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A simple representation of a complex urban transport system based on the analysis of transport demand: the case of Region Ile-de-France

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Abstract

In densely urbanised areas the structure of the transport systems becomes quite complicated. Many types of transport services are available and many types of modes are being used, thus offering a wide palette of transport options. How do all these transport services and modes relate to each other? In practice it proves to be quite hard to define such a structure. A number of classifications exist, based on transport modes, or on organisational characteristics. However, they often lack a theoretical underpinning, which makes them not always easy to apply in practice.

This paper presents a new methodology that focuses on the traveller's perspective: how does the traveller use the many transport services and modes that are available? This method to determines the functional structure of a transport system on the basis of observed trips. This method is illustrated for the case of Region Ile-de-France, the urban area of Paris, using household travel survey data.

The methodology consists of three steps. First, transport services and modes are grouped into "service modes", which are homogenous from the perspective of travellers. Second, the zones served by each service mode are identified. Third, the relationships between the service modes are identified: Spatial complementarity; Hierarchical relationship (combining a fast mode with a scarce network and a slow mode serving a dense network); and Competition. As a result, we obtain a strategic representation of the structure of the urban transport system of Region Ile-de-France.

Keywords: Public transport; systems analysis; network structure; network hierarchy

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1. Introduction

In large urban areas, travellers can use and combine several transport modes to achieve trips. These modes can be private (walk, bicycle, motorcycle, car, etc.) or public (bus, tramway, metro, intercity train, etc.) or somewhat hybrid (taxi, car-sharing, on-demand transport, etc.). In a given urban area, each mode allows travellers to move among a given set of locations, and travellers can combine two modes or more – thus making multimodal trips – in order to reach destinations which would otherwise be inaccessible (at all, or within a reasonable travel time).

The transport systems of large urban areas are characterised by their complexity. This has a direct consequence in terms of planning and operation: a decision concerning a line, a service, or a mode (e.g. the frequency of a given bus line, or the width, or speed limit, of a given street) influences the whole transport system. Three types of impacts can be distinguished: first, on the demand for the mode itself, through re-routing, and possibly induced demand; second, on competitive modes, mainly through mode shift; third, on complementary modes, e.g. when two modes or more are used together to achieve multimodal trips, a modification of the first mode can have an impact on the demand for the other modes (on these effects, see e.g. Ortuzar and Willumsen, 2001; Quinet and Vickerman, 2004; Jara-Diaz; 2008.)

Despite, or due to, this complexity, designing a correct model of a global urban transport system is in many respects essential to assess correctly the impact of planning decisions. It might be over dimensioned for marginal changes; but it is required for strategic decisions implying large-scale, significant and irreversible impacts. In particular, it is crucial that the relationships between the transport modes are correctly understood.

For example, in order to determine if the average stop spacing of the metro in a given area is adequate, one should be able to assess the impact of that variable on the whole transport system, not only on the metro alone. This applies to planning decisions, as well as to all kind of strategic operation decisions (such as pricing, frequency, etc.) especially if they impact a large perimeter. Unfortunately, cost-benefit studies often disregard the interactions between modes. They are generally limited to a single line, based on the principles presented in Mohring (1972), and reviewed and improved in Jara-Diaz and Gschwender (2003). Network-based approaches are more recent (Holroyd, 1965; or, more recently, with a review of intermediate works, Daganzo, 2010), but less frequent, and are limited to a unique network. Multimodal approaches to optimal network structures are still rare; an example is Van Nes (2002).

One could argue that the transport system of a large urban area is of so complex that modelling it in a both usable and realistic way is unfeasible. This difficulty might be overestimated. As a matter of fact, the objective of this paper is to illustrate how, by a simple statistical analysis of a transport survey, it is possible to derive a simple and realistic representation of the complex urban transport system of a large urban area. This is illustrated with the case of the urban area of Paris, also known as Region Ile-de-France. Thanks to a detailed analysis of a travel survey of Region Ile-de-France, we identify the structure and the main characteristics of the urban transport system of Region Ile-de-France.

The paper proceeds as follows: first, some definitions and concepts useful to the global analysis of transport systems are reminded in Section 2. Then, Region Ile-de-France is briefly described in Section 3, together with a short description of the transport survey EGT 2001, which is used in the remaining of the paper. Section 4 presents the detailed analysis of the transport survey, and its outcome is summed up in Section 5. Section 6 eventually concludes the paper.

