

Geographical Information and Urban Transport Systems

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Edited by
Arnaud Banos
Thomas Thévenin

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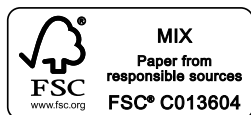


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Introduction

Cities are often interpreted as being a kind of spatial organization which favor functional interaction. However, this is a fragile property, as urbanist Jane Jacobs pointed out in 1961: “when we make cities more accessible, the intertwining uses of different urban functions invariably get smaller”.

Opening up urbanized space to the largest number of people possible remains both a societal factor, and a target for urban development which is difficult to achieve. Of course, since the 1960s, the matter has evolved considerably in Western countries, even if our dependency on cars is still being spoken about.

Thus, society has undergone heavy transformations in terms of its organization (feminization of labor, temporary jobs, increased professional mobility, flexibility, part-time hours, etc.) as well as attitudes and ways of life (ruptures within home lives, individual autonomy, mass but individual consumerism, etc.) or its spatial foundations (discontinued, heterogeneous, low density and multi-polarized cities).

Introduction written by Arnaud BANOS and Thomas THÉVENIN.

These major changes inevitably result in changes regarding the needs for mobility, which are admittedly becoming more and more urgent. But these are also changes which concern more evolutionary, and more complex needs, to such an extent that the traditional “right to transport” maxim from the 1970s has gradually been substituted by a “right to mobility”, including individual mobility which has become a key to the metaphorical safety-deposit box of urban space management. In this ever changing context, both a better characterization and estimation of transport supply and demand is vital.

It was therefore logical for the ANR’s program for *Villes durables* (French National Research Agency, *sustainable cities*), via one of its funded projects, to help spread the most recent practices in this both rich and fertile domain.

The chapters in this book focus on the double issue of characterizing the supply of transport and estimating its demand.

Part 1. Characterizing transport supply

The issue of urban transport systems requires us to answer at least two pressing questions, namely: which mode of transport, and for which users? Here we will focus on the public’s mobility. It is true that the question of mobility in goods and commerce domains is a whole other universe in itself, which might even justify the publication of another book in the French IGAT series on this theme. In addition, it would be difficult to attempt to deal with *transport systems* without tackling the difficult yet fundamental question of intermodality. These different points are dealt with in the following seven chapters, in directions which are as varied as they are complementary.

Part 1 is dedicated to characterizing transport supply, and the first four chapters within paint a detailed picture of the technological and methodological investment needed in order to accurately describe transport supply in urban areas.

In Chapter 1, Thomas Thévenin willfully roots his reflections in the recurrent and largely detrimental problem of dispersion and the lack of interoperability of data-bases dedicated for uses within transport domains. He thus proposes a model using generic data, both temporal and spatial, which could bring together approaches, and those authorities within the domain, around a common theme. Using very specific information, organized and structured on what he refers to as “GIS-Transport”, he shows that it is possible to carry out performance measurements on modes of transport over the entire mobility chain, on the global scale of a community.

In Chapter 2, Robert Chapleau hammers the point further: characterizing the urban public transport supply is above all a communication problem between those involved, between methods and softwares, and between objects. He shows how to model a transport system, public transport in particular, in order to describe it in terms of its spatial, temporal, static and dynamic components. In doing so, he demonstrates the important role played by GIS (Geographic Information Systems), regarding user information as well as supports for those making important decisions. This underlines the irreplaceable contribution of these tools to the technical credibility of the many interventions carried out on public transport networks.

Chapter 3 goes into more detail on this matter, as difficult as it is fundamental, with regard to collective transport networks. Alexis Conesa and Alain L’Hostis define multimodal and intermodal accessibility, by introducing an essential component; travel time accessibility. They show that in order to assess the way in which a given transport

system adapts to the rhythm of urban life, it is vital to specify accurately certain time-related constraints. As difficult and unrewarding as it is, creating data bases for travel times using graphs gives us a relevant and realistic representation of mobility conditions. This is a major asset for those wishing to consider both the organization of transport systems and their inclusion in urban areas.

Finally, Chapter 4, written by Cyrille Genre-Grandpierre, allows us to question the previous three chapters, concerning their spatial base in particular, due to the fact that the formalization of transport networks by using graphs – mathematical abstractions with properties which are perfectly known and controlled today – is not, therefore, exempt from certain biases. The relationship between a transport network and its designated service area (the land) is either hardly or not taken into account by these approaches, to the extent that other options bringing into play fractal geometry may be put forward.

Part 2. Estimating transport demands

Characterizing a transport supply independently of the underlying demand would be quite paradoxical. Accurately defining real and desired mobility on the scale of a city or community is nonetheless a sizeable matter. As a concept which is complex, multiple in form, and ever changing, mobility in daily life is really only offered progressively and partially with regard to the analyst. How, in these conditions, can we claim to approach this concept with enough precision in order to adjust transport services to it, these services which are adapted to the needs and expectations of the public? The following three chapters tackle this difficult question, using three complementary angles of approach.

In Chapter 5, Patrick Bonnel gives both a broad and thorough review of the methods used to estimate demands

for transport in urban environments. Within the ever irrefutable *four step model*, he shows how aggregate and disaggregate models may be combined to produce reliable predictions of the demand for transport. He takes advantage of this in order to propose a pragmatic and realistic vision of modeling and its irreplaceable heuristic qualities. Modeling's potential for exploration is largely reinforced today by the power of computer tools for visualizing information, letting us bypass traditional approaches of *input/output*, based on rigid "black-box" interfaces between the modeler and his/her data.

This is precisely what Olivier Klein demonstrates in Chapter 6, with many supporting examples. At the risk of surprising non-specialists, he shows that visualization is both a scientific and artistic activity, rooted in soils as varied as they are fertile. Interactive strategies, directly involving the user in the processes for analyzing his/her data, may be imagined and carried out today, within ergonomic computer processing environments. The future seems widely open to GIS, which are truly interactive systems, directly involving the users within the virtual universes they control, and providing them with many alternative and complementary methods to do so, methods which are specifically adapted to the geographical nature of the information. These approaches, applied to the dynamic visualization of daily urban mobility, let their potential shine through.

Finally, in the 7th and last chapter, Olivier Bouhet combines supplies and demands for transport in all their varied and rich ways of expressing themselves, within a multiple criteria procedure which is particularly relevant when it is a matter of guiding decisions in a multiform environment. Applied to the *tram-train* project around the French region of Grenoble, this procedure shows its strengths when it is fed with geographical data correctly from different origins (multiple sources), which are essentially heterogeneous.

PART 1

Characterization of Transport Supply

Chapter 1

Modeling Transport Systems on an Intra-Urban Scale

1.1. Introduction

Plans for mobility within urban environments or businesses, regional schemes for transport, territorial coherence schemes; together, these guidance documents aim for a global approach to managing mobility. This approach challenges those in charge of dealing with transport, in order to renew the assessment criteria for mobility policies and to establish a real joint procedure which brings together both institutional partnerships on all territorial scales (from counties to regions), and transport operators (Véolia, Kéolis and SNCF, France's national state-owned railway company, for example).

To fulfill this double imperative, sharing information between partners is an essential procedure. But, sharing data still remains an often tricky operation, mainly due to technical problems. In 1995, a report issued by the European Union reiterated the dispersion and lack of interoperability

Chapter written by Thomas THÉVENIN.

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between databases in the world of transport [CEN 95]. Issued ten years ago, this official report seems to be enduring. To overcome this technological hitch, GIS offers a suitable solution for bringing together data from multiple partnerships. This methodological preconception involves developing protocols for communicating and exchanging information. Thus, this article is a test for modeling transport systems in a GIS designed to provide a potential measurement of accessibility on a community scale.

The permanent changing nature of GIS leads us to retrace the history of software and geographical information so as to specify the issues concerning these tools. This bibliographical review will enable us to show, from a formal point of view, the main components of a transport system and the relationships which motivate them in a model of conceptual data. Organizing the model in this way will be illustrated by an analysis of the potential accessibility around two average-sized French regions: Besançon and Dijon.

1.2. GIS-transport experiments

From very early on, research on transport has focused on GIS. From the end of the 1950s, a group of quantitative geography students from the University of Washington [GOO 00a] started investigations into the subject. One of them, D. Marble, followed up this work by developing a prototype of a GIS-T dedicated to the Chicago transport network. After this pioneering research was completed, we would have to wait another 30 years for the GIS to be fully recognized in terms of its capacity to respond to specific transport requirements [THI 00].

1.2.1. *The three stages of evolution of GIS-T*

The lengthy evolution of GIS-T can be broken down into three stages, according to M. Goodchild [GOO 00a]. Firstly, a

cartographical study of the networks was carried out so as to fulfill planner requirements. Industrialized countries saw large programs being developed. From the end of the 1960s, the USA saw all their roads being numbered, in the DIME program (*Dual Independent Map Encoding*), in order to reference the results of a population census in 1970. At this time, the network was organized as a graph made of arcs and nodes. The graph is *planar*, meaning that the intersection of two arcs on one plane may only take place when a node is present. This topological representation of the networks has been copied by other data models. The most well-known amongst them is the TIGER (*Topologically Integrated Geographic Encoding and Referencing*) model in the USA, and the GDF (*Geographic Data File*) model, recommended by the European Union [CEN 95], [DUE 00].

The development of navigation tools is the second stage in GIS-T evolution. At this stage, it is a matter of proposing devices which are able to inform users of the optimum route itinerary in relation to traffic problems. Algorithms taken from graph theories are particularly well adapted for determining the best route according to the distance in kilometers, the journey time or the cost of the journey.

There is, however, in-depth information available to show the full complexity of a transport network. The planar graph, used in the previously mentioned data models, must be completed using attribute data, particularly regarding traffic direction and prohibition of making left or right turns. Next, we must use dynamic attributes, in particular of traffic lanes and speeds according to the time of day. We will now integrate two other constraints, inherent to network properties, which will facilitate transport user navigation:

- the first one being that people and vehicles do not necessarily appear on a network, and private roads and car parks do not always show up in databases. The information

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systems intended to guide vehicles must take this problem into account;

- the second constraint concerns navigational aid which must integrate all modes of transport for the selected option to be the best adapted to the user's requirements.

Put forward by many researchers [STO 96], [KWA 00], [MIL 07], representing the behavior of discrete objects such as vehicles or people is the third stage making up the GIS-T. These tools have made it possible to increase the size of samples to be surveyed, and to obtain more thorough information on the programs used for individual activity, at the same time helping to reduce survey costs. One survey, carried out in 1998 in Montreal by R. Chapleau's team, was able to geocode activity programs for more than 70,000 households by a telephone interview [TRE 01]. GPS monitoring of the people interviewed means that at the present moment we can improve information retrieval regarding activity sequences [BUL 03], [STO 04], [WOL 04]. The changes with regard to surveying techniques, however, need to be represented and compatible visualizing methods to be developed or directly integrated into a GIS-T in order to analyze data on behavior.

1.2.2. Between time and operational dimensions

The transition from a static idea to a dynamic vision of a transport system has deeply affected the use of GIS-T in different transport related jobs. Firstly used as planning tools, GIS used solely for transport have been used to structure and visualize the data taken from models predicting demand. Integrating dynamic attributes, such as traffic speed, has enabled us to satisfy operational needs, such as the organization of bus time-tables throughout the day. The connection between ICT (Information and Communication Technology) and GIS systems now make it

possible to satisfy operational requirements in real time, like detecting incidents on roadways or navigational aid.

Table 1.1, based on work carried out by K. Dueker [DUE 00] and M. Trépanier [TRE 02], shows that information accuracy varies greatly according to the nature of operational needs or planning. The GIS-T used for planning does not necessarily require an accurate representation of spatial and temporal data. Intended to ease decision making in the medium and long term, however, information updates are only carried out irregularly and not very often.

Using GIS-T for operational purposes however unmask situations which need to be solved over a short term period, and in real time. The spatial and temporal context requires an adjustment representing reality as faithfully as possible, and involves frequent, regular information updates in real time.

	Planning	Operational	Real-time operational
Help with decision making	Long and medium term	Short term	Immediate
Accuracy of spatial and temporal data	Low	High	High
Data updates	Varied and infrequent	Regular and frequent	Continuous transmission of information
Visualization of the studied case	Static Cartography	Semi-dynamic Animated mapping	Dynamic visualization Direct phenomenon
Application example	Traffic estimates	Route organization	Navigation help

Table 1.1. *GIS-T use and data accuracy*

First designed to solve planning objectives, databases now make it possible for GIS-T to satisfy the needs of operators.

1.2.3. Evolutionary perspectives of GIS-T

These three stages of development lead the GIS-T into a stage of maturity. Thus, H. Miller [MIL 06] proposed to the Association of American Geographers (AAG) congress to identify perspectives for geographical research on transport.

According to Miller, five themes in particular can be distinguished:

- financing and renovating infrastructures;
- limiting network congestion;
- integrating the environmental dimension;
- limiting accidents;
- preventing terrorist attacks.

GIS-T plays an important decisive role in responding to these many different challenges [THI 00], [MIL 96]. In this light, there are many paths for investigation which need to be taken. First of all, high resolution geographical information provides a fundamental basis for creating a tool used for observing transport systems and its environment in real time. It is also a matter of developing ICT systems suitable for specifically marking out vehicles or even individuals in space and time. In order to do so, it is without a doubt very important to improve the capacity of integrating and analyzing GIS in spatio-temporal data processing.

When perfectly understood, these two dimensions make it possible to create simulation tools on scales of an entire city, of vehicles, or even the individual. So that all these conditions can be fulfilled, it is then essential to ease the integration of data into GIS via the implementation of generic models which specify the relationships bringing the transport systems to daily mobility.

1.3. Towards an urban GIS-T

The many institutional and operational authorities in the world of transport collect lots of information each year on infrastructures, urbanism or mobility demands. Total mobility management then requires data collecting, imposed in France in particular by urban mobility plans. But, information transfer between the different organizations involved is often slowed down, or even made impossible, due to technical reasons.

In fact, many studies have revealed that software and file formats are often incompatible and difficult to unify [CEN 95]. The role given to GIS-T systems is to integrate the different data-bases and to make them available for transport authorities.

1.3.1. *Norms for facilitating information transfer*

According to J.C. Thill, the federal role of GIS-T cannot be guaranteed without an accurately defined communication protocol and exchanges of information [THI 00]. In this context, designing generic models is a valuable tool for avoiding errors related to topology or the formulation of certain toponyms [GOO 00]. Moreover, specific tools must be developed in order to facilitate information transfer and possibly detect problems of incompatibility. A certain amount of research has been led in this vein, and we choose to highlight three examples of this here. The LRS (*Linear Location Referencing System*), developed for storing information on transport in commercial software (Map Info, ArcGIS, in particular), is currently evolving towards integrating data in real time [ADA 98]. K. Dueker and A. Butler [DUE 98] then proposed an architecture dedicated to sharing information between transport applications and authorities. More recently, the team from the Polytechnic School of Montreal put forward a data model adapted to

producing information on users via the Internet [TRE 02]. These proposals for generic models will enable us to fulfill one of the most important missions for GIS-T: interoperability [THI 00]. The first mission for GIS-T consists of facilitating information retrieval by proposing data models designed for representing the functional organization of the transport system.

The second mission is to be based on this standardization in order to develop real exchange mechanisms with software for processing statistical surveys or analyses. To this effect, some procedures have already been put into action, such as the INTRANS software in Chicago used for studying data taken from a transport model. The GIS SPANS model was coupled more recently with the traffic modeling software EMME2 in the USA (Maryland) [FOT 00a].

This type of information transfer refers to concepts of *unidirectionality* or *static integration* proposed by L. Anselin and his associates [ANS 93], [ANS 90]. Here the GIS will structure the input data whereas the model for forecasting traffic will process the data. The level of integration between GIS and spatial analysis methods may be improved and enriched by a bidirectional link. The data taken from GIS is processed by statistics software, and the results are imported into the GIS in order to start the cartographical process. This type of relationship requires a specific menu which proposes data exchange formats with the most popular GIS, so that the information transfer is as convenient as possible.

From this attempt to formalize spatial and temporal data on transport networks, the third mission consists of starting to think of modes of representation to be implemented in a GIS-T. In order to take some of this information without changing the initial content, it is a question of proposing visualizing tools which can reveal spatial structures and the dynamics which bring the transport system into daily

mobility on a local scale, whilst keeping a global vision in mind at the same time [FOT 00b]. Thus, standardization, integration and visualization make up the three major aspects of building a GIS-T dedicated to analyzing urban transport.

1.3.2. *Data model for urban GIS-T*

Data formalization is a procedure which consists of specifying the relationships between the information collected in a conceptual model. Widely spread in computer systems and in the world of geographic information science, UML formalism makes it possible to reach this objective. The freeware prototype *Perceptory*, developed by the team led by Y. Bédard at the Laval University in Quebec [PRO 02], has been used because this tool is particularly well adapted for understanding the evolution of geographical objects over time.

The architecture of this model is based on the following question: how are transport networks in a position to link the supply with the demand of urban services? To do so, we chose to break down the main types of information on cities into three sub-models:

- the sub-model *activity* collates information on the resident population and available jobs in companies (class: *work*). Urban services have also been represented to satisfy needs for consumerism, studying and leisure. Opening times have also been added using ground surveys as instances of class;

- the sub-model *land use* describes the city's buildings, such as residential buildings (class: *built-up area*). Post codes (class: *address*) have been used for geocoding places of work, whereas the cadastral parcel (class: *parcel*) collates more specific information on buildings, particularly the function and number of homes;

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– the sub-model *network* groups together classes intended for modeling the individual (class: *pedestrian*, *car*, *taxi*) and public modes of transport. Collective transport, which is particularly difficult to represent, requires a representation of the fleet of vehicles available with the station timetable hours. Organizing this data enables us to represent the most unexpected modal combinations.

These three sub-models have been collated together according to two very distinct processes.

1) Associations between the two sub-models *activity* and *land use* correspond to localizing activities in cities.

Four classes have been distinguished as both the place of work and places for social activity.

– *work*: industrial and civil workers (outside the business sector);

– *business*: shopping areas (retail businesses and department stores);

– *study*: students and school children as well as teaching and administrative staff;

– *leisure*: supervisory staff and club users.

These classes have been temporalized through an association with the *time survey*, followed by an association with the *building* class by a geocoding procedure using the *address* class. The association between *resident population* and *building* is defined by rules concerning population redistribution developed in previous works [BAN 05a].

2) The associations between sub-models *network* and *territory* refer to the *node* class. This class connects the four modes of transport considered here. The sub-model *network* is made up of nodes and arcs (*arc* and *node* classes) and the network's topological relationships are modeled according to

the instance of class *traffic direction*. The collective transport network is broken down into three different elements: the line (buses, trams, underground), the vehicles and the stops along the route (class: *station*). The interconnection between networks is ensured by the fact that a network node may belong to public *and* private transport networks at the same time.

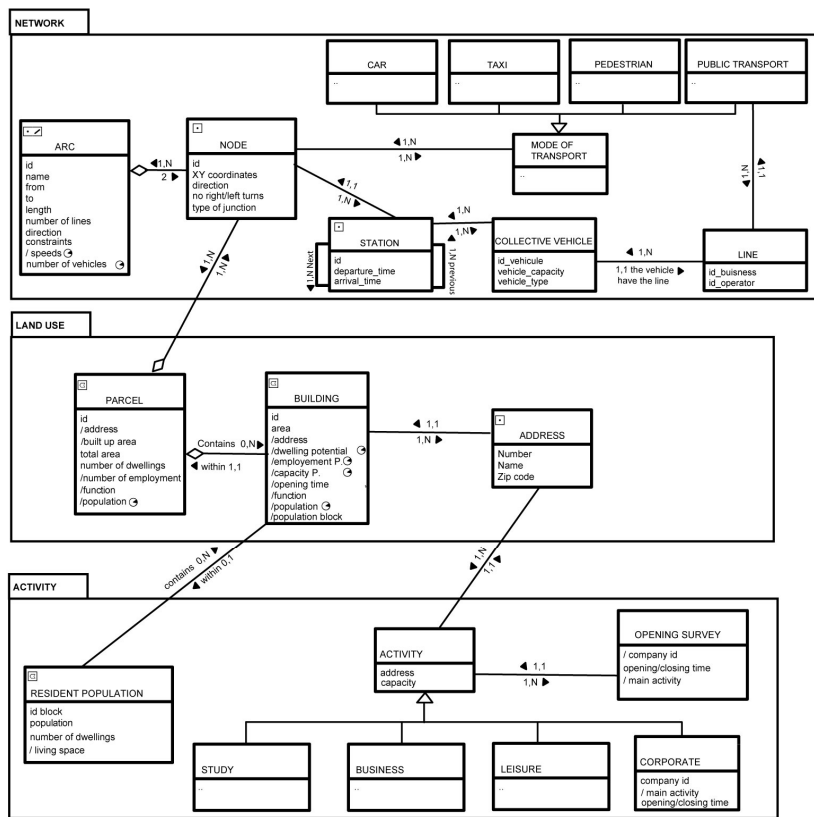


Figure 1.1. Conceptual model of an urban GIS-T

1.3.3. From integrating the demand...

Describing transport supply and demand is a matter regarding two types of spatial constructions. Information on

mobility is collected in a zoning, which is represented in the GIS by an area symbolized by arcs and nodes (whereas data on transport supply is structured onto a graph). A basic methodological problem is then raised: how do we collate these two types of geographical objects?

With information on the population in residential areas being unavailable, the most accurate reference spatial unity, *housing blocks*, has been disaggregated into punctual information, at best approaching the distribution of this population. In this vein, an allocation method based on the concept of the field of potential has been thought up in order to define the capacity of each place (ideally each building) to emit and attract people. The information classes *housing blocks*, *parcel* and *buildings* have thus been combined in the aim to estimate the resident population for buildings belonging to this category. The distribution of the population has been achieved using a proportional allocation rule, which takes the housing block population and the number of houses per parcel into account.

The potential of each building (i.e. its resident population) is then estimated by the following equation:

$$Potential (B_j) = Population (I_k) \times \frac{\#Housing (B_j)}{\#Housing (I_k)}, \forall B_j \subset I_k \quad [1.1]$$

with: B_j as the building j ; I_k as housing block k ; and $\#Housing$, the number of houses in a given entity.

The potential of non-residential buildings (places of study, shops, and businesses) was determined more directly using a geocoding procedure.

In France, the national statistics department registers a company's employees with more than 10 employees over the

zipcode area. By associating this data with the zipcode layer, each company has been specifically located over the urban area. This database, however, suffers from a particular inaccuracy because the number of employees is represented as a set of classes. Here, then, we are limited to choosing the mean from each class in order to determine the employees. Next, places of study, business and leisure have been determined more directly, using data from counts taken by the local education authority and the trade register.

1.3.4. ...to structuring transport supply

In order to structure transport supply, the road network is divided into four means of transport represented in the GIS-T. In order to describe the pedestrian network, we assume that walking is not subject to traffic constraints. According to a study issued from SETRA [SET 92], a pedestrian moves at an average speed of 5 km/h. This value was retained in order to calculate times taken for accessing a given place. Coding relating to cars (or taxis) is, on the other hand, much more complex to carry out. Traffic direction and forbidden left or right turns were integrated into the GIS-T.

Average traffic speeds were added to this information, on the network arcs. They were determined according to the permitted speeds according to the administrative class of the lane and the sinuosity of the road. With the aim of improving the average traffic speed estimation, it might be interesting to add new constraints such as waiting at traffic lights or traffic congestion at different times of the day.

However, we must break away from the endless pursuit of using more accurate parameters because companies seem to be powerless when faced with the multiple constraints and hazards which pop up each day on the urban transport network. Moving away from the principle that the eye of the

expert is irreplaceable, it has been recommended to call upon municipal service technicians to carry out validation work.

The integration of the public transport network reaches an important degree of complexity because it is a matter of restoring the spatial and temporal dimensions in the GIS-T. To guarantee an accurate result and to avoid a long process of manipulating and validating data, it has been recommended to take information from the Vehicle Scheduling Control System which is available from the conveyor. This software centralizes travel times for all modes of public transport across the urban area.

The aim is to add a spatial dimension to this strictly temporal data. To achieve this, a specific model, christened the TimeNet, was developed within the GIS. TimeNet works according to three different stages. First of all it was necessary to shape the database in order to obtain the table in Figure 1.2A.

This table describes, in a series of lines, each vehicle's journey between a starting and destination station. These links are then characterized, in a series of columns, by journey times – the route as well as the number of the vehicle conveying the journey. In the second stage, this “table of temporal links” is associated with the thematic data layer of bus stations, in order to generate what we have called the spatio-temporal graph. The result of the first stage (Figure 1.2B) allows a representation of the links between stations according to Euclidean distance, since the arcs do not follow the real geometry of the road system. This structure is good enough for calculating journey times, but is not suitable for calculating distances in kilometers, which must include all the characteristics of the road network. The third stage consists of bringing together the Euclidean distance with the network's real geometry (Figure 1.2C).

The architecture of this GIS-T model over the urban area makes it possible to collate all the information needed on transport supply and demand, on a more accurate scale. More than just a simple database, this sort of digital city is open to a wide variety of hypotheses and tests, intended to gain knowledge about and simulate the behavior of public transport networks.

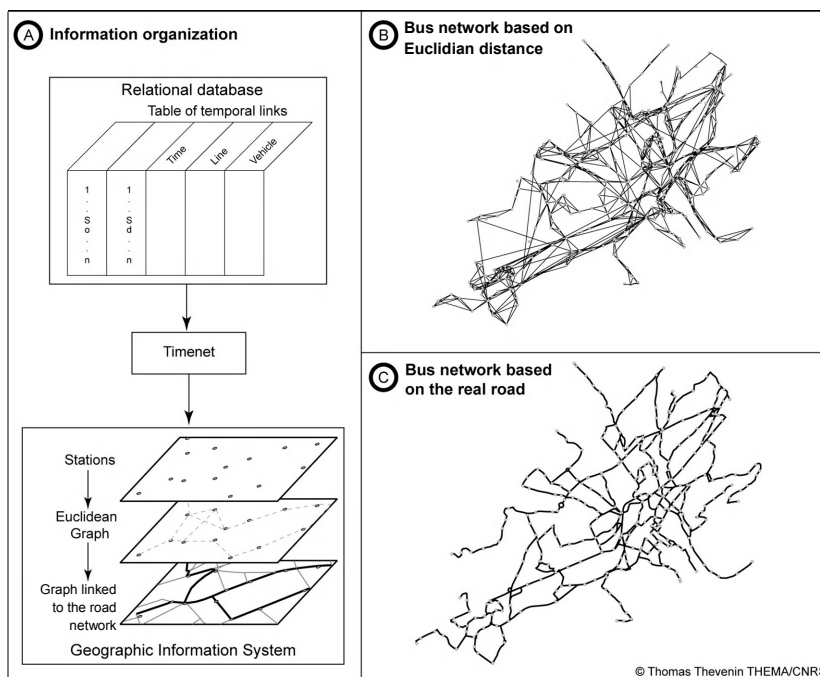


Figure 1.2. Construction of the public transport network

1.4. Towards an analysis of accessibility

Generating these databases on a fine scale involves much manipulation, which is sometimes difficult and laborious to implement. Two essential questions are then raised: on the one hand, how do we extract data from such rich information without reducing and changing its content too much? And on

the other hand, is this data organization applicable to many urban areas? We have presented two indicators in order to provide an assessment of the efficiency of public transport networks over two French cities of comparable size: Besançon and Dijon.

1.4.1. Potential accessibility measurement

Potential accessibility is based on the hypothesis stating that the quality of the transport service in a given area varies according to the mode of travel at a given time. The aim of this measurement is then to determine the potential accessibility to the urban transport network and to mark out the possible inequalities with regard to access on the first experimental site: the Besançon commune. To highlight these disparities, the method proposed here is based on the confrontation between the accessibility offered by busses, and the mode which offers the *richest potential interaction*, namely cars [BOR 00].

We have retained an operational accessibility for these two modes, proposed by R. Diederich [DIE 98]:

- for cars, accessibility is the result of “minimizing” a distance, the time-distance, between a specific location *i* and a given place *j* using a private vehicle using any path desired;

- as for accessibility by coach, it is also the result of a time-distance minimization, between a specific location *i* and a given place *j*, but using a city bus line taking an imposed route, allowing “minimization” but within the regular working of the network’s routes.

Two terms have completed this definition. First, in terms of space, it is not a matter of using one traffic generator over another, but a question of using all the places likely to form a trip.

Next, from a temporal point of view, the observation period takes place over the whole day. Accessibility is measured in terms of time, but the calculation method differs according to the mode. Figure 1.3 represents the three components needed to describe a theoretical trip between a house and a destination station. Each of these three elements has undergone specific calculations. Firstly, the closest station to the 17,000 residential points in Besançon studied was determined according to time-distance. Next, a second table was generated in order to measure the average waiting time at the station. Lastly, the station-to-station journey times were determined according to average speeds over the bus network, in a third table.

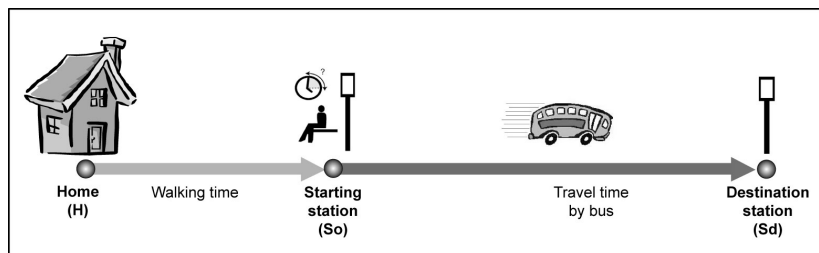


Figure 1.3. *Three components of the trip chain*

Collating these three values means that we can then measure the multimodal accessibility, door to door from the passenger's house to his/her final station. The potential accessibility allows us to summarize this measurement using an aggregation operation. Taking into account the symmetrical distribution of the journey times, aggregating this information was achieved by calculating the generalized accessibility, meaning the average time needed to access all the stations in the communal area from one place. The potential accessibility using public transport (PT) between a house and a destination station is thus defined by:

$$PT(H, Sd) = t(H, So) + \frac{\sum_{i=1}^{l_{So}} t'_i}{l_{So}} + \frac{\sum_{j=1}^n t''_j}{n} (So, Sd) \quad [1.2]$$

where:

- H: home;
- So: starting station;
- Sd: destination station;
- t(): walking time using the shortest route;
- t´: waiting time at the station;
- lso: number of lines at the starting station;
- t_i´´: transport time i between So and Sd;
- n: the number of buses between So and Sd.

This temporal indicator relates to an average access time, including walking, waiting and travel time. It makes it possible to recreate an image of the accessibility potential which considers the difficulties encountered at each link in the mobility chain. The map (Figure 1.4) shows good accessibility zones in light shading. Potentially, these places can be reached in ten minutes from any point in the communal area. Outside the city, we find the areas with a low level of potential accessibility, at around 40 minutes from all other places. The areas shown in dark colors relate to the least densely populated areas of Besançon. It relates to both the hilly areas in the South end of the city and the main forest in the commune which is located towards the North.

Calculating accessibility for cars is simple to implement because it does not involve a full representation of the mobility chain.

For problems of comparison, the theoretical journey always takes into account the journey between home/station, but at this time there is no intermediate stage.

A matrix of distance was also calculated according to average road speeds. The potential accessibility by car (CA) between a home and one of the stations S_d from the study area was established as:

$$CA(H, S_d) = t(H, S_d) \quad [1.3]$$

where H represents the home, S_d is the destination station, and $t()$ is the travel time by car using the shortest route (without taking into account congestion). On this basis, we can calculate a total accessibility indicator, from each home to all stations S_d :

$$A(H, S) = \sum_{i=1}^{\#S_d} \frac{t_i(H, S_d)}{\#S_d} \quad [1.4]$$

with S as the group of stations S_d , and $\#S_d$ as the (cardinal) number of stations.

Figure 1.4 shows that the accessibility potential hits a maximum of 15 minutes around the main part of the city. To reach our objective which consists of marking the problems of inaccessibility between public transport and private modes of transport, a third map was drawn up by using this simple ratio:

$$R_{(H,S)} = \frac{PT_{(H,S)}}{CA_{(H,S)}} \quad [1.5]$$

First of all, the map in question displays high problematic areas (dark shading), with access times on buses reaching five times higher than those for cars. However, these areas are very limited, ranging from dense hilly areas in the South

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of the city on the one hand, to an industrial zone (Trepillot) on the other. The smallest difference clearly concerns the most densely populated districts, namely the city center as well as the new part of the city (Planoise).

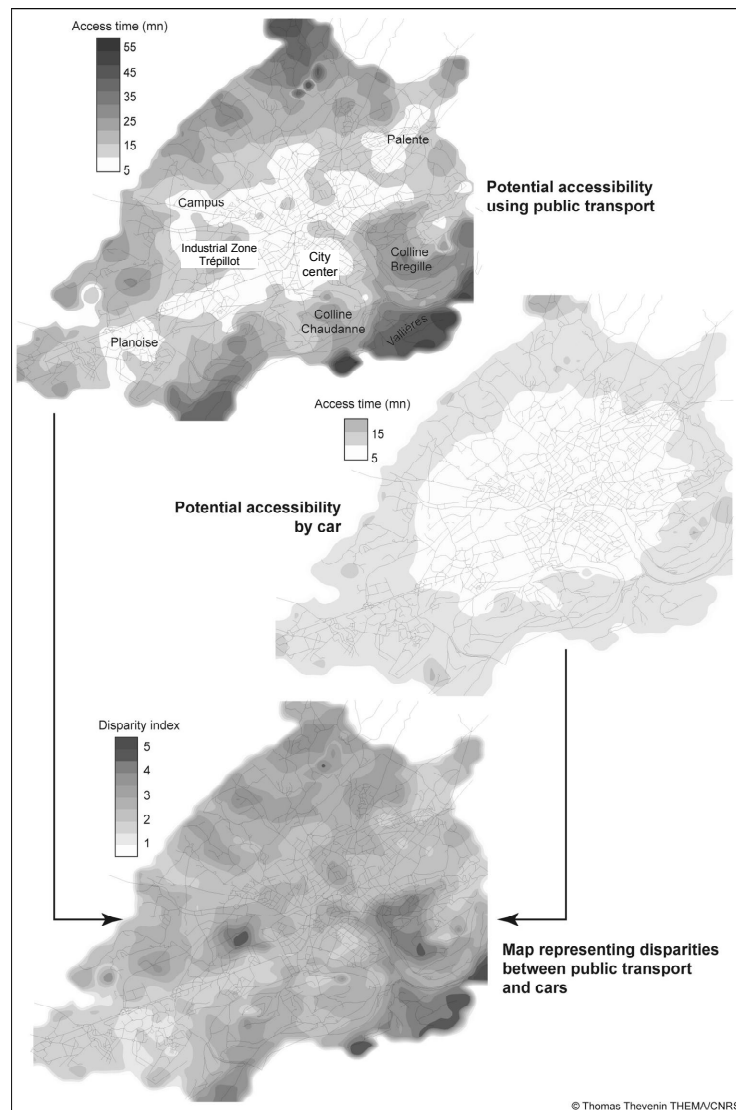


Figure 1.4. *Disparity of accessibility between public transport and cars*

The map showing a disparity of accessibility definitely highlights the low speed of public transport compared to cars. However, we must point out here that integrating walking times into this indicator certainly amplifies the imbalance between the two modes of transport.

1.4.2. Towards a measurement of “urban potential”

Potential accessibility is the first attempt at a broadened design for assessing a public transport network. However, this concept “displays the disadvantage of above all expressing the attraction capabilities of a place”, recalls F. Ascher [ASC 98]. The same author then proposes that we complete the concept of accessibility by the idea of “urban potential”. This indicator is based on a composite measurement which links together housing, urban equipment and activities. In order to pursue our thoughts upon assessing the efficiency of public transport networks, here we put forward an urban potential measurement around Dijon. From our point of view, this measurement is similar to the index developed by R. Davies [DAV 78]. This indicator takes into account both the number of establishments in a city center i , within a category of services j , and the rarity of this type of establishment, which is measured by the opposite of their total number N_j for the spatial unit i :

$$C_i = \sum_{j=1}^k \frac{N_{ij}}{N_j} \quad [1.6]$$

This index has been used in our work by considering, for each trip generator, the number of jobs and businesses, as well as the number of places available in education institutions. The urban potential indicator is distinguished from the centrality index as an additional criterion, since these three criteria have been determined for a journey using

public transport over a given length of time. We must specify that the trip chain is taken in its entirety here. Effectively, the journey is understood to be from the place of residence to the place of activity. Thus, we have added a fourth table which measures the access time between the starting station and the final place of activity to the three tables generated previously for determining potential accessibility (Figure 1.5).

Consequentially, the sum of these 4 measurements means that we can estimate the journey time for each starting place and destination, and to calculate the urban potential index as follows:

$$P_H = \frac{N_{Hb}}{N_b} + \frac{N_{He}}{N_e} + \frac{N_{Hw}}{N_w} \quad [1.7]$$

where:

- Hb: number of accessible businesses;
- He: number of accessible educational institutions;
- Hw: number of accessible places of work;
- Nb: total number of businesses;
- Ne: total number of educational institutions;
- Nw: total number of work places.

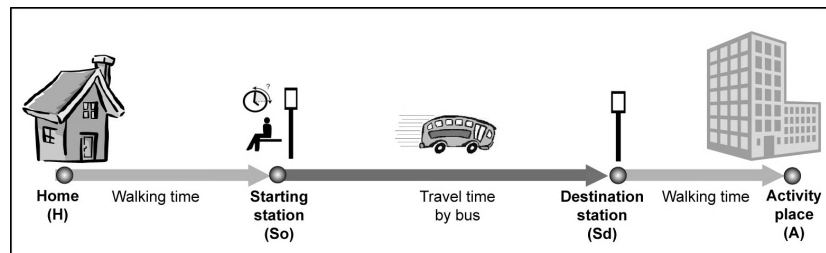


Figure 1.5. Complete trip chain

With the size of the data tables being consequential, the limitations in the capacity to process and store database management systems have quickly been overcome. In these circumstances, the expected data table has been generated using an interface which was designed specifically to facilitate calculation sequences. The results then enabled us to determine the urban potential (P_H) of all the residential areas in and around Dijon.

