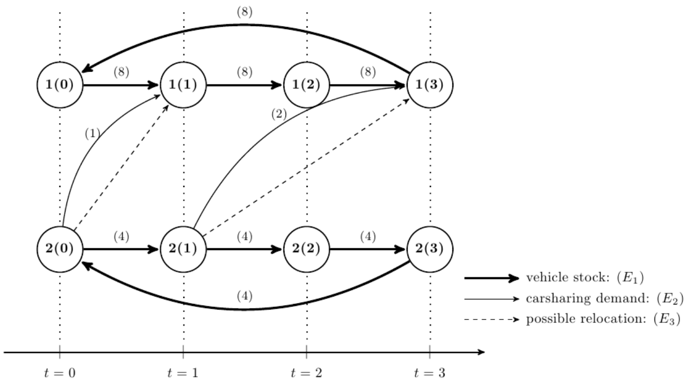

Fig. 2 Time Expanded Graph example for the carsharing fleet dimensioning problem with two stations and four time-steps

Fig. 2 *r*epresents the time-states of two stations named "1" and "2" placed horizontally over four time-steps. Capacities are put in brackets over each arcs, except those of relocation operations. The arc of demand which starts from node "$2(0)$" to node "$1(1)$" means that a possible passenger wish borrow a vehicle from station "2" to station "1" at time $t = 0$. The same reasoning stands for all the arcs of demand and relocation. Let's also note the cyclical aspect of the resulting graph. All the arrival time-steps used for the arc definition are calculated modulo T such that the time space $\mathcal{H}$ must represent a classical and homogenous time situation, as an average week day for example.

Thus, the resulting problem consists in finding a maximal flow of vehicles transiting through the graph, maximizing the sum over the arcs of demand and respecting the classical constraints of flows problems: capacity constrains over each arcs and flow conservation over each nodes. Every cut between two distinct time-steps will give the number of vehicles used in the system.

Using a random generator, which produce such time-expended graph with realistic data, we started looking problem solutions with the open-source linear programming solver GLPK [33]. A good manner to study multi-objectives optimization is to use Pareto frontiers. Thus, we present thereafter a 3-dimentionnal Pareto frontier giving optimal demand for different values of two other objectives (total number of relocations operations and total number of vehicles transiting through the system; see Fig. 3). The later both objectives are intended to be minimized, while we are interesting into the greater number of satisfied demand. The instance generated is a simple case study: 50 demands over 3 stations during 144 time-steps (an entire day with a time-step each 10 minutes). The travel times take into account two key moments of a classical week day in our urban area: morning and evening rushes. For those time slots, penalties are integrated in the travel time computing process in order to be more realistic.

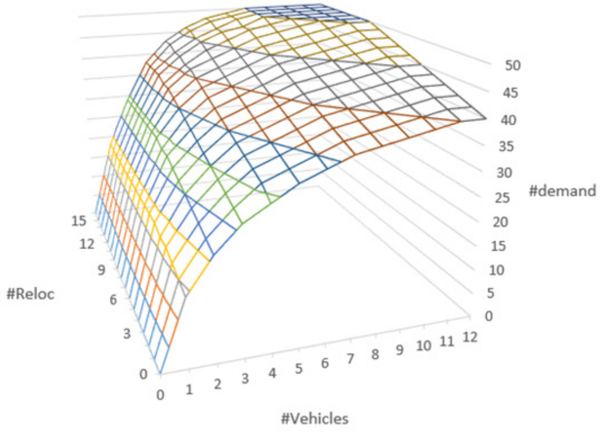

Fig. 3 3-dimentionnal Pareto frontier of a case-study generated instance

As expected, the more relocation operations or vehicles in the system, the higher the satisfied demand. The different colored strata provide a first insight of the front looks for different range of demand values. Number of vehicles allowed during the optimization also seems to have more impact on the demand than the number of relocations, while appearing to be correlated. Further research will clarify such link between the two objectives as well as testing the optimization computing on bigger instances with real data. Actually, first numerical results on those topics are currently pending publication. Also, future research shall look forward to investigate the system's behavior when relocation operations are done with autonomous cars.

5 Conclusion

From the previous study, it appears that dimensioning and optimizing a car sharing system cannot be trivially deduced from the desired behavior of every single vehicle of its fleet. Indeed, such a system has to handle many different factors and issues specific to multimodal transportation: from both the designing and the topology; but also to the various challenges we previously outlined: in terms of governance and demand prediction, planning, business model and supervision. Also, in the case of multimodal transportation, finding optimal solutions for a specific mode is probably not be possible as long as it is sidelined [26]. Consequently, considering multimodal transportation as a system of systems will allow the simultaneous integration and merging of multiple transport modes. This is the research scope of the MIC (Modelling-Interoperability-Communication) project within Technological Research Institute SystemX which is looking forward to enabling the sizing, the positioning, the optimization and the supervision of multimodal mobility systems, using simulation models.

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