2. Concepts and definitions

When addressing complex objects such as urban transport systems, it is useful to identify their components, to study their properties, and their relationships. In this paper, the distinction of components is based on the preferences of travelers. From their perspective, the relevant characteristics of a transport service are its availability at the origin and destination, its speed, price, accessibility, and more generally its level of service. Transport services sharing similar characteristics are grouped within categories called "service modes", on which the distinction below is made, together with geographic areas.

Geographic area. Large urban areas do not consist of a uniform, isotropic land-use pattern associated to an equally uniform transport demand. Thus, it is important to keep track of the spatial context of a given transport service. Insofar as we opt for a global approach, a basic segmentation is sufficient, particularly if transport services and demand are sufficiently homogenous inside each zone.

Service mode. Transport services differ by many characteristics. They are traditionally regrouped with respect to their production technique (the corresponding categories are the *vehicle modes*). In this paper, the perspective of travelers is prioritized. The transport services are categorized into groups called *service modes*, characterized by a relative homogeneity regarding their level of service. Vehicle mode and by service mode are close notions, but not strictly identical. In some cases, two categories of transport services are produced with the same technique, and yet differ substantially from the perspective of travellers: this can be the case of omnibus train services, and intercity trains; in other cases, two distinct techniques can produce similar transport services, such as the tram and the bus in some cities.

Then, many definitions stem naturally from the concept of service mode:

- A *multimodal trip* is a trip where a traveller uses two distinct service modes (excluding walk).
- The *leg* of a trip is a part of a trip during which the traveller does not change of service modes. As a consequence, monomodal trips consist of a unique leg, whereas multimodal trips contain two legs or more.
- The *main mode* of a multimodal trip is the service mode used on the longest leg of the trip.

One word should be said of the notion of *hierarchical relationship* between service modes. Consider a service mode serving sparse stations, but at a high commercial speed, and another service mode with many stations and a low commercial speed. The first mode is there for long trips, while the second one allows local trips, as well as access to the first mode. In that situation, the two modes share a hierarchical relationship. In general, a hierarchical level can be associated to each service mode. For a given transport system, it is crucial to identify the number of hierarchical levels, and the hierarchical relationships between the modes.

3. Description of Region Ile-de-France and of the EGT 2001 database

Region Ile-de-France contains the French capital Paris. About 11,746,000 inhabitants live in Region Ile-de-France in 2009, on an area of 12,011 km², for an average density of 978 /km². The land-use pattern of Region Ile-de-France is mainly monocentric. The geographic segmentation used in this paper is coarse, but sufficient for our purpose. Region Ile-de-France is divided into three main zones, namely "Paris", the "Petite Couronne" (PC, or close periphery), and the "Grande Couronne" (GC, or distant periphery). The public transport infrastructures of Region Ile-de-France consist in 2009 of 1,525 km of regional train and RER lines, 217 km of metro lines, and 42 km of tramway lines. Besides, 24,660 km of bus lines are available to the travelers (OMNIL, 2009). The inhabitant density, the geographic segmentation and the heavy infrastructure networks are visible on Figure 1, with a zoom on Paris.