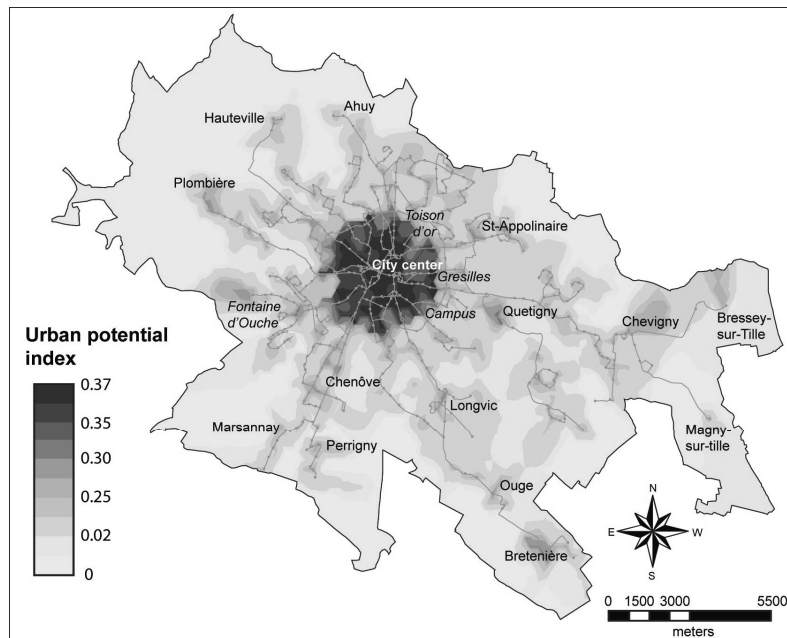


Figure 1.6. *Urban potential in and around Dijon*

We used a spatial smoothing procedure to construct the urban potential map of Dijon (Figure 1.6). The areas which can be accessed in 30 minutes by bus have also been measured here for each place of residence. The urban potential creates a more complex map than for those previous, with an index which varies between 0 and 0.37. The highest potential is found along the major roads using

public transport services, and particularly in the old city center.

Areas with low urban potential are found around the urban district. However, some communes which are far from the urban center display a moderate potential, such as for example Plombière or Bretenière. Only the three large activity categories (work, business, study) were considered in this analysis. A more in-depth analysis would require much more criteria which are less exclusively linked to work, such as the number of accessible inhabitants or the number of leisure centers.

1.5. Conclusion

In this chapter, we have raised issues involving the availability of very accurate information, but managed by multiple authorities in the world of transport. To bring together these authorities and the knowledge built up on mobility, we have shown the extent to which a formal approach to transport systems is essential. This modeling test seems to be generic enough in order to be applied to an average-sized urban district. In future works, we will develop similar procedures on bigger urban districts to confirm this first statement.

The specific information for these two experimental sites shows that it is, in fact, possible to provide performance measurements of different modes of transport over the set of mobility chains on a global scale. Other works have been carried out in our care on very small scales [THE 03], for roads or even people.

These analyses concerning urbanism on a local scale open up wide perspectives for implementing simulation tools which are capable of reproducing the pace of life in cities, and their inhabitants.

The provision of navigational databases (Navtech, and Téléatlas), the development of online georeferencing (Google Earth, Géoportail), and the diffusion of high resolution geographical information are all moving in the direction of rebuilding a digital city. This “geo-computation” revolution represents a considerable potential for leading research on the organization of networks and the individual’s interaction with daily life. Integrating this mass of information structured as a set of models will enable us to bypass planning requirements in order to develop transport services which are becoming more and more innovative and capable of reconciling individual constraints with general interest.

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Chapter 2

Determining Urban Public Transport Supply

2.1. Introduction

Characterizing urban public transport supply is, above all, a problem of communication. The relationships which must be established are found between different entities:

- the planner/analyst (according to the types of models to be developed);
- the applications (available instruments, GIS in particular and various calculation algorithms);
- the objects used in the transport systems themselves (networks, lines, stops, users) according to various perspectives (owners, operators, users).

Information, and its organization based on different schemes, plays an important role in this context, taking into account different pre-existing technologies. Most of the time, the sought-after perspective determines the most appropriate level of resolution. Planning an urban transport

Chapter written by Robert CHAPLEAU.

system where the generalized concept of accessibility is predominant involves a simplified representation of the transport network. Simulating the network load, using a trip assignment procedure, requires the precise coding of transfers. A user information system, on the other hand, must include both geometric changes and schedule changes for every trip situation which may arise.

The modeling of an urban transport system using a topological network preceded and greatly influenced today's representations which use a GIS (Geographical Information System [HEN 04], [LON 05], [MIL 01], [OSU 03], [SUT 04], [THI 00], [THE 01]). However, what distinguishes the modeled object in public transport systems in relation to traffic on a road network (where the individual and the vehicle together are considered as one object for the entire journey) is the fact that the individual who is travelling must use various sub-networks (bus, train or subway lines) which are governed by different spatio-temporal constraints.

In road network modeling, the route choice may be determined in terms of nodes and links, where the general cost of the trip remains as the sum of the unit costs of the links used (*all-or-nothing* or equilibrium assignment). In public transport where vehicular routes are predetermined, the general cost of making a trip will include an element of access (walking, fare), an element of waiting (according to the level of service or travel times) at the initial boarding and at each transfer, as well as an element for transport on board the vehicles.

As an example, Figure 2.1 shows the general cartography of the Urban Community of Machiaville (an imaginary, timeless region); a stage for apprentice transport planners. This example will allow us to distinguish the various objects involved when characterizing public transport supply.

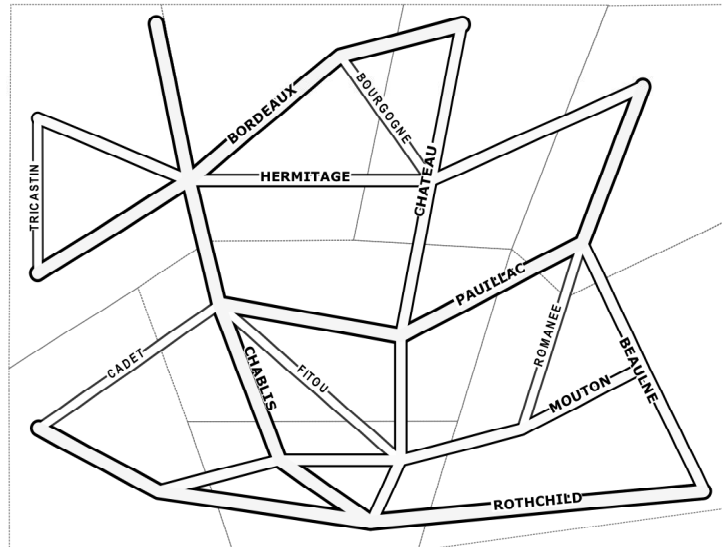


Figure 2.1. *Road network plan of the Urban Community of Machiaville*

By using an initial characterization of the road network, Figure 2.2 shows a map comprised of 19 nodes (at-grade intersections, see Table 2.1) and 31 road links which correspond to the original city plan in Figure 2.1. For a road traffic simulation, we have also added 8 centroids of zones which make up the region's different districts. In the aggregate approach, an origin/destination matrix for the different trips will be defined. This first model is a classic filamentary (line) network.

This aside, it is important to underline here that modeling a transport network should proceed from traditional concepts of graphs and networks, the fundamental and advanced elements of which can be found in the following references: [BER 63], [ROD 98], [MAT 10].

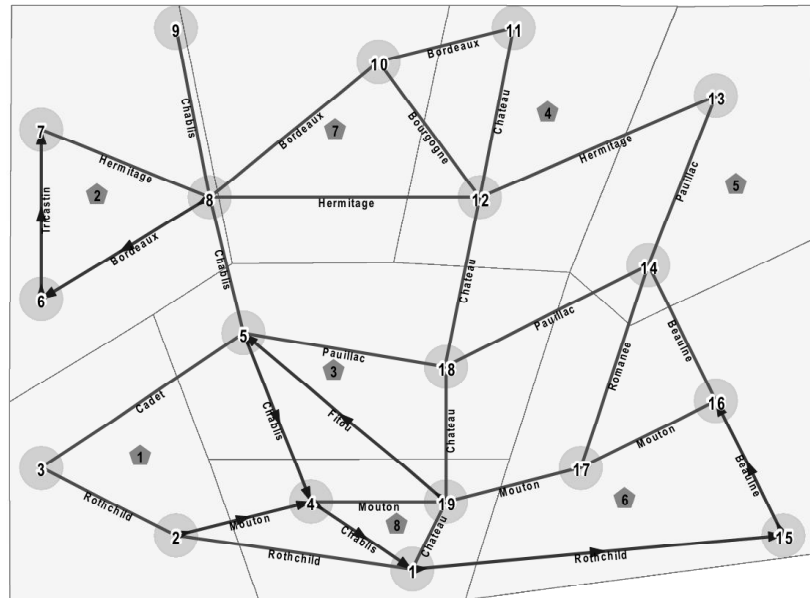


Figure 2.2. *Filamentary road network for Machiaville*
(for color version see www.iste.co.uk/banos/GIS.zip)

In order to reach the equivalent of modeling roadway networks, modeling public transport connections requires the explosion of each node where walk links permit transfers between the stops of connecting lines. This matter is usually dealt with implicitly by using route calculation software.

According to the chosen characterization objective (medium-term planning models, the establishment of a passenger information system or journey calculator, assessing the attractiveness of public transport), the level of resolution of the analysis will be the most important factor when defining supply. The following sections will illustrate these issues.

NODE	X	Y	ROAD INTERSECTIONS
1	12000	0	Château/Rothchild
2	5000	1000	Rothchild/Mouton
3	1000	3000	Rothchild/Cadet
4	9000	2000	Chablis/Mouton
5	7000	7000	Chablis/Fitou
6	1000	8000	Tricastin/Bordeaux
7	1000	13000	Tricastin/Hermitage
8	6000	11000	Bordeaux/Chablis
9	5000	16000	Chablis
10	11000	15000	Bordeaux/Bourgogne
11	15000	16000	Bordeaux/Château
12	14000	11000	Château/Hermitage
13	21000	14000	Pauillac/Hermitage
14	19000	9000	Pauillac/Beaulne
15	23000	1000	Rothchild/Beaulne
16	21000	5000	Mouton/Beaulne
17	17000	3000	Mouton/Romanee
18	13000	6000	Château/Pauillac
19	13000	2000	Château/Mouton

Table 2.1. *List of nodes in the line network*

2.2. Considering time in journey planning

According to the application of the envisaged model, characterizing the supply of public transport services is conducted over different periods throughout the day. For example, this may be when the network geometry is line-based and has a predefined level of service, or when it is schedule-based [WIL 07], in which case the journey time for each vehicle at each stop is predetermined according to a planned schedule. In particular, when the concept of supply is defined in relation to the demand for urban transport, the concept of generalized average costs must integrate fares, access on foot (or in a private car) to the origin and destination, waiting (a function of frequencies and reliability) and journey times. In standardized units, these *times* are subject to weight coefficients which reflect the concept of difficulty or unpleasantness in the context of chronological time.

Typically, the respective weights of 3 (walking) and 2 (waiting) are used to convert general time into time units on board a vehicle. The service reliability for a given transport mode or line will be taken into account using the formula for calculating average waiting time:

$$E(w) = \frac{E(x)}{2} \cdot (1 + (Cx)^2) \quad [2.1]$$

where x is the time interval and Cx is the variation coefficient of the interval distribution between two consecutive vehicles.

In this context, normal practice is to geocode the transport network in order to determine access distances and to define the level of service by using commercial frequencies and speeds.

2.3. Geometry of a collective urban transport network: expressing interconnectivity

An approach oriented towards the *object* is the strictest method for defining public transport supply [CHA 82], [CHA 92]. A transport analyst must, then:

- model a network according to the *node-line* model for traditional planning (determining, in a medium- or long-term horizon), which includes coding the network's geometry and its level of service (ordered list of nodes passed for each line, periods of operation, average intervals, commercial speed);
- carry out a geometric representation of the network according to the *line-stop* model;
- identify and distinguish the various *objects* within a transport network (networks, modes, lines, stops, termini, injection points, depots, vehicles, drivers, runs (tours), departures);

– determine some fundamental equations for the circulation of these objects and for the calculation of operational statistics.

What differentiates the public transport network from the automobile network is the fact that the object “*person*” must use one or many *vehicles* during their *itinerary* (*passenger’s route*). This involves a *linear organization* (road, track) of vehicular movement according to specific routes called lines (or circuits). Thus, the user is subjected to *transfers* as well as *waiting times*, with these different epiphenomena increasing the level of difficulty for the journey. The need to access services by *foot* and to regularly *validate* fares is added to this.

The following process is written within a context to model for the purpose of planning. The codification of a public transport network for Machiaville is based on the following elements:

a) The network’s geometry (*network modeling*: $G(N, L) + g(L)$)

The geometry of a (public) transport network refers to different *node* and *link* elements which define its “appearance” and its structure. *Digitizing* a network makes it possible to give a *spatial* existence to the different *entities* involved. This may be achieved using GIS-type tools. The network’s *geometric* perspective supports:

– studies related to the provision of transport service: spatial location of *stops* and proportion of the population within maximum access distances, *coverage* over the community, etc.;

– *user* information in terms of general services for different districts (the existence of the network in certain areas);

– drivers’ itineraries (directions in terms of right/left turns).

b) The level of service (*kinematic modeling*)

Coding makes it possible to add attributes to the different entities in the transport network. Within a planning context, the level of service establishes an *accounting mechanism* for the network and is expressed in terms of:

- commercial speed;
- average intervals for different times (peak, off-peak, etc.);
- specific attributes of the different *nodes* on each line (sequence, service characteristics: boarding, alighting, etc.).

c) Resource assessment

The resources needed to operate a public transport network, given a certain geometric layout as well as a given level of service, are expressed in terms of:

- the fleet required: number of vehicles required to operate the service supply;
- vehicles/kilometers: kilometers travelled by the set of vehicles;
- vehicles/times: total operation time for all the vehicles.

For these indicators, different accounting mechanisms must be used to assess the *productive* resources (allocated to operating the service directly for passengers) and the *effective* resources (required for total service operation, for example: waiting times, entering and leaving garages, etc.).

d) Comparison of resource estimation methods

In terms of methodology, a distinction is made between resource assessments according to two schemes:

- *permanent scheme (continuous operation)*: a classic (mathematical) estimate of the average resources required for operating a service;

– *dynamic scheme (with transition)*: discrete monitoring of the vehicles needed for operating the service at a given a level of service.

We find it essential to go into more detail with regard to this difference between these two methods of estimation.

e) Routing: optimizing vehicle assignment; drivers assignment and runcutting

The last phase comes under the context of vehicle use, in terms of looking for the best way to save on resources (coming and going between the depot and termini), and then the way in which the operators' duties are organized according to minimum costs under collective bargaining constraints.

2.3.1. Linear routes: ordered sequences of stops

The following steps cannot be overlooked when defining a public transport network:

- the coding of stops along the lines in the network (vehicle itineraries for a given mode of transport);
- coding lines and their features (intervals, lengths, speeds, application periods);
- intermodal association and fares (or intermodal penalties);
- service types, vehicle types, capacity.

In a micro-simulation as well as in the context of building a user information system, the representation of the transit line is in terms of directional half-runs by the description of the stop sequence.

In the example of Machiaville, the network is defined in detail using 7 routes, 12 half-runs and 54 stops (see Figure 2.3 and Table 2.2).

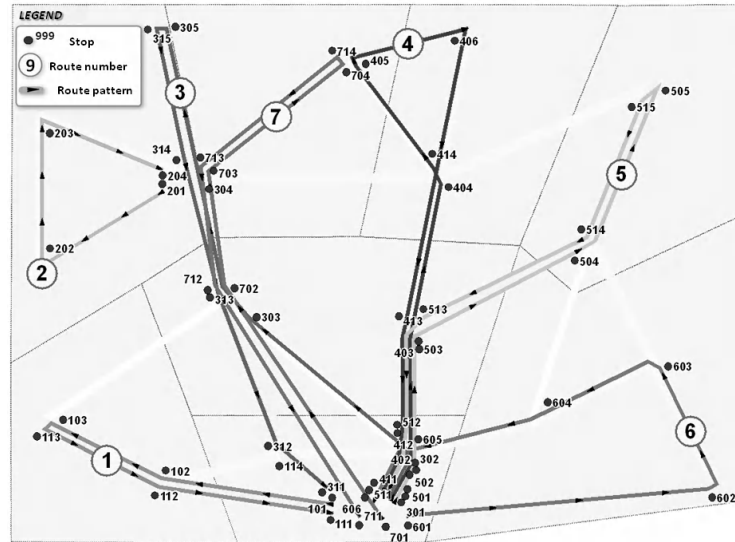


Figure 2.3. Definition of public transport network in line-stops
(for color version see www.iste.co.uk/banos/GIS.zip)

LINE_STOP	ROUTE	DIR	NODE	X	Y
101	1	IN	1	12000	0
102	1	IN	2	5000	1000
103	1	IN	3	1000	3000
113	1	OUT	3	1000	3000
112	1	OUT	2	5000	1000
111	1	OUT	1	12000	0
201	2	IN	8	6000	11000
202	2	IN	6	1000	8000
203	2	IN	7	1000	13000
204	2	IN	8	6000	11000
301	3	IN	1	12000	0
302	3	IN	19	13000	2000
303	3	IN	5	7000	7000
304	3	IN	8	6000	11000
305	3	IN	9	5000	16000
315	3	OUT	9	5000	16000
314	3	OUT	8	6000	11000
313	3	OUT	5	7000	7000
312	3	OUT	4	9000	2000
311	3	OUT	1	12000	0
401	4	IN	1	12000	0
402	4	IN	19	13000	2000
403	4	IN	18	13000	6000
404	4	IN	12	14000	11000
405	4	IN	10	11000	15000
406	4	IN	11	15000	16000
414	4	OUT	12	14000	11000
413	4	OUT	18	13000	6000
412	4	OUT	19	13000	2000
411	4	OUT	1	12000	0
501	5	IN	1	12000	0
502	5	IN	19	13000	2000
503	5	IN	18	13000	6000
504	5	IN	14	19000	9000
505	5	IN	13	21000	14000
515	5	OUT	13	21000	14000
514	5	OUT	14	19000	9000
513	5	OUT	18	13000	6000
512	5	OUT	19	13000	2000
511	5	OUT	1	12000	0
601	6	IN	1	12000	0
602	6	IN	15	23000	1000
603	6	IN	16	21000	5000
604	6	IN	17	17000	3000
605	6	IN	19	13000	2000
606	6	IN	1	12000	0
701	7	IN	1	12000	0
702	7	IN	5	7000	7000
703	7	IN	8	6000	11000
704	7	IN	10	11000	15000
714	7	OUT	10	11000	15000
713	7	OUT	8	6000	11000
712	7	OUT	5	7000	7000
711	7	OUT	1	12000	0

Table 2.2. Informational characterization
of transport routes in line-stops

2.3.2. Coding connection nodes

When modeling demand, it becomes necessary to fuse together the line-stops in order to express the transfer potential between lines and modes of transport. In this context, the network used for planning takes the following shape (Figure 2.4, Tables 2.3 and 2.4) where the trips made by both people and vehicles occur over 19 nodes.

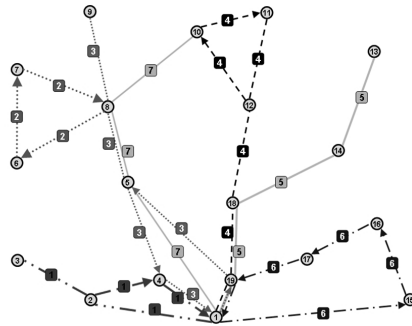


Figure 2.4. *Machiaville public transport network*
(for color version see www.iste.co.uk/banos/GIS.zip)

ROUTE	PATTERN	NAME	DESCRIPTION	GEOMETRY (LINE-STOPS)	GEOMETRY (MADITUC)
1	0	Fettucini	Route with two distinct patterns	101-102-103-113-112-111	1-2-3
1	1	Fet.a.romana	Pattern 1 uses a detour on return for PM peak	101-102-103-113-112-114-111	1-R4-2-3
2	0	Tortellini	Loop with a termini at node 8	201-202-203-204	8-A6-A7-8
3	0	Lasagna	Route in operation only during peak periods and with distinct pattern by direction	301-302-303-304-305-315-314-313-312-311	1-S4-A19-5-8-9
4	0	Spaghettoni	Route with only one termini and a loop at the end	401-402-403-404-405-406-414-413-412-411	1-19-18-12-12-A10-A11-12
5	0	Involtini	Bidirectional route for AM and PM peak periods	501-502-503-504-505-515-514-513-512-511	1-N19-18-14-13
6	0	Espresso	Express route only in operation during peak periods	601-602-603-604-605-606	15-A16-A17-B19-1
7	0	Capucmetro	Subway line	701-702-703-704-714-713-712-711	1-5-8-10

Table 2.3. *Characterizing the geometry of public transport routes*

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ROUTE	PATTERN	INBOUND DIST. (KM)	OUTBOUND DIST. (KM)	INBOUND SPEED (KM/H)	OUTBOUND SPEED (KM/H)	TYPE	SERVICE PERIOD	INTERVAL PER SERVICE PERIOD (MIN.)
1	0	11.5	11.5	28.0	28.0	3	AM, off-peak and evening	5,30,30
1	1	11.5	12.5	27.0	27.0	3	PM	30
2	0	16.5	0.0	31.0	0.0	13	AM, off-peak, PM and evening	20,20,20,20
3	0	19.0	18.0	36.5	36.5	3	AM, off-peak and evening	30,30,30
4	0	25.5	11.5	34.5	34.5	3	AM, off-peak and PM	30,30,30
5	0	19.0	19.0	35.0	35.0	3	AM and PM	45,60
6	0	16.0	11.5	38.0	42.0	3	AM and PM	10,10
7	0	20.0	20.0	45.0	45.0	1	AM, off-peak, PM and evening	10,30,10,30

Table 2.4. *Characterizing public transport service*

2.4. Calculating resources according to transport network coding

The different data contained within the coded network determine the resources involved in service supply. The commercial speed (speed the passenger is subjected to, including dwell-times) and the distances between stops fix the assigned journey time, to which is added the layover time (minimum of 3 minutes or 10% of the journey time) when estimating the time needed to put a vehicle crew back into operation.

The level of service is established according to these conditions, or according to a basic service with no relation to demand (e.g. an interval of 60 minutes), or according to the volume of passengers on board the vehicle when it is full – the maximum load point. This load, divided by the load factor for the period in consideration (the nominal vehicle capacity), determines the minimum journey frequency. From

this we can derive the vehicle-kilometers calculation, the vehicle-hours calculation, the necessary fleet size (which depends on the time needed to put a vehicle back into service), as well as factors of spatial and temporal use (weighted ratio of load to capacity). Calculations are more accurate when we are dealing with the service's operation in a dynamic scheme (discrete events) rather than in a permanent scheme.

2.5. Visualizing the transport network from different perspectives

Characterizing public transport supply is preferably achieved using a totally disaggregate approach [CHA 92]. The concept of a trip by public transport is illustrated in Figure 2.5.

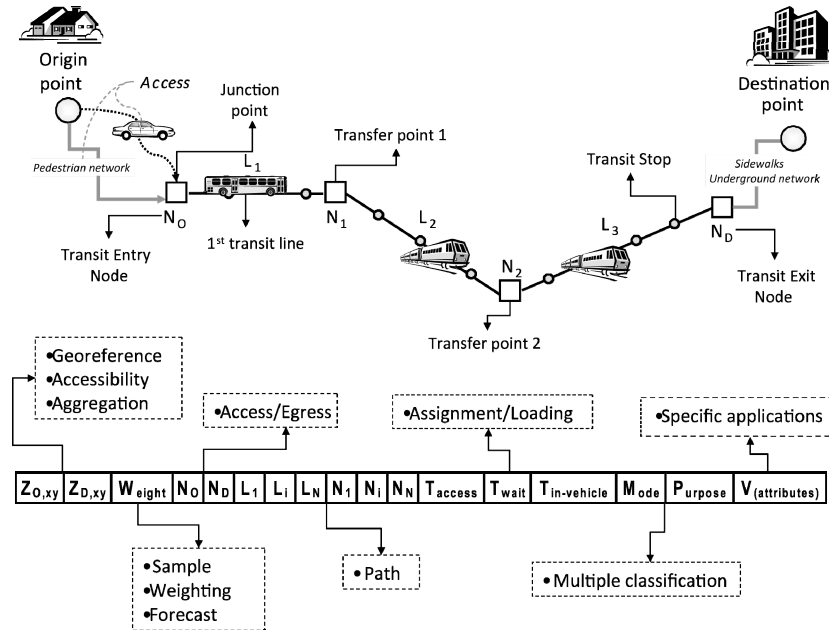


Figure 2.5. Completely disaggregated itinerary and informational characterization

Elements regarding access to the origin and the destination, and elements concerning transfer and travelling in a vehicle include simultaneously the impedance weights and the times and fares which are derived from the network's attributes. For a non-negligible proportion of all trips made, the characteristics of road networks (access by car and parking) and pedestrian networks must be integrated into the model. The diagram also illustrates the various fields associated with the trip coming from a typical origin-destination survey: the characteristics of the person and their household (including car ownership), may also easily be related to their demographic weight (weighting coefficient), the time and purpose of the trip, and the spatio-temporal elements of the chosen itinerary. This makes it possible to carry out analyses on the accessibility of the spatialized population, and, at the same time, on the elements of the network itself (the type of ridership passing over a link or through a station).

As an example, the following sections show a few illustrations of analyses performed when characterizing public transport supply.

2.5.1. Load profile for a subway line

The aforementioned informational organization of data enables us to observe the potential impacts of a breakdown of a subway line on traveler mobility [CHA 97].

Figure 2.6 shows the total number of people entering and exiting the set of subway stations of the subway line as well as the total number of passengers travelling on the subway at a given moment. Generally, this type of diagram is more often applied to the temporal evolution of the number of in-service vehicles on the network.

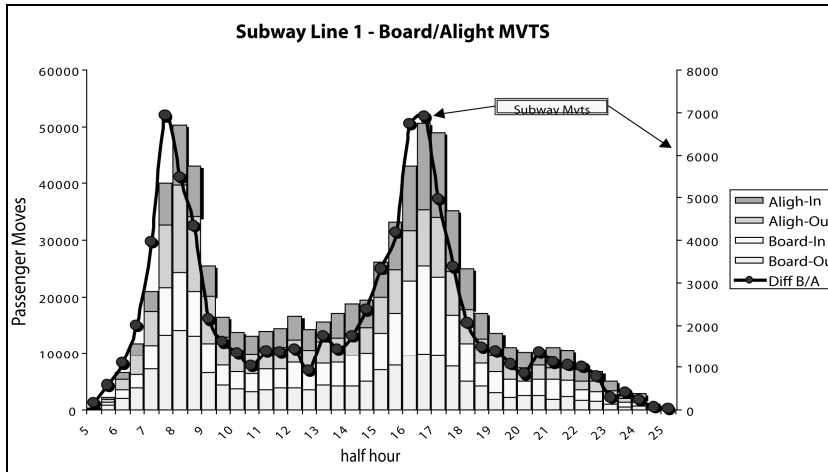


Figure 2.6. Summary of temporal data (number of passengers, subway line no. 1) (for color version see www.iste.co.uk/banos/GLS.zip)

2.5.2. Load profiles for transport lines

Figure 2.7 illustrates the load profile for the Montreal subway lines and two suburban railway lines during the morning rush hour. This is following the assignment of trips which are representative of an average day in Fall, based on a household travel survey carried out in the Fall of 1998. This representation also includes the details of the number of travellers entering and exiting at each station served by these particular modes of transport.

According to another type of analysis (Figure 2.8), the subway network in Montreal is examined according to the different types of activities undertaken by its passengers; effectively, for the morning peak period, we illustrate passengers’ trip purpose (work, study, shopping, other) over each network segment, as well as the trip purpose of those passengers who access the subway system on foot.

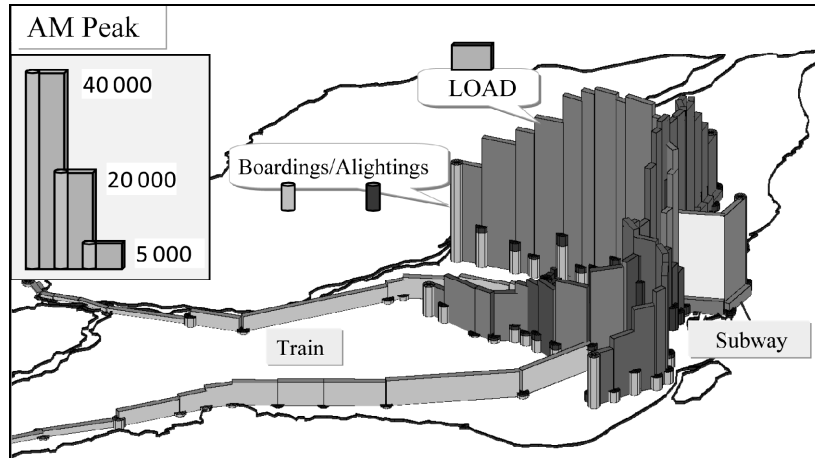


Figure 2.7. Load profile for the subway and suburban railway in the morning peak period (for color version see www.iste.co.uk/banos/GIS.zip)

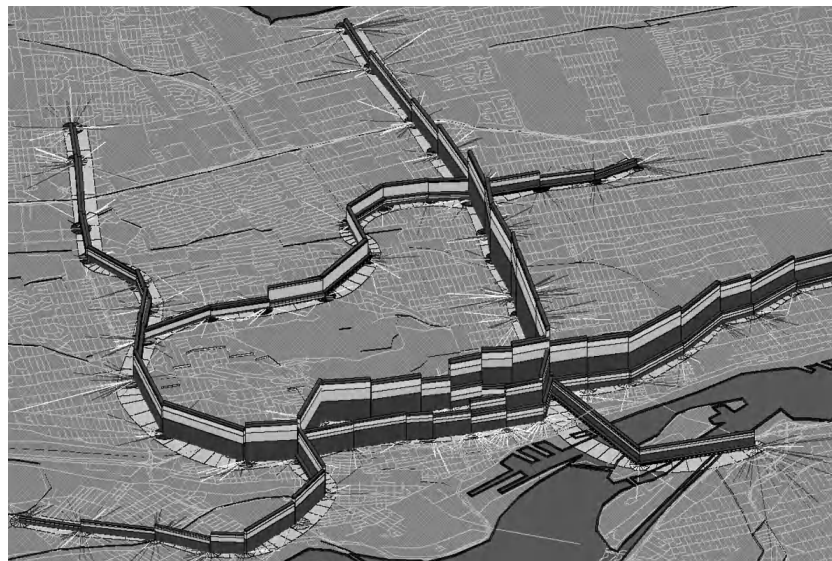


Figure 2.8. Load profile of the Montreal subway in the morning peak period (segmentation according to trip purpose) and on-foot access for subway users (for color version see www.iste.co.uk/banos/GIS.zip)

2.5.3. Measurement of accessibility to the public transport network

Traditionally, urban public transport is valued primarily for its spatial accessibility. The results of the usual norms for establishing a service is illustrated in Figure 2.9 by a “coverage” calculation. A typical survey in Montreal consists of a sample which is stratified spatially around 5% of households. Each sampled household (out of 65,000) is georeferenced, which makes it possible to assess the proportion of households and cars in buffers of 200, 400, 600 and 800 meters from 10,000 bus stops and subway stations. It thus becomes clear that the households with few cars or none at all are relatively well served by the public transport service.

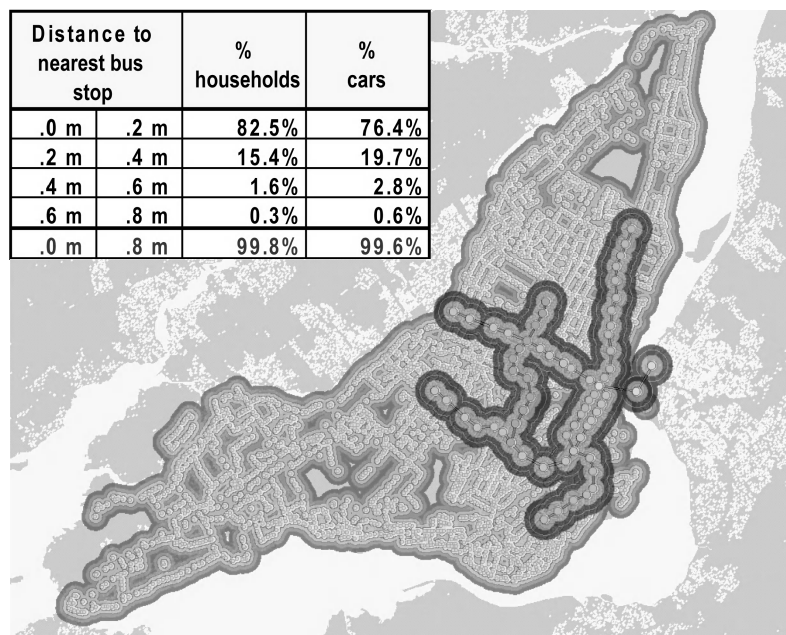


Figure 2.9. Network coverage and accessibility to public transport networks on the Island of Montreal (for color version see www.iste.co.uk/banos/GIS.zip)

2.5.4. *The importance of public transport*

More generally, public transport supply is in competition with other modes where ageing, car ownership and urban sprawl continue to manifest themselves. In a mono-centric urban context, the place and role of public transport is expressed as in Figure 2.10, where its modal share (calculated using data from the Origin-Destination survey in 1998) declines according to the distance from the city center, ageing population, low income, population density, etc.

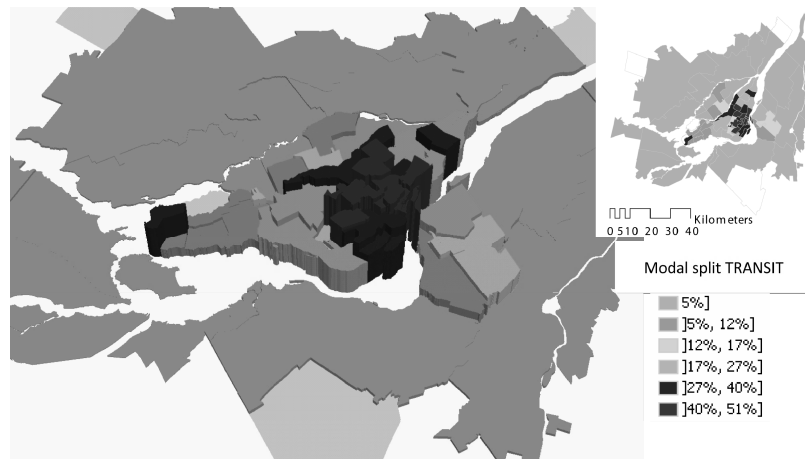


Figure 2.10. *Modal share of public transport: Origin-Destination Survey 1998 (divided into 65 municipal districts) (for color version see www.iste.co.uk/banos/GIS.zip)*

2.5.5. *Detailed measurement of public transport: surface area of the transport demand for the line*

Urban public transport remains a totally artificial system, meaning a system created by mankind. With the current evolution of information technology systems, we must understand that the organization of the service will gradually develop in a more refined way. There is currently a

process to facilitate this when the demand for transport may be monitored on an individual level.

Figure 2.11 shows the potential for characterizing precisely each run in the public transport network. In the figure, we find the load profile for each departure of line 44 on the STO network (Canada), on February 10, 2005.

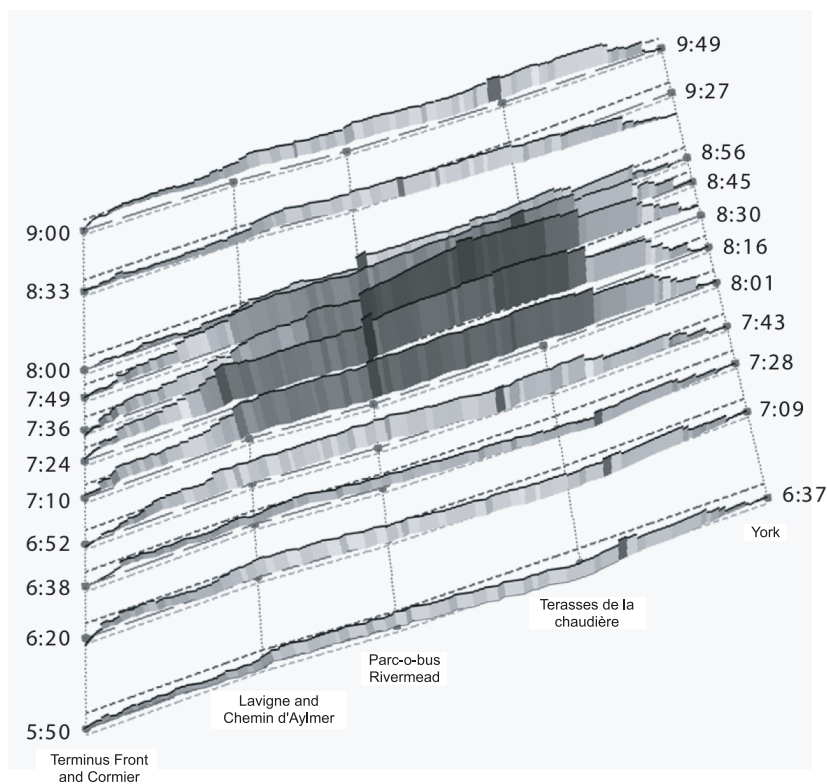


Figure 2.11. Detailed 3D load profile (route 44, towards city center, morning of February 10th 2005. Sources: smart cards, STO, disaggregated data); planned departure and arrival times, intervals and position of maximum load points are recorded (for color version see www.iste.co.uk/banos/GIS.zip)

Using data from smart cards and operational georeferenced data, it becomes possible to deduce the passengers' stops as well as detailed journey times for vehicles [CHA 07].

Thus, the performance and productivity of public transport may be characterized appropriately... to the point where the choices for managing the network will become clear.

2.6. Conclusion: GIS as an analysis and intervention platform

Even if the traditional methods of characterizing public transport supply were available well before the instruments specific to GIS, it still remains that the intrinsic organization of a GIS brings about (particularly with the SHP – the ESRI *shapefile* format) the attachment of a DBF data table to each layer of information, in addition to a remarkable potential for 3D visualization.

At the cost of a new method for organizing information (e.g. producing a load profile for a transit line within a space-time diagram, such as in Figure 2.11) where the entity “line” is explicitly composed of a set of ordered links, each having its own attributes, new methods for measuring performance may be developed in order to build advanced monitoring, adjustment or intervention techniques. Modern operational concerns [CED 07], [VUC 05], [THE 01] convincingly demonstrate the importance of such techniques.