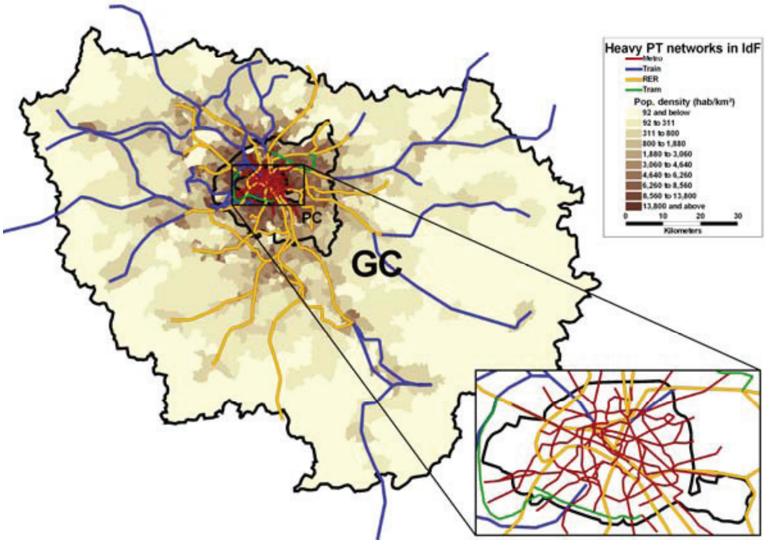

Fig 1: Heavy public transport networks in Region Ile-de-France in 2008

There are a total of 35.2 millions trips per day in Region Ile-de-France in 2001; the average number of trips per day for individuals aged of six years or more is 3.5. The total distance covered is 165 million pkm, and the average length of the trips is 4.70 km. These trips can be analyzed in more detail thanks to the EGT 2001 database. EGT 2001 is the latest travel survey available for Region Ile-de-France. It concerns all individuals of age six or more living in Region Ile-de-France. It consists of four tables, describing respectively 10,478 households, the 23,656 individuals constituting these households, the 81,386 trips made by these individuals during the time of the survey, and the 104,541 legs constituting these trips.

This database is therefore particularly adapted to the analysis of how travelers realize their trips. Note that the notion of mode used in the EGT is that of vehicle mode. A conversion was thus realized to transform vehicle modes into service modes. This identification is based on the qualitative knowledge of the authors of urban transport systems and of Region Ile-de-France, and on the data available. The categories resulting from this conversion are: Car driver, Car passenger, Regional train, RER , Metro, Tram, Bus, Motorcycle, Bicycle, Walk, Other.

4. Transport demand analysis

The identification of the functions and relationships of the service modes proceeds in three steps: first, the trips are analysed in general in Section 4.1, with a focus on multimodality. Second, multimodal trips are examined in more detail in Section 4.2. Close attention is paid to the extremities of the trips. This is completed by a basic geographic analysis of travel demand in Section 4.3.

4.1. General analysis

Table 1 gives the proportion of trips by main mode, with their average length, the proportion of multimodal trips, and finally the average length of multimodal trips per main mode.

Table 1: General analysis of trips (the table reads as follows: for 1.94% of all trips, the main mode is Regional train; 79.71% of these trips are multimodal; they are 19.99km long on average and the multimodal ones are 22.51 km long on average; there are 1,308 multimodal trips with Regional train as the main mode in the data)

Main mode	Frequency	Prop. multi	Length	L multi.	N. multi.
Regional train	1.94 %	79.71 %	19.99	22.51	1,308
RER	4.86 %	74.58 %	15.22	16.16	2,783
Metro	6.51 %	16.79 %	5.11	7.91	710
Bus	6.66 %	7.90 %	3.87	8.54	390
Tram	0.18 %	44.80 %	5.37	7.55	57
Car driver	35.25 %	0.12 %	6.75	17.71	37
Car passenger	10.19 %	0.58 %	4.96	17.21	48
Motorcycle	1.26 %	0.10 %	7.13	11.59	1
Walk	31.81 %	0.03 %	0.55	4.73	5
Other	0.42 %	1.13 %	5.76	5.76	4
Bicycle	0.90 %	0.00 %	1.94	-	0
All	100.00 %	6.99 %	4.70	15.60	5,343

Table 1 is already informative regarding the transport network. First, the average trip lengths show that the service modes clearly do not have similar functions: the metro and bus networks are used to make much shorter trips than, say, the regional train network. The heterogeneity of service modes is also illustrated by the proportion of multimodal trips for a given main mode. The private modes (car driver, car passenger, motorcycle, and bicycle) are virtually never the main modes of a multimodal trip; whereas the heavy public transit modes (regional train and RER) are used to make long trips, and are almost always part of a multimodal trip. There is finally a third category: public transport modes (metro and bus) which are generally used alone, when they are the main mode. These observations suggest the existence of hierarchical relationships, particularly between public transport modes. Note that this analysis lets the tramway aside; due to its marginal role in the public transport system of Region Ile-de-France, it has a sort of hybrid status which makes its analysis delicate. This is somewhat confirmed by Table 2, where the contributions of the modes to multimodal trips are given.

Both the metro and the bus appear to play an important role in the transport system by the possibility they offer to travelers to use other transport modes. Indeed, the metro and the bus are most often used in multimodal trips without being the main modes. Also, the private modes, the car in particular, are seldom involved in multimodal trips. At this stage, it is legitimate to state that private modes and public modes share a mainly competitive relationship in Region Ile-de-France. Besides, it can be observed from Table 2 that one fourth of the total distance covered by travelers is done in the frame of a multimodal trip. The role of multimodality in the transport system of Region Ile-de-France is thus important, more important at least than the mere proportion of multimodal trips (6.99 %) can let imagine.

Table 2: Contributions of service modes to multimodal trips (the table reads as follows: 82.85% of trip legs made by Regional train are part of a multimodal trip; 89.53% of kilometers made with Regional train are part of a multimodal trip; there are 1,929 trip legs made by Regional train in the database)

Service mode	Contribution	Contrib. wt. by L.	N
Regional train	82.85 %	89.53 %	1,929
RER	76.23 %	78.70 %	4,382
Metro	45.14 %	41.07 %	6,492
Bus	41.25 %	37.66 %	7,972
Tram	73.59 %	71.67 %	270
Car driver	2.23 %	1.48 %	30,440
Car passenger	4.96 %	4.22 %	9,124
Motorcycle	0.41 %	0.18 %	953
Walk	12.13 %	4.22 %	40,579
Other	25.76 %	4.11 %	480
Bicycle	5.76 %	0.36 %	714
All	18.75 %	25.05 %	103,335

4.2. Analysis of the home-based and activity-based parts of multimodal trips

This section analyses in detail the service modes used in multimodal trips, and particularly the non main modes. To do so, the concepts of home-based part and activity-based part of multimodal trips are introduced. The home-based part of a trip is defined as all the legs between the home of the agent (identified by the motive of the trip at the corresponding end) and the main leg of the trip. The activity-based part of a trip consists of all the legs between any end of the trip which is not the home of the agent, and the main leg of that trip. Note that the home-based or the activity-based part of a trip may be empty. In addition, a trip can have two activity-based parts. Consider the following example: an agent makes a RER-bus-car trip from its work to a retail center, with RER as the main mode. Then the trip has two activity-based legs, and one of them is empty. The home-based and activity-based parts of multimodal trips are analysed in Tables 3 and 4.

These two tables allow the identification of the hierarchical relationships in the public transport system. Let us first focus on the heavy public transport modes. Trips by RER and regional train are both long and multimodal. Furthermore, they are virtually always the main modes of the trips during which they are used; the home-based and activity-based parts of these trips are made with other modes. From these observations, it is possible to conclude that the RER and the regional train are high-level modes, which allow passengers to cover long distances, and that other modes are necessary for passengers to use these heavy modes. On the contrary, bus, metro and, to a lesser extent, private car are the modes used most frequently for the home-based and activity-based parts of these trips: they are the modes by which passengers access the heavy public transport networks. This is consistent with the fact that their contribution to multimodality, as measured in Table 2, is much larger than the proportion of multimodal trips made with these modes, as measured in Table 1.

Table 3: Analysis of the home-based parts of multimodal trips (the table reads as follows: 68.05% of Regional train trips have a non-empty home-based part; the average length of these home-based parts is 4.68km; the most frequent mode of these home-based parts is Bus, with a frequency of 49,17%; the second one is Car driver, with a frequency of 22.40%; this corresponds to 794 observations in the data)

Main mode	Prop.	L (km)	1st Mode	2nd Mode	N
R. train	68.05%	4.68	Bus (49.17 %)	Car D. (22.40 %)	794
RER	68.96%	3.79	Bus (53.19 %)	Metro (16.77 %)	1,719
Metro	84.27%	2.53	Bus (75.70 %)	Car D. (5.95 %)	525
Bus	43.38%	3.09	Metro (23.77 %)	Car P. (20.77 %)	154
All	68.81%	3.72	Bus(54.08 %)	Car D. (13.71 %)	3,261

Table 4: Analysis of the activity-based parts of multimodal trips (the table reads as follows: 74,72% of Regional train trips have a non-empty activity-based part; the average length of these activity-based parts is 4.21km; the most frequent mode of these activity-based parts is Metro, with a frequency of 47,26%; the second one is Bus, with a frequency of 20.38%; this corresponds to 1,089 observations in the data)

Main mode	Prop.	L (km)	1st Mode	2nd Mode	N
R. train	74.72%	4.21	Metro (47.26 %)	Bus (20.38 %)	1,089
RER	65.61%	2.98	Metro (63.05 %)	Bus (24.93 %)	2,033
Metro	28.91%	2.23	Bus (73.25 %)	RER (9.91 %)	224
Bus	57.54%	3.86	Metro (53.79 %)	RER (13.61 %)	246
All	60.79%	3.37	Metro (52.76 %)	Bus (26.00 %)	3,690