Within the applied context of integrated fare revenue-sharing between the public transport operators in Montreal, the use of GIS allied with the totally disaggregated approach enables the equitable assessment of the respective consumption, in terms of passengers/kilometers on each network, and by each mode of transport of the inhabitants of the various districts in the urban area.

Thus, for its role in the provision of user information systems as well as an aid to the city's decision makers, GIS contribute to the technical credibility of many interventions on public transport networks.

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Chapter 3

Defining Intermodal Accessibility

3.1. Introduction

In the modern city, transportation systems are clearly identified objects. They are subject to multiple constraints (they must not use up too much space or too many resources). They are also accused of generating problems (locally as well as on a global level), but there is also much expected of them (they have to provide services for all the areas in the city, and they have to be efficient). Within this partly contradictory sheaf of injunctions, accessibility is one of the concepts which may be used to help with responding to these matters, in order to introduce measurements and to assess the system's potential for modification.

The aim of this chapter is to present the concepts of multimodal and intermodal accessibility. Initially, we will propose a definition of accessibility.

In the urban transport domain, we will focus on collective transport by pointing out certain specific characteristics regarding the way they function, which must be taken into

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account in order to understand the accessibility they provide. We will end this chapter by demonstrating an application which involves intermodal accessibility measurements across an urban region.

3.2. Accessibility

3.2.1. A definition of accessibility

Accessibility may be defined simply as the possibility of accessing equipment and/or resources. However, beyond this general definition, the meaning and use of the term differ, in particular according to the fields of application and disciplines [HUR 94], [MAE 98], [RIE 98]. This leads us to distinguish two concepts.

An initial definition seeks to identify the problem arising from the (either appropriate or inadequate) skills of the person trying to access the resources. Therefore, accessibility begs the question concerning difficulties encountered by people with reduced mobility using different means of transport or gaining access to public places. It is, then, a matter of adapting spaces and areas so that all members of the public may have equivalent use and accessibility.

The second definition refers to the conditions which allow individuals to get around and go places, or the conditions in which goods can be shipped. Our chapter is written according to this second meaning. Accessibility is, then, essentially a spatial concept which aims to give an account of the effort needed to travel, so as to reach resources in a given place. As a measure of the space or distance between two places, accessibility is distinguished from the concept of distance by its more contextualized character, meaning its more “realistic” nature [DUM 99]. Once this general definition had been put forward, we found many other definitions of accessibility in other references [CAU 05],

[KOE 75], [IZQ 92]. If the emphasis on spatiality puts the concept into the domain of geography, then the concept of “effort”, meaning the distance to be travelled, may also be understood as a cost, and renders accessibility the favorite tool in the domain of spatial economy.

Here, we propose to define accessibility as the possibility of reaching a place with the aim of carrying out an activity there. We may measure accessibility in order to give an account of the level of ease involved in reaching the said place.

Measuring accessibility from, or to, a considered geographical area brings many factors into play that can be broken down as follows [VIC 74]:

- the position within the reference space, meaning a place located in the center will always be more accessible than a place in the suburbs, and this is independent of the transport network. This factor stems directly from the geometry of the space considered;

- the transport network performance plays an important role when measuring accessibility by facilitating the conditions of accessing the area; this performance also depends on many different factors:

- the shape of the network influences the extent of accessibility by creating favored routes and ignoring areas which do not call for high demand;

- the transport system’s performance according to speed, which is often greatly differentiated according to the modes of transport considered, or according to the frequencies or timetabling regarding collective transport. Prioritizing the network in this way will also favor the main routes to the detriment of less well equipped areas.

3.2.2. *Measuring accessibility*

The previous definitions put the ways of measuring accessibility into order. Effectively, the purpose of making a trip is usually for performing an activity, and the interest in such an approach is mainly based on a potentiality analysis. In other words: what can we do with a given level of accessibility? What do we have access to?

Thus, calculating activity potential (in terms of accessible jobs, the population able to gain access, or opportunities to be taken) is abundant in territorial analyses [CHA 04], [CHA 07], [KAL 97]. In particular, the measurements for economic potential have led to specific indicators [HAN 97] [REG 98], [VIC 96]. These measurements are added to other more traditional measurements in econometry or spatial economy based on the gravitational model [GEU 01] or on calculating utility functions [GEU 04].

On the other hand, these calculations must not only measure distance, but also accessibility. It is therefore important to take into account the contextual and particular nature of accessibility. As R. De Crécy said: *“Measuring by distance (either as a Euclidean distance or by a specific route) must be excluded: accessibility is, then, once again becoming a simple indicator of urban structures and no longer takes into account the qualitative nature of the transport network”* [CRE 79]. From this point of view, traditional indicators, based on absolute spatial separation measurements between different places [KEE 88], [LIN 92], [POO 95], seem insufficient.

With the help of a GIS, the indicators which neutralize location importance (e.g. peripheral areas are undoubtedly less easily accessed, and this is in spite of the transport network performance) have therefore been developed [GUT 98]. The objectives for planning and prospective reflection in the transport domain is favored here. The social

dimension of accessibility is then gradually substituted for a simple physical distance [MON 88].

Let us also make a note of the efforts needed in order to consider transport performance over an entire region, with indicators being applied to an area and not simply to a node [CHA 97], [MUR 98]. In this case, the network's performance is wholly favored in terms of formalism, and the spatial and temporal constraints are underestimated.

Therefore, the two aspects with regard to accessibility (spatio-temporal constraints and transport network performance) are considered more or less according to these methods. Choices concerning these spatial and temporal parameters are necessary in order to justify the indicator.

Effectively, spatial parameters are defined by the choice of destination, or origin where the accessibility measurement will be implemented. It may be a matter of locating equipment, a residential area, or a retail area, for example. Generally, we are interested in key places or those places generating a lot of traffic. Determining spatial order parameters raises the question of transport chains between the site in question and the location of the entrance to the transport network. We will use such terms as "egress modes" or even *pre-* and *post-routing*. Walking is also part of the mobility chain (whatever the other available modes of transport) including cars where it is necessary to walk between the place where the car is parked and the starting or destination location. On the other hand, temporal parameters concern the constraints linked to the transport system's operation as well as the urban pace of life.

Measuring accessibility amounts to establishing either a distance in a mathematical sense, i.e. a function which re-examines a measurement associated with a pair of places and fulfilling a series of specific properties. We notice here that the criterion for calculating the shortest routes may

integrate the duration of the journey, the cost, the journey length, but also the different modes of transport (with links in between which may, or may not, be homogeneous) or even the nature of the object being transported.

3.2.3. “Best time” limits

Sociologists have postulated that time was the most appropriate metric in order to understand accessibility; more exactly, minimizing travel times is the main factor in route choices [DIE 95].

Accessibility calculations have also often used the notion of minimum time as an expression of the cost of the trip [BAV 05], [GUT 96], [SCH 97] [SPI 99]. Modeling collective transport manifests specificities, related to timetabling and waiting times in journeys with transfers, which require specific calculations [KAL 97].

In the domain of collective transport, we retain the total time spent on the line of transport and sum up the various parts of the journey encountered when using the optimum route, taking into account any possible transfers. Within this framework, in order to deal with transfers, we retain an average frequency and are often led to distinguish a peak and off-peak time. According to a probabilistic approach, we then generate an indicative journey length in a transport network.

This approach has been adapted in order to analyze transport systems which are characterized by high frequency levels. If the average journey time between two trips is low, then access into the system is nearly instantaneous. The total trip time is only slightly increased. However, the approaches for best time and frequencies lose their relevance when the frequency decreases. The length of any trip is a function of the best measured time, and is then completed by

a length taken to be between zero and the maximum value separating two different vehicles setting out in succession.

In this situation, measuring average transfer times no longer really takes into account real life situations. For example, for an interconnection between two bus lines with a difference of half an hour between them (fairly frequent in urban transport systems), the transfer time varies, in theory, from zero to thirty minutes. The cost in terms of time after a missed connection, when we “miss our bus” for example, may actually be prohibitive when added to the total journey time.

For these reasons, we propose focusing on transport timetables in order to understand and measure accessibility by collective transport, according to a movement which operates in a similar way as in traffic modeling [NUZ 01]. Effectively, questions regarding transport and spatial planning have benefited from the contribution of timetable investigations in many cases [JAN 96], [NUZ 99], [CHA 99].

Moreover, the progress made in different techniques, particularly geo-computational algorithms, has recently led to the development of time considerations in works on accessibility. Thus, methods for measuring spatio-temporal constraints have seen great changes since taking into account the spatial distribution of amenities (the place where the individual will spend time [KWA 98], [KWA 99]), the temporal availability of these amenities (opening and closing times and maximum and minimum opening hours [MIL 99], [MIL 00]) or even a combination of the two [KIM 03].

3.2.4. *Schedule accessibility*

For collective transport operating via timetables, it is relevant to use schedule information in order to understand the service and to analyze the system’s spatio-temporal

performance [BAP 10], [LHO 04]. We define schedule accessibility as a measure of directional accessibility, with two different possible directions:

- the arrival times to any place from a fixed origin and departure time;
- departure times from any place to reach a destination before a fixed arrival time.

Travel time accessibility requires us to multiply the measurements and maps which correspond to as many points of view and trip requirements identified. This type of measurement is adapted to the very specific concerns which come up within a region. However, it is necessary to put average aggregation measures into place over a certain time interval [LHO 06], in order to construct a global analysis.

Nonetheless, this approach is not without its limitations. Effectively, we take the timetables to be reliable. However for a collective transport system which operates according to car traffic, then congestion and hazards may alter the reliability of travel times. Consequently, the quality of transport time measurements is indeed altered when we do not take *hazards* into account.

3.3. Intermodality and multimodality

The transport system can be broken down into different modes with very different characteristics. Articulating these modes is one of the essential matters concerning the general make up of a transport system. By using literature with pre-established terminology [BOZ 05], [LHO 00], [NOU 93], [MAR 96], we consider that two modes of transport used in one trip define “intermodality”, whereas “multimodality” refers to distinct journeys travelled with different modes or combinations of modes of transport.

According to this distinction, we qualify intermodality as a single trip which combines both a car and a subway line, for instance. Multimodality, however, is used to describe the possibility of a trip made in a car, compared to a journey made using collective transport.

Intermodality refers to the transfer between one mode and another, whereas multimodality enables us to consider many sorts of transport chains in parallel, whether they are monomodal or intermodal.

Intermodal accessibility describes the way in which we reach the places where we want to go, by combining many different modes of transport to complete each trip. Multimodal accessibility, however, considers the concept of access by using all the modes or combinations of modes possible. The two concepts allow us to ask different questions. Intermodal accessibility questions the connection of different modes within a transport chain (intermodality), and therefore improving the existing transport system.

Multimodal accessibility raises the question of performance via the comparison of different modal chains, and therefore focuses on modal transfer from one chain type (mainly passenger cars) to another (mainly collective transport), which is considered to be more satisfactory from a sustainable development point of view.

In this chapter we will show an example of the problems concerning intermodality applied to collective transport in an urban area.

3.4. Modeling the transport system: networks and graphs

Graph theory is part of a framework which is particularly well adapted to representing transport networks [MAT 10].

Nodes and arcs on the graph correspond to the places and links within the transport network.

The concept of *weighted graphs* means that we can extend the general framework of graph theories in order to describe the geographical and technical properties of links and nodes within the networks. The length of a highway lane, its angle, and the width of the roadway are as many characteristics as we can associate with the weighting in the graph. This is the same for the frequencies, travel times, level of comfort of the connections, or even the assigned routes for collective transport networks.

From a methodological point of view, the frame of reference here is graph theory: as a basis, we are using a weighted p-graph model which integrates either the travel times for the considered transport systems, or the lengths of connections by foot or a high frequency mode of transport. Figure 3.1 shows how the algorithm calculates accessibility for average length journey times. The route $p = (f, g, h, e, d, b)$ has a length of 16. It is the shortest route connecting points f and b. In this p-graph the values represent journey times in minutes.

Our p-graph works in an equivalent way, but by integrating travel times with each timetable period represented by a layer of the graph. The algorithm for the shortest routes must establish the possible routes, where each departure time in a given place must be higher than the arrival time for the same place, or equal to it for an assigned route by collective transport. To achieve this, we have implemented algorithms introduced by Floyd and Dijkstra and adapted them to schedule times and intermodality [MAT 10]. The algorithm is implemented in two different ways. By fixing a departure time in a node, we then construct all the quickest journey times towards the other nodes on the graph, which leave after this fixed time. We may also indicate a maximum arrival time into a place. In

this case the algorithm reconstructs the journey times when leaving from the other nodes as late as possible, thus arriving at the reference node before the necessary fixed time.

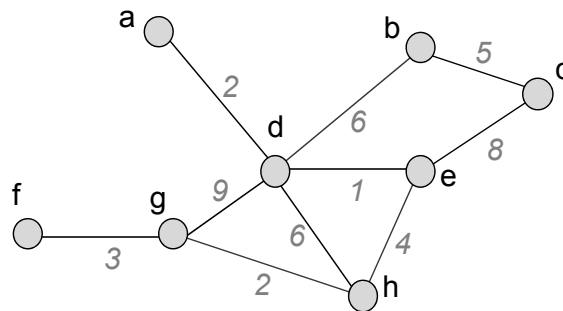


Figure 3.1 Shortest route principle in a weighted p -graph in average journey times [SEG 05] (for color version see www.iste.co.uk/banos/GIS.zip)

3.5. Example on an urban scale: access to the Lille campus

We propose to give an example of intermodal accessibility measures with an application over the urban area of Lille, within the region of Nord-Pas-de-Calais in the Northern tip of France. Inspired by approaches developed on an urban scale [TRE 96], [MCF 97], we propose a method based on three principles:

- segmenting users;
- identifying main key places;
- identifying urban pace of life.

We will focus on students because this segment of society brings together more than half the regular rail users in the Nord-Pas-de-Calais region.

To begin our transport service analysis, we must first identify the main places which generate traffic associated with this segment of demand.

Figure 3.2 shows the location and widespread area of the five main campuses in the Lille metropolis, as well as the urban transport system based on the regional rail network. Firstly, we will only consider the main railway stations, Lille-Flandres and Lille-Europe, which are still currently the best way of entering the city. In this view, the “rail network map” for TER, France’s regional rail service brand, which is published in the rail timetable by the Regional Council and SNCF (France’s state-owned railway service, TER is operated by SNCF) reiterates this idea that arrivals into the city should come into the two central stations. Because of this, the other possibilities of accessing the city via the other 40 TER stations located around the urban community are not shown.

Urban network maps must show mobility possibilities for users of a regional rail network. Even though the rail network (as for the majority of network maps for French cities with more than 100,000 inhabitants) is shown in the current network map for the urban community around Lille, it does not show interconnection possibilities other than those around the central stations. The principle of representing networks in Lille is to juxtapose the urban transport system and the regional transport system, but *not* an interconnection system. However, documents such as these contain privileged public information and could be geared to favor intermodality. Analyzing transport user network maps today focuses almost exclusively on access via the central stations.

The main criterion that we propose for analyzing the transport service which fulfills the needs for mobility is a travel time accessibility criterion: the departure time from the original starting point to reach key areas before a certain

time which is predetermined by this area's peak and off-peak times of activity.

This criterion is a spatio-temporal unipolar indicator, meaning the concept of going from many different places towards one single place. It enables us to consider the threshold effects related to problems concerning timetabling coordination within a transport system. This, however, is not possible when using traditional accessibility indicators which use average travel and waiting times.

3.5.1. Villeneuve d'Ascq campus: access via central rail stations

The two Villeneuve d'Ascq campuses total approximately a third of the effective student population in the Nord-Pas-de-Calais region, and represent the main university center in the region.

As Figure 3.1 shows, the collective urban transport system was initially designed to link these campuses to the Lille-Flandres railway station by an automatic subway known as the VAL. For a regional railway user, access to the Villeneuve d'Ascq campus was made by transferring at Lille-Flandres station using subway line 1. The normal access to the USTL campus establishes the reference accessibility measure in Figure 3.2. The transport service which would fulfill requirements for students at the *Université des sciences* arrives at the campus before 8 am, which is the usual starting time for classes. Within this campus (which is spread over a relatively vast area in the *Cité scientifique*), we have chosen the *École centrale* as one of the key places which represents access conditions.

Figure 3.2 shows the best departure times from each station towards the campus, in three different categories: departure after 7 am, between 6 am and 7 am, and departure

before 6 am. The category choices are formulated in response to an analysis which focuses on the point of view of the transport user: it is a question of analyzing the quality of the transportation service for destinations within the Lille metropolis. The class bands were chosen according to trips made on a daily basis: one hour represents an acceptable limit, whereas two hours is an extreme limit for every day mobility.

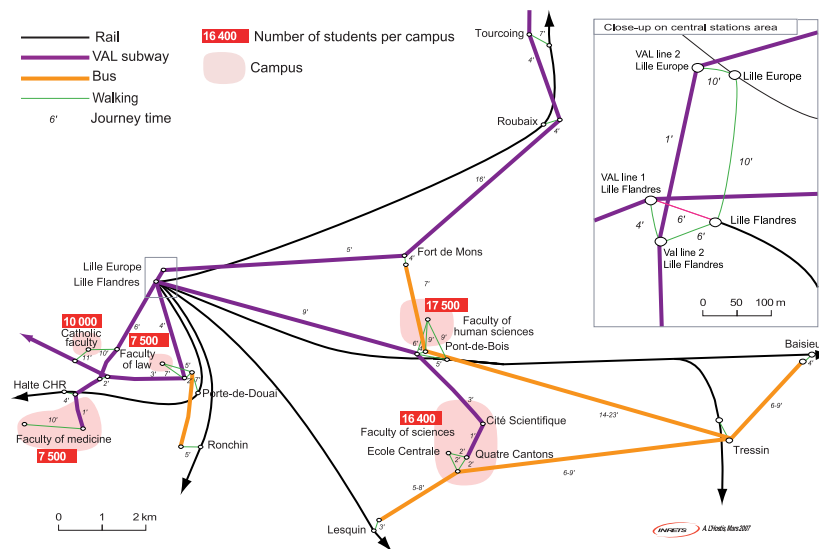


Figure 3.2. *Collective transport network for access to university campuses in Lille (for color version see www.iste.co.uk/banos/GIS.zip)*

This first measurement (Figure 3.2) is not very beneficial because, with the exception of Douai, none of the region's urban centers are located an hour away from the Science campus. The level of accessibility to the Science campus is lower than the level of accessibility to the city center of Lille.

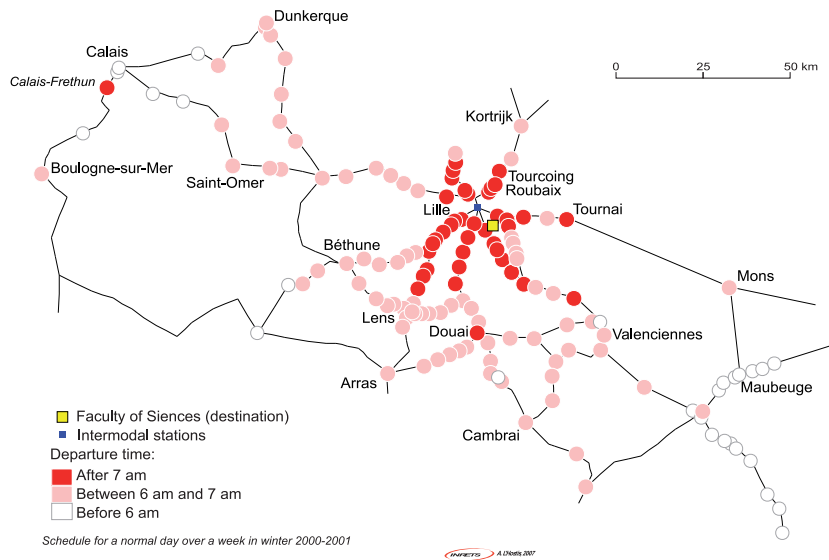


Figure 3.3. Schedule accessibility leaving from Nord-Pas-de-Calais railway stations towards the Lille Science campus, departure times to arrive before 8 am

3.5.2. Medicine campus: making use of Halte CHR

As a second application of this method, the following map (Figure 3.4) shows the conditions of accessing the University Medicine campus. To access this campus, which is located towards the South-East region of the metropolis, we should not consider access only by using the Lille-Flandres station, but consider the station Halte CHR which is located in the immediate vicinity.

By introducing this second gateway into the city, Figure 3.4 shows a better level of accessibility by leaving from stations on the route going towards the Halte CHR station, than for the route previously studied going towards the Science campus. Therefore, the town of Béthune comes into the group of stations which are less than an hour away. However, accessibility from Douai station, with a departure

time of 06:58, is slightly less convenient when going to the Science campus. Yet, these travel times remain within an acceptable timescale.

Could this improvement in accessibility by introducing the new entrance from the station at Halte CHR be useful for the city's other campuses? If we refer back to Figure 3.2, the University's Law campus can be reached using the Halte CHR subway line.

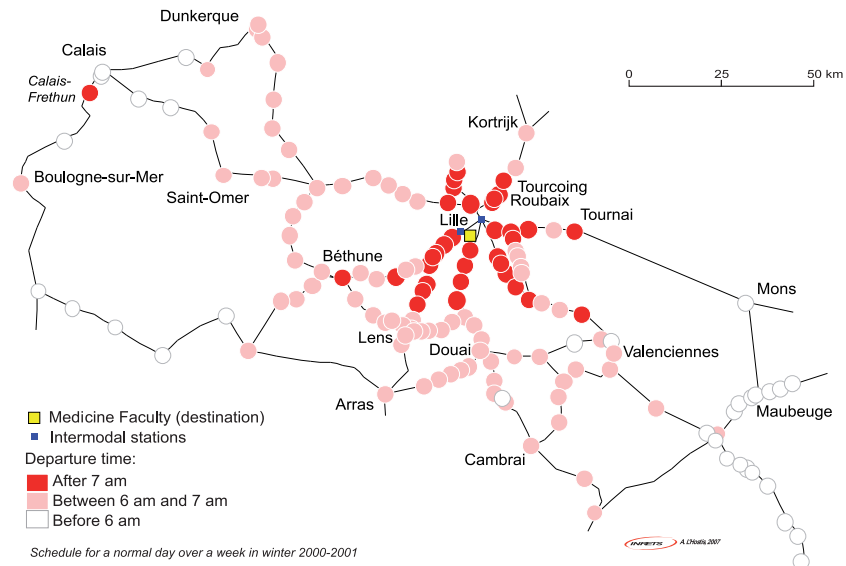


Figure 3.4. *Intermodal schedule accessibility leaving from Nord-Pas-de-Calais railway stations towards the Medicine campus, departure times for an arrival before 8 am*

This hypothesis does, however, require an additional transfer (inter subway), we will compare it to the traditional access via the Lille-Flandres station. Yet, because of the high frequency of subway trains during rush hour (a minute and a half between trains) and the quality of the footpath (just one minute needed to get between the two platforms), this

additional interconnection may be considered as being only slightly detrimental.

Moreover, train times are likely to be more reliable at Halte CHR than at Lille-Flandres due to busy lines and platforms in this station.

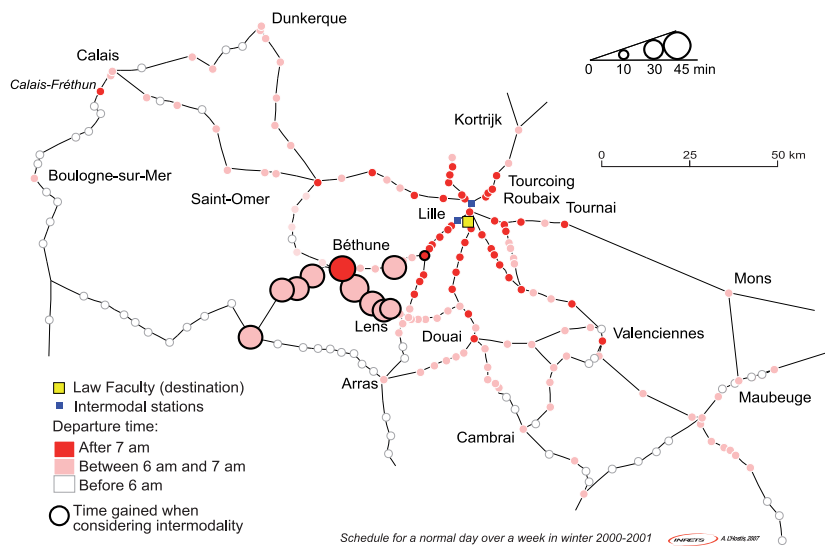


Figure 3.5. *Intermodal schedule accessibility to the Law campus, departure times for an arrival before 8 am and time gain by using intermodality*

The effect of this hypothesis on accessibility is obvious, because on the map in Figure 3.5 we can see the difference in departure times towards the Law campus with and without travelling via Halte CHR. An important threshold effect occurs here because those few minutes gained by travelling via Halte CHR means that we could take the next train leaving from Béthune and the surrounding stations under the same time conditions, meaning an arrival before 8 am. As a consequence, we can see a 45 minute gain over all the stations of the old coalfields (Béthune, Lens, Douai, and Valenciennes), which puts Béthune at less than an hour

away from the Law campus. Thus, using an additional interchange with only a small amount of time consumed (just two minutes needed to change between subway lines), users can gain extra time. Any new interchange is a handicap from a traveller's point of view, but if it means that the passenger can leave the starting point later than planned, then it will be a sure advantage, as it is in this case.

This result demonstrates the advantages which could be gained by making use of and valorizing intermodality. We must point out that the hypothesis presented here does not envisage any changes to the regional or urban transport system; it imposes no investment on the infrastructure, no changes to the timetables, but it does suppose some work on communication for users.

We know that transfers and connections are often negatively viewed by transport users, and such interchanges tend to damage their perception of getting around by using collective transport [BAI 79], [KAU 02], [OFA 74]. In this light, what we are putting forward aims to optimize this intermediate break in travel, in order to make public transport more favorable.

3.5.3. Valorizing intermodality to access the Lille campuses

Based on this result which advances the potential benefits of intermodality, we will extend this process to the entire metropolitan area. Effectively, the regional rail network consists of 40 railway stations located within the metropolis, some of which are located close to the campuses.

In order to make better use of the existing network, we based our approach on the principle of a virtual network developed by Dupuy [DUP 91]. By exploring all the possible ways of reaching the main key places, then using a virtual

network means that we can establish a *real* network which considers good alternative routes, making good use of the network's connectivity. Thus, the virtual network in Figure 3.2 shows other possible interchanges to link the campuses: between rail and subway (with Halte CHR, Porte-De-Douai and Pont-de-Bois stations) as well as interchanges between trains and coaches at Ronchin, Porte-de-Douai, Tressin and Lesquin.

The principle of the virtual network may be applied to the campuses in the East of the metropolis by making use of all the coach lines which link the stations at Baisieux, Tressin, Lesquin and Pont-de-Bois.

To identify credible alternative routes, the method consists of exploring the possible links towards the indicated key places over an entire day. If, at a point during the day, an alternative route with minimum time comes up, then the transfer is considered to be worth studying. This analysis proposes a route via Lesquin, arriving via Halte CHR and Pont-de-Bois.

Note that university campuses which are used as destinations in terms of regional mobility are nearly all associated with areas of activity, making up the key traffic areas for those travelling to work: e.g., the Medicine faculty is located on the regional hospital site, the biggest employer in the metropolis, whereas the *Cité scientifique* is linked to one of the region's dynamic activity areas, the Haute-Borne park.

Here we will turn the discussion to the connections at Lesquin station, which may be useful for students coming from Valenciennes and other stations on the Lille-Maubeuge line towards the Villeneuve d'Ascq campus. In previous works [MEN 00], we showed the potential of using this station to get to the campus. Here the analysis carried out in this chapter leads to similar conclusions.

From Lesquin station, it is possible to take a bus which goes to Quatre-Cantons station, located within the Science campus without any stops in between. The transfer between the train platform and the bus stop at Lesquin can be done in satisfactory conditions, with a walking time of three minutes. The bus completes the connection in five to eight minutes. In total, in an ideal situation which does not take any waiting times into account, the entire trip from the platform at Lesquin to the *École centrale* takes between 10 and 13 minutes by bus, compared to 28 minutes (at best) if we were to go through Lille-Flandres. In these conditions, there is real potential here since we might gain quarter of an hour's travel time, without taking timetables into account. To validate this potential, it is important to analyze the bus and train timetables to Lesquin.

In Figure 3.6, we show the train arrival times (4 departures) coming from Valenciennes, as well as coach departure times towards the *Université des Sciences* campus (10 departures). Out of four trains in the morning rush hour, despite the high level of urban service demands, only one train is connected to the buses, if we consider three minutes walking time between the rail station and the bus station. Today, intermodality is clearly not part of the criteria when planning the bus timetables to Lesquin.

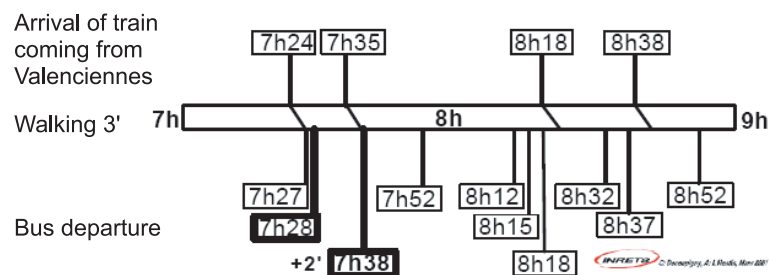


Figure 3.6. Adapting the bus times to Lesquin

Nevertheless the high bus service frequency means that we can envisage marginal changes in the timetables in an aim to promote rail/bus interchanges.

In this light, Figure 3.6 shows a change of two minutes in the departure times for a bus going to Lesquin which enables a transfer from the urban transport system to the trains arriving between 7 am and 8 am, which could be used by students to get to the Villeneuve d'Ascq campuses before 8 am. We should point out that this idea would have no effect on fare costs, since Lesquin belongs to the urban transport system: going to the *Université des Sciences* by bus from Lesquin costs the same as the subway when leaving from Lille-Flandres.

The route offered does not have a negative impact on the urban network usage, because it uses the same operators as the normal route (SNCF and Transpôle). On the contrary, this alternative route may even act as a way of decreasing pedestrian crowding at Lille-Flandres station between the rail and subway platforms and could help to balance out the influx of journeys taken in the center. The improvement in accessibility brought about by changing the bus times to Lesquin is measured against the *Université des sciences* in Figure 3.7. This shows the difference in departure times both with and without using alternative arrivals via Lesquin and Halte CHR.

With 15 minutes gained when leaving from Valenciennes, the effect is noticeable and corresponds to the expected theoretical gain. But above all, this improvement would make it possible to put Valenciennes at less than an hour away from the campus, rather than more than an hour when travelling via Lille-Flandres. In Figure 3.7, we notice that when leaving from Saint-Armand, Orchies and Templeuve (the three main stations in terms of volume of people over the first part of the line), the same 15 minutes can be gained

as with Valenciennes. Beyond this station, the time gained is very high with half an hour for Le Quesnoy and 45 minutes for Maubeuge.

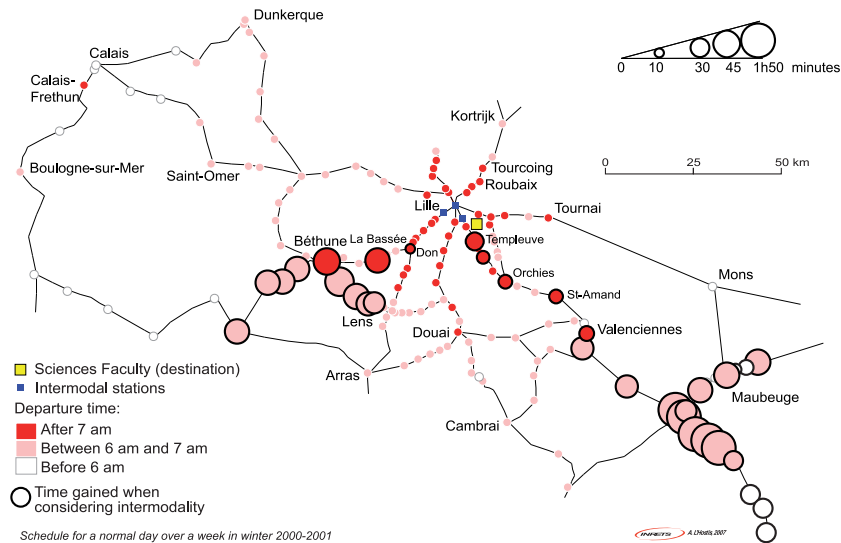


Figure 3.7. Intermodal schedule accessibility from Nord-Pas-de-Calais stations towards the Science campus, departure times to arrive before 8 am and time gain when considering improvements in intermodality

Regarding Halte CHR, the expected improvements after promoting intermodality to access the Law campus (Figure 3.5) could also be used to gain access to the *Université des Sciences*. Effectively, the subway line between Lille-Flandres and the Eastern campuses goes through Halte CHR: for these reasons, students coming from the Béthune area can take the subway from Halte CHR instead of alighting at Lille-Flandres. In this way, they avoid congestion at the main station and they gain a few minutes allowing them to take the next train. The potential advantage is then a significant improvement in accessibility when leaving from Béthune and the surrounding stations.

Moreover, the accessibility measures are the same for the University of Human Sciences (see Figure 3.2) as for the University of Sciences. The development (at Lesquin station) and the valorization (at Halte CHR station) of intermodality produce the same effects on both campuses. These changes could also greatly improve the conditions for accessing the two main campuses in Lille, where effectively a third of students are congregated.

With this application we notice that the travel time accessibility measure is a suitable tool for measuring the spatio-temporal performance of the collective transport network, including the element of intermodality. Moreover, the graph-based method enables simulation and therefore optimizing breaks in travelling related to changing modes of transport or vehicles.

3.6. Conclusion

Measuring accessibility is a privileged tool for analyzing “territorial performance” in transport networks [STA 97]. We have demonstrated the need with regard to collective transport to model the system by taking travel times into account.

In this methodological framework, we have shown how to act on the set of time dependent variables (frequency, regularity, speed, adapting to urban pace of life) in a demand-based approach based on key places, segments of users and time constraints, which enables us to point out mass influx, a relevant area in public transport.

If the interdependency between modes of collective transport is necessary due to the widespread nature of key areas, it nevertheless conceals an unexploited potential. The property of inter network connectivity (degree of linkage) is widely used for modes of road transport where the user is not

dependent on a collective operator to determine his/her route. This cannot be said for public transport, however, which is clearly and necessarily less flexible by the services it provides. For public transport, bringing the network together to convey mass influxes generally leads us to associate a particular route with an influx (e.g. train + VAL to get to the Villeneuve d'Ascq campus) and therefore tends to cover up the network's potential. With a direct application of G. Dupuy's *l'Urbanisme des réseaux* (Urbanism of networks) [DUP 91], our approach leads us to design a system which integrates all the collective transport networks, with an aim to unmask all the alternatives, including those making use of much smaller routes.

In order to assess the way in which a transport system adapts to the pace of urban living, we need to point out the time constraints involved. The schedule graph allows us to specifically model the system's operation and its connections between urban and regional modes of transport. We may, then, point out the threshold effects due to bad timetabling coordination, which is likely to create a vast decrease in accessibility. Lengthening the procedure, based on simulating potentially new elements in the system, has allowed us to establish ideas which aim to reduce service problems. Cartographical representations help to fully represent such matters in their spatial dimensions.

Collecting and processing travel time data is a difficult task, but enables us to gain access through graph-based models to a realistic representation of mobility conditions. It allows us to reflect on network organization and its function in urban environments.

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Chapter 4

Characterizing Form and Functioning of Transportation Networks

4.1. Introduction

The characterization of transport supply and, particularly, the characterization of the quality of accessibility is a domain where scientific literature is in abundance. For example, K.T. Geurs and J.R. Ritsema [GEU 01] give an excellent review of the measurements which describe accessibility, and they propose a definition which we will take up here: “accessibility: the extent to which the land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)”.

Among the different descriptor indices for transport supply, the vast majority comes from graph theory [BER 83] or its derivatives from operational research. Modeling transport networks as graphs is a very common and convenient practice. The different places which need to be

Chapter written by Cyrille GENRE-GRANDPIERRE.

connected (cities, villages, stations, etc.) are considered as nodes (which may or may not be valued according to importance, in terms of population for example) and the arcs of the graph represent the physical connections between nodes (roads, railways, etc.). They also can be or not be valued according to a given impedance (length, time etc.).

Modeling networks as graphs, whatever the network type (transport, social, etc.) allows a powerful description of their topology and of the service they provide in terms of accessibility. The somewhat simplicity of modeling (limited to points and arrows) [KAU 70], the ease of calculating indices (mainly based on matrix calculations) and their general relevance may explain the wide, almost monopolistic, usage of graph theory. As a consequence, only a few additional or competing approaches have come forward. Also, the vast majority of descriptor indices for transport supply dates back to the 1970s which was a period of development for the graph theory. Yet, many aspects of transport supply are still badly or not even included in this modeling. In addition, the wide spreading of the graph theory has led us to no longer question its limitations or the precautions which must accompany its use and the interpretation of results.

In this context, the aim of this chapter is primarily to show, from a pedagogical point of view, the components making up transport supply which are currently hardly or badly described, particularly in the graph theory, by pointing out a few precautions which must be taken in order to use this method wisely. Possible improvements will sometimes be introduced.

We will discuss three main points:

- the problems raised by describing network shapes and, in particular, the way in which a network fills space, i.e. the spatial coverage of the networks;

- the limitations in current descriptions of the accessibility provided by a network;
- the question of describing the way networks route the flows, which leads us to focus on the type of routes provided by the networks.

Secondly, using two different examples, we will show why it is a strategic approach to better describe the “*object network*” in terms of form and functioning, in order to be able to relate them to possible induced effects.

We will illustrate this discussion by showing to what extent:

- the level of walking depends on the structure of road networks;
- car dependency may be considered as one of the induced effects of the type of accessibility provided by current networks.

4.2. Precautions and limitations in describing form and functioning of transportation networks

4.2.1. *Describing network shapes*

Are there road networks which are more likely to cause accidents than others? Are there forms which intrinsically favor the use of a certain mode of transport, which lead to more or less concentrated activities, which are more inclined to favor crime?

In order to answer these questions, an essential initial stage consists of categorizing the networks according to their shape, using one or several descriptors. Then these indicators will be linked to different types of induced effects. As I. Thomas and H. Béguin [BEG 87] point out, unfortunately “no indicator or group of indicators is able to

characterize the shape of a communication network with complete certainty”. Without using their shrewd critical analysis of the descriptor indices for network shapes (see also [THO 02]), here we will remind readers that the major problem of the majority of indices, particularly those in graph theory, is being almost entirely based on the number of nodes (or vertices) and the number of arcs (or edges) of the graphs which represent the networks. Because of this, their powers of discrimination are low, particularly for large networks [BED 87]. This is why it is easy to find two topologically distinct networks which possess the same shape descriptor indices (Figure 4.1).