An asymmetry should also be noted between the modes used for the home-based and activity-based parts of these trips. While home-based parts are mainly made by bus, then by car, or metro, activity-based parts are mainly made by metro. This, together with the spatial specificities of these modes (the metro network serves only Paris and – partially – its close periphery, while bus lines are present everywhere), suggests that the home-based ends of these long, multimodal trips made by RER or regional train are mainly peripheral, while the activity-based ends of these trips are closer to the centre. Finally, it should be noted that there is no evidence that the RER and the regional train share a hierarchical relationship. Let us now say a few words about the less numerous multimodal trips made by bus or by metro. From

Table 3 and Table 4, when the main mode is the metro or the bus, then the other mode is most probably the bus or the metro. This does not mean that these two modes are closely integrated: this only describes how these modes are combined when they are combined, which happens rarely. The second most used access mode is the RER at the activity-based end and the car at the home-based end of trips, which, again, is consistent with our statement that the activity-based ends of multimodal trips are more centered, whereas their home-based ends are rather peripheral.

4.3. Spatial analysis

As suggested by the density of inhabitants and the layout of the transport infrastructures, and by the differences in the characteristics of the home-based and activity-based parts of multimodal trips, the structure of the transport system of Region Ile-de-France shows a strongly spatialized pattern. This is quickly investigated here, based on the simple P-PC-GC partition of Region Ile-de-France. The mode share of public transport modes is analyzed with respect to this segmentation, and so is the share of multimodal trips, in Tables 5(a) and 5(b).

Table 5: (a) mode share of public transport, among all trips and, between parentheses, among non-walk trips, per origin and destination; (b) proportion of multimodal trips, and, between parentheses, of multimodal trips among public transport trips, per origin and destination. For both tables, the trips of which the origin or destination is outside Ile-de-France were discarded.

(a)

		Destination		
		P	PC	GC
Origin	P	28.36 % (63.30 %)	56.52 % (58.14 %)	60.65 % (62.16 %)
	PC	56.23 % (57.66 %)	12.14 % (22.35 %)	21.44 % (22.01 %)
	GC	61.01 % (62.21 %)	21.73 % (22.26 %)	7.00 % (10.12 %)

(b)

		Destination		
		P	PC	GC
Origin	P	1.62 % (5.62 %)	27.96 % (48.68 %)	53.26 % (85.00 %)
	PC	28.87 % (50.37 %)	3.43 % (27.42 %)	16.08 % (70.85 %)
	GC	53.68 % (85.43 %)	16.68 % (73.39 %)	1.29 % (17.47 %)

Table 5(a) presents the share of trips made by public transport, depending on their origins and destinations. The distinction between public transport and multimodality is important at this stage of the analysis, particularly in the case of the Paris to Paris trips, for which metro is used a lot, while the trips are predominantly monomodal. This can be explained both by the network layout and by the limited lengths of these trips. In addition, the share of public transport trips among non walk trips (in other words of mechanized trips, where the bicycle is considered as a mechanized transport mode) can be read in Table 5(a). Limiting the analysis to these trips allows to avoid the distortion induced by the very large amount of walk trips in the Paris-to-Paris category (Paris is much smaller than PC and GC). It appears that a condition for the share of public transport among mechanised trips to be large (higher than 57%) is that the origin or destination of the trip is Paris. In the other cases, the share of public transport among mechanized trips drops drastically, below 23%. This is consistent with the fact that the networks of the RER and regional train (the two public transport networks which account for most of the multimodal trips) are radial.

Table 5(b) gives the share of multimodal trips per origin-destination pair among all trips and, in parentheses, the share of public transport trips which are multimodal (it is similar, but not exactly equal to the ratio of the share of multimodal trips to the share of public transport trips, due to the existence of multimodal trips of which the main mode is not a public transport mode). From these two indicators, it appears first that multimodal trips are predominantly long and radial trips, and, conversely, that long, radial, public transport trips are generally multimodal. Short trips, i.e. trips contained within a zone (even if this zone is large) are neither made by public transport modes, nor multimodal.

5. A representation of the urban transport system of Region Ile-de-France

This section synthesizes and summarizes the previous statements. On the basis of the analyses of mobility led up to this point, it is now possible to identify the functions effectively supported (in the sense that travelers actually use them) by the public transport system of Region Ile-de-France. They also reveal the functional relationships (or lack of) between the components of this system, i.e. the modes. Altogether, these results mirror the structure of the public transport system of Region Ile-de-France.

- Short trips are monomodal. Non-walk short trips are mainly done by public transport in Paris, and by other modes outside Paris.
- Long, radial trips are mainly multimodal and made by public transport modes. The main modes of these trips are the RER and the regional train.