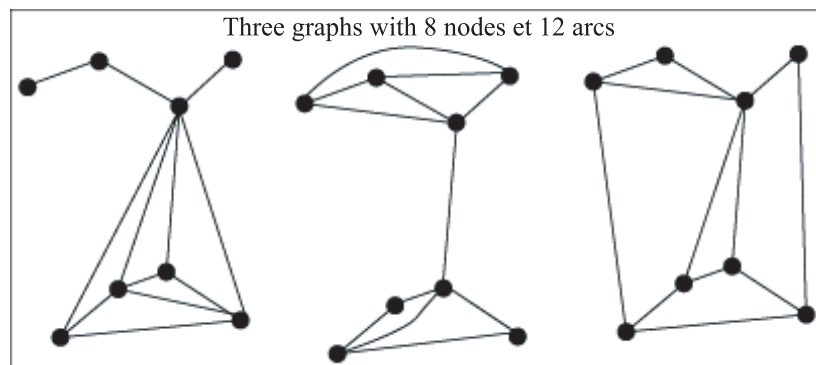


Figure 4.1. *Three different undirected planar graphs¹ with the same connectivity index*

Thus, the most used indices such as:

- the connexity index, which describes the possibility to go from any node of the graph to any other node;
- the connectivity index, which describes the complete nature of the network (e.g. the index γ is the ratio between

¹ A graph is *planar* if it can be represented in the plane without two edges crossing over outside the vertices.

the real number of arcs and the maximum possible number of arcs connecting directly every pairs of nodes);

- nodal indices, which describe the number of arcs which converge or diverge from each node at a given topological distance etc.

All these indices though well known and used are insufficient for describing network shapes, even small ones.

As these indices are not very discriminant when used globally, we may suggest that for large networks these descriptor indices should be used locally, by calculating them into “moving windows” and then interpolating the values. For example, this is the only way of gauging an idea about the connectivity of road networks in cities which include thousands of arcs and nodes, for which using global indices is highly unsatisfactory.

4.2.2. The spatial coverage of the networks

In response to the article by Béguin and Thomas cited previously, D. Pumain writes: “summarizing shape is without a doubt a geographer’s dream as any numerical summary is essentially ambiguous. For all this, must we abandon wanting to characterize this shape?” A positive response would leave out one of the main components of transport supply, spatial coverage, forever badly characterized. In fact, as surprising as it may seem, describing the spatial coverage of a network, the way it fills the area, is still assessed by a measurement which is simple but full of limitations. Here we are referring to density.

The first limitation using density in order to describe the spatial coverage of a network is related to the fact that it does not take into account the network’s topology and the nature of arcs. Whether the network branches are connected or not, and whether the allowed speeds on arcs are high or

not, the density will stay the same but the quality of the spatial coverage will not. In addition, as seen in Figure 4.2, density is a measurement which is easily affected by the scale used for the analysis. Thus, it would be suitable to specify the scale on which density has been calculated.

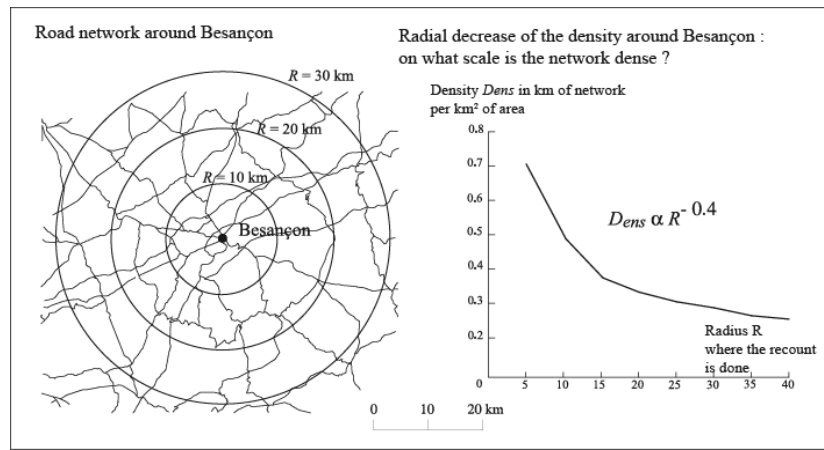


Figure 4.2. Density: a measurement affected by the scale of analysis

The graph theory no longer provides an adapted response. With this approach being *aspatial*, two networks which are topologically identical but which provide a very different level of spatial coverage are not differentiated by traditional indices.

Without an acute awareness of the fact that graph theory does not take into account the spatial aspects of networks, and particularly their spatial coverage, then serious errors of interpretation can be made, above all when comparing different sized graphs. Consider, for example, a tram network where 10 stations are connected in pairs by rectilinear and fast infrastructures but which covers a small part of a city. This network will be considered as being

excellent, with maximum connectivity, zero circuitry², and high nodal accessibility, etc. Should we consider this to be better, as a quick interpretation may indicate, than another network for the same area with 50 stations which are somewhat less well connected but which provide a much more complete service in terms of spatial coverage?

As remarked upon by P. Haggett: “whatever the gain that accrues (sic) from viewing a network in terms of its basic topology, it is clear that large and significant parts of its spatial structure are missing, for example the fundamental relationship to area” [HAG 69].

How should we qualify the spatial coverage of a transport network? How can we describe the way in which its morpho-functional structure enables it to cover an area, which leads to trying to characterize the service area polygons, representing the distance that can be reached from a node within a specified amount of distance or time?

Answering these questions is particularly important when considering problems regarding spatial equity and space duality [PLA 92], i.e. the coexistence of areas which operate according to different metrics³. In the end, this may cause problems involving the concentration of the population and activities in areas where the metric is the quickest.

2 The degree of circuitry for an origin vertex i going to all vertices j on the graph is given by the mean of the square of the differences between the lengths of the shortest routes measured on the network, and the corresponding Euclidean lengths.

3 So as not to weigh down this chapter, we will say that the *metric for a road network*, used by any given vehicle, corresponds to the change it produces in the relative position of the places if we use a network distance rather than a Euclidean distance, even if all mathematical hypotheses speaking of metrics in the strict sense are not always verified.

Due to its highly geometric nature, one of the most suitable approaches is undoubtedly *fractal geometry* [BEN 91], [BEN 95], [FRA 94]. We will remind readers here that for Euclidean geometry a dot has a topological dimension of 0, a line a topological dimension of 1, an area of 2 (the ² in π^2), and a volume of 3 (the ³ in $4/3 \pi R^3$ for the volume of a sphere, for example). However, a set of lines (i.e. a network) covers more the area than just a line, but not so much as to cover it entirely. Therefore, topologically a network is more than a line but less than an area. To characterize such a “figure”, the way in which it fills the area, fractal geometry proposes intermediate dimensions, *fractal dimensions*, which make possible to deal with complex figures which cannot easily be measured by Euclidean geometry. For a network, the closer the fractal dimension is to 2, then the more the figure will fill the area, and the figure will be closer to 1 if it moves towards the line.

There are many fractal dimensions according to the algorithm of the measurement used, such as radial dimension, box-counting dimension, etc. To measure the spatial coverage of a transportation network, the spreading dimension seems to be the most useful, because it makes it possible to consider the morphological, topological and operational components of networks at the same time [GOU 92], [GEN 99], [GEN 00]. We will present the logic of this now, without going into detail on its implementation.

The spreading dimension, which varies between 1 and 2, is a matter of characterizing the more or less “perforated” aspect of the service area polygons produced by a network. For Euclidean geometry, with a homogeneous and isotropic space, the area that can be reached from a point within a specified distance R is equal to πR^2 because the service area polygons are full (complete), they correspond to concentric circles. Here, the spreading dimension will be 2, because the whole surface area is accessible.

For real transport networks, the service area polygons are no longer full but, moreover, the polygons are extended more or less in different directions according to the speed on the road sections. The reference to the fractal geometric model will allow us to analyze the distribution of the holes inside the service area. Effectively, in fractal geometry there is a power relationship between the size of the geometric elements (the holes in the polygons of the service area) and their number. This means that there are many small holes, less average sized holes, and even less large holes. Thus we will analyze the shape of the service areas according to this geometric, inhomogeneous and hierarchical model.

If the network allows a complete and homogeneous spatial coverage (e.g. for a rectilinear network), then the spreading dimension will be 2. On the other hand, the more we move towards an incomplete and unhomogeneous spatial coverage, the more the spreading dimension will tend towards 1, which is the topological dimension of a line. The spreading dimension will then express what the network “lacks” in terms of accessing the surface area in relation to the Euclidean case where the entire surface area may be accessed.

Figure 4.3 shows (on the left) the road network leaving from Baume-les-Dames (France) which has a dimension of 1.52. The morpho-functional structure of the network provides a spatial coverage which is more complete than that provided by a single road (topological dimension of 1), but less than that provided by a complete and homogeneous network which will cover the whole surface area (topological dimension of 2). Here the spatial coverage appears unbalanced as the isochrones tend to extend from East to West which is the direction of the highway.

In the same figure (on the right), we see that if we simulate roads with high vehicular suitability at the exit of the highway, then the spatial coverage becomes more

homogeneous. The polygon of service area fills the surface area more, and it is then less extended/perforated, which results in the spreading dimension increasing to 1.71.

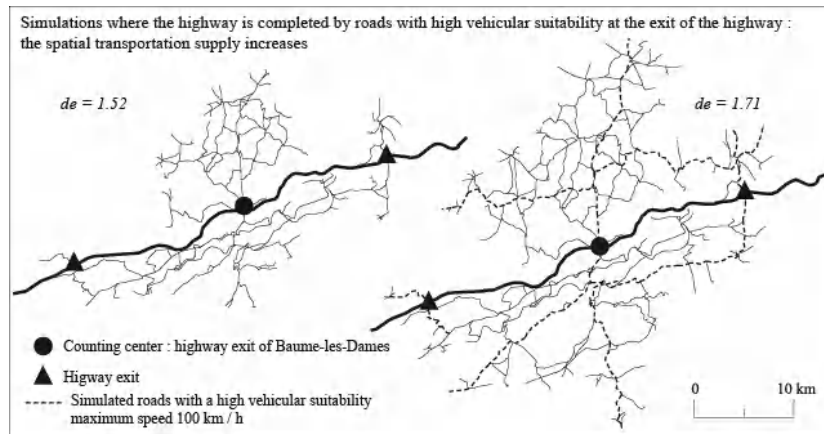


Figure 4.3. *Spreading dimension for measuring the quality of the spatial coverage*

Although the spreading dimension is interesting from a theoretical perspective, particularly because it remains invariable according to the scale of analysis, it is nonetheless difficult to use in practice. This is due to the laboriousness of its implementation which involves the calculation of service area polygons on the one hand, and because it requires knowing *a priori* the logic behind fractal geometry which is still little known, on the other hand. Therefore, measuring the spatial coverage provided by the networks is still a question of research which remains very open.

If measuring network shapes is under researched, measuring accessibility has made way for a prolific amount of literature. This is both to measure accessibility provided by a transport service (the way it allows us to reach different places) and the accessibility to a certain resource, which depends both on the differentiated quality of the connections

and the distribution of the resource. In the following section, we do not propose a critical analysis of the indices of accessibility which are mainly based on graphs, but in fact want to remind readers of a few precautions common to using them.

4.2.3. Assessing accessibility provided by transport systems: a few precautions

4.2.3.1. Which network are we measuring?

In network analysis, the first problem is to define the network. We have to choose the nodes, the places to be connected and the arcs of the graph, which figure the connections between nodes. This choice will, then, determine the accessibility measurement. This choice, which is mostly “obvious” and done silently, of arcs and nodes, may sometimes prove to be problematic. For example, this is the case when we want to assess the quality of accessibility in an urban environment. There are several possibilities available for the choice of nodes. Should we keep the district centroids, the network’s main crossroads, or even all the nodes in the network? The values of the chosen descriptor indices will largely depend on this choice, which can lead to strong changes in the hierarchies between places in terms of their accessibility.

This “subjectivity” in the choice between vertices and arcs when it does not come naturally requires us to point out from the beginning which network is being measured, and means that we must justify the choice of nodes and arcs. In addition, it is then necessary to be extremely specific when formulating the results. Thus, it is incomplete to say, according to the measurement of a global accessibility index (mean of the distance between all the nodes of the network), that the railway network for one region has a better accessibility than the railway network for another region,

without specifying that this result was obtained for cities with more than n inhabitants. This conclusion could be perfectly turned around for another choice which would only take, for example, the biggest cities into account.

4.2.3.2. Analyzing accessibility on different scales

Whether local or global, descriptor indices for accessibility are expressed as a global value, often as an average, whose composition is ignored. Thus, the frequently used *multipolar nodal index of accessibility* which expresses the ease with which one place can be reached from a set of other places, is nothing other than the average of the distances in kilometers, or the time needed to connect this place to the other places. In the same way, the circuitry index Cir_i which expresses the degree of detours for each node i imposed by the morphology and topology of the network (Dr_{ij} : network distance between i and j) in relation to the Euclidean distance between i and j (Dv_{ij}) is also an average which makes any differentiation impossible according to the route type.

$$Cir_i = \frac{\sum_{j=1}^N (Dr_{ij} - Dv_{ij})^2}{(N-1)} \quad [4.1]$$

However an interscalar analysis of concepts such as *accessibility* or *circuitry* seems to be necessary. Effectively, a network may ensure excellent short range connections but very bad long range connections. Unfortunately, such subtle differences disappear in the calculation of global index values.

As Figure 4.4 shows in a somewhat draft way, if for a network of 10 vertices, 9 of them are well connected but the tenth is not, then the circuitry appears to have a high level, because one distanced point will weigh heavily in the calculation of the circuitry index. A hasty conclusion would

then be to affirm that point A is badly connected to the other points, while it is just the case for one point.

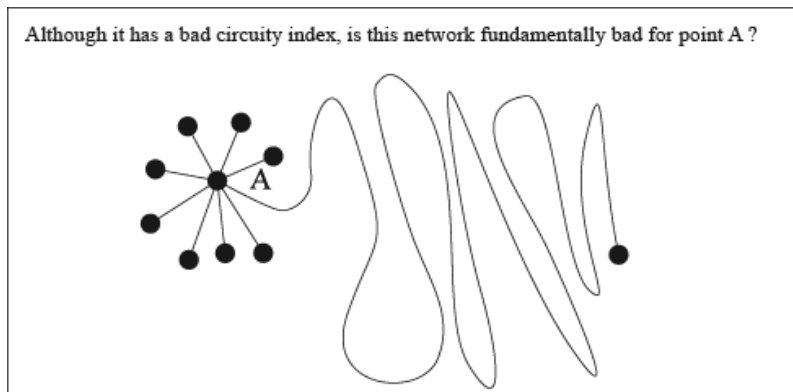


Figure 4.4. *How do we know what weighs the most in a single scale index value?*

However, this uncertainty regarding the composition of the index value makes interpreting them a tricky task. It also makes the link between the index value and a physical, tangible reality difficult. Physically, what does a difference of 10, 20 or 30% mean in a circuitry index value where the square enhances the importance in the calculation of the furthest points?

In truth, only the curves with the transport times or the kilometers travelled (abscissa) and the resources to be accessed (ordinate) which correspond to these times (number of cities, population, number of jobs, etc.) give a full vision of the level of accessibility. As C. Grasland [GRA 99] notes, far too often we try to summarize the accessibility for each place using a single numerical indicator, to the detriment of the most qualitative approaches which focus on the shape of local accessibility curves. Effectively, we can read the scalar variations of accessibility on such curves. We may observe, for example, that the same total of the population which is

accessible in an hour may correspond to two different aspects of reality. Firstly, the majority of this population may be accessed in the first half an hour, whereas this would be the other way round in the opposite case.

In the same way for the assessment of indices for network performances (circuitry, Marchand index) it seems necessary to differentiate them according to the range of trips, seeing as network performances vary widely according to the type of trips considered.

4.2.3.3. *Measuring accessibility versus assessing network performances*

The last precaution that we will mention here with regard to assessing transport offers relates to the confusion which may arise between assessing the accessibility and the performances of a transport system. Let us remind readers first of all that the accessibility of a place i in relation to a set of other places j depends on two elements: the quality of the connections between i and the other places j , and the geometric location of place i in relation to places j . This location means it will be predisposed to being more or less accessible even before considering the potential links offered by the network.

Therefore, a central place in Euclidean space will have a higher probability of being accessible than a peripheral one. Finding a node which is not easily accessible according to its nodal accessibility index does not necessarily mean that this place is badly linked to other places by the network. This low level of accessibility may simply be due to its peripheral location in Euclidean space, that the network's metric does not necessarily balance. Forgetting this geometric component of accessibility may cause problems when interpreting results, which may lead us to confirm that these peripheral places are badly connected.

As a consequence, to rebalance the accessibilities of these peripheral places, investments in the infrastructures may be decided on, whereas their lack of accessibility is linked to their geometric position and not to the quality of the infrastructures which are already in place. To truly assess the efficiency of a transport system, it is preferable to use a measurement of the efficacy of the routes, rather than measurements of accessibility [GUT 98].

Efficacy is a measurement which uses the ratio between the Euclidean distance between the origin and destination of the trips and its real duration. This measurement, in km/h, indicates the average speed of the trip if it was performed as the crow flies. It assesses the real performances of the network and not the accessibility of the places. It is, then, a much more appropriate measurement than the traditional average speed index for trips, because it erases the bias related to the detours imposed by the network's structure. Indeed, as shown in Figure 4.5, for a network requiring large detours but with a higher level of speed, the average trip speeds will be higher without the network performance necessarily being good. In this case, we can drive quickly but still cannot access our destinations easily.

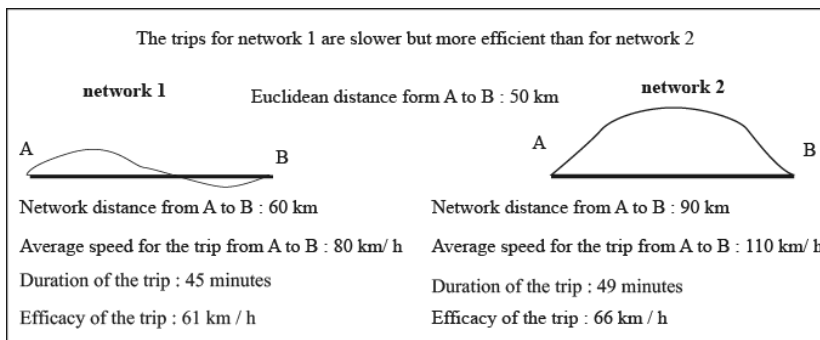


Figure 4.5. Speed and efficacy of trips

Measuring efficacy, however, makes the difference between such a network, which is quick but not very efficient, and a network, which may be slower but which offers good levels of performance in terms of accessibility, thanks to relatively direct routes. Therefore, accessibility does not strictly depend on trip speed.

Calculating route efficacy allows us to relativize the real performance levels of transport systems (for cars, in particular), which use very hierarchical networks with low connectivity. Therefore, even when not considering congestion problems, the efficacy of car trips in urban environments for trips less than 30 km in range rarely goes over 50 km/h [GEN 07].

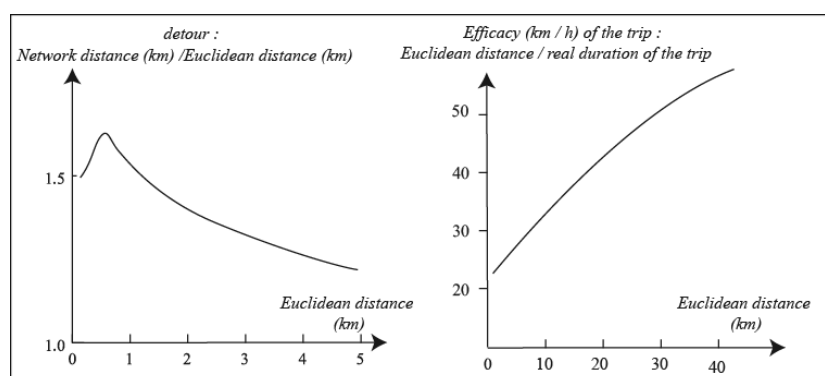


Figure 4.6. *The efficacy of road networks increases in proportion to the trip range (urban area of Avignon)*

With the same concerns for separating in the measurement of accessibility that which deals with the geometric position of the places, from that which deals with the lack of transportation infrastructures, J.F. Gleize [GLE 07] puts forward a new and performing indicator which compares the shortest traditional routes with another category of optimum routes called “Delaunay routes”. To

construct these Delaunay routes, we go from the straight line (optimum route) which can be “bent” so that it goes through the nodes which are located closest to its route. The point of reference is not, therefore, the straight line which does not take into account the shape of the space, but another category of best route which is anchored more towards the nodes existing already in the network.

4.2.4. Routing flows

In current characterization of the transport supply, the network is still considered as a black box. Effectively, with the help of algorithms for calculating the shortest routes, we can know with a good level of accuracy and reliability the times or distances necessary for reaching a couple or a set of couples of places. However, nothing is known about routing the flows, meaning the way in which the morpho-functional structure of the network definitively organizes the routes. Using this statement, the following section will try to show that the knowledge of the way the networks are routing the flows is an important component of the characterization of the transport supply. More specifically, we will highlight the fact that a part of the network’s performance (particularly in terms of congestion) and a part of its induced effects depend on routing the flows.

4.2.4.1. A plea for route analysis

In line with route characterization in terms of efficacy, it is also equally as important to focus on route composition. This is in order to understand how journeys are completed physically, to know which types of sections are involved in the routes. Here we make the assumption that journeys made over a network are generally performed according to the shortest path logic (in terms of time or distance).

To propose a convincing argument, we will take an example relating to traffic road accident analysis. An

accident involving one or several cars is a punctual event which occurs in a given place at a given time. Diagnostics for road safety study whether there are actually some places which are more likely to produce accidents than others (crossroads, road type, etc.) or even whether certain times are more dangerous than others (night time, twilight, etc.). As we may presume that the accident occurring in place i at time t depends (at least partially) on what happened before the accident, and particularly on the routes taken by the vehicles involved, we can see the point in focusing on routes in terms of their physical components.

Without this knowledge of the different routes generated by the different network categories, how can we know if a network generating routes which are structurally homogeneous (meaning the section taken are of the same type) is more favorable to accident than another type of network which generates heterogeneous routes (where the driver is constantly changing the type of road used – main roads, local or arterial streets)? The latter is the case particularly for networks which have a high hierarchy between the roads in terms of speed.

Therefore, two networks may show the same characteristics in terms of efficacy, average speed, etc. but however they may produce different types of routes, whose composition will have an effect on the dangerousness of the network or on fuel consumption (for identical origins and destinations, do the networks which produce hierarchical routes consume more or less energy than those networks generating homogeneous routes?) Using this example, we insist on the advantage of route analysis which is often ignored, although it is not a problem from a technical point of view (the “Route-System” of the Arcinfo Software allows us to store route composition).

4.2.4.2. *Accessibility and congestion*

If accessibility is being able to quickly reach a set of chosen places, it is also being able to do so at the same time for a large number of individuals. Here we are touching on the “capacity” component of accessibility, which is often not considered enough, if it is not through studying the theoretical capacities of roadways in terms of traffic flow. But, studying these capacities for each roadway considered individually does not give enough information on the network’s ability to support and route traffic flow.

Indeed, it has been shown before (particularly for dense urban areas where mobility is high and mobility matrices are complex) that the pattern of traffic flows depends more on the transport network structure than on the origin/destination matrix of the trips [PEN 98], [GEN 00]. For individuals making trips more or less according to a logic of minimizing transport time, it seems that it is the network’s structure which determines the routes taken and which will design the traffic flow map in the end. In other words, two different networks linking the same set of origin/destination pairs will not produce the same flow map. Some networks (the most hierarchical in terms of speed) will intrinsically tend to concentrate the flows over the quickest roads. In this case, the users looking to minimize transport times are effectively led to take these fast roads, and not the more direct roads in terms of geometry but which are slower. With the same origin/destination matrix, more homogeneous networks will tend to distribute flows all over the network, which is less likely to create congestion problems.

Understanding the way transport networks route the flow, in particular for car systems, seems to be an important element in transport supply which should be characterized, particularly in order to tackle the capacity component of accessibility which goes back to problems of congestion.

In addition, urban planning may use these differences in routing the flows for different networks. By changing the morphology and topology of the road network, we can, for example, make sure that over a given area that pedestrian trips will be concentrated on the same roads in order to create a sense of safety, conviviality, and create business opportunities. We may also try to produce favorable flows for public transportation systems. This may be achieved by decreasing the connectivity of the road network in order to group car flows on particular roads, rather than favoring routes which are more spread out spatially, and thus which are not suitable for public transportation systems [GEN 11].

Even though network and accessibility analysis, widely based on graph theory, is not a new topic and thus has already produced many works, this first section has shown there are still many limits in these domains and that many precautions have to be taken. Achieving a better description of the form and functioning of networks is still a major scientific issue. In particular, this would enable us to make progress in network economy which is still only now just starting. Economic analysis often consider networks (whatever their type) as black boxes which are assessed by linking inputs and outputs. For example, this is the case for public transport networks whose performances are assessed by bringing together the number of kilometers covered by the different transport lines, the energy consumed, the kilometers crossed, etc. and the result which is expressed in the number of people transported [EMA 91]. In this type of analysis, the networks' internal characteristics, particularly in terms of topology, are totally ignored. However, the quality of the service offered depends on these intrinsic characteristics of the network, which determine the level of performance and thus the attractiveness of the public transport system.

The economic analysis of the networks must try to study the effects of the form and functioning of the networks on their economic performances, as: “it is the structure of the black box which determines the network’s economic performances, both in terms of costs as well as utility” [DUP 93].

To conclude this section, we will add two perspectives of research to what we have already discussed:

– the first one concerns safety within the networks. In particular, it goes back to the concept of alternative routes. What happens when the best route cannot be taken (construction works, traffic jams, etc.)? What is the quality of the alternative routes when they exist? How do we assess a network’s fragile nature? If literature has already been written on these matters, particularly by J.F. Gleyze [GLE 05], then this concept of safety within networks is still not sufficiently qualified;

– the second one deals with the concept of network readability, which constitutes an integral part of transport supply. Why do we manage to memorize some city maps or public transport network maps more easily which are not necessarily the simplest to remember, when others are a lot more difficult to define? Knowing that the perception we have of transport networks partly depends on mobility behavior (the choice of shortest route, for example), we can fully understand the advantage of responding to the problems concerning network readability.

After having underlined that there are still some limitations in the characterization of transport form and functioning, the second section will focus on showing the extent to which this description is strategic, as it determines the use of the networks, and some of their induced effects. This discussion will be illustrated by showing first of all that walking habits greatly depend on the structure of road

networks, then by showing that car dependency may be considered as one of the induced effects of the types of accessibility generated by current networks.

4.3. Examples of induced effects related to the form and functioning of transport networks

4.3.1. Network shapes and pedestrian mobility behavior

For the past 30 years so, walking has seen its market share drop remarkably. The splitting of places of life, the generalization of car access, the increase in population incomes and the increasing complexity of everyday trips seem to be the major causes for this. However, if we perform a detailed analysis of the modal share of walking over an area, then we may be able to note its high level of variability (sometimes a ratio of 1 to 3).

This leads us to question the potential influence, both quantitative as well as qualitative, of geographic contexts on pedestrian habits [FOL 03]. More specifically, we tested the hypothesis according to how the spatial organization of urban structures, understood to be the different modalities of building layouts, road networks and empty spaces, which defines the “pedestrian transport supply” could influence pedestrian mobility behavior. Above all, this hypothesis stems from the apparent obvious fact that the efficacy of the transport supply for a given mode is that which determines the intensity of its use. In the case for walking, we can easily imagine that a network which provides a good level of accessibility, by minimizing the detours of the trips, is a good way of encouraging walking practice.

In order to be able to analyze the links between urban structures and pedestrian mobility behavior, firstly we generated an indicator which describes the intrinsic capacity

of each place to favor journeys completed by walking. This “local walking potential” is based on the quality of accessibility provided by the road network for pedestrian mobility. It corresponds to calculating the area which is accessible from a point within 12 minutes using the road network, which is crossed at 5 km/h (average walking speed). The values chosen for the calculation of this indicator ensure the possibility of grasping the variations, even small ones, in the quality of service provided by the road network. This would not have been the case if the value chosen for the duration of the trip (12 minutes) had been larger, with a smoothing phenomenon occurring and then erasing all local changes. The results obtained for Besançon and Lille (France) show the large spatial variability in the level of accessibility offered by the network for walking (with the absolute values of the indicator varying in a ratio from 1 to 10). If this spatial variability of the transport supply is often highlight for cars or public transport, it is rarely the case for walking, or only from a qualitative point of view (noise, safety). Globally, the values of the indicator of suitability for walking decrease from city centers towards the suburbs. Historical city centers are characterized as having the greatest capacity to promote walking, thanks to the high density and connectivity of road networks. On the other hand, the outskirts, where the networks are often organized around one main road with a system of dead-ends, have the lowest potential.

Secondly, a database on mobility behavior in intra-urban environments was created using two surveys taken for 560 Besançon inhabitants and 523 Lille residents over a standard week. These surveys showed the distinctive aspects of geo-referencing the participants at home, in order to study their mobility behavior in any given geographical context, and to geo-reference journeys taken on foot. In order to allow a good representativity, different zones were defined for the surveys by interpolating the values of the walking potential

calculated for 7,000 different points in Besançon and 10,000 in Lille. We then retained five different zones, from A (low walking potential) to E (high potential).

Lastly, we have tried to statistically link the level of the walking potential and mobility behavior in order to verify the hypothesis regarding the influence of urban form on mobility behavior:

- by assessing the influence of the walking potential on pedestrian mobility behavior when leaving the home;

- by assessing the influence of the walking potential on the local level of pedestrian frequentation. The pedestrians going through a particular area may, effectively, be from this area but may also be taken there (transit), or may wish to go through the area by departing from places which are more or less far away.

Without going into detail on the set of results obtained [FOL 03], we may nonetheless point out for Lille that if 50% of the residents in zone A (high potential) complete at least 6 weekly journeys by foot, then only 27% of residents from zone E (low potential) will show similar behavior. In Besançon, the orders of magnitude and the differences in behavior are lower but the trend is still identical, since the proportions are 35% in zone A and 20% in zone E.

On an aggregated level, there is certainly a link between the level of walking potential defined by the local structure of the road network and the level of walking, even if the variability in individual behavior within a given zone tends to moderate this statistical relation.

With the amount of walkers in an area being the result of local walkers (endogenous practice) but also walkers in “transit”, i.e. those coming from other districts (exogenous practice), we have tried to verify the ratio between the local level of the potential of walking and the degree of

frequentation of walkers. For this, grids were implemented where each cell is characterized both by its potential (from a local average) and its load, which is equivalent to the sum of the journeys going through it, weighted by their frequency.

If, globally, the walking potential and the degree of frequentation are statistically closer when the cells are larger, then tests have shown that cells of 400 m were suitable, by ensuring a high correlation and making it possible to retain a large number of cells, and therefore a high level of spatial precision.

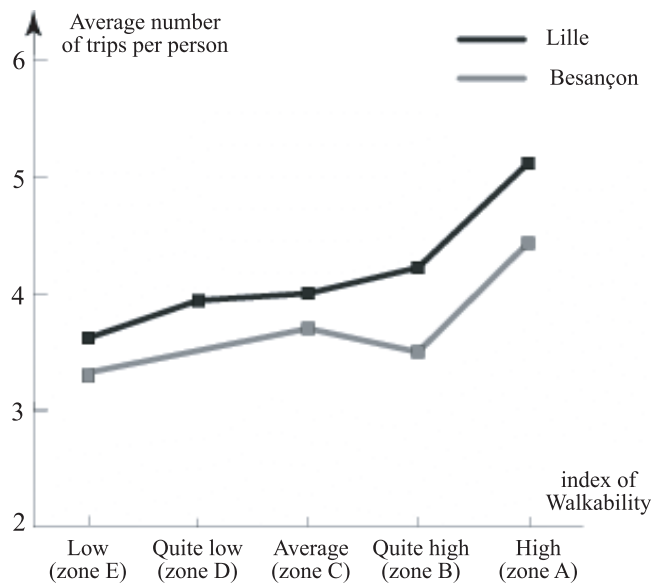


Figure 4.7. Link between the walking potential and the average number of trips made per person by walking

In Besançon, the high positive correlation ($r=0.85$) confirms the favorable role of the potential of walking on walking practices, and makes it possible to construct a regression model where the grid load is determined by the

potential of walking. If the structure of the residues, which are not distributed homogeneously, does not completely validate the model, then we may nonetheless conclude that the potential of walking seems to be a decisive factor for the intensity of pedestrian frequentation in Besançon (Figure 4.8).

Using this example, we can see that the need to describe transport supply with adapted indices (here the walking potential) in order to be able to identify the possible induced effects of the different network's structures (here on the use of walking).

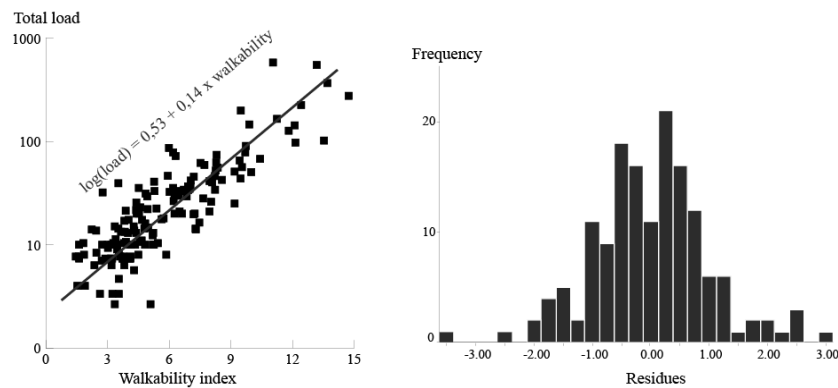


Figure 4.8. *Load/potential linear model for Besançon*

4.3.2. Car dependency as an induced effect of the type of accessibility provided by current networks

The first part of this chapter showed the importance of a multi-scalar analysis of network performances which greatly vary according to the scales considered (Figure 4.6). In this section, we will show the extent to which it is possible to consider urban sprawl and car dependency as two induced effects of this metric, which varies according to the range of the trips.

In Figure 4.6, we can see that route efficacy grows largely with the range of the trips: from less than 20 km/h for ranges of less than 5 km, to more than 55 km/h for ranges higher than 40 km/h. If this increase in efficacy with the range of trips has variable intensities according to the cities involved, then however it is verified everywhere in its principle. Also, accessibility, understood as being what we can gain access to, is not in proportion to the journey length. With the metric of current networks, each additional second spent on the network is therefore more productive in terms of accessibility than the previous second.

The explanation of this “accelerating metric” stems from the hierarchy of the roads in terms of speed, which encourages drivers to take the quickest routes as quick as possible, using a logic of minimizing travel time. The further we go, the larger the proportion of journeys completed on fast infrastructures, and because of this, the efficacy is then greater. With the metric of the current car system, it is then economically preferable, in relation to the ratio of number of opportunities/transport time, to go a bit further within the limit of maximum travel that we fix ourselves.

The effects of this accelerating metric are double, although partially linked. First of all, this metric which allows splitting places of life (such as home and work) may be seen as a catalyst for urban sprawl. Effectively, with the choices of opportunities growing quicker than travel times, car users are naturally forced to make their journeys longer. For example, a person working in the center of an urban area and looking for land to build on in the suburbs will be pushed to go further in terms of economics, within the limitation of a certain time budget. This is because with each extra second spent on the network, which weighs little in the final duration of the journey, the amount of land extends in an “over-proportional” way. This reasoning can be applied in the same way for the choice of workplace, social activity, etc.

The second consequence of the accelerating metric, only valid for cars, is making modal competition impossible. In fact, for other modes of transport, accessibility is only proportional to travel time, since their speed is relatively constant, regardless of the infrastructures used, including public transport which is penalized due to the necessity to make stops along the way.

On the one hand we have car efficacy which increases with the range of journeys, and on the other, efficacy for the other modes which is more or less constant. The difference in performances between these modes increases with the range of the journey, a range which tends to increase due to the fast metric of the networks, in a vicious cycle. Everything takes place as though the superiority of cars were written into the very structure of the networks, particularly when the range of journeys gets bigger.

This second example shows the importance of accurately defining transport supply and its performances in order to be able to deduce its possible induced effects. In addition, it offers a line of thinking which incorporates the aim for longer lasting mobility, which involves a more balanced modal share, from the network design stage onwards [GEN 07], [GEN 11].

The lessons to be learned from the first and second example consist of asking ourselves questions regarding the possibility of building networks which, through their form and functioning and their induced effects, intrinsically contribute to an aim for durability. Developing “slow networks” with a metric opposite to the metric of current networks and therefore which does not lead to the same external factors, figures in this logic [GEN 07].

4.4. Conclusion

In this chapter, firstly we pointed out, from a pedagogical perspective, the precautions needed to be taken with regard to characterizing form and functioning of transport networks, with a use which has become commonplace in the graph theory and its indices tends to make us forget. In line with this, we underlined that there are still limitations in descriptions of form and functioning, particularly with regard to describing their spatial coverage. This theme therefore calls for us to continue in our research, not so much for the network description itself, but more to be in a position to be able to categorize networks so that we can link these categories to the possible effects induced by the networks. Examples of a network structure's induced factors offered in the second section show the issues regarding the possibility of modifying the network structure in order to be used in urban planning.

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PART 2

Estimating Transport Demand

Chapter 5

Estimating Transport Demand

5.1. Introduction

The aim of this chapter is to provide some ground knowledge regarding the modeling tools used for transport demand and for planning purposes. Therefore, our time scales go from 5 to 10 years, not including the tools developed for short-term forecasting (including real time) found in the traffic engineering domain. Evolving in the broad field of transport economy, we chose to limit our investigations to journeys made by those living in urban environments. However, as we will see further on in the chapter, it would be purely fanciful to think that we could develop a model which would meet all these objectives. On the contrary, a model must be developed in order to deal with already identified issues, as J.-M. Legay confirms: “there is no such thing as a model without an objective... [because] we do not make tools without knowing what they should be used for” [LEG 90].

We will begin this chapter with a brief history of modeling before continuing on to a few elements regarding

Chapter written by Patrick BONNEL.

methodological frameworks which are essential for fully understanding the range, but also the shortcomings of forecasting tools. Coding networks, zoning and the choice of the field of study will figure in the following section. We will then present the most globally used tool to respond to problems regarding transport planning: the “four-step model”, with the construction of an origin-destination matrix (generation and distribution stages, then mode choice and route assignment).

5.2. Modeling history

The use of transport planning models began at the end of the 1940s in the USA [DUP 75]. Many factors helped to contribute to its rise, primarily the progress made in computers, those carriers of powerful calculations necessary for implementing the models, and all this was within a context which promoted their development. At the end of WWII, the American industry underwent a reconversion phase after having fully turned itself around after efforts made in the war. The car industry quickly showed itself as a spearhead in this dynamic, which spurred a growth in the economy. A road infrastructure program was launched in order to support this fast growth. Models were supposed to prioritize needs by forecasting traffic and accompanying studies in profitability.

The first models were based on the growth factor method. Future traffic T_{ij} is expressed by using current traffic t_{ij} in the following formula:

$$T_{ij} = f(t_{ij}, F_i, F_j) \quad [5.1]$$

Growth factors F_i and F_j represent both the growth in origin and destination areas measured using the predicted growth in the population, jobs, activities, car ownership...or

the increase in any variable which represents the high trend of making or creating journeys. These models replace the methods used in the last ten years which consisted of measuring, by counting, the traffic flow on a given route in order to deduce capacity requirements, and therefore the need to widen lanes when constraints were found. Growth factor models are “simply a management instrument in a system which is entirely directed by growth and maintaining this growth, in the same way that counting alone was a management tool in a stable system” [DUB 75].

Using growth factor models requires an origin-destination matrix (O-D) for the journeys taken, and from this the first origin-destination surveys were born. These models relate to a new problem which results in two modifications:

- adopting an extended time range;
- considering an entire network rather than an isolated route.

However, these models quickly showed their limitations when used alongside car industry growth, due to the evolution of American cities. The development of the car contributed to the urban sprawl and the urbanization of newly created areas. An area which is hardly or not urbanized at all will inevitably have a low flow, which is most often a zero value in O-D matrices. We can still multiply these zero flows by higher growth factors. They will still be zero, however, and will not allow us to forecast the development of trip flow in periurban areas which are to be urbanized.

Thus, the new generation of models known as the “four step models” were born, whose principle is still in force today. This new kind of modeling corresponds to a new set of problems which results in two modifications:

- systematically adopting a long-term time range;

– abandoning the contextual reference to already existing trips [DUP 75].

Increasing the number of trips made is no longer the result of these growth factors, but from a pair of steps, namely “generation” followed by “distribution”. “Generation” aims to estimate the number of trips produced and received for each area in the land studied. It is based on variables which characterize the population and the activities in trip production and receiving areas (see section 5.5.1). “Distribution” aims to connect the producing and receiving areas in order to generate the O-D matrix. For this, we use the gravity model taken from an analogy to Newton’s universal law of gravity (see section 5.5.2). These two steps include all trips using all modes of transport. Here we will introduce a new step, that of “mode choice” (see section 5.6.1) which allows us to retain only “useful” trips, namely completed in cars [DUP 75]. The final step, “route assignment” (see section 5.6.2) enables us to determine the routes chosen, and therefore the load on each main route. The first route assignment models were based on the shortest route principle which leads drivers, in fact, to choose and favor new infrastructures, particularly highways, because they show better performances (logically) than existing infrastructures.

The four step models were designed to satisfy the needs of the developing car industry, then as a result of this, urban sprawl.

In line with the development of these models, new data was produced by including information in national censuses on trips between home and the work place, and also by carrying out surveys on trips back to the home. This procedure was in place during the 1950s in the USA.

In the post WWII reconstruction period, France found itself in a similar position to the USA. The high growth in

the car industry (production tripled between 1953 and 1962) and its democratization quickly triggered the phenomenon of congestion. Road management then gave way to a true transformation: frequent visits from equipment engineers in the USA enabled a stream of technical transfers. During the 1960s, all the American devices for producing data using household trip surveys and models were put into place. It was even institutionalized in the official document 72-67 from May 3rd 1972 which enforces the use of the four step model for all transport planning studies for all communities wanting to benefit from state funded financial help.

We then have an entire planning structure at our disposal based on models, and data production in accordance with the aims and objectives of the time. This attractive structure was then shaken up with the first oil crisis: challenging this growth continued and was in full swing, the rise in concerns for the quality of our surroundings and the raised awareness with regard to the environment led the population to question this all-car mentality. This gave way to an additional mode with “soft” modes. Critics of the appropriateness of models were increasing, but the four step model stood its ground and kept its position.

Over time, these models benefitted from several developments, but their structure did not. This is why planning problems today relying more on the control of cars in urban areas rather than on their exclusive development, the coherence of this device is shattered to leave room for tools which only partially fulfilled the needs of the time. But if the four step model is still the basic tool for all transport planning, then other tools are also used additionally to meet the many objectives.

5.3. Methodological framework

Presenting our forecasting process design in 5 steps willingly isolates the mathematical model. We will reduce it to the role of a simple tool which is clearly important, but which must not out shine the roles of the other steps, without which the model is only an illusion only giving poor results. This separation also means that we can distinguish the model's design stage, meaning the theoretical representation of an object, from its mathematical formalism. A model is only a "simplified representation of reality, intended to understand it better or to act upon it" [GUI 64]. We will show that this simplification is carried out twice.

If a model is a simplified representation, then it is necessary to question its capacity to simulate the evolution of the magnitudes we wish to project in the future. Analyzing the model's operationality lets us analyze this capacity. We may then show that there are three necessary conditions for ensuring this operationality.

5.3.1. *Forecasting procedure*

Figure 5.1 aims to demonstrate the important stages in the modeling process for forecasting or simulation.

The *first stage* brings us to specify the objectives and issues related to the phenomenon that we wish to forecast, which is a valid precondition for any study. Stated as such, this precondition goes without saying, but we cannot help but notice that in practice this is not always the case. Often, these objectives and issues are implicit or blurred. Yet we can easily conceive of the fact that a partial definition of these objectives will not enable us to answer the different precise questions which bring us to the choice of model used. During the same stage, we include the model choice in terms

of the theoretical construction which should represent the reality of the phenomenon we are looking to forecast:

- this choice involves defining the model's input variables. Primarily it is a matter dealing with explicative variables of the object for study as well as control variables which are supposed to transform the policies to be implemented;

- this choice also requires that we define the model's output variables, enabling us to produce indicators which transform the effects of the policies whose effects we wish to simulate;

- this choice involves a definition of the relations between the model's input and output variables.

Lastly, being a model which simulates transport demand, we should specify the model's temporal and spatial dimensions.

The *second stage* makes it possible to collate the data necessary for an initial validation of the theoretical model during the following stage. This stage is obviously fundamental, because the data is considered as being a measurement of the reality that we are trying to represent. It is clear that any error will reflect upon the model's capacity to predict the future. The data collection process must follow the objective definition. It must provide data which can validate or amend the proposed theoretical model by testing certain formulated hypotheses (object of study for the following stage).

The reverse order means that there is a risk of making it impossible to feed the model with certain data which may not have been included in the survey, or disallowing certain hypotheses in the test. The model would then be incomplete, and its capacity to answer certain questions could be compromised.

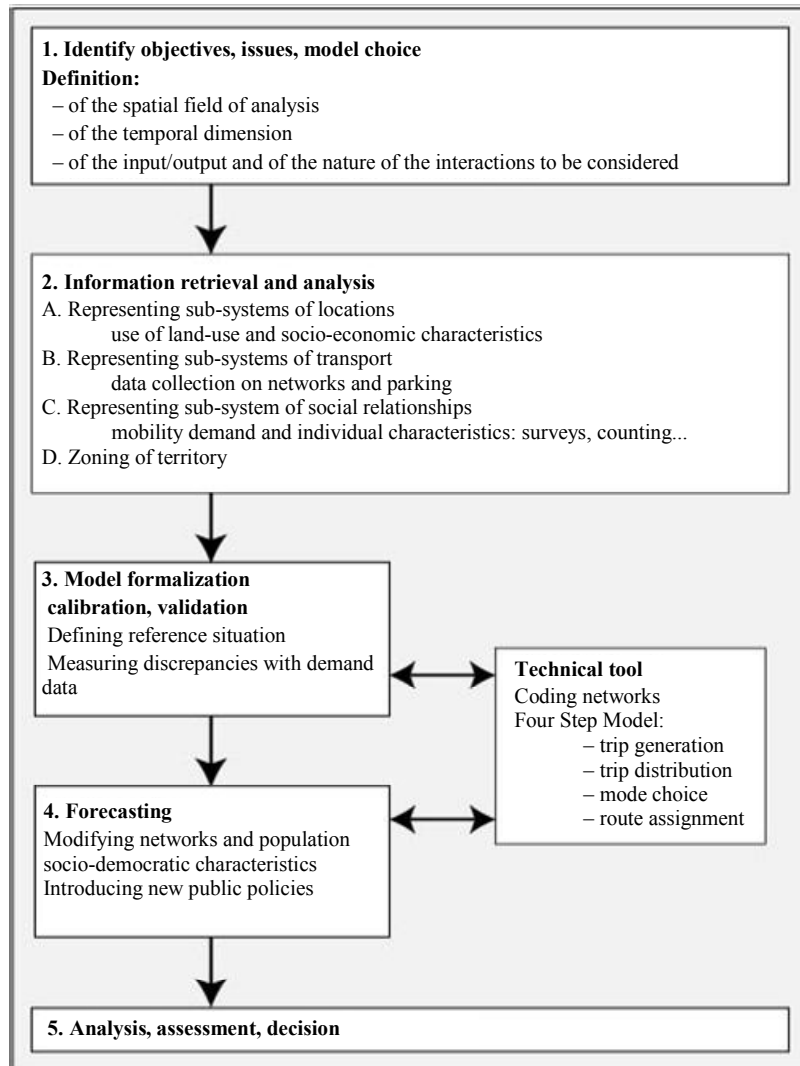


Figure 5.1. *Forecasting procedure*

During the *third stage*, formalization, model calibration and validation procedures enable us to face theoretical construction head on with the data available. These operations aim to ensure the model's capacity to reproduce

reality, or rather a certain extent of this reality in relation to survey data. It is therefore a matter of reproducing the situation observed by survey data. Bad reproduction quality may bring us to modify the model or to ask ourselves questions regarding the data quality and possibly produce new data. Once again, we reiterate that this stage is fundamentally important. If the model is not capable of reproducing the observed situation, then there is a high risk of the differences in values increasing when forecasting. At this stage, the technical tool is developed, meaning the model in the classical sense of the *mathematical model*. In fact, at this stage two distinct procedures are carried out:

- the mathematical formulation of the model, i.e. the relations between variables being put into equations;
- model calibration, i.e. determining the unknown factors for mathematical equations.

Lastly, the model just needs to be validated. This involves verifying that the direction or order of magnitude of certain indicators or changes conform to what we already know about the studied phenomenon.

Once the model has been calibrated and validated, meaning that it is ready to reproduce the studied phenomenon, then the mathematical model can be used for forecasting, in a *fourth and penultimate stage*. This involves modifying the model's input data and, by using the technical tool, obtaining the output values for the sought indicators. Therefore, the forecasting stage seems the simplest of all, if it is only the modification stage (forecasting, in fact) of the input data which is a hazardous exercise. In fact, the model is only unable to forecast what may happen if the context changes according to the input data, all things being equal. This "all things being equal" is theoretical fiction; it is obviously necessary, but is also simplifying. The forecast quality will therefore depend on the quality of the theoretical construction, meaning its capacity to represent the

phenomenon and its evolutions correctly. However, it also depends on the forecasting quality of the input data used during the forecasting stage.

Lastly we present the *fifth* and final stage, the result analysis stage, which may lead onto an assessment and decision phase. At this stage, a looping procedure is possible, as much for the fourth stage for testing new scenarios as for prior stages if the results are not satisfactory.

The presentation of this process is obviously quite theoretical. Often, the objectives are actually amended when the process is up and running.

For example, during the calibration stage, confronting facts may lead to a reduction in the model's range. The unavailability of certain data may lead to a modification of the model proposed. In practice, the analyst is often confronted with several stages going back and forth, according to the modeling context (see sections 5.5 and 5.6).

This schematic representation is important because it allows us to remind readers of the fundamental contribution of each stage to the quality of the results produced by the model. All too often the first two stages are dealt with far too quickly, in particular the production and the data collection stage, which is very "time-consuming". Moreover, this stage allows us to make the distinction between the model (in terms of theoretical construction), its mathematical formalization and its calibration and validation, to make it into an operational tool to be used for forecasting.

5.3.2. The model: the result of a double simplification process

As we have already pointed out, the model is only a "simplified representation of reality, used for a better understanding or to be able to act on it" [GUI 64]. In a

mathematical model, this simplification may be broken down into two procedures. Firstly, for the construction of the theoretical model, we only retain a proportion of the variables and the causal relations that may affect the studied phenomenon (see section 5.3.2.1). Next, the second simplification is mathematical formalization, where we choose mathematical functions, variable measurability, internal coherence or even calculation complexity (see section 5.3.2.2).

5.3.2.1. *First simplification: theoretical construction*

“There is no economic object that a restricted number of concepts can entirely clarify” [BON 89]. This comment is probably not specific to the field of economics. It means that understanding an object involves considering a very high number of dimensions which we have known for a long time due to mobility analyses. A quick scan of existing literature allows us to highlight several determiners for this mobility (economic, demographic, individual, lifestyle, household, urban spatial structures, transport supply, etc.). In order to take up the “multidimensional challenge” [BON 89], the analyst must decrease his study. This reduction is a question of selecting a few variables amongst a set of variables which could influence the object for study. Therefore, it involves a choice made by the analyst which favors certain variables within a larger set of variables.

The choice is made based on the knowledge acquired on the object for study, which mainly comes from analyzing the survey data. This choice involves considering that the other variables have no influence, or at least, hypothesizing that we may ignore the effects of other variables on the object for study within the context where the model must be used. We may, however, formulate this choice in another way. This means stating a *ceteris paribus* clause, judging that all things are equal or, more precisely, if we are within a dynamic perspective, that anything that is not taken into

account will continue to evolve as in the past. It is clear that the object for study is greatly reduced.

After this choice of explicative variables for the object of study, we then choose the model's output variables which make it possible to give information on the object(s) evolution. Again, it is necessary to limit ourselves to a few variables (like the number of trips, the distances travelled, pollutant emissions, etc.). Finally, the last choice for the model's theoretical construction consists of determining the causality relations between the model's input and output variables. Here, the analyst is once again led to make hypotheses on the nature of the relations between these variables and the separation of different factors.

With us coming from a forecasting perspective, we must conduct hypotheses on the evolution of the considered relations. Whatever the type of these relations, the analyst is led to postulate the invariance of certain relations which in fact become laws. For example, to say that car ownership will increase is only of use to forecasting if we define its growth rate, which will then constitute an invariant for the period considered. If we have reason to believe that the growth rate will not remain constant, then we may define the law for its evolution by supposing a relation with income (frequent hypothesis for several models). This new relation will then become an invariant.

We could complicate the relation even further by including time. Or by introducing asymptotic phenomena (market saturation), we will always come back to the expression for a relation invariant. However, nothing is allowing us to confirm that these laws will remain valid, whatever the evolution of the context around the object for study.

5.3.2.2. *Second simplification: mathematical formalization*

Mathematical formalization, or even mathematical specification, consists of choosing the mathematical form which reflects the relations between variables in the model. It also leads to a simplification process.

There are several reasons which can be put forward, particularly [BON 04]:

- if we wish to apply the model, the variables used by the mathematical functions must be measurable, regardless of the measurement used. Let us take an example to illustrate this problem. In an assignment model (route choice), most of the time we come to the hypothesis that the person knows the set of possible routes to go from a zone i to a zone j and that he/she is able to compare them in order to choose one (generally the shortest one). In fact, we know that this hypothesis does not correspond to what we already know about individual behavior. Users do not know all the routes available, and they have a certain perception of all the routes they know, which is not necessarily the same as the perception for another user. Therefore, we are confronted with a kind of bending filter. This filter concept for transport supply causes an obvious measurement problem that we will usually attempt to solve by using the concept of generalized costs and stochastic processes which aim to translate the variability of individual situations;

- several of the mathematical functions used require continuous variables. Yet, some variables are not continuous or, even, the available data regarding these variables do not show themselves as being continuous. The most often seen case is regarding income, which is generally collected in intervals, in order to reduce instances where participants refuse to respond. It is then still possible to smooth the curve, but it is necessary to make distribution hypotheses within each category;

– data is not always available to feed the model for a variable or a relation. This is often the case for parking in a model for mode choice. We know that the provision of a parking space in the work place is an important explicative factor for mode choice. But such information is often unavailable, meaning that the analyst has to modify his theoretical model, which often leads to a reduction in its quality.

5.3.3. Operationality and problems regarding the model

If the model is the result of a double simplification process, it is a legitimate approach to question the quality of the model. Firstly, we propose a definition of it: “a model which is capable of achieving the performances we expect from it will be called operational”. The model’s operationality is therefore its base quality” [BON 89]. The operationality of a model cannot be defined in a general way. It can only be characterized using a definition of the objectives assigned to the model.

The model may prove to be operational in order to answer certain questions formulated in a certain context. Or, it may no longer be operational at all for answering either other different questions, or the same questions but formulated in a broader context. There are three conditions which must be fulfilled for the model to be operational: relevance, coherence, and measurability. We may show that these three conditions are necessary and sufficient [BON 89].

Relevance relates to the model’s ability to conform to what we believe we know about reality, and that state of things. We may easily think that this condition is necessary for the model’s operationality. An irrelevant model would not conform to the state of things. When there is no relevance, it is mainly due to two factors:

- the choice of explicative variables;
- the relations between the variables.

In both cases, forgetting certain variables or relations, or even problems to do with definition or specification, may induce a reduced level of relevance. As a consequence, we find it hard to understand how the model could forecast in accordance with how the state of things will be on the forecasting horizon. On the other hand, we have everything to believe that the difference will increase with forecasting, except for in a “happy” combination of circumstances.

The model’s *coherence* covers two concepts:

- the model’s *internal coherence* or the *logico-mathematical coherence*. The model must not contain internal contradictions, whether this is with regard to the definition of the variables, the values taken by these values, or the retained causality relations. Moreover, the model must respect the hypotheses for applying the mathematical models or estimation methods. This first concept seems to be the least that we can expect from a model. However, its implementation may sometimes raise a few difficulties;

- the model’s *objective coherence*. This involves ensuring that the model is capable of answering the questions for which it was designed. We can use an example to demonstrate this concept: forecasting the demand for a new infrastructure sometimes relies on a unimodal model (e.g. forecasting demand for a subway line can be based on a model of the only collective transport network), with results which are often satisfactory. Since forecasting must be accompanied by a socio-economical assessment, this forecasting is no longer sufficient because we need to know the share of the users coming from the road, from walking, etc. A multimodal model is then necessary. An absence of objective coherence would make it impossible to fulfill the... objectives.

Measurability makes up the third condition for the model's operationality. This requirement is according to three dimensions:

– *the measurability of causal relations*, which relates to the need for being able to formalize these relations so as to use them in forecasting. What would be the advantage of forecasting a causal relation for the “increase in car ownership leading to a growth in the number of trips made in a car”, for which we cannot propose a mathematical function linking car ownership and car journeys? At the most, we could predict a growth in car traffic when there is an increase in car ownership, but we would not be able to quantify it, or meet the objective;

– *the measurability of the quantities used* in the model is essential. The lack of measurability for an explicative variable stops it from being introduced into the model due to risks of biasing it;

– *the measurability of the parameters of its equations*. The indeterminacy of a coefficient means that we cannot estimate the model which will remain undetermined, preventing it from being used in forecasting.

Data production is necessary in order to meet these measurability criteria. When there is no survey data, there is a high risk of the variables not being defined. But above all, formalization cannot be confronted by the “reality” which is represented by the data.

The three conditions of relevance, coherence and measurability are therefore essential for the model's operationality, and they are also sufficient [BON 89]. But these conditions are contradictory, as improving one of these conditions is most often done to the detriment of the two others.

Looking for a better level of measurability is often at the expense of other conditions. Let us take the example¹ of income that we have already discussed. Income is rarely asked for directly in a survey, because refusal is so frequent and therefore often gives a mediocre measurement of actual income. Thus, we sometimes use income bands, meaning that the participant is not asked to give his/her income, but to indicate which band they belong to. This “trick” means that we can reduce the number of refusals by half. We are then able to define a new variable, the income category, which is easy to measure. On the other hand, it creates problems with regard to internal coherence. To fulfill the objectives for quantifying the model, it is generally necessary to have an income which varies continually, and not in terms of band. The solution consists of smoothing the curve. To do so we must introduce hypotheses on the distribution of incomes within each band. But the relevance of these hypotheses has not been proven, which is a problem of not knowing the effective distribution of... income! Introducing the income bands reduces refusals, but does not entirely stop them. Moreover, according to the level of income and professions, the information provided by the surveys is frequently willingly erroneous, on the increase or decrease. Therefore the information remains mediocre in terms of quality. This is why it is often standard practice to replace income by a socio-professional category. This time we have a variable which can easily be measured, which is, moreover, available in INSEE data, allowing for rectifications on different geographical levels. However, we agree that this involves an approximate substitute for income whose relevance is more than debatable.

In response to these difficulties, A. Bonnafous proposes two solutions: “the first is quite simply reducing the model: reducing its objective, its object of study, or both” [BON 89]. The second one consists of dealing with the problem by

1 A more detailed example can be found in [BON 89], [BON 04].

methodological innovation. More often than not, it requires moving the problem in order to put it in another perspective. This is obviously the preferred output, but is clearly more demanding.

We feel that this method provides a framework for analyzing or constructing its model, as well as for assessing its limits and therefore its operationality in relation to the questions it is meant to shed light on. The following developments demonstrate the main modeling structure which is used in trip planning: the four step model.

5.4. Constructing geographical information: from the zonal system to the network structure

Any transport demand model requires that we choose an area of study for the model to be built in. This very important choice allows us to define an *isolate* inside the area where we will try to represent the relationships between the elements making up the modeled system.

In the same line of thinking, we will postulate an isolated relationship with the system's exterior (without meaning a fixed exterior). On the other hand, we generally make hypotheses with regard to the evolution of this exterior. Yet, we hypothesize that the evolutionary dynamic of what is inside the system has no effect on the evolution of the exterior.

We will use an example to illustrate this simplification. Constructing a model for the urban community of Millau (before the viaduct was built) by applying this principle would lead us to define a study area around the community. Therefore we hypothesize that transit traffic will not be affected by transport policies or investments made within the community. For a case such as the Millau viaduct, this restriction is impossible: this structure has an impact on the

large transit routes from the North to the South. In this precise case, it becomes clear to us that simplification is not acceptable and requires a different approach.

Choosing a study area and therefore an isolate inevitably depends on the modeling objectives and its temporality. The more restrained the temporal horizon, then the more acceptable it will be to reduce the study area, because the level of interaction with the outside could be considered as low. Analyzing the restructuring of a crossroad or a non structured bus line in a network could be achieved by just using a study area which is virtually limited to just that project. On the contrary, extending the horizon generally requires that we widen the study area. Forecasting traffic for the subway line often requires a study area which surrounds the entire area of urban transport. This is because it is not possible to postulate that the interaction between current collective transport lines and a new line will be insignificant. Therefore the choice of study area stems from the nature of the interactions to be considered within the modeling procedure. This choice is a result of the model's theoretical construction carried out during the first stage of the forecasting process (see section 5.3.1 and Figure 5.1).

The study area is then divided into a number of zones to constitute what we call *zoning*. This zoning is then used to build demand matrices for the first three stages of the four step model and for route assignment. The zoning choice must enable us to meet the objectives for the study with the desired level of precision, while taking into account constraints to do with cost and data availability. The compromise between these two contradictory dimensions is generally achieved by considering the following aspects:

– *the coherence with the study objectives*: for example, assessing a new subway line generally requires dimensioning the traffic expected at each station, even stations with connection lines if necessary. This means that

the aforementioned division must be in a position to fulfill requirements. If two stations are included in the same zone, it will not be possible to determine the share of each station in the line loading. On the other hand, if the area around the station is too wide, then there is a risk of the station load being over estimated. The zoning choice therefore imposes a primary definition of the study objectives as we have mentioned in Figure 5.1;

– *internal coherence*: zone homogeneity, considering natural borders, etc. Zone homogeneity is generally sought out in order to try to reduce the diversity in individual behavior and situations. Generally we will try not to mix wealthy populations with a high rate of car ownership with underprivileged populations with a more limited access to cars in the same zone. Physical or natural borders, such as rail lines, rivers, etc., often constitute separations which limit exchanges between bordering zones;

– *coherence with the definition of networks*: zoning must consider the structure of collective and road transports (we can use the example of subway stations). A precise description of road network must be supported by a precise zoning, at least if we want to analyze the networks in a detailed way;

– *measurability*: data availability, division compatibility, etc. It is obvious to us that, at the most, these divisions must consider the current divisions for data production. This evidence is, however, often difficult to manage insofar as where these are often rarely compatible between them and generally do not have the same level of conformance. In France, certain data from INSEE is available to housing blocks, housing blocks divided into zones for statistical indicators (French IRIS project) or to the community. The data from household trip surveys are generally produced on another division. The O-D matrices for collective transport generally benefit from another division which is adapted to the problems concerning this mode of transport. The data

taken from other organizations are often available to the community...;

– *cost and calculation time*; the more precise the division, the higher the cost of development and estimation of the estimation. In the same way, the calculation time rapidly increases with the number of zones. In both cases, the evolution will not be proportional but, rather, exponential.

Network coding is achieved by following the principles of the graph theory. A network is made up of nodes and links to which we can add lines for collective transport (Figure 5.2). We distinguish two types of node: zone centroids (only one per zone) and network nodes. The zone centroid represents the whole zone. It concentrates the entire population within the node, as well as jobs and activities from that zone. This means that the zone’s space no longer exists. There is more of a distance between this zone as, by definition, it is reduced to its centroid. It is essential to fully understand this simplification. It means that we can get a better hold searching for zoning precision, because the more extended the zone, the bigger the simplification. Through trying to compensate for this simplification, we will introduce the centroid connector.

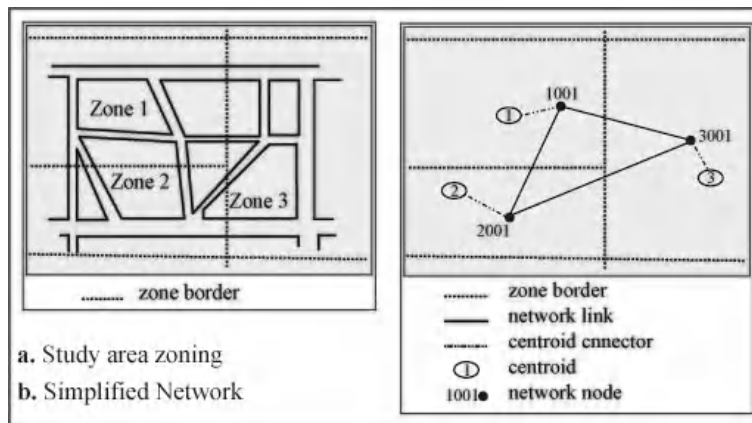


Figure 5.2. Illustration of zoning principles and network coding

We may distinguish two types of links. The centroid connector makes it possible to link the zone centroid to the network, so as to make mobility possible. There is at least one connector per zone, but there may be others. The choice depends on the extension of the zone, on the network's conformity, the objectives, etc. The second type of link is the network link. This is what allows for the network's connectivity and therefore journeys to be made between zones. The network link has several attributes which reflect the characteristics and the level of network service. Amongst these attributes, we will use:

- the length;
- no-load speed, meaning no traffic;
- capacity, which makes it possible to determine the maximum number of vehicles able to run over the infrastructure in one hour;
- a time/flow ratio which allows us to represent congestion. This ratio determines the increase in journey time when the infrastructure flow (meaning the number of vehicles to flow in one hour) reaches the capacity, or even exceeds it.

All these characteristics contribute to the general time calculation between each of the zoning origins/destinations. General time aims to reflect journey time on the one hand, but also the way it is perceived by individuals as this perception will guide their choices. It is also well known that during a trip made using collective transport, walking and waiting times are perceived as being more tiresome than the in-vehicle time. Finally, general time makes it possible to add the temporal and monetary components of a trip according to the following generic formula:

$$Tg = P/V_i + \left(\sum_i \alpha_i T_i \right) \quad [5.2]$$

where:

- Tg is the generalized cost;
- P is the cost of the trip;
- V_t is the value attributed to time by the individual;
- T_i is an elementary part of the time needed to complete the trip (e.g. walking, waiting, in-vehicle time, etc.);
- α_i is a weighting coefficient of elementary time T_i .

The generalized cost is calculated during the route assignment step for transport demand. But this generalized time is necessary for inputting the distribution and mode choice steps which take place before route assignment. To alleviate this contradiction, in practice the process is initialized by using the demand matrix generated using the available input data for the route assignment model which we implement first. This allows us to produce generalized time matrices and therefore run all four steps consecutively. However, for the generalized time matrix produced in the output of this chain, there is a high chance that it will not be identical to the one used to initialize the modeling chain. This is why an iterative process is sometimes put in place. We get the generalized time matrix taken from the entire four step chain and we then restart the whole modeling chain again. This process is repeated until satisfactory convergence is obtained.

To process the zoning and network codification, GIS have quickly been imposed. They make data processing quicker and easier, and allow for an analysis of coding coherence. All transport modeling software today proposes either a network publisher with most of the GIS functions at hand, or certain interfaces which allow us to import or export networks from or to the GIS. In addition, the development of road data bases (Navteq, Teleatlas, Géoatlas) also modifies network

construction practices which tend to increase the number of zones and links needed to describe the networks.

5.5. Constructing origin/destination matrices

Traditionally, the origin/destination matrix is built in two steps, namely by generating the transport demand and its distribution.

5.5.1. Generating transport demand

The purpose of the generation model is to generate trip productions and attractions per zone:

- productions relate to the set of trips produced by a zone (Figure 5.3), i.e. the trips whose origin is within the zone (including intrazonal trips);
- attraction corresponds to the trips received by a zone (Figure 5.3), i.e. the trips whose destination is within the zone (including intrazonal trips).

The generation step constitutes the origin-destination matrix margins which will be produced by the following distribution step. Analyzing available trip data (often household trip surveys) generally segments the trip market according to trip purpose. The following segmentation is often used:

- home-based work trips;
- home-based study (sometimes with a distinction according to level of study);
- home-based shopping trips;
- home-based leisure trips;
- home-based other trips;
- non-home-based trips.

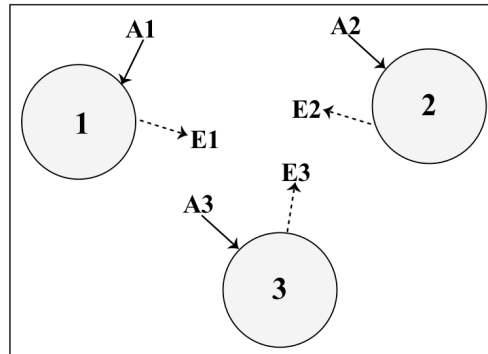


Figure 5.3. *Trip generation: production and attraction per zone*

Some of these categories may be grouped together or split according to the objectives and the accuracy of the data available. The last purpose, “non-home-based trips” relates to all trips that neither begin nor end at home, where modeling is often tricky because there are several factors explaining these trips which are difficult to identify.

This trip-based approach still causes many problems, however. It still does not allow us to identify the true purpose for leaving the home. A person leaving his/her home to go to work, who stops along the way to buy gas before getting back on the road to go to work, going directly back home in the evening will have made three trips:

- home-based shopping trip;
- non-home-based trip (between buying gas and going to work);
- work-based home trip.

However, we may think that the shopping purpose is not the one which justifies leaving the house, and is therefore not the main purpose for leaving. The second problem shown by this example, through the following steps, is that applying

the modeling chain leads us to make all the home-based trips symmetrical. Yet this does not correspond to the data used for estimating the model. Lastly, we may think that the transport mode used for each trip will be identical. Except for rare exceptions, this is actually what we observe in the survey data. On the other hand, during the mode choice step, each trip will be analyzed independently from the other trips. For example, the first trip may be completed on foot, the second may be taken in a car and the return trip may be completed by using collective transport, depending on the performance of each mode for each trip.

It is in order to alleviate these incoherencies that approaches based on leaving the home (putting all trips and activities into a chain between a consecutive departure and return to the home) or on activity schemes (putting all trips and activities in one day into a chain) are developed [ETT 97].

The explicative variables for trip production often relate to the characteristics of the population living in the considered zone. We find the following most often in generation models:

- household income (sometimes individual);
- household car ownership, generally expressed in terms of number of cars available or useable in the household, although it may be preferable to keep a definition in terms of number of cars per household individual or per individual in the household over 18;
- household composition when generation takes place according to household;
- number of people or households in the zone;
- number of school age children, defined according to age or the level of study if the corresponding purpose is segmented;

- age of the individuals, or more generally, distribution per age band.

With regard to trip attraction, we use the variables characterizing the activities which are available within the zone more, including the population as a source of attraction for leisure (visiting families or friends, etc.):

- number of jobs in the zone, often segmented into part time and full time, and isolating the jobs in the business sector from part time jobs;
- number of places in schools, colleges and universities;
- number of individuals or households in the zone.

When a split according to purpose is used and isolates the shopping purpose, then data on jobs in business sectors are sometimes used.

This data is not excluded from other sources of data concerning a community when they are available. However, the difficulty in using other data concerns availability of information regarding the reference situation, but also and above all, the possibility of simulating the corresponding information in the forecasting situation.

We primarily distinguish two model families for generation: regression and categorial models.

The principle for construction of the regression model is rather simple. It requires having a set of data giving the trip productions and attractions per zone in the reference situation, and the characteristics of the zones in terms of population and activities. We must then determine the variables which explain the trip production and attractions per zone the best. For this, we use the multiple linear regression model.

This model boils down to implicitly creating an average individual with average behavior. Yet mobility analyses show that daily mobility behavior is not homogeneous within the population. It is in order to try to meet this limit that the categorial model may be introduced. It requires segmenting the population in the zone into groups which present larger behavior homogeneity. This is a question of minimizing intra-group variance and maximizing inter-group variance. Next, for each of the groups, the regression method is used. Obviously, we gain more relevance here, with the fiction of the average individual being less simplistic within each of the groups than for all the population in each zone. On the other hand, we lose some measurability because the effective measurability of the number of trips in the household trips survey does not always allow us to cross over the population segmentation with the purpose segmentation. This crossing over may lead to too low a number of surveyed trips, and therefore to a poor estimation of the magnitudes to be explained. Consequentially, there is an increased risk of biasing the model.

Disaggregated models try to act on this limit and look to reproduce not only average behavior, but also the behavior for each of the participants individually. The application consists of estimating a sequence of probabilities. Initially, a first model will estimate the probability of making a trip and its complement, namely not making a trip. Secondly, amongst the individuals who make the trips, we will estimate the probability of making at least two trips, and its complement, only making one trip. We will return to these disaggregated models later (see section 5.6.1).

The main limits stem from the method itself. In terms of coherence, applying the linear model requires we respect constraining hypotheses, particularly those which concern the linearity of functional relations between variables, and the homoscedacity of the residual variance. In terms of

relevance, the model does not use the transport supply. This means that the number of trips made in a zone is independent of the available transport supply. This contradicts the observations made during the creation of new structuring infrastructures. The choice of making a trip is made independently of the trip conditions, as these conditions are determined during the following distribution, mode choice and assignment steps. Estimating the model is generally done using data from a single survey and not over chronological series which are not available. As a consequence, it is then not possible to consider generalized coefficients in time. Finally, with regard to measurability, we must question the accuracy and quality of the data used to estimate the model, as well as the accuracy of the data relating to the future explicative variables in order to use the generation model for forecasting.

5.5.2. Trip distribution

Distribution is the second step in the four step model after generation, and uses its production and attraction outputs. Distribution relates to choosing the trip destination in the sequence of the individual's choices.

Mathematically, this step makes it possible to calculate the O-D matrix for the trips using its margins. We can illustrate these two stages graphically (Figure 5.4).

The first distribution models were based on the growth factor principle. To tackle these limits head on (see section 5.2), today we mainly use the gravity model. We will give a quick presentation of the growth factor models although they are practically no longer in use, because their algorithms are used for the gravity model.

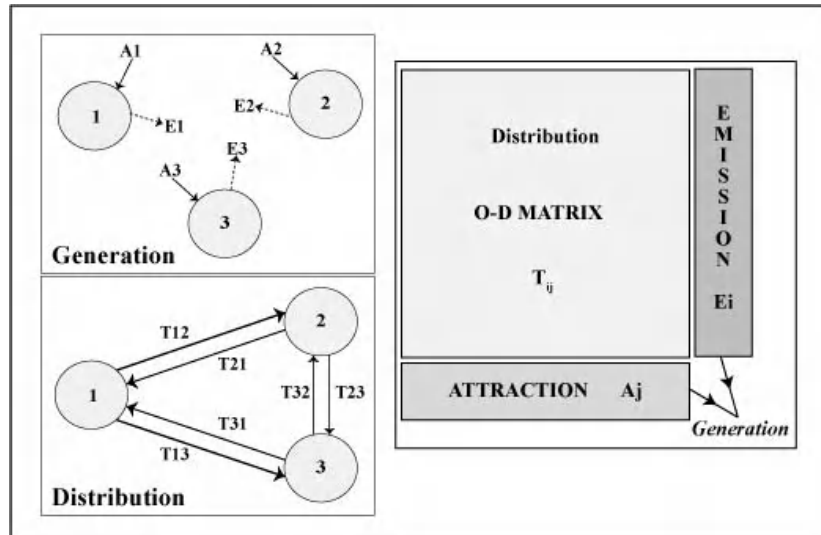


Figure 5.4. Trip distribution

The principle behind the growth factor model is simple. It consists of calculating growth factors for each zone and using these factors to gradually reshape the O-D matrix for reference trips (i.e. the matrix taken from survey data) in order to give the study horizon. The growth factor for trip production in each zone comes from the generation stage by putting the trip production on the study horizon in ratio with the reference situation.

Thus, in trip production:

$$F_i = \frac{E_i (\text{horizon})}{e_i (\text{reference})} \quad [5.3]$$

with F_i as the growth factor in trip production; E_i the trip production on the horizon study and e_i the reference trip production.

In attraction, the calculation mode is identical, if it is only by replacing the trip production by attractions.

$$F_j = \frac{A_j \text{ (horizon)}}{a_j \text{ (reference)}} \quad [5.4]$$

We will present the Furness algorithm, even if another algorithm (Fratar) is used more often in practice [BON 04]. However its calculation mode is more laborious and would complicate our presentation unnecessarily.