- Long, peripheral trips are made by car.
- The RER and the regional train are high level public transport modes. They do not share a hierarchical relationship.
- The bus is a low-level public transport mode; it provides local mobility as well as access to higher level networks in all areas of Region Ile-de-France.
- The metro is also a low-level public transport mode; it allows local mobility as well as access to higher level networks in Paris and its close vicinity.
- In Paris, the bus and metro networks do not appear to share a hierarchical relationship.
- Car and public transport are almost completely complementary. Car plays a very limited role as an access mode to the regional train network in the periphery of Region Ile-de-France.

Two remarks can be made regarding the public transport system of Region Ile-de-France: first, there is little evidence of any relationship, apart from competition, between car and public transport. Multimodal trips involving transport modes from both categories are rare. Second, there are only two network levels in Region Ile-de-France. In particular, contrarily to what intuition may let think, there is no hierarchical relationship between bus and metro in Paris (here again, their relationship is probably best referred to as competition). There is no hierarchical relationship either between the RER and the regional train (in that case, it is more relevant to assess them as spatially complementary.)

A simple, graphical representation of the transport system of Region Ile-de-France is provided with Figure 2, as an attempt to summarize graphically the discussion above, with the focus brought on the relationships between the public transport modes. Private modes are ignored on this figure, but they can be considered as present everywhere, although not everywhere with the same quality of service. In addition to the statements above, it can be observed from Figure 2 that a difference between the RER and the regional train is that RER lines are fairly well connected in Paris, contrarily to the regional train lines, which are virtually independent.

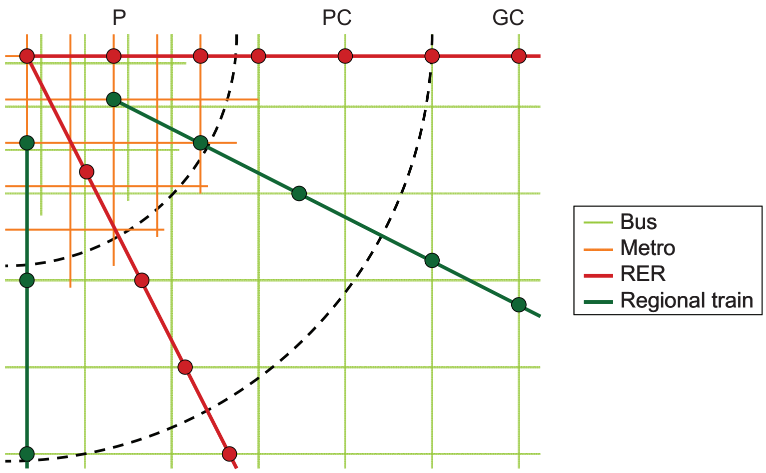

Figure 2 : Representation of the public transport system of Region Ile-de-France

6. Conclusion

The objective of this study was to show, on the example of Region Ile-de-France, how the analysis of passenger mobility in a given urban area is a useful approach to analyze the structure of its transport system. Using the EGT 2001, a travel survey for Region Ile-de-France, it was possible to analyze the function and relationships of each public transport mode, including spatial complementarity, competition, and hierarchical relationships. As a result, a simple, strategic representation of public transport in Region Ile-de-France was obtained, focused on the interdependencies between the various modes.

The requirements to apply this methodology are not demanding: a standard trip database and a basic knowledge of the geography of the transport networks of the studied urban are sufficient. The outcome can prove useful from many perspectives. It can be a basis for the global diagnosis of a transport system. For example, in the case of Region Ile-de-France, it appears that despite all the efforts to improve the multimodality between car and public transport, these two modes remain almost purely in competition. Another example: perhaps counter-intuitively, no evidence is found that bus and metro share a hierarchical relationship in Paris. This statement can have important practical implications. For example, it implies that the accessibility of the metro is fairly independent from the characteristics of the bus network in Paris. However, this is almost surely not the case for the accessibility of regional train.

Of course, this type of representation should not be confused with a fully-fledged quantitative model of transport demand. Indeed, a transport demand model is much more accurate as regards travel demand, the preferences and behavior of travelers, and transport supply; however it is inadequate to analyze transport networks at a global scale. Strategic diagnosis and decision support are out of the scope of accurate models, because of the overwhelming amount of data, scenario specifications and computing time they would require to address such issues. Simple, strategic representations, focused on the structure of the transport systems, should be preferred for such applications.

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