The O-D matrix for mobility T_{ij} is obtained by consecutively deforming the reference matrix t_{ij} according to the following algorithm, and by trying to respect the margin constraints:

$$\sum_j T_{ij} \approx E_i \text{ and } \sum_i T_{ij} \approx A_j \quad [5.5]$$

Furness algorithm:

– 1st iteration:

$$\text{calculating } F_i^{(1)} = \frac{E_i}{e_i}, \text{ then calculating } T_{ij}^{(1)} = t_{ij} \times F_i^{(1)} \quad [5.6]$$

by the calculation mode, the margin constraint is respected on the lines, but not on the columns;

– 2nd iteration:

$$\text{calculating } F_j^{(1)} = \frac{A_j}{\sum_i T_{ij}^{(1)}}, \text{ then calculating } T_{ij}^{(2)} = T_{ij}^{(1)} \times F_j^{(1)} \quad [5.7]$$

by the calculation mode, the margin constraint is respected on the columns, but not on the lines;

– 3rd iteration :

$$\text{calculating } F_i^{(2)} = \frac{E_i}{\sum_j T_{ij}^{(2)}}, \text{ then calculating } T_{ij}^{(3)} = T_{ij}^{(2)} \times F_i^{(2)} \quad [5.8]$$

by the calculation mode, the margin constraint is again respected on the lines, but no longer on the columns.

Thus, we then know that generally 4 to 6 iterations on the lines and columns are sufficient for obtaining good convergence.

The limitations of this model (particularly the impossibility of making changes to the null squares in the reference O-D matrix as we already mentioned, see section 5.2) have led us to use the gravity model. Its principle is very simple. It is based on a comparison with Newton's universal law of gravity:

$$F_{ij} = \frac{G \times (M_i \times M_j)}{d_{ij}^2} \quad [5.9]$$

where F_{ij} represents the attraction between two bodies of mass M_i and M_j , and where d_{ij} is the distance separating these two bodies and G is a constant.

The analogy is rather intuitive. The attraction between two zones, meaning the traffic, will be much higher when the weight of each zone is high, but this attraction is weighted by the size of the distance separating the two zones. This model was used in the 19th century to estimate traffic between two communities. Its transposition to the urban context goes back to the 1950s. The weight of each zone is often represented by trip production and attraction. Distance is replaced by time or generalized cost. The matrix T_{ij} is therefore obtained by the following formula:

$$T_{ij} = a E_i A_j f(Cg_{ij}) \quad [5.10]$$

The function f of the general cost is no longer the inverse square as in Newton's formula, but a power function or a negative exponential function. We find that a combination of these two functions is being used more and more:

– Power function:

$$f(Cg_{ij}) = Cg_{ij}^{-b} \quad [5.11]$$

– Exponential function, where the coefficient b is sometimes called the conductance coefficient:

$$f(Cg_{ij}) = e^{-bCg_{ij}} \quad [5.12]$$

– Combined exponential and power function:

$$f(Cg_{ij}) = Cg_{ij}^{-c} \times e^{-dCg_{ij}} \quad [5.13]$$

The direct application of equation [5.10], however, does not respect the margin constraint, hence the need to use the Furness or Fratar algorithm. Calibrating the gravity model consists of determining the resistance function coefficients (equations [5.11] to [5.13]). It may seem surprising to use an analogy with a law taken from physics to justify the distribution model on the theoretical front. In fact, we may also justify the gravity model by grounding it on economic theory (maximization of individual utility), or using the entropy maximization principle [BON 04], [WIL 74]. The main limits for this step can be analyzed using the three conditions for the operationality of a model:

– *Relevance*: analyzing the gravity model shows that the generalized cost is the only variable which explains the destination choice under the limitations of respecting the margin constraint. This explains the opportunities available in each zone obtained during the generation model. The calibration coefficient of the resistance function expresses

the highest or lowest distance resistance (measured in generalized costs). As for generation, the model is only calibrated generally on the data from a single survey. It is, then, necessary to hypothesize the stability of the influence of generalized cost which is far from being certain when we observe the tendency to stretch trip distances in urban environments. The generalized cost cannot be calculated from the network descriptions for intrazonal trips, as it is a matter concerning the movement from a centroid towards itself. On the network, time is, then, null. To overcome this limitation, we must introduce a generalized cost value for the intrazones;

– *Coherence*: what value should we use for generalized cost? We may envisage weighting according to the weight of each transport mode. But, however, the mode choice is only calculated after distribution! In practice we often go back to the mode value which shows the lowest cost, which is often the car. In this case, how do we take congestion into account when the mode assignment is carried out after the mode choice and therefore after distribution? In practice, only one looping over the model's four steps will let us deal with this problem, in the hope that the process is convergent;

– *Measurability*: here, we mainly find the problem of data accuracy. We will use the example of a division into 100 zones, which is low considering most recent studies. This gives a matrix of 10,000 squares. The last household trip survey for the Lyon community in 2006 contains nearly 100,000 trips. Therefore, there are on average 10 trips observed by the cells to be distributed in as many matrices as there are purposes. The precision of each matrix cell is therefore clearly insufficient to calibrate the model. This is why we are not looking to reproduce this matrix during the calibration, but only the distribution curve for generalized costs.

5.6. Mode choice and route assignment

Mode choice means that we can distribute transport demand according to the modes considered (see section 5.6.1). The demand is then assigned to the networks in order to determine the load on the road links or collective transport lines (see section 5.6.2).

5.6.1. Mode choice

Mode choice aims to estimate the modal share of each transport mode for each origin-destination. Therefore it produces as many O-D matrices as there are transport modes.

We primarily distinguish two approaches for mode choice: aggregated or disaggregated one. In the first instance, for each origin-destination, the information available in the surveys is aggregated in order to create a fictional individual: a sort of average of all the trips made over the origin-destination considered. By using this average individual, next we are looking to reproduce the market share for each mode for each origin-destination. For the disaggregated approach, we abandon the average fictional individual in order to keep the available information with regard to each individual. We are no longer looking to reproduce a market share, but the choice made by each individual for each trip completed. The disaggregated approach is clearly more relevant because it is based on individual behavior and not a fictional average individual. Experience tells us however that estimating a disaggregated model may turn out to be complicated if we do not retain the restrictive hypotheses on the individual utility functions for each available mode. Moreover, forecasting with the help of a disaggregated model creates specific problems for enumerating the population and simulating explicative variables in the forecasting situation [ORT 01]. If, from a

theoretical point of view, it is clear that the disaggregated model must be privileged, then in terms of operability it is not certain whether the disaggregated model is always superior.

Disaggregated models were developed to counteract the shortcomings of aggregated models on the theoretical front [DOM 75] [BEN 85]. They are based on the theory of maximizing random utility which stems from the neoclassic micro-economic theory of consumer choice. This theory postulates that the individual looks to maximize his individual satisfaction, which is expressed through a utility function. Applied to the economy, this maximization is carried out under particular constraints to do with income or available time.

The application in the transport domain is somewhat a matter of considering an isolate, as the income or time constraints cannot simply be refused. The application in the mode choice limits the choice to a finite and whole number of alternatives, hence the frequent use of the name “discrete choice model”.

Discrete choice models postulate that each individual has a utility function allowing him to assess the utility of each available alternative, and therefore to choose the alternative with the highest utility, which is generally expressed in the following way:

$$U_{in} = V_{in} + \varepsilon_{in} = f(X_{in}) + \varepsilon_{in} \quad [5.14]$$

– where U_{in} is the probabilistic utility of alternative i considered for the individual n , and V_{in} is the deterministic component defined as a function f of the explicative variables X_{in} of the individual’s choice n :

– ε_{in} is a random vector with a zero mean corresponding to the errors terms. These error terms mainly reflect the fact

that we cannot identify or completely explain the utility of a given alternative for a given individual. Therefore, it corresponds to everything which influences the individual's choice, but which is not taken into account in the retained explicative variables. It also reflects all the measurement errors related to the survey data.

Function f is most often an additive function (or transformed to an additive one using proper variable transformations) for analytical convenience:

$$V_{in} = \sum_k \beta_{kin} X_{kin} \quad [5.15]$$

– X_{kin} corresponds to the different variables k making it possible to estimate the utility of product i considered for individual n ;

– β_{kin} is the coefficient of variable X_{kin} .

Building a disaggregated model requires us to mathematically formalize the utility function, then estimate it using trip survey data. When the approach is deterministic, the alternative choice is easily expressed as the individual will always choose the alternative with the highest utility:

$$P(i) = 1 \text{ if } \forall j \neq i, V(i) > V(j) \quad [5.16]^2$$

This is no longer the case for the probabilistic approach, as utility U is no longer known exactly, insofar as it contains a probabilistic term. We will present its formulation for two alternatives (only to simplify notation), but generalizing a large number of alternatives does not cause any problems:

² We will note that in this case $P(j) = 0$.

$$P(1) = P(U_1 \geq U_2) = P(V_1 + \varepsilon_1 \geq V_2 + \varepsilon_2) = P(V_1 - V_2 \geq \varepsilon_2 - \varepsilon_1)$$

[5.17]

where $P(1)$ relates to the probability of alternative 1 being chosen.

The solution to the problem involves knowing the error terms of the two alternatives for each individual. But, by definition, these terms are unknown; otherwise we could integrate them into the utility function. The solution therefore involves the choice of hypotheses on the error term distribution. It is precisely this choice which gives different families of disaggregated models.

The most restrictive hypothesis gives the logit model, but its relevance causes problems and may lead to incoherent results, as we will show using the well-known red bus/blue bus paradox. On the contrary, the most flexible solution will give the probit model whose estimation is formidable as soon as the number of available alternatives is higher than 3. Between the two, there is a battery of models which depend on: the choices which are made on the variance/covariance matrices of the error terms for each alternative, and on the introduction/non introduction of the individual component in the error terms, known as *taste variation*.

The *logit* model comes from a very restrictive hypothesis on the residual variance distribution for each alternative. These distributions are taken to be independent and identically distributed (same standard deviation, often written IID). The variance/covariance matrix may be summarized as a diagonal with identical values. Moreover, we hypothesize an identical perception of the elements making up the utility function by each individual, and an identical distribution in terms of error terms between individuals. If we choose a Gumbel distribution [BEN 85], we

lead onto the multinomial logit model whose formulation and estimation are simple:

$$P\langle i | C_n \rangle = \frac{e^{V_{in}}}{\sum_{j \in C_n} e^{V_{jn}}} \quad [5.18]$$

where $P\langle i | C_n \rangle$ represents the probability of the individual n choosing alternative i amongst the set C_n of alternatives available to individual n .

This formulation leads onto the property of independence with regard to other alternatives (often written as IIA) which can be explained by the fact that the ratio of two probabilities is a constant, independent of the other alternatives:

$$\frac{P\langle i | C_n \rangle}{P\langle j | C_n \rangle} = \frac{e^{V_{in}} / \sum_{k \in C_n} e^{V_{kn}}}{e^{V_{jn}} / \sum_{k \in C_n} e^{V_{kn}}} = \frac{e^{V_{in}}}{e^{V_{jn}}} = e^{V_{in} - V_{jn}} \quad [5.19]$$

In other words, this ratio is independent of the existence or non-existence of other alternatives. This property gives the blue bus/red bus paradox. Let us suppose that we have two modes, car and bus, and that each mode has an identical probability in order to simplify the presentation:

$$P_n(\text{VP}) = P_n(\text{bus}) = 0.5 \quad [5.20]$$

Let us suppose now that by a stroke of genius, the bus operator decides to paint half the buses blue, knowing that all the buses were red before. Now we have 3 modes available. If the frequency is not an asset of the bus utility, the utility of the blue bus mode is identical to the utility of the red bus mode (which remains unchanged in relation to

the previous situation). Taking into account the IIA property, we still have:

$$\frac{P_n(VP)}{P_n(\text{red bus})} \text{ which remains constant, therefore } = \frac{0.5}{0.5};$$

and $P_n(\text{red bus}) = P_n(\text{blue bus})$, therefore:

- $P_n(VP) = 1/3$;
- $P_n(\text{blue bus}) = 1/3$;
- $P_n(\text{red bus}) = 1/3$.

The operator has then succeeded in increasing his market share to the detriment of the car. This example is obviously a caricature, as it is very clear that we cannot postulate on the independence of error terms of the blue and red busses, and that the frequency inevitable enters into the utility function. However, this illustrates a frequent situation when certain models are close, as the choice of car, bus, subway, etc. In this case, the hypothesis of independence is not longer realistic, when the closeness between the bus and the subway is taken into account. The most commonly used solution consists of building a decision tree (Figure 5.5) which leads onto the hierarchical Logit model (*nested* Logit).

Hypotheses of the Logic model are postulated on each level of decision (on the nested structure). But this is no longer the case for the set of alternatives, contrary to the horizontal structure.

The *Probit model* imposes no conditions on the variance/covariance matrix of error terms for each alternative. This means that estimating a Probit model requires we estimate the utility function coefficient for each alternative. It also means that it is necessary to estimate the variance/covariance matrix. Consequentially, we understand

that the exercise is increasingly more complicated, as the number of alternatives is increasing. On the other hand, the Probit model shares the perception homogeneity hypothesis with the Logit model. Only the mixed multimodal models enable us to partially relax this hypothesis [ORT 01], [BON 04].

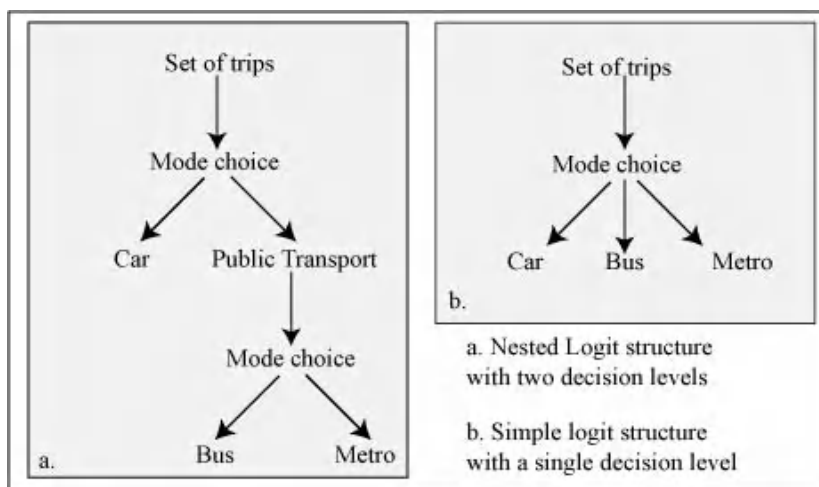


Figure 5.5. *Multinomial Logit model structures*

In the case of an aggregated approach, we use the same models. The hypotheses are identical, if it is only because they are not formulated according to each individual, but according to the average individual for each origin-destination.

The main limitations of mode choice models come directly from the relevance of the hypotheses retained for distributing the residual variance. Beyond this, there are limits which are similar in nature to those that we were able to formulate for the previous steps: relevance of utility function formulation, temporal stability of the estimated coefficients, coherence between steps, data accuracy.

5.6.2. Demand assignment

The aim of an assignment model is to determine the route choice for each origin-destination for each transport mode. This then enables us to estimate the load for each infrastructure and therefore the level of congestion for the road networks. In addition, we will note that the assignment modes are increasingly more paired with pollutant emission models, making it possible to estimate the amounts emitted for the different pollutants.

The theoretical foundations of the assignment model are similar to those for the previous steps. The individual chooses the alternative which maximizes his/her utility. Considering the nature of the choice relating to this step, a route choice considering a given origin-destination and mode, the utility (or more precisely the disutility) is measured via the general cost. The basic principle of all assignment models is therefore to consider that the individual is looking to minimize the general cost of his/her trip for a given origin-destination and mode.

If the models have a shared fundamental principle, it is that they are generally classed according to two dimensions [THO 91], [ORT 01]:

- *Consideration of capacity constraints.* Some models do not taken into account the capacity of the links. Therefore the general cost (and therefore travel time) is independent of the load, even for congestion when the load reaches or exceeds the capacity;

- *Deterministic or probabilistic utility.* In the first instance, we consider that each individual perceives the cost of a link or an itinerary in an identical way. Experience will easily show the opposite of this, for two main reasons. Firstly, the perception of the different elements making up the general cost may be different according to the individual. For such an individual, walking will be considered as very

time disadvantageous. However, for another, it might be considered as only slightly disadvantageous, maybe because he/she likes to walk, or maybe because the journey's surrounding environment lends itself well to walking (shopping area, park, etc.). Moreover, individuals most often only have a partial amount of information on all the possible routes. The second reason concerns the set of choice factors which are not considered in the general cost function: comfort, information quality, the attractiveness of the area travelled through, the weather, etc. In fact, estimating the inputs into the general cost itself is smattered with uncertainties. The combination of these two dimensions is classified in Table 5.1.

The all-or-nothing, or shortest route method as its name indicates, affects the entire demand of an origin-destination on a single itinerary, which corresponds to the shortest itinerary in an application of the utility maximization principle (deterministic). The method may also lead onto loads which exceed capacities insofar as it does not take into account congestion or capacity constraints. This type of model is clearly hardly relevant for route assignments when the networks are congested. However, it is often used for collective transport whose capacity limits are not often reached.

		Itinerary choice procedure	
		Deterministic	Probabilistic
Capacity constraint	NO	All-or-nothing, or shortest route method	Pure stochastic procedure (Dial multipath, Burrell, etc.), cost/time
	YES	Equilibrium method (Wardrop equilibria, split assignment)	Equilibrium method with stochastic method

Table 5.1. *Classification of assignment models*

This approach leads to the choice for a single route. It is no longer the case for multi route stochastic procedures such as the Dial or Burrell types, or the cost/time method. For these route assignments, the general cost of a trajectory is not unique, because each individual will not have the same perception or measurement of the elements constituting the general cost function. However, the non-consideration of capacity constraints is maintained. Stochastic procedures consider that the utility function can only be known in its deterministic aspect, but it must remain an error term which can be interpreted as for the mode choice. The models coming into this family can primarily be distinguished in terms of the position of the random term: on the utility of all the itineraries, or on each network link and on the choice of the error term distribution. The most common two models in this family are:

- Dial route assignment: error terms for full itinerary and IID Gumbel distribution for each existing itinerary;
- Burrell assignment: error terms for each link and uniform distribution of the error term whose span must be specified during the model calibration.

These assignments enable us to distribute demand over several origin-destinations, but they do not taken into account congestion problems. Their relevance is therefore much reduced for road networks because of congestion. These methods are used mainly for collective transport networks as the network has a good enough grid structure in order to give alternative routes.

In the cost/time model, we postulate an identical perception of the generalized cost for each individual. On the other hand, we consider a distribution function of the time value within the population. This type of assignment is particularly relevant for route assignments including toll roads in an uncongested network (mainly interurban).

These methods are no longer adapted as there is congestion. The equilibrium methods were introduced in order to solve this problem. The principle was created by J.G. Wardrop [WAR 52]. An assignment is balanced when, in a congested network, all the itineraries used in the same origin-destination have an equivalent and minimum cost, whereas all the other possible itineraries which are not used have a higher cost. If this condition is not fulfilled, then there will be at least one driver who will want to change route because he/she can find a shorter route. In an equilibrium assignment, no drivers will want to change route, because in doing so, he will encounter an equal or higher cost. This is known as the Wardrop or Wardrop equilibrium principle. It may also be known as Wardrop's first principle, or Wardrop's individual optimization principle.

In a Wardrop equilibrium assignment, for each link it is necessary to define the travel time according to the link's load. This calculation is conducted using the flow/time curve which provides the travel time over the link according to the flow on the link (more precisely, the ratio of the link load on the link's capacity). Therefore it is vital to define a flow/time curve for each network link. The available data does not allow us to calibrate this curve for each link. Practice generally consists of defining roadway classes according to the nature of the roadway and the type of intersection there, and allocating a single curve per road class.

In a Wardrop equilibrium route assignment, each individual is said to have an identical perception of the possible itineraries, which presumes that each person knows all the characteristics of all the routes possible. This is hardly a realistic hypothesis. It is precisely for this reason that the equilibrium models using stochastic utility were developed. They combine the principles of the stochastic models with those from the Wardrop equilibrium. In practice

these models give time calculations which are clearly higher, with necessarily making a notable improvement on the assignment results. This explains why they are not used very often, despite their high relevance.

Beyond the hypotheses specific to each model, the route assignment models must face two main limitations head on. The first concerns network measurability. Building a network and its calibration (particularly, its capacity, no-load speed, and flow/time curve) is an extremely long and costly process, even if new technology may make it possible to anticipate future simplifications. So it is not certain if the sophistication of route assignment methods will make it possible to gain a higher level of accuracy during assignment. The second limitation concerns the hypothesis of all users knowing the network. It is well known that individuals only have partial knowledge of the possible routes. The stochastic approach tries to correct this bias but it is only partial. Other approaches proceed by a gradual learning process [DEP 97].

5.7. Conclusion

In this chapter³ we focused on the main limitations of models belonging to the four step model family. It may seem like these limitations are in abundance, and actually they are. In particular, each model is highly dependent on the quality of the input data needed to develop it, its estimation and its validation (Figure 5.1).

This quality often depends on the precision of the data which can be broken down, on the one hand (from a statistical point of view) according to sample size and on the other hand, according to geographical precision which is

³ We recommend the reader to refer to [BON 04], [ORT 01] for more information.

highly dependent on the divisions specific to each production of data. The development of data georeferenced with x and y coordinates is an important issue as it means that we can be free from the constraints of pre-established zonings.

The development of geographical databases dealing with networks (road networks in particular) means that we can also advance zoning accuracy in network modeling and representation.

Much research is in development to study the contribution of new technology in data production (GPS data, mobile telephones, ticketing technique, microchips⁴, etc.).

The limitations on these models do not mean that they cannot meet the needs we impose on them. But, it is necessary however to take them into account and not to take the model outputs at face value.

For us, models are used above all to conduct simulations which answer questions such as: “what might happen if we introduce this type of measure, and how will the general context evolve?”

A posteriori modeling results analysis shows that the main source for error regarding forecasting does not concern the model itself, but more generally the errors made in the changes to the general context in which the projects or policies are implemented (evolution of the population, jobs, economic growth, etc.). This is the reason why it seems more reasonable to speak of simulation models rather than forecasting models.

The model is, above all, a tool used to help the analysis of the problem of understanding the dynamics at play. Therefore, it is a powerful tool to aid in decision making. In

⁴ See in particular publications on the latest conference on transport survey methods www.isctsc.let.fr/.

addition, all forecasts should give way to uncertainty calculations, even if it is a difficult exercise, one which still has a long way to go in terms of research...

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Chapter 6

Visualizing Daily Mobility: Towards Other Modes of Representation

6.1. Introduction

Space/time representations (and more particularly spatial mobility) are essential for an in-depth knowledge of the structures and processes operating daily in urbanized environments. Whereas the need for graphically representing the daily operation of our land is established in a somewhat unanimous way [BAI 01], [HER 01], space/time geography is still trying to seek out relevant graphic representations [OFF 00].

This difference could be due to the difficulty of crossing spatial dimensions (x,y) with thematic dimensions (z) which evolve in time (t). In other words, the complexity of finding a cartographical answer to the three fundamental geographical questions: “who?”, “what?” and “where?” combined with an explicit temporal dimension embodied by

Chapter written by Olivier KLEIN.

the question “when?”, in order to better understand the “how?”, namely in spatio-temporal processes.

Faced with this double acknowledgement of a need and also a lack of representations, it is therefore vital to renew the cartographic approach to daily space/time. This chapter will be devoted to revealing an approach centered on visualizing daily mobility in order to have a fundamental analysis and communication support for structures and processes of geographical space. This will be with the aim to explore, represent and analyze the city in all its dimensions (spatial, temporal, thematic). In addition, we will explore three recurring problems in spatial/temporal studies more thoroughly.

Firstly, the entire emphasis will be put on the procedure prior to visualization, namely acknowledging the lack of pre-existing spatio-temporal information and their structuring which must be adapted in order to carefully combine spatial, thematic and temporal dimensions. Next, by conducting an analysis of the “classic” cartographic representations, this will allow us to show their limits and their shortcomings, so as to finally tackle other perspectives and solutions for visualization.

6.2. Essential preconditions

On a daily basis, cities are constructed of several interacting elements, which relentlessly show a dynamic element. However, the approach used is limited to daily activities and trips of inhabitants, and therefore putting aside issues regarding transit by those not living in the study zone, and questions regarding the movement of goods, information or capital.

Through this choice, visualizing the city in motion boils down to understanding its component of daily mobility as the

set of urban trips linking human activity together on a daily basis.

By focusing on the information needed for studying daily urban life, the activities may be approached by three fundamental questions (Figure 6.1):

- *What?* Which defines the nature of the activity.
- *Where?* Their location.
- *When?* Within their schedules.

Questions	Information to be collected
What?	- daily activities (buildings and places of activities)
Where?	- location of the places of activities
When?	- activities schedules (with start and finish time)

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Figure 6.1. Characteristics of “activity” information to be collected

This relatively simple vision of daily space/time, with activities located and limited by working hours, becomes more complex still when we introduce the possibility of changing spatial positions over time. Trips are then considered as an element of transition, making it possible to consecutively connect activities which are removed from each other in terms of space, and in this way, fulfilling a certain number of needs. It may then be defined as the movement made by a person for a specific purpose, between an origin and destination, according to a departure and arrival, using one of several trip modes.

In fact, this approach is limited to the initial meaning of the word “movement”, namely the action of “changing places” and the result of this. Obviously, the intervention of the concept of movement complicates the set of steps taking

place after the procedure, in terms of data collection as well as in terms of structuring and representation (Figure 6.2).

Questions	Information to be collected
Who? and with who?	- individual / households <ul style="list-style-type: none"> • associated characteristics (age, occupation...) - copresent individuals
What?	- daily activities <ul style="list-style-type: none"> • places of activities and associated characteristics
Where ? <div style="display: inline-block; vertical-align: middle;"> </div>	- location of residents' housing - location of daily activities - trip routes between activities <ul style="list-style-type: none"> • origin(s) • destination(s) • itinerary(ies) between origin(s) and destination(s)
When? <div style="display: inline-block; vertical-align: middle;"> </div>	- make up of daily schedules <ul style="list-style-type: none"> • days and times of activities • days and times of trips • journey times • frequency of activities and trips
Why?	- trip purposes
How?	- means of transport

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Figure 6.2. *Characteristics of “daily trip” information to be collected*

6.2.1. *Indisputable data to collect*

Understanding urban time through the thematic input of daily mobility leads us to reason on multiple scales. These may go from a macroscopic level (the zone of study) in order to get a global picture of the daily dynamic over the entire population, or to a microscopic level (individual or the household) so as to conduct a more detailed analysis of the individual spatio-temporal routes. It is also very important to collect the most disaggregated data possible and then to proceed by consecutive aggregations to go from one scale to the other.

An inventory taken for the main institutions and organizations makes it possible to extract two large categories of organizations which provide data:

- firstly, organizations which collect data for internal reasons, where the information is centered on their obligations and their areas of study which are often not suitable for other studies or research;
- secondly, organizations intending on giving or selling the information (such as statistical institutions), this time with a better thematic similarity than before.

However, having to fulfill several and more demanding needs, the collected data often turns out to be too general and lacks accuracy, both spatially as well as thematically and temporally. We should not ignore in situ legislation which makes it difficult or even impossible to access precise information (addresses of individuals) due to the regulations put into place by the CNIL (*Commission nationale de l'informatique et des libertés*, French national agency ensuring the application of the data protection act).

Up until very recently, creating databases has only rarely been triggered by the set of issues regarding daily time. With the exception of extremely global approaches, both spatially as well as thematically, with a determined sociological orientation such as the surveys conducted by Chronopost International [MOU 02], there is a severe lack of data on daily time and movement. Without using available data inventories, this evidence is a relative poverty in terms of spatialized temporal data. In most cases however, spatial and temporal data are detached from each other and can no longer be combined together afterwards. The available spatial coverage often turns out to be inappropriate due to a lack of precision in locating spatial elements (data on the scale of the district and not address, for example). Only the Household Travel Survey developed by CERTU (*Centre*

d'études sur les réseaux, les transports et l'urbanisme, the French institute developing knowledge in transport and the urban environment) combines a relatively precise division (housing blocks) and possibilities for refining the routes taken by using models [CER 05] (Figure 6.3).

	Household travel survey	Communes - Mobility	Time table survey	Internal company data
Main theme	Daily trips	Home to Work trips Home to Study trips	Daily activities	Home to factory trips
Sample	2 625 households i.e. 6 157 individuals	Exhaustive	8 186 households i.e. 16 136 individuals	Only workers using transport
From?	Small area unit	Commune	?	Bus Stop
Going to?	Small area unit	Commune	?	Factory
Via?	?	?	?	Bus routes
When?	Every minute	?	Every 10 minutes	Bus schedules
How long?	Every minute	?	Every 10 minutes	Computed

Sources : "Communes-Mobilité" file, RGP, INSEE(1999) - "Enquête Ménage-Déplacement" survey, Certu (2005)
"Enquête Emploi du Temps" survey, INSEE (1998-1999) - Maison du Temps et de la Mobilité (2005)
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Figure 6.3. Comparative summary of trip surveys

Therefore, having a good idea of the land does not necessarily involve using surveys for completing rare available data. However, simultaneously monitoring all inhabitants over an urban area with high spatial and temporal precision is currently proving to be highly complicated, but above all, very expensive. In addition, short of giving each individual a GPS system, it seems somewhat impossible to have precise information on daily individual movements. Recording their successive positions in the city using a satellite positioning system seems like a relatively attractive idea. A certain amount of research and studies has already been led in this direction with, however, a far too small a number of participants. Therefore, although it is technically possible, the question regarding the number of GPS receivers (as many as there are survey participants) forces us to go back to using more traditional paths.

Not having any efficient and generalizable methods at hand for monitoring an entire population in its totality, it is

then vital to restrict the survey to a particular type of trip. In a city where different paces of life coexist in a setting of generalized mobility, within a society which is becoming increasingly more out of sync, particular moments appear unexpectedly which reunite and temporarily resynchronize each individual's schedule. This is the case for certain sporting events, such as a football match, the "most serious triviality in the world" [BRO 98]. The stadium, a meeting place, and an enclosure dedicated to the event, knows the periodical buzzing with excitement within its walls which causes a good number of problems regarding mobility and accessibility. The example used is based on work carried out in the *Maison du Temps et de la Mobilité*, a French Time and Mobility Agency in Belfort, concerning evening activities in association with football meetings [OBE 03], [MAI 03].

	Household travel survey	Bonal Stadium survey
Main topic	Daily trips	Home to Stadium trips
Base population	approximately 300 000 inhabitants	approximately 20 000 spectators
Sample	2 625 households i.e. 6 157 individuals	1 075 spectators
From?	Small area unit	Postal address or commune
Going to?	Small area unit	Stadium
Via?	?	Modeled
When?	every minute	every minute
How long?	every minute	every minute

O. Klein - 2008

Figure 6.4. Comparison between a household travel survey and the football survey

By focusing on the questionnaire and more precisely on the aspect regarding "trips", the collected data gives us places of residence or pre-event activities, departure and arrival times to and from the stadium, the trip modes used,

etc. In fact, this survey is similar to household travel surveys with, however, an additional spatial precision (Figure 6.4). We should point out here that the information regarding routes used by individuals were estimated using survey data via journey algorithms [KLE 07] constructed using the shortest route algorithms proposed by E. Dijkstra [DIJ 59] and R. Floyd [FLO 62].

When the set of data necessary has been collected (or possibly simulated), then it is important to create a data structure which is adapted to later multidimensional analyses and visualizations.

6.2.2. Towards an adapted data structuring

This indisputable structuring stage makes it possible to organize data in such a way that the many requests to do with the different elements making up the structuring step are possible. For the geographer, the suitable tool seems to be the geographical information system (GIS). However, in looking to represent the dynamic world which surrounds us, these systems have to integrate space and time in an adaptive way.

Moreover, where GIS (based on recognized standards) are proving to be tools designed to represent spatial information, the problem is more complicated when it is a matter of structuring data with a temporal dimension. In fact, at least for the moment, GIS are restricted to a far too static vision of information, with a structuring which is exclusively organized around the spatial dimension.

The singularity of the spatio-temporal approach lies in the fact that the handled information is a combination of three dimensions: spatial, temporal, and thematic. It is, then, necessary to replace it with an approach conforming to that proposed by B.A. El-Geresy *et al.* [ELG 02], where any

spatio-temporal object written as O and present in the data base is defined by the theme-space-time triplet, written as $O = \{c,e,t\}$ (c being an instance of the thematic dimension defining the handled object, e as an instance defining its spatial properties, and t as an instance of its temporal properties).

This spatio-temporal object O is therefore positioned in a three-dimensional space-theme-time space, as presented in Figure 6.5.

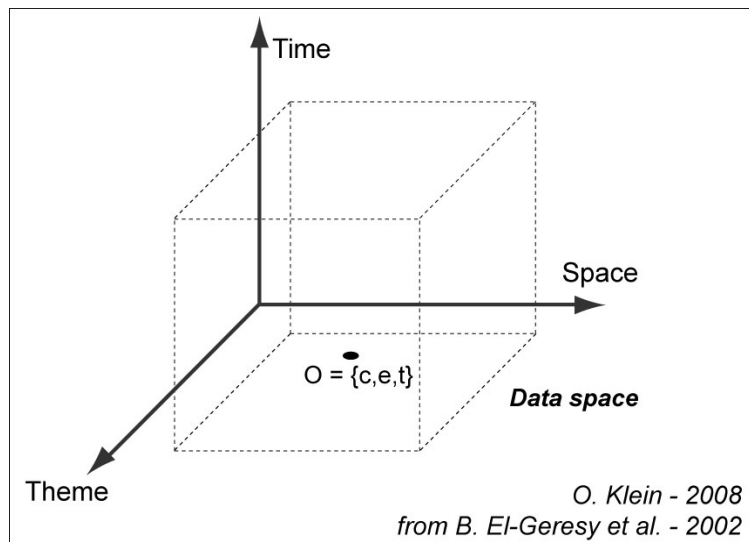


Figure 6.5. Spatio-temporal object positioning in a three-dimensional space

6.2.2.1. Single-based model

Using this more conceptual approach, the simplest spatio-temporal data models are based on one of the elementary dimensions previously identified, in order to use it as a central factor in data organization (Figure 6.6).

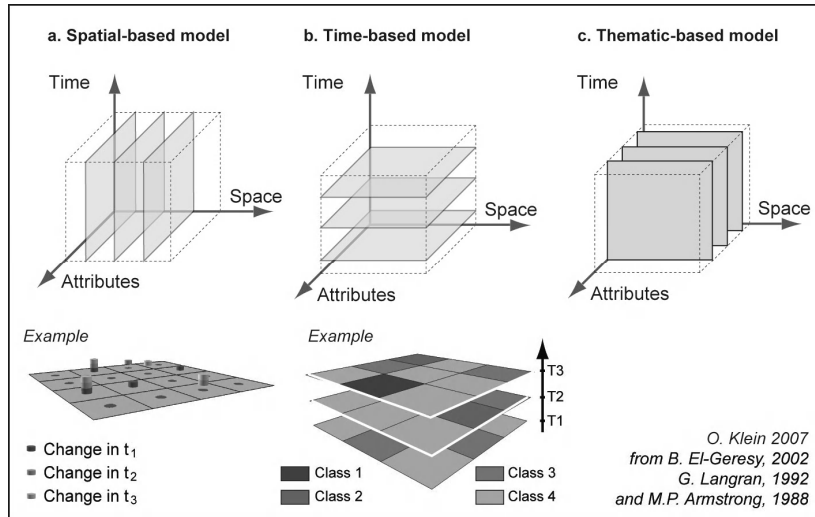


Figure 6.6. Single base data models

6.2.2.1.1. Spatial-based model

In this first instance of single layer structured databases, space is used as an organizational base. Using the conceptual approach developed by B.A. El-Geresy [ELG 02], this model enables us to have a collection of time characteristics along a spatial axis at hand (Figure 6.6a).

This approach is similar to the structuring models that can be found in raster-type GIS, where each grid cell contains a list of changing features. It has the advantage of being able to solve the problem of information redundancy by only storing attributes which change their spatial position (Figure 6.6b). However, keeping such a structuring solution is only appropriate for cases when the spatial elements are relatively stable, meaning that there is little or no modification to the geometry and position of the objects.

6.2.2.1.2. Time-based model

By using time as an organizational base for the data model, then the recordings relate to a collection of space-thematic associations along the time axis (Figure 6.6b); each state or change is collected at a specific time which may be established at either regular or irregular intervals, meaning only when significant changes occur.

We can differentiate three different approaches according to the type of representation for the adopted time:

- the state-based model, or *Snapshot Model* [ARM 88], introduces a state based temporal model, meaning a chronologically ordered series of photographs of land. The structure of an information system is then built as a stack of space-characteristic layers according to time. However, as the information structuring is established according a sequence of states, then information redundancy is very high as only few changes occur. Moreover, the spatio-temporal evolution of objects cannot be controlled due to the absence of possibilities for managing spatial relationships in time;

- the event-based approach, or *Event-based Spatio-Temporal Data Model* (ESTDM) [PEU 95] offers data structures which only store a list of events ordered according to time with the associated changes. The main advantage of this approach then consists of sorting out the problem of the redundancy of irrelevant information when only few changes occur. Obviously, only the temporalities related to the changes are present in the base;

- the processual approach [CLA 95] relates to a particular case of event-based modeling. Returning to the principles of the previous approach, this enriches the concept of change by taking into account the transformations of spatial entities in particular.

6.2.2.1.3. Thematic-based models

The third and last large category of models structured around a single organizational base is theoretically possible according to a thematic base. It is built with a collection of space-time bases, laid out along the thematic axis (Figure 6.6c). This structuring is based on the concept of the object, from identical computer science programming where an object is considered as a representation of a real world entity with specific associated attributes and processes. The information system is then envisaged as a collection of objects defined by different properties, meaning data which describes the state of the object, with a location in our case, a geometrical description and a temporality, which are all associated with operations which describe its behavior. To our knowledge, with this approach being thematic and coming from the computing domain, it does not seem to be applied to the geographical domain.

Definitively, this computing modeling of data organized around a single base has, in each case, the same disadvantages related to the pluridimensional characteristics of data. Therefore, it is essential to develop a model according to a multiple base organizational model, so as not to limit the possibilities for analysis and visualization later on.

6.2.2.2. *Structuring possibilities according to multiple-based organizational structure*

Approaches built upon a multiple based organizational structure are based on the fundamental questions previously dealt with which correspond to the following questions: what? where? and when? Amongst all the multiple-based model, the Triad model [PEU 94] seems the most open and flexible for building a data structure which is organized around the interrelation between the elementary dimensions (Figure 6.7).

This model takes up the elements previously seen, namely space with the location of spatial bodies in two- or three-dimensional space, with time defined along a temporal line and the theme characterized by observed or measured attributes in a particular location and time. In its design, the Triad model allows storage, adapted querying and multidimensional data exploration for researching structures and interdimensional relations. Such structuring also makes it possible to query the database on several levels – not only according to the elementary dimensions but also according to the combination of two dimensions, even by the union of three dimensions in an extreme case (Figure 6.7b).

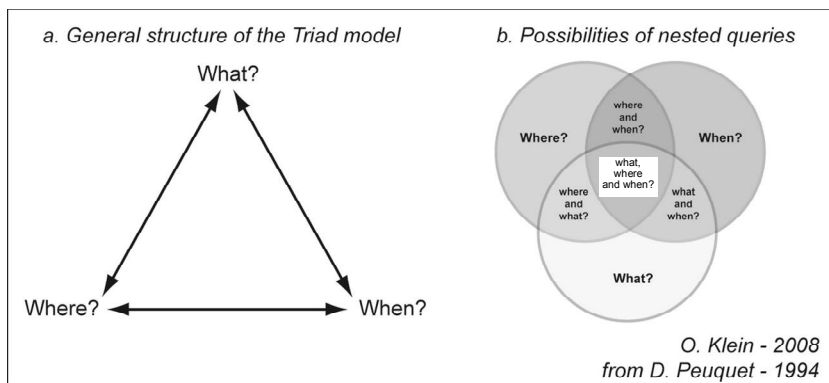


Figure 6.7. Dimensions making up the Triad model structure

The application of this Triad model structures information according to the three organizational dimensions previously defined: spatial, thematic and temporal.

6.2.2.3. *Towards the proposal of a data model*

The information related to a trip is structured according to three organizational bases which we defined previously: spatial, thematic and temporal. In the extract taken from the proposed data model (Figure 6.8), the thematic dimension contains an individual class which groups together the

different information on the profile of the person who is making the trips (age, occupation, level of study, etc.). This class is related to an O-D journey category which describes all the journeys taken, and which includes in particular the trip purposes and the modes used. This journey is spatially defined by an origin and a destination, both located in (x,y) and defined temporally by a departure and arrival time. It is also comprised of elementary sections, each delimited by a transport hub. In a case where the origins and destinations are not connected to the network, then they can be joined by the nearest transport hub. This can be characterized by a journey time, broken down into an arrival and departure time, possibly allowing us to include time for overcoming obstructions (complicated junctions, traffic lights, etc.).

The relations between the other elements are built using the same approach, by distinguishing the different sources of data such as HTS (household travel surveys), mobility-commune data from INSEE, or data taken from surveys conducted in a specific way.

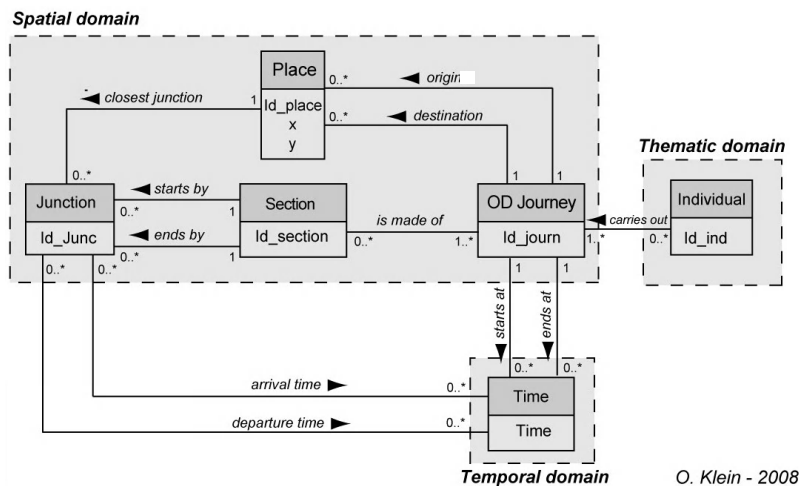
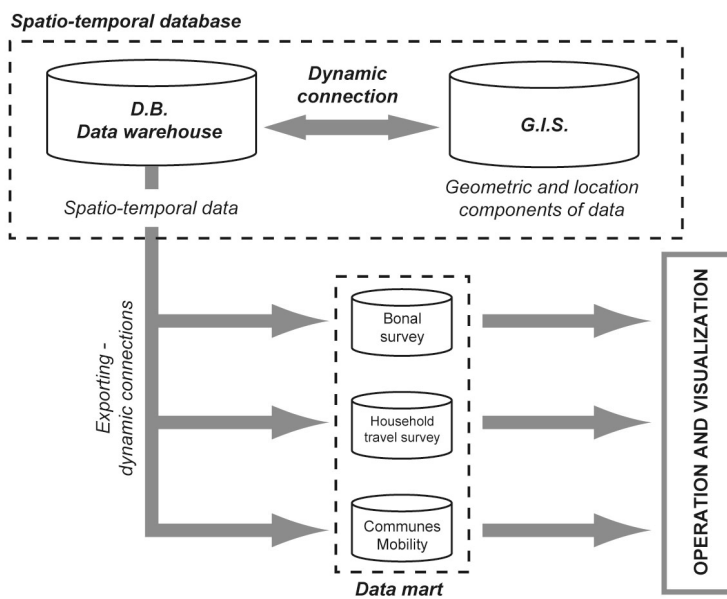


Figure 6.8. Proposal for a simplified conceptual data model

6.2.2.4. General structure of the information system

The spatio-temporal data model we proposed is implemented in both a GIS and a DBMS (Database Management System). The GIS integrates the geometric component and the spatial dimension of data, whereas the DBMS manage the rest of the information (Figure 6.9).



O. Klein - 2008

Figure 6.9. Organizational principles of the DBMS

Technically, the link between the DBMS and the GIS has been made possible by an OLE link (*Object Linking Embedding*) and an ODBC connection (*Open Database Connectivity*), which are two functions specific to Microsoft Windows. As the consequences of such a structure, the processing stage can be conducted indifferently, interfacing from the GIS towards an DBMS, or from a DBMS towards the GIS.

The system currently in place may be paired with a visualization interface in order to appropriately restore the information stored in the base.

6.3. Classic limited cartographical approaches

Integrating time into representations is the main challenge for the changes in cartography, because their format is, traditionally, 2D and still is. However, some solutions have been brought to classical cartography, particularly in semiotics and in time geography as well as in the approach developed by W. Tobler.

6.3.1. *Limited classic semiotics*

Semiotics may be defined as a set of rules which allow the use of a graphic sign system for transmitting information [BEG 94]. It is an element of the communication process which is based on visual apprehension.

6.3.1.1. *Classic Bertin approach*

In his approach, J. Bertin [BER 67] [BER 05] considers visual perception to be made up of three sensitive variables: variation in perception functions and the two dimensions of the plane, all of which are not in relation to time. As a consequence, we may query the possibilities of representing time, whereas visual perception systems are atemporal. Moreover, if we decide to introduce a temporal component, then this will be to the detriment of another component. Therefore, by simply crossing time with another dimension, we can obtain a chronological (aspatial) diagram [MON 90]. At all costs, by connecting the two spatial dimensions to the temporal dimension, the representation over a planar and still surface limits representation possibilities, even if J. Bertin proposes a few solutions for this.

Firstly, building a series of images means that we can break down time (Figure 6.10a). Alone, this series is greatly restricted by the number of easily acquired images during the reading process. A long series over the spatio-temporal activities supplied in an urban environment would need 24 maps with a time split of equal extended time. Highlighting the general trends in the simultaneous reading of these 24 images does not seem very probable.

Secondly, in order to comprehend changes in location through time, J. Bertin proposes that we represent the route and direction of moving bodies (Figure 6.10b). This alternative suggests continuous movement (or continuous per sequence) by plotting the body which is moving. Even if the plots move in a direction, a too high number of moving bodies associated with complex movements compromise the readability of the resulting image.

Thirdly, he proposes that we use a three-dimensional visual variable by dividing the time component into ordered categories which are represented by the plateaus of an ordered retinal variable (Figure 6.10c). These retinal variables are relatively short, and only a small number of categories can be represented, which greatly limits the possibilities of representation.

Finally, the arrow, a directional marker from a point, is often considered to be the most efficient formula in order to represent the complex movement of a moving body. However, as before, multiplying arrows and their entanglement may cause problems for the final reading of the document. However, this static representation has a high dynamic and symbolic connotation which is rooted in several cultures, which in spite of everything, give it a high visual impact.

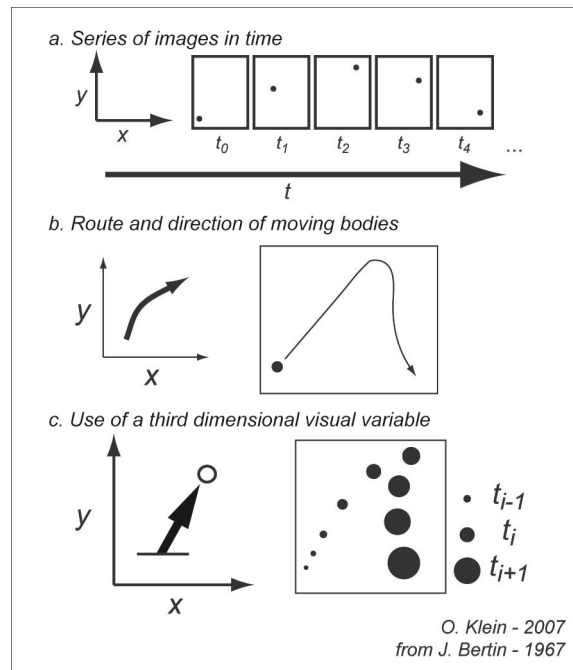


Figure 6.10. A few examples showing the adaptation to change of semiotics

In spite of these attractive proposals, the options formulated by J. Bertin regarding the representation of changes often turn out to be unsuitable, mainly when there is too high a number of moving elements. The main problem of the semiology of graphics of changes stems from the double difficult which consists of instantaneously perceiving changes, and of restoring their dynamic on a static support.

6.3.1.2. Vasiliev approach

In the continued works initiated by J. Bertin [BER 65], other possibilities for representing time have been put forward. I. R. Vasiliev [VAS 96], [VAS 97] proposes a summary, partially based on research led by M. L. Hsu [HSU 78] and J. K. Wright [WRI 48], with several different

categories of time using a symbolization depending on the geometric implantation of data.






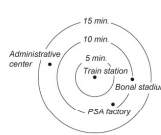

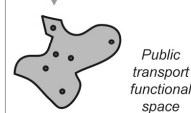
Time is divided into five categories built from a series of questions which highlight the way in which geographers and cartographers include it in their analyses.

“Is it time which has an advantage, or is it the duration of the event?”, “Does time organize space?”, “Is time used as a distance measurement or does space show temporal relations?” By formulating these questions, we can differentiate five time categories:

- *Moments*, simple instances (dating back to the events) represented as zero-dimensional punctual elements at the core of a unidimensional temporal referential number;
- *Durations*, one-dimensional linear elements expressing intervals, meaning the temporal continuity of an event;
- *Structuring time*, reflecting spatio-temporal frequencies as sequences, ordered events or space organized by time;
- *Time as distance*, measurement of distance according to spatialized time intervals and distances associated with temporal distances;
- *Space as a clock*, considers space as a measurement of time. For example, a time zone representing a portion of Earth space where time is identical in every respect.

In a similar way to the measurement levels, these temporal categories may be assimilated to a kind of implantation (punctual, linear, areal) in order to show all the possibilities in terms of graphical expression.

Despite the original and well adapted proposals, in some cases the high temporal variability and large amount of information which needs to be charted are forced to explore other channels to try to represent daily space-time.

Category	Geometric dimensions		
	Point	Line	Area
Moments Events dates	● June 2007 Opening of the high speed train station in Lorraine	June 2007 High speed East line put into service	Flooding of the Savoureuse river 2005 
Durations Events continuity	Station not served from 25 th to 29 th December 2006 ● Bus stations for the route 12 9:45 ● 9:56 ● 10:02 ●	German attack on Douaumont, 21th to 25 th February 1916  9:45 ● 9:56 ● 10:02 ● Bus route 12 (stops and connections)	North PSA car park use from Thursday to Saturday 
Structuring time Frequency Standard time	Opening days for ticket office at Sochaux FC ● Monday ● Tuesday ● Wednesday  Central time zone UTC	Frequency of 3 bus lines  — once a week — twice a week — daily	
Time as distance Time interval Temporal direction and/or distance	Temporal locations of places from the train station 	Time-distance by train Mulhouse 1:23 0:57 Strasbourg	Geographic reference space  Public transport functional space 
Space as Clock	East: sunrise West: sunset		Time zones

O. Klein - 2007
 from C. Cauvin 2005, O. Klein 2000 and I. Vasiliev - 1996

Figure 6.11. Time and semiotics, classification proposal

Figure 6.11, grouping together the many possibilities for graphical expression according to implantation and the category of time, very quickly shows us the limitations of semiotics in a two-dimensional format.

Thus, the high temporal variabilities and the large amount of data to be charted strive to explore other channels in order to represent daily space-time.

6.3.2. *Relatively old innovations*

Other relatively old approaches propose less conventional forms of cartography which were developed mainly by T. Hägerstrand and W. Tobler.

6.3.2.1. *Time geography*

Time geography is integrated into the description of daily activities simultaneously in space and time on an individual scale. Although this old approach driven by T. Hägerstrand [HAG 70] has seen its importance dwindle over time, it has been sparking an interest during these last ten years, which can be partially explained by the progress of computer data processing.

From a conceptual point of view, this research is applied to various domains, concerning spatio-temporal practices in public spaces [CHA 99], as well as public transport [MIL 91], and highlighting gender disparities [KWA 98], [KWA 00], [KWA 02]. This can also be seen from a methodological point of view, for example by integrating the principles of dynamic segmentation taken from GIS [MCB 02].

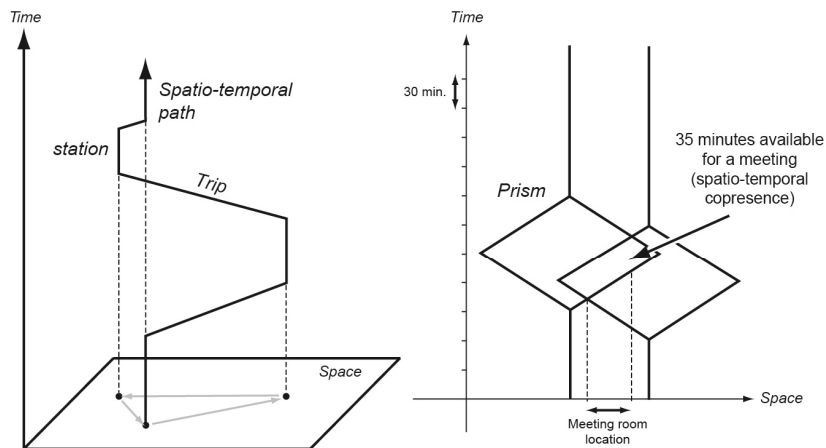
The major interest in this approach is to provide an interpretation of spatio-temporal processes by offering the possibility of drawing and considering movements in space and time.

This approach uses a graphic language which is part of a three-dimensional space, which is comprised of two spatial dimensions connected with one temporal dimension. This is comprised of three elementary primitives [MCB 02], [YU 06] (Figure 6.12):

– a spatio-temporal trajectory, representing the spatial positions of an object over a period of time (consecutive positions of an individual over a given period of time in a defined environment). It transmits an explicit spatio-temporal representation of the activities and trips made by an individual. Thus, the diagonal lines symbolize trips and their gradients represent their speed; the vertical lines indicate no movement in one place over a certain period of time;

– a station representing an object’s fixed position in space over a period of time;

– a spatio-temporal prism, representing a time budget which characterizes the space-time of the possibilities of carrying out an activity. The geometric shape makes it possible to visualize the spatio-temporal area which is potentially accessible according to a given transport mode and available time (function of the starting and arrival point as well as speed).



O. Klein - 2008
 from H. Yu, S.L. Shaw - 2005 and T. Hägerstrand - 1970

Figure 6.12. Elementary primitives taken from time geography

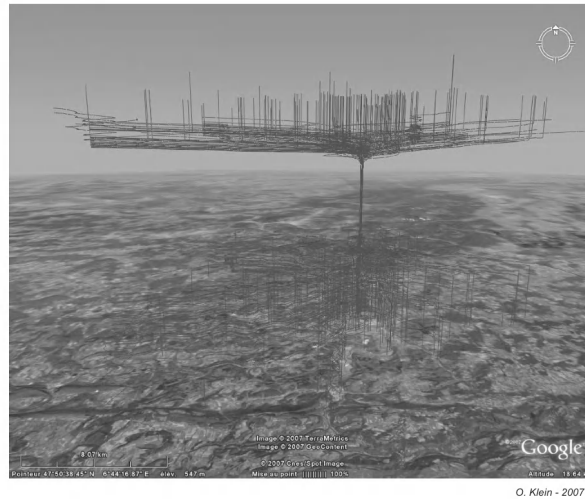


Figure 6.13. *Spatio-temporal routes for nearly 400 individuals going to Bonal stadium for a football match*

This solution for a cartographical representation of daily movement is cartographically relevant when we limit ourselves to a restricted number of individuals representing the total population. S. Chardonnel [CHA 99] refers to a readability threshold fixed to 20 individuals within the framework of its application. Nonetheless, this is highly dependent on the spatio-temporal configuration studied. Thus, in the framework of trips made linked to a football match [KLE 07], nearly 400 spatio-temporal routes are represented in order to highlight synchronization, and to draw out the spatial and spatio-temporal trends with regard to this single image (Figure 6.13). We must point out that the trajectories both before and after the event are still difficult to interpret.

6.3.2.2. *W. Tobler approach*

Trip representation is often implicitly associated with the cartography of flow patterns for studying population migration. These flows take up a large domain in

cartography with very varied content, but they still represent quantitative information: a quantity which has moved or been transmitted between two points.

Yet, this cartography of flow patterns still raises a good number of problems today. Generally and without exception, graphic solutions boil down to variations in the thickness of the line according to the amount of movement. Moreover, in spite of its considerable importance, the question of flow is relatively little written about in works on general cartography, and only has a limited place in relation to the more usual forms of cartography. Generally, only the variations in thickness by proportional bands are dealt with. In this vein, W. Tobler is an exception, with research aiming to propose more original but relatively unknown models and representations.

Flows and quantities in motion may appear on maps in all directions. Thus, because of a disturbance [RIM 73] caused by weaker flows, map reading may be made more difficult and some information should be removed in order to guarantee a more communicative image. In fact, flow maps become unreadable when the number of origin-destinations gets too high. As a general rule, the threshold is located below the exchange matrix of 10×10 , given that the amount of potential movements increases according to a quadratic function of the number of connected places. Thus, for n places, there are $n(n-1)$ oriented links and $n(n-1)/2$ non-oriented links. It is necessary to process the information using a selection of relevant information, because representing each flow is impossible and even pointless; at most, it may be problematic for reading the map [CAU 89]. It is very important to limit the amount of information contained in the document to just the quantity which can be easily processed when reading and to avoid any superfluous information.

Faced with such difficulties, the stance taken by some cartographers is to remove the element of flow movement. Consequentially, they prefer to change the implantation, going from the linear to arealizing choropleth maps. This new implantation assumes data aggregation by only representing the sums on the exchange matrix margins. For intercommunal migration between home and work, this boils down to charting the total number of those coming in and those leaving, or the sum [entering + leaving] for each district. As a consequence, the map's signification changes from a representation of interzonal movements, to the cartography of an index which summarizes these movements.

In his research in the mid-1970s, W. Tobler tackles the question of flows and their representation, due to their role in the geographical mechanisms of change. A first software which has recently been adapted to current systems and which was initially developed by W. Tobler [TOB 79] has made it possible to conduct a number of tests, in part querying standard semiotic rules. In his work on flows, the main objective is to get a representation of migratory flows whilst keeping their geometric implementation, direction and volume in order to respond to various applications. His proposals are split into two groups: descriptive representations on the one hand, and modeling on the other.

6.3.2.2.1. A simple solution: selecting information

In the first category, we are mainly interested in the flow components in order to better adapt their representation. The first proposition put forward directly by W. Tobler consists of reducing the number of flows in response to the problems of superfluous information mentioned previously (Figure 6.14).

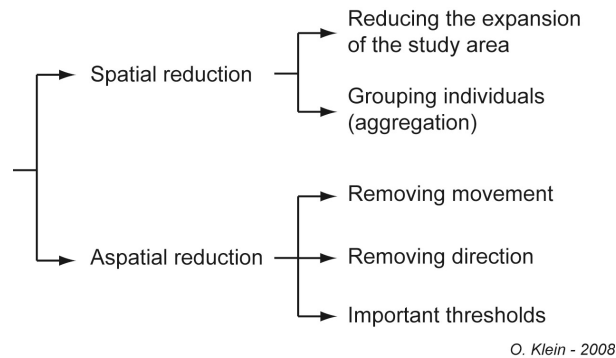


Figure 6.14. *Possibilities for reducing information*

In order to reduce the exchange matrix, we may act upon the spatial dimension of these representations by reducing the number of origins-destinations, either by reducing the study zone, or by grouping these places together (for example, going from intercommunal migration for the 36,000 French communes to interregional migration). Reducing the information may also be done thematically. Firstly, we may delete the movement component as seen previously, then proceed by removing direction, followed by no longer working on total or net movement between two places, or only using significant thresholds and removing the least important flows. For W. Tobler, the best threshold for the value choices to be represented is the average flow size.

This simple data selection rule may extend to 80% of flows, and keeping 20% of the flow volume. However, if small flows are not essential on an individual level, then their global consideration affects a network's life by contributing in particular to excess traffic and network saturation. Despite the reduced amount of information, there may still be difficulties in reading the map, particularly due to superimposed symbols. In addition, by using the flow components, there are many graphic options available. It is then vital to respect rules of both syntax and perception.

Proposals have been put forward by C. Cauvin and H. Reymond [CAU 89], based on W. Tobler's works. Respecting these rules is essential for guaranteeing a better level of readability for the final map. But W. Tobler explored another more open way.

6.3.2.2.2. Modeling: from a flow map to a vector field

Amongst the solutions for reducing information, W. Tobler proposes a series of them based on the mathematical principles of vector calculation [TOB 75], [TOB 76], [TOB 78]. An initial type of map is comprised of isolated vectors [TOB 75] where the flows represented previously are compared to average vectors whose norm is equal to the mean of the flows leaving from each place (Figure 6.15a). The coordinates for each vector are obtained from M_{ij} , the quantity in motion between places i and j with respective positions (X_i, Y_i) and (X_j, Y_j) , such as:

$$\vec{V}_i = \frac{1}{n-1} \sum_{\substack{j=1 \\ j \neq i}}^m \frac{M_{ij} - M_{ji}}{M_{ij} + M_{ji}} \times \frac{1}{d_{ij}} \times [(X_j - X_i), (Y_j - Y_i)] \quad [6.1]$$

with: $d_{ij}^2 = (x_j - x_i)^2 + (y_j - y_i)^2$.

Vector v_i has (X_i, Y_i) for its origin, on the scale of the final map [TOB 75].

The given result goes beyond a simple sum on the exchange matrix margins, as the information on the map for each place not only has the total flow, but also its average direction.

If the phenomenon represented here may be considered as being spatially continuous using this first proposition, and if point values which are unknown in the same space may be determined using the values known in some points, then interpolation is possible.

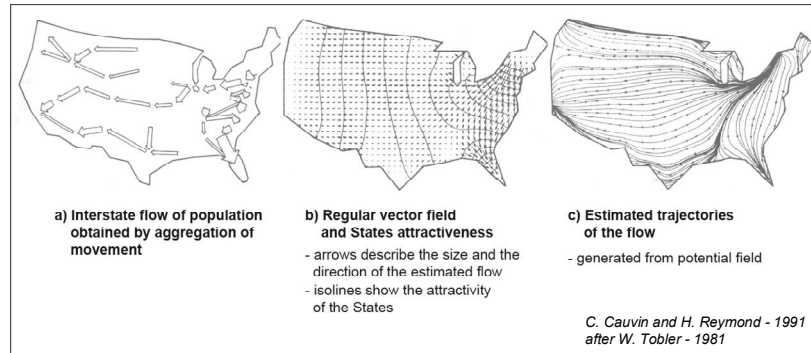


Figure 6.15. *Movement modeling and representation by W. Tobler*

This transformation ensures the transition from a map with isolated vectors to a regular vector field whose points of origin are distributed over the entire zone studied. Interpolation gives a vector field which indicates the direction and magnitude of the movement in each node from a regular grid covering the surface area (Figure 6.15b). We can combine an isopleth map of the activities which represent the scalar potentials which induce the movement.

In this isolinear representation, the model proposed by W. Tobler makes it possible to estimate net flows according to attractiveness levels (calculated using the differences between the marginal frequencies in an exchange table). Attractiveness, expressing the potential which triggers movement, is assessed either by a matrix calculation or using the Poisson equation, according to whether the model has a discrete or continuous formulation [CAU 91]. The data obtained by interpolation in a node of the regular grid may also be represented by continuous oriented lines (Figure 6.15c).

Ultimately, the global approach proposed by W. Tobler is rich in terms of cartographic propositions and solutions (Figure 6.16c). These are varied in their nature and

complexities, and they are aimed at different societies which distinguish illustrations from models in particular.

Despite the relevance of the results offered by W. Tobler, their contribution to the cartography of daily movement remains limited. This is because, on the one hand, by their very construction these models are intended more for definitive or more long-term migrations. On the other hand, they only offer partial solutions for studying individual, daily trajectories.

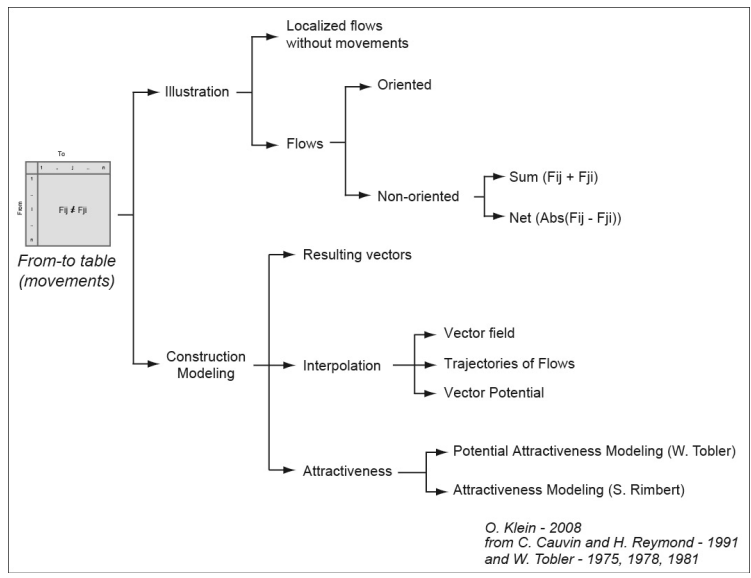


Figure 6.16. Main propositions by W. Tobler

6.4. An answer by geovisualization

Following the example of W. Tobler or D. R. F. Taylor [TAY 83], we have kept a type of reasoning and communication centered on the image, in relation to other approaches: “seeing” and “understanding” are based on the idea that cartographic or spatialized representations are essential to any geographical problem. Maps (and more

generally, spatial representations) are considered as important geographical research tools. The possibilities of classically representing spatial dynamics are very limited, insofar as being reduced to static maps. Therefore, this leads to large problems, particularly for representing daily movement.

In order to better understand the dynamics of a land, it is vital to see it move and evolve through time. This could be either in a continuous way (or continuous by sequences), using a recording of real life reproduced at a later stage, or in a discontinuous way at regular or irregular intervals. In order to satisfy this need, the process used up until now must be improved by representation techniques using animation, which have been made possible due to the progress in computer science and by taking into account the repercussions that these techniques could lead to.

In fact, the progress made in ICT has not only drastically changed the practice of cartography, but also the way in which we understand this discipline. This progress is endlessly throwing out new challenges, offering new possibilities which are apparently limitless on the technological front, thanks to the ease of developing maps and speeding up creation time. These improvements simultaneously lead to a democratization of cartography. But if the fact of being opened up to a wide public is a positive asset, on the other hand it is often accompanied by a misuse of software and not respecting the basic rules of cartography [MUL 83]. Maps run the risk of losing their relevance because they are no longer being created correctly. The new abilities of image production unfortunately trigger an expansion (often hardly structured) in cartographic production which transgress the most elementary rules of readability [CHE 88].

If the computer makes it easier to handle a large amount of data, then it also makes it possible to simply produce

several versions of the same map, with varied layouts, scales and shapes, on permanent or temporary mediums, which is essential for this type of research [TAY 80]. These multiple displays of the same set of data not only help to highlight certain aspects of the data, but also to adapt this representation to the intended public. However, computer usage brings the map closer to multimedia tools by facilitating the direct representation of movement and its immediate variation according to different views. It allows the user to interact with the map or the combination of maps with graphics, text and sounds [MAC 92].

In this quest to represent movement, animation is one of the newest modes of display with the development of ICT systems, which offers interesting alternatives to the semiotics. In fact, animation rejects the frozen frame which biases the representation we have of the world we live in which is constantly evolving. It improves the frozen image which can only contribute one photograph at a time t , where only the states and results of a process will appear, and the processes themselves are invisible.

6.4.1. The paradigm of scientific visualization

When faced with a large amount of data, using computers alone is simply not enough. Although the machine can operate quicker, the user's speed of interpreting the results remains constant. The only way of understanding the enormous amount of information is, then, visual representation by means of a variety of views and displays to give a better interpretation of the phenomena which occur. Moreover, other approaches such as scientific visualization should be favored.

Scientific visualization, often initially associated with information technology, is considered as a way of gaining understanding, based on a graphical exploration of the data.

This graphic process, similar to digital data analysis, is much more than just a simple representation. In fact, the willingness to understand and explain processes, and not just to reproduce them, is a part of scientific visualization. It can be defined as the “use of information technology to create visual displays, with the aim being to facilitate thinking about and solving problems” [MCC 87].

Using these visual tools means that we can help scientists in the exploration of their data and the development of their hypotheses [MAC 92] by directly interacting with visual displays. In fact, and very often, the sets of data which need to be analyzed are very important, and it is relatively difficult to extract relationships or structures. This technological contribution is vital in the research process as a revealer tool. For example, with an interactive data visualization, the researcher may visually manipulate his/her set of data and modify it dynamically during calculations in order to see the consequences of certain parameters. Instant visual feedback also helps him/her to better understand and even detect anomalies and distinctive features.

From this paradigm (an understanding made easier by sight), visualization may be transferred onto spatialized data, thus introducing the concept of geovisualization. This refers to all the tools and techniques which make it possible to solve geographic problems by using current technology. It gives it the role of a revealer, in a way which underlying spatial structures which are hardly visible or entirely invisible can be identified directly and considered in analyses. This procedure, based on new forms of spatio-temporal representations, has been made possible thanks to the many choices of technology today, like the use of animation and interactivity which also form another way of communicating information better.

Geovisualization (Figure 6.17) extends from the initial processing of data, just after the data has been collected, to verifying the previously stated hypotheses. The many possibilities of interaction, combined with the feedback during the graphic displays, make it possible to act on the processing, modeling, and representation in order to manipulate the sets of data and to conclude the examination process.

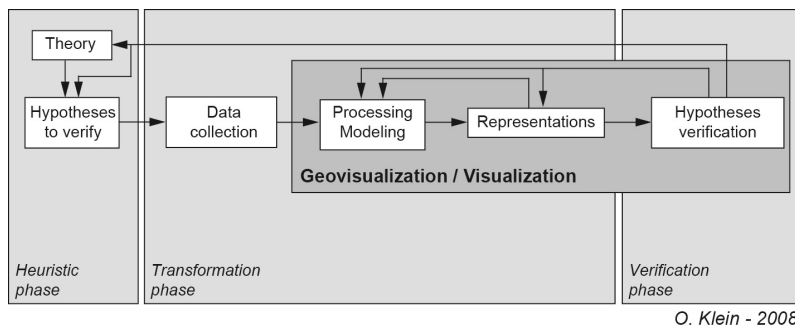


Figure 6.17. *Place of (geo)visualization in the cartographic process*

By looking to visualize daily mobility, the main challenge resides in the willingness to present movement, not in a static way, but in a dynamic and highly interactive way. Putting this computerized environment into place enables us to answer the following questions [OPE 94]:

- What is happening?
- Is there something interesting?
- Where and when will something interesting happen?

In order to go a bit further and to propose some alternatives to the current situation, we can add another question to these previous ones: “what will happen if?” Putting this approach into action requires a greatly interactive environment, combining multiple sources of data, and being relatively easy to use.

6.4.2. Adapting cartography to multiple potentialities

With classic approaches being unsatisfactory, then many proposals for representations are presented, integrating in particular 3D, animation techniques, interactivity and the possibilities of multiscalar visualization.

6.4.2.1. 3D for highlighting and better perception

The first solution contemplated in order to solve this problem consists of subjecting the flows to a transformation into a dimension other than the (XY) plane, namely the Z plane.

This third dimension makes it possible to transform linear elements which symbolize changes in a volume, thus using height Z as a visual variable which is equivalent to the size (Figure 6.18).

Problems regarding too much data and inadequate discretizations may be solved. In three dimensions, the discretization step can be rather easily set aside, as the variables are then represented in volumes, without categories, with a height which is proportional to their thematic value, in a continuous way (and not discrete). For all this, the data properties are retained: the order of magnitude, the distribution, dispersion, and particular cases associated with the variable remain readable on the map. In order to keep an overall view, integrating 3D brings an interesting and suitable alternative. Where all the information is stored on the map, extruding flows according to their level of importance means that we can introduce a contrast between the most important and the least important values. By adding navigation possibilities, such representations means that we can move in virtual space in order to focus on a specific area or particular point to be developed in a study.

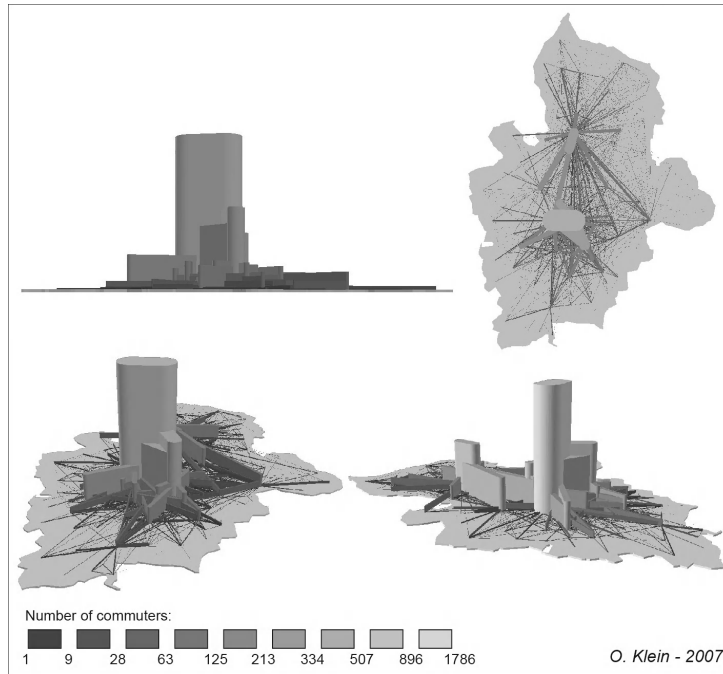


Figure 6.18. *Geovisualization and cartographic process (for color version see www.iste.co.uk/banos/GIS.zip)*

6.4.2.2. A technical solution: animation

Limiting observations to a static temporal series considerably reduces the chance of discovering and identifying processes, which is more often than not the luck of the draw [OPE 94] and led by the researcher's guidance.

Clearly, to optimize daily mobility investigations, the classic approach (classic, graphic maps) must be completed using new forms of interactive and animated cartography which reveal underlying spatial structures which are not directly visible. These forms make it possible to both perceive and transmit information better, meaning that we can ensure the transition from an exploratory dimension to an adapted form of communication [ANT 03].

The introduction of animation has several implications for cartography. Firstly, the user's relationship with the map may be modified by the change in representation format, moving away from the classic sheet of paper to a computer screen. Consequentially, the map is becoming virtual [MOE 80], [MUL 02]: visible on a screen (visible and non-tangible), stored in digital formats (tangible and non-visible) and available on the internet (non visible and non-tangible). Using animation involves adding new visual variables, integrating new interactive functionalities, a transformation towards cartography using multimedia resources and a modified form of communication.

Using a new type of format (screen) and new kind of information communication (animation) brings about an evolution and changes the rules of semiotics. The visual variables which are becoming wholly multimedia based are improved. In fact, by moving away from a static cartography to an animated one, then dynamic variables can be added to J. Bertin's "static" visual variables [DIB 92], [PET 94], [MAC 94]:

- duration, a period of time which runs, in relation to a phenomenon between two observed limits;
- rate of change, relationship between the magnitude of the change and the duration of each scene;
- order, sequence where the basic elements are presented.

Some authors add other, secondary variables, which derive from these three main variables. The display date which defines the point in time from which the changes appear in the animation. The phase, considered as a sub-variable of the rate of change which expresses the regular repetition and the rhythm of certain events, is used in order to look for the temporal connection between many temporal series. The frequency expresses the number of states per time unit.

Although a change in the displayed data, without any outside interference, remains an animation, the addition of potential actions for the user changes this animation into an exploration tool [SLO 99], which is the main interest in this type of representation.

6.4.2.3. *An essential constraint: interactivity*

Interactivity is an added value, impossible to circumvent, for animated cartography, without which the usage potentialities would be too limited. This possibility of interacting with a map (a major advancement in computer cartography) has serious repercussions for the links between geographic databases and GIS, as well as for the most recent forms of cartography, whether they are multimedia forms or pervasive (omnipresent) as with the Internet. Interactivity is often associated with an error in recent technology; it has existed for a long time, even before these computer processing innovations. In fact, it can be found in all forms of exchange communications, including feedback or collaboration processes, and thus naturally opposes one way communication.

Consequentially, it may be considered as being inherent to the very basis of the map concept [PET 98]; each map is designed according to its capacity to communicate and therefore its interactivity between at least two individuals, the map author and reader.

Today this minimalist interaction is very outdated and conveys a strong technological connotation, which expresses an explicit dialog between a computerized system and a user. Therefore, it may be defined as an activity which requires the cooperation of several beings or systems which act together by adjusting their behavior according to a final goal. Within the context of communication via a computerized map, interactivity refers to both a reciprocal activity and a two directional electronic communication (Figure 6.19).

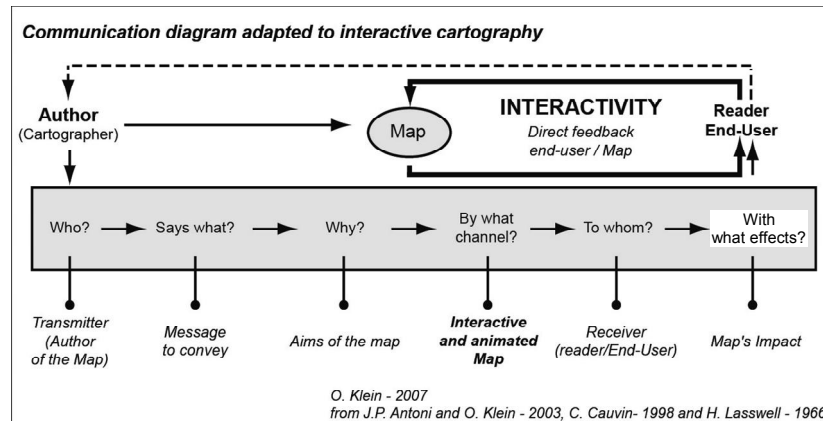


Figure 6.19. Consideration of interactivity in the communication scheme

Moreover, interactivity may be perceived as such: a process which focuses on the exchanges and capacities of responses using a set of devices and made possible by multimedia characteristics and by the experience gained by the user of such a device [MCM 02]. In this context, possibilities of interaction are brought back to the level of a device where a communicator and an audience may interact in order to facilitate communication needs. For a good interaction between a person and a map, specific devices (software and hardware) must be used, and the quality of the result depends on six major components: user control, the device's response capacity, its personalization, its handling ability, its interconnection possibilities and its reactivity.

By using these components which characterize interactivity, then different levels of interactivity can be defined in cartography (Figure 6.20), by going from the traditional static map with an interactivity level of nearly zero, to a single, universal and totally interactive map (going to the extreme and in an ideal world). Such a map could fulfill any demand, in a personalized way and in real time; a

kind of virtual globe explorer, combined with a spatialized search engine. This is what the Google organization is researching with its product, GoogleEarth.

Between these two extremes, we can create all the possible stages of animation: simple animated maps with temporal controls over reading sequences, interactive maps with predesigned scenarios where the possibilities of interacting with the map are limited and predefined by the author, etc.

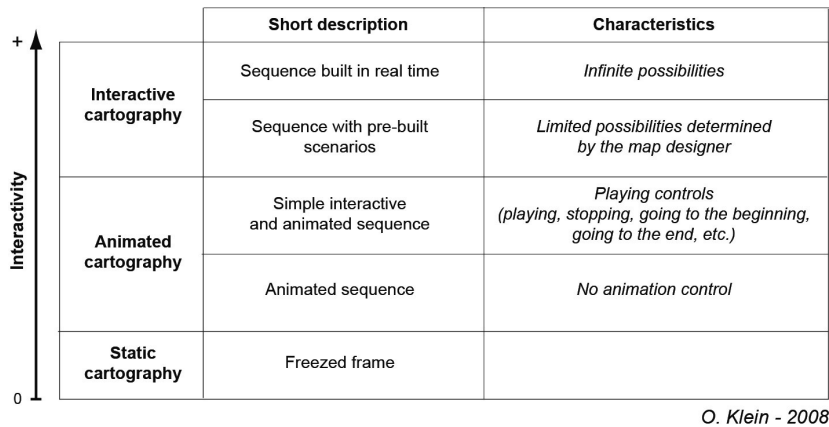


Figure 6.20. *Cartography and interactivity levels*

Consequentially, the interactive animated map may be implemented in two distinct ways:

- firstly, by simply accumulating pre-built maps which are stored in the computer’s memory, whose sequential display depends on the user’s demand;
- secondly, by a specifically developed program which designs maps in real time and displays them in an adaptive way under user control.

Thus, animation takes its shape on maps by using a certain number of manipulations, made possible by

techniques which can be put into three main categories: navigation, query, and exploration. Navigation groups together relatively basic functions like, on the one hand, panning, zooming or rotation in spatial elements of animation. On the other hand, it brings the ability to stop, read, speed up or slow down for the temporal aspect. Querying consists of using information search and request tools in order to obtain database results. Exploration is the most complex form of interaction, where selections and combinations of data coexist, for a display as graphics and/or maps.

With added interactivity, a computer makes it possible to achieve what other technologies did not know how to do: creating a dialog between the map and the user. This digital interactive property dramatically changes relationships with the map, and transforms this document into a topic of conversation, both adding to and participating in the conversation. Through his/her navigation in this world of interlinked maps, the map reader/user becomes a true “maponaute” (map-user).

The last element to be described is the legend, whose role has increased thanks to new functions which have been made possible by interactivity. As with all maps, an animated map requires, in fact, a key whose function is to identify the map's authentication (element that defines all the symbols on the map). But when the map becomes (inter)active, the legend has to provide a double role: a role which controls the sequence display, and one which provides information on the image content [PET 99]. In temporal animations, this new role involves dynamically controlling the animation by indicating its temporal progression, and in addition, by making it possible to navigate the map [KRA 97].

In reality, interactivity associated with animation offers a solution to the problem of an overabundance of information

(Figure 6.21). By using the example of intercommunal daily home-based work trips in the urban area of Belfort-Montbéliard, these trips are concentrated into 6,335 flows. The cartographer looking to build a suitable representation is led to question the quantity of information which should be transferred to the map.

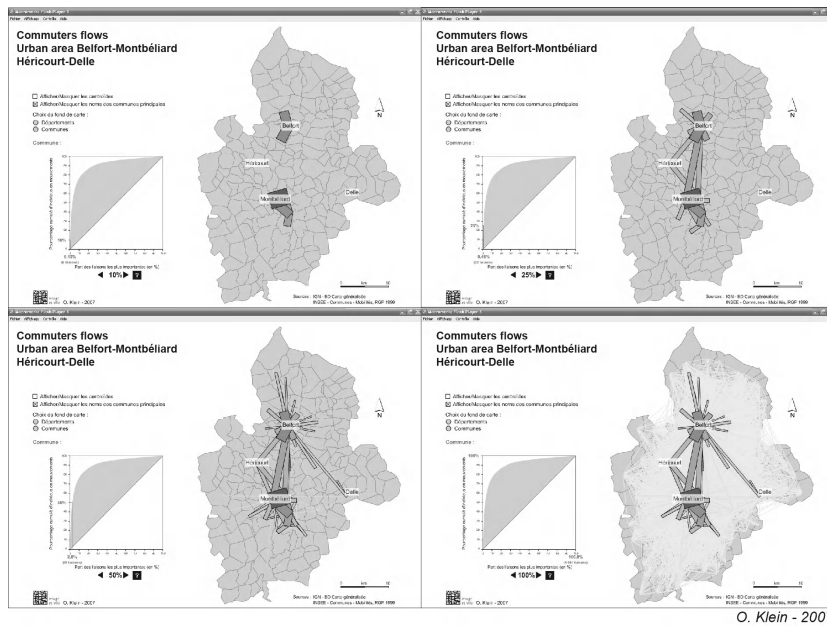


Figure 6.21. Interactivity: a solution for choosing the data to display

This choice may inopportunately bias the message to be conveyed. By building the Lorenz curve (see the map legend in Figure 6.21) which brings together the share of most important connections with the cumulated share of individuals in motion, then a large disparity in the flow weight may be observed. The Gini index which is close to 0.8 confirms this unbalanced distribution of motion. Rather than *a priori* reducing the information, here interactive animation offers the chance of giving the choice of the amount of

information to be displayed to the user. It can, for example, be limited to representing 2% of the connections whose weight corresponds to 50% of daily trips. But, by giving the reader the freedom to choose the quantity of information to display, the cartographer gives him/her the responsibility of keeping the right solution, taking into account his/her thematic knowledge to carry out his/her analyses.

6.4.2.4. *Towards multiscalar visualizations*

Creating animations on daily trips for our example relating to the urban area Belfort-Montbéliard is based on different techniques with an image by image display, automatically generated by a GIS database and a display which has been generated dynamically with a process similar to animations by algorithms. However, for practical reasons (rather long calculation time), the results corresponding to the algorithm are precalculated and stored outside the visualization interface. This interface provides access to the results which are precalculated and stored in the database, using consecutive requests (at regular time steps). This makes it possible to generate the information contained on the map (Figure 6.22) via a dynamic link towards the DBMS (ODBC link).

Developing animation and interactivity techniques and combining them into our procedure for understanding daily movement is not enough. It is necessary to include them into a more global process of examining data, in order to try to reveal unknown elements: trends, spatial and spatio-temporal shapes. Thus, there are three objectives to the procedure:

- identifying spatial shapes at a moment in time;
- comparing spatial shapes to different moments in order to identify and quantify variations and evolution in time;
- identifying spatio-temporal shapes over a period of time.

To do this, it is vital to have a highly interactive computerized environment at hand, in order to better fulfill exploration requirements with links towards other views of the same data (multiple display), and different modes of representation combined with tables and graphics.

This data exploration includes several stages, such as input data processing, variations of symbology, view-point changes, valorizing a proportion of the data, using multiple views, animation techniques, combined with other forms of displays (tables, graphics, etc.) [SLO 99], or even the automatic interpretation of maps with principles taken from *Data Mining*.

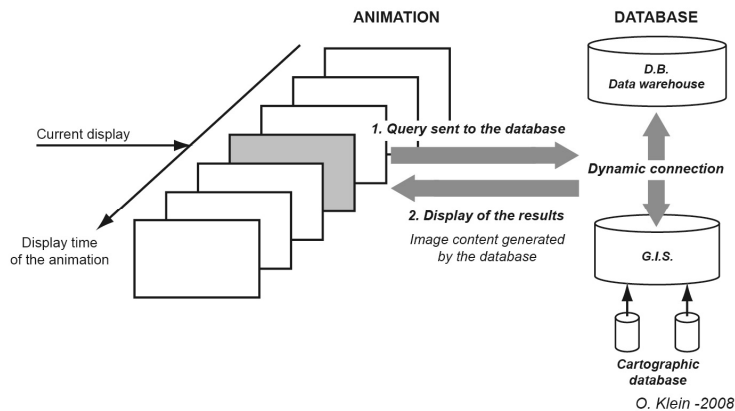


Figure 6.22. *Theoretical architecture for building an animation image by image*

6.4.2.4.1. From the visualization of individual journeys...

Each moving individual is reduced to a zero-dimensional point, defined by its coordinates (xt; yt; zt) over a given period which is characterized by variable t.

As a consequence, in a 3D space E, the set of trips made by each individual can be analyzed as a series of scattered points evolving in time.

However, we still have some questions (Figure 6.23) regarding the behavior of certain groups in the studied area's spatio-temporal environment, in order to acquire the maximum amount of knowledge possible to be explained later on.

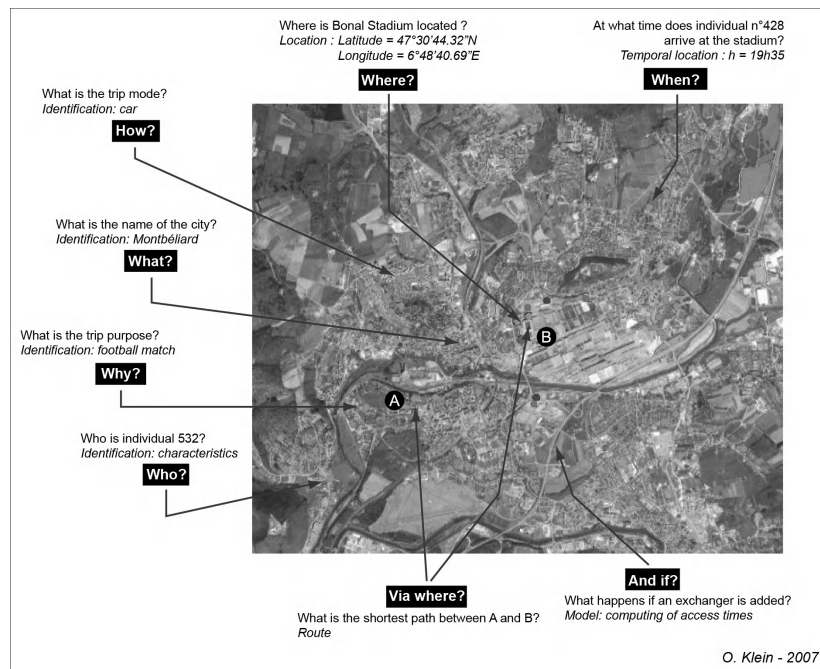


Figure 6.23. Examples of questions faced with scattered points
(for color version see www.iste.co.uk/banos/GIS.zip)

The most basic questions correspond to identifying objects (“who?”, “what?”) as well as geographical locations (“where?”, “via?”, “to?”), temporal locations (“when?”) and spatio-temporal locations (“where?” and, “in what time?”) We may also consider the possibility of simulation, with questions such as “if?”

However, when finding ourselves faced with a set of scattered points which can evolve spatio-temporally, it is

then fundamental to contemplate all the possibilities for change. Next, we bring in the questions specific to thematologists, such as “where and how?” and “where and why?” in order to try to explain locations and trips.

In a spatio-temporal context, the possibilities of the set of scattered points evolving is limited by three parameters which may be, in turn, constant or variable: the number of objects, the distance between the objects and their mass variation. This implies that there are $2 \times 2 \times 2$, meaning 8, configurations of changes in state imaginable.

By applying the animation procedures we defined earlier, thanks to a simple image linking, then the trip image is recreated. This animated display of the city recreates the urban hot spot, as defined by A. Banos [BAN 05] and [BAN 06]. These relatively basic types of visualization show the city’s dynamics well (one of our initial objectives) but require additional elements to give more in-depth analyzes. One of the possible solutions is to make use of descriptive spatial statistics which enable us to calculate parameters which describe distributions, their characteristics, and their evolution in time (mean center, dispersion ellipse, *hot spots*, etc.).

With each person being represented by a dot, with possibilities of evolving in a spatio-temporal environment, then the tools’ capacity limits are quickly reached for urban studies, for megaregions as well as average sized urban areas.

Within the framework of trips in connection to a football match, visualizing moving points which represent individual trips produces a global image of the impact of an event on the area considered (Figure 6.24). This really helps in the decision making of local participants. By focusing on certain key areas, congestion problems on certain interchanges or

main roads, then we may identify problems concerning parking.

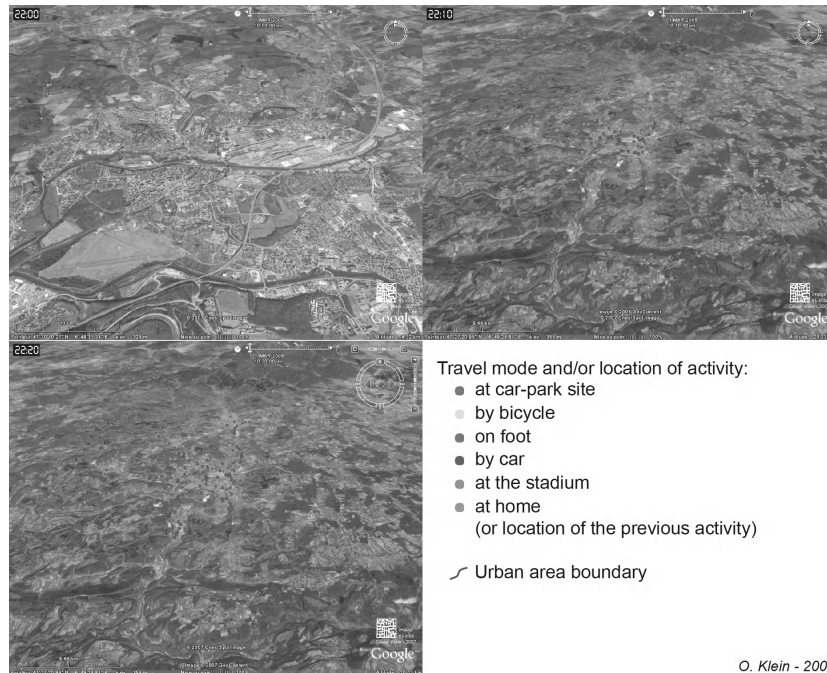


Figure 6.24. Visualizing moving points (for color version see www.iste.co.uk/banos/GIS.zip)

From this, the event managers know spectator trends and may consider putting in place public transport solutions or car park shuttles in areas which are further out from the event.

By combining this approach with other statistical elements (temporal graphics, dispersion ellipse) then areas blocked up in space and time can be pointed out more efficiently. For football, if before the match there are not too many problems concerning arrivals spread out over two hours, then the post-match is indeed problematic because the entire crowd gets back on the road, essentially in a car, in less than half an hour (Figure 6.24).

6.4.2.4.2. ...to the synoptic visualization of the land in motion

As the opposite of the microscopic approach to individual journeys, a macroscopic approach may be considered in order to know the real land use of inhabitants in a given area (Figure 6.25). Through this approach we are trying to go beyond the traditional methods which do not reflect the dynamics of urban living, and which only suggest a simplistic vision of the city: a city which sleeps and is inhabited by *homo sleepius*, thus brutally cutting it off from a large part of its components. This type of cartography, intended for land developers, means that we can focus development procedures on precise spaces and times, by means of a dynamic spatio-temporal visualization, which then visualizes the real land-use of space in specific zones: the city center, factory exits, administrative services, cultural equipment, etc.

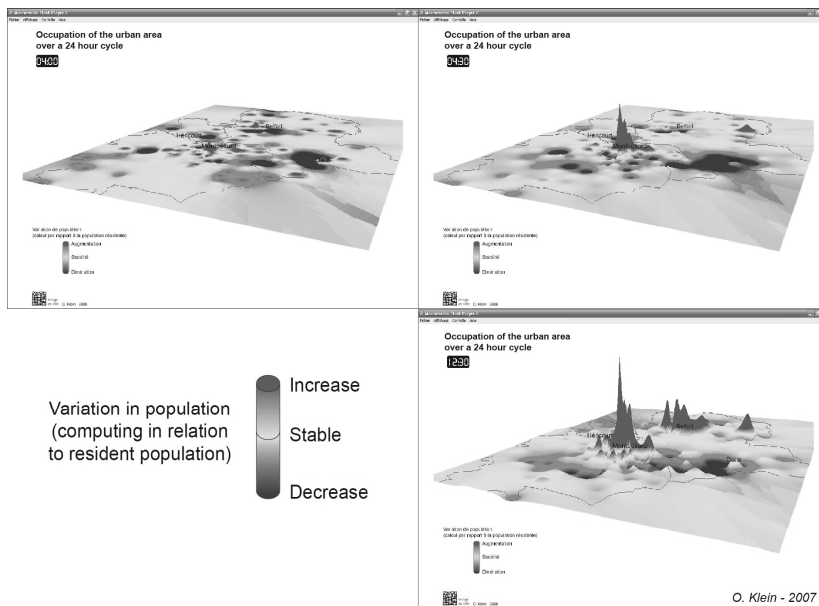


Figure 6.25. Global visualization of urban dynamics (for color version see www.iste.co.uk/banos/GIS.zip)

6.5. Conclusion

In the continued use of classic cartographical approaches, which are often unsuitable for current demands, the technological advances which are integrated into new forms of representation bring a truly positive value to the study of daily mobility. Placing the *image* at the heart of the procedure enables us to multiply the types of representation and to diversify approaches according to the demands of those involved. Moreover, the map's functions evolve including:

- a land diagnostic tool in order to feed dashboard software with indicators for observatories;
- a tool to help with decision making used by developers, particularly when implementing trip maps;
- a tool for dialoging when implementing participative procedures, including all those involved with the land.

However, increasing the variety of cartographic products is not always enough to fulfill the needs of different urban inhabitants. Resorting to specific surveys, both laborious and costly, is still a step which cannot be overlooked in order to generate images which are relatively faithful to the reality of urban life prior to any representation.

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Chapter 7

Guiding a Tram-Train Installation: a Necessary Multi-Criteria Approach

7.1. Introduction

It would be simplistic to consider periurbanization as the simple distribution of housing in rural environments. For many decades, this phenomenon has been part of reality [DUP 99] and reflects a drastic change in the lifestyles and aspirations of the individual [BAU 76], [DEZ 98]. The way in which the land is used by city-dwellers has evolved: the distinction between the place where we work and the place where we live is becoming increasingly more defined [ASH 98], [ORF 01].

Trip requirements not only exist on an intra-urban and inter-urban scale, but also on a peri-urban scale. Thus, we observe the increased distances to be travelled, in particular to go to work. In this case, the car is the only mode of transport capable of fulfilling the trip requirements for those living in peri-urban areas [DUP 95]. This is not, however,

Chapter written by Olivier BOUHET.

without its harmful daily effects such as traffic jams, accidents, pollution, etc. If in urban areas public transport (networks, modes) is relevant, functional and credible (even if there is still room for some improvement), then faced with car use, their usefulness in peri-urban and rural zones remains limited to non-car owners, who are consequentially held captive by the public transport system.

Improving the service in these suburban areas is vital, but also creates problems which are tricky to solve, and especially for areas where there is seemingly no perfectly adequate classical mode of transit (bus, tram and train). If the improvement to regional train services is a real fact, nonetheless there is still progress to be made and more especially as the efforts made in each region is unbalanced. However, implementing a system to serve peri-urban areas in addition to existing services would make it possible to remedy certain problems. One possible solution, without restricting the right to mobility, may consist of valorizing existing equipment (rail networks) in order to reconsider trips made within districts and suburban areas, and the relationships between the two entities. The rail system, used as a link between urban and peri-urban areas, would partially contribute to solving problems of mobility and accessibility between two spatially distinct yet closely linked entities. In order to do so, this mode must be safe, fast and, above all, offer a good quality of service, be frequent and serve communication nodes to allow passengers to make multimodal trips. This is a question of integrating peri-urban public transport with exclusive right of way (UPT/ERW) with the view to improve mobility and accessibility over a given area. Serving peri-urban areas by public transport must not be bound to revolutionizing transport modes, or the appearance of new propulsion technologies, but in fact to the evolution of techniques in the transport domain (rail, for example) and in different disciplines.

Innovative rail solutions already exist, and amongst those put forward, the tram-train which already exists in Karlsruhe in Germany, seems the most relevant to us¹. Having its own exclusive right of way, this form of public transport clears problems of traffic build-up which are inherent to the lanes shared with other modes. Nonetheless, installing a tram-train raises several questions:

- the demographic and economic characteristics of the zones served;
- the institutional context (administration, regulations);
- technical constraints imposed by user safety;
- the impacts on spatial development.

We are raising this non-exhaustive list here to avoid the pitfalls of technical expertise. It is not possible to tackle all these questions in this chapter, but this simple reminder points out the problems related to developing transport systems.

The study carried out prior to a project which is heavily laden with consequences for the areas concerned and served by the transport system, justifies the design of a method to help make decisions which take its spatial, social and economic aspects into account. This method aims to throw light on the choices of the areas used for installing a tram-train (lines and stops) which reveal both political and technical perspectives:

- the first section will define the tram-train;

¹ The first French tram-train (the French-German link Sarrebrücken-Sarreguemines has been running since 1997) between Bondy and Aulnay sous Bois does not currently resemble a true tram-train [BOU 06] as there is no interconnection between networks.

– the second section will study the area of the average Grésivaudan valley, between Grenoble and Crolles, able to install a tram-train;

The third section will present a method for researching potential zones for establishing tram-train stops, based on the paired usage of GIS and the multi-criteria analysis (MCA);

The fourth and final section will analyze the results from the two simulations.

7.2. The tram-train

Thanks to an interconnection between different rail networks, this hybrid vehicle between a tram and train provides, without transloading, rail links between a district and its peri-urban zones. It therefore runs on existing networks.

7.2.1. *Tram-train philosophy*

The innovative aspect of the tram-train lies in the interconnection of existing networks in order to run a vehicle which is adapted to two kinds of rail techniques [BOU 06], and considering the limitations common to both networks. The *Transport Technologie-Consult Karlsruhe GmbH* (TTK) organization which specializes in transport planning has studied the reliability of a tram-train in Karlsruhe in Germany [ADT 98]. The running of this tram-train, which has been in place since 1992, teaches us that it is possible to overcome technical, institutional or even political obstacles.

From the peri-urban zone to the hypercenter, and the hypercenter to the peri-urban zone (Figure 7.1), such interconnection enables links between stops in the peri-urban and hypercenter zones with transloading (the tram-

train line is a dotted grey line). With a station transfer the travelers can be picked up from their starting point. This interconnection between urban and peri-urban transport networks, paired with the creation of multimodal stations [CER 98], contributes to a better service for the areas traveled through. By removing a transloading step, the number of destinations with just one tram or bus connection is increased.

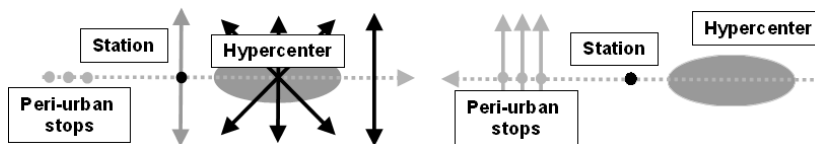


Figure 7.1. *Interconnected rail network (source: TTK)*

On a non-interconnected network (Figure 7.2), in-station transloading is a real fact for the user. Whatever the direction of the route, the destination possibilities without transloading are reduced, because the user must change at the station for the given transport mode to get to the hypercenter.

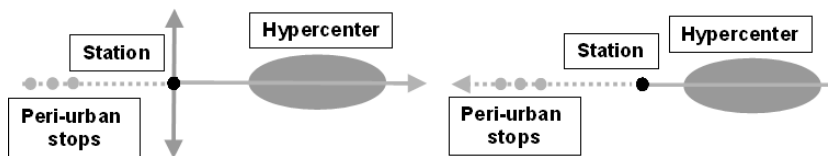


Figure 7.2. *Non-interconnected rail network (source: TTK)*

An interconnected line presents many opportunities for commuting by bus, or car park shuttles than simply a connected line [BOU 06]. Implementing a transport system on demand [BAN 01] as an addition to existing services would reinforce the network’s attractiveness. Installing stations must take the land into account, and fulfill existing, unfulfilled demands. This combination (multimodal

transport policy and peri-urban transport with exclusive right of way such as the tram-train) is the response to user expectations who “are always looking for more choices” [ASC 93]. The repercussions of removing a forced connection can be foreseen, as much in terms of the quality of the transport (more attractive tram-train and network) as the network’s operation.

Thus, the organization of a network with interconnected routes is part of a point of view where “the various modes have their relevant zones and respective usage outcomes. The essential factor is not to move the boundaries of these zones and the use of the various modes, but to optimize the complex devices that they form together for both individuals and communities” [ASH 93].

7.2.2. Tram-train operation

The tram-train’s capacity to accelerate and decelerate [BOU 06] give it the advantage, with the help of a few adjustments, of being integrated in the pre-existing rail traffic by limiting disruptions (Figure 7.3).

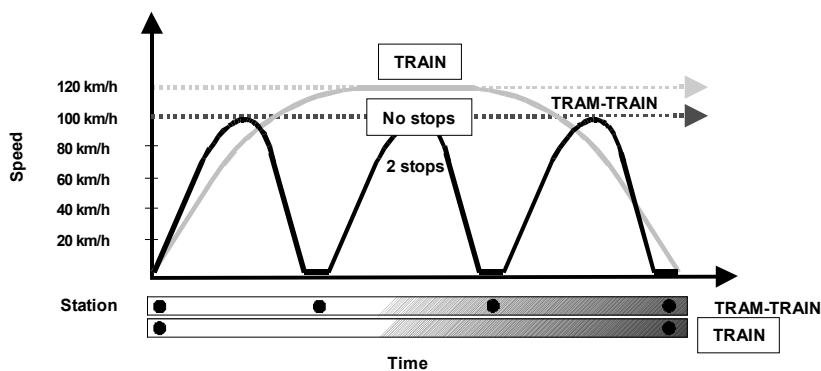


Figure 7.3. Diagram representing tram-train circulation on RFF tracks (source: SNCF)

The tram-train can stop more often than a classic train. The number of stops over a journey (Figure 7.3) may be increased without excessively increasing the journey time. Before the tram-train was up and running in 1992 on the Karlsruhe-Bretten line, the journey time for a train serving 8 stations was 30 minutes. With the tram-train, the journey time goes to 32 minutes for 17 stations (besides tram stops in Karlsruhe) [BOU 06]. The journey is extended by 2 minutes for an extra 8 stops. The technical characteristics of the vehicles contribute to this irrefutable fact.

Three weeks after its implementation, more than 8,000 travellers² took the line every day (trains in the Deutsche Bahn carried 2,200 travellers per day before)³. The installation of new stops is then possible, but the choice of where to stop is important.

Several elements are taken into account in order to comprehend the implementation of this vehicle, to ensure its development and its success. To illustrate this point, let us use the specific development of routes and stops, urbanistic procedures, etc.

With the multiplication of active commuter destinations and the diversification of their residential locations, the creation of a peri-urban public transport system with an exclusive right of way (UPT/ERW) is envisaged within a regional framework. Such a system justifies the creation of an organizing authority for transport in charge of managing duty assignment, concerning areas of intervention, costs and revenues [BOU 06]. The system's success relies on the removal of at least one transfer, putting into place an intermodal policy which favors using collective transport,

² Source: TTK.

³ The quasi-quadrupled frequentation can be attributed to the increase in frequency (doubled supply) and the extended time serviceability [SYS 94].

and the development of multimodal stations in order to increase the tram-train's efficiency (creating park-and-rides, changing the interchange station, normally considered as a waiting area, into a working area).

7.3. The tram-train project in the urban region of Grenoble

Largely limited by the hilly geography of the region, peri-urbanization around the Grenoble area has been developed along the lines of communication which flow into the steep-sided valleys in a Y-shape (Figure 7.4).

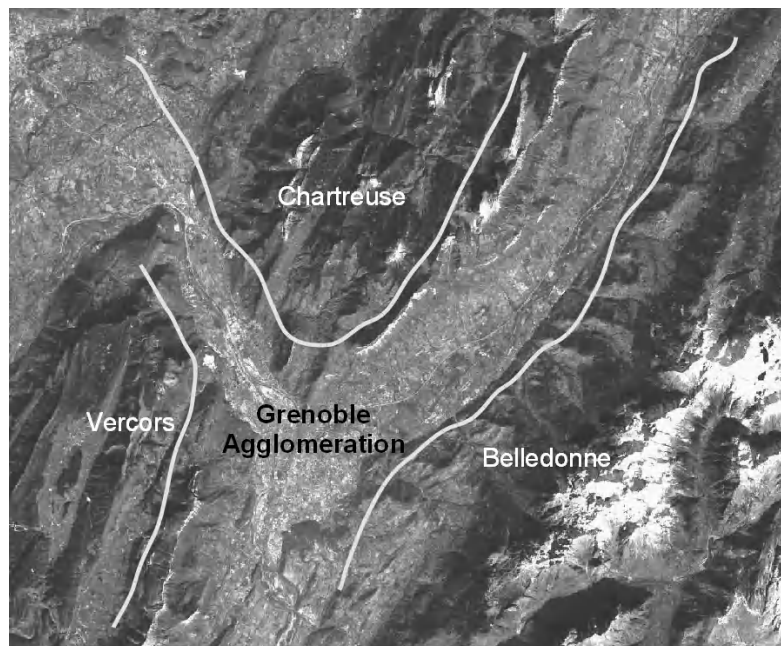


Figure 7.4. Location map (map source: GoogleEarth)

The spatial separation of the employment and housing functions is partly responsible for the increased flow of cars. In fact, the individual car is the main vector which will

ensure these links. There are alternatives to the individual car for links within the area, namely due to an efficient and attractive public transport network over several exclusive right of way lines (4 tram lines). However, the usefulness of public transport as an alternative to using an individual car in peri-urban areas must be enhanced. The supply in favor of an increase in public transport in peri-urban environments would involve using existing rail lines to run a tram-train and fulfill the supply offered by TER (France's regional train service).

7.3.1. The agglomeration and Grésivaudan sectors of the urban region of Grenoble

The tram-train's choice of route and served area must be suited to the reality of trips made within the considered area. The observation of spatial relationships on different scales (district, communities, etc.) is therefore essential.

Grenoble, and the three valleys which flow into it, embodies the difficulties encountered in large French cities of similar sizes: rapid peri-urbanization, high housing costs, car congestion, etc., which are made worse by the hilly geography and areas of risk. Studying the installation of one (or several) tram-train lines is enforced, and even though such a device could be developed in each valley, the Grésivaudan valley in the North-East of Grenoble has quickly appeared as a possible choice for a potential tram-train line in the near future. There are many reasons which contribute to choosing this zone:

- the area's characteristics;
- the extension of tramline B to Gières station (March 2006);
- job dynamism (areas of activity, developing industrial zones, Innovallée technopole) and demography dynamism

(natural conditions: geographical assets above all concerning communities on the right bank of the Isère river).

In order to define the zones in the region of Grenoble and the Grésivaudan valley, we have retained the network guidelines for the urban region of Grenoble, passed July 12, 2000. The area studied covers the agglomeration and Grésivaudan sectors, and includes 72 districts (Figure 7.5). To enhance the map's readability, only some of the districts are shown.

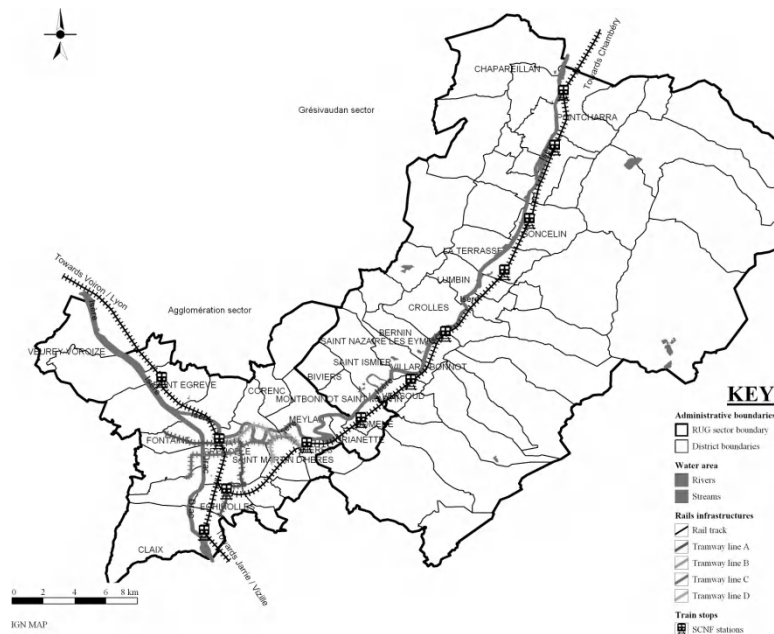


Figure 7.5. Rail network for the agglomeration and Grésivaudan sectors of the urban region of Grenoble (for color version see www.iste.co.uk/banos/GIS.zip)

7.3.2. Traffic problems

In terms of spatial congestion, such problems are mainly due to trips made by commuters during the morning and

evening peak hours. These interchange flows between 72 districts take place between the home and workplace.

The residential zone essentially relates to districts at the bottom of the valley. Communities located on the slopes have smaller populations. The concentration of the population is higher in the Grenoble agglomeration, as well as in the suburban districts which are relatively close by (between Gières/Meylan and Villard Bonnot/Crolles). The hilly geography explains the Y shape of the urban task.

The employment zones remain concentrated around Grenoble. On the one hand, some stations stand out in the Grésivaudan valley, and on the river Isère on the other hand. There are two types:

- traditional activities are located on the left bank (Domène, Le Versoud, for example);
- activities linked to new ICT systems essentially concern districts on the right bank (Meylan, Crolles, for example).

The study of commuter migration taken from the RGP 1999, INSEE (National Institute for Statistics and Economic Studies), shows that inhabitants do not live exclusively in their employment area. Studying the road network for these trips (mainly carried out in an individual car) makes it possible to identify nodes, places of traffic, etc., and to characterize the area of traffic and frequentation in this territory.

The cartography of flows depends entirely on the following procedures:

- splitting each road line into as many sections as there are intersections (crossroads, interchanges) with another line. The transport corridors correspond to county and national roads, and also highways;

– assigning commuting workers to the road sections used for each pair of districts, thanks to the O-D matrix for the 72 districts studied from the RGP in INSEE 1999.

Migrant workers are assigned to sections⁴ under constraints of journey times. From their place of work and/or home, they access the highway network provided that their access does not result in detours or a longer journey time than by using a second rank solution. The constraints of the distance traveled are taken into account when assigning the workers (those living on the sloped districts are the main ones concerned). Neither the constraints regarding the capacity of the roads and interchanges, nor the movement of commuters are taken into account. The Nystuen/Dacey (1961) analysis method of the RGP 1999 O-D matrix flows prioritizes districts in relation to each other, and identifies the important aspects (employment and living hubs). Although simplified, the sought after objective is to visualize the most used sections, the major nodes, in order to distinguish the road section according to the volume of traffic. The analysis is static because it is based on data from the RGP 1999, INSEE.

We may put forward two conclusions:

– those entering the road networks are according to the population concentration (around Grenoble and between Gières and Crolles). The commuters in these districts generally do not work in their home district;

– those leaving the network relate to districts which concentrate economic activities, attractive in terms of employment, and mainly around Grenoble and districts closest to the Savoie region.

⁴ By only having data on commuter trips taken from RGP 1999 from INSEE, we were able to consider steps 3 and 4 (mode choice, assignment to different networks) of the canonic form of road traffic models.

7.3.3. *The tram-train solution*

The separation of home and activity functions, both the cause and consequence of peri-urbanization, and the problems it generates such as noise and atmospheric pollution, traffic related accidents, slow-moving traffic, etc., show the limitation of using an individual car for making trips. The peri-urban public transport networks are under developed with regard to the issues of mobility, and they mainly concern Grenoble and its surrounding suburbs (Figure 7.5).

The organization of peri-urban public transport with exclusive right of way must try to reduce the unpleasantness of a journey, or to heighten the attractiveness of public transport for users. The means of action taken concern journey time, frequency rate of the mode or transloading, comfort, regularity, service quality safety, route speed, etc.

Increasing the attractiveness of public transport in urban environments, faced with individual vehicles [GUY 00], would involve using the existing rail (left bank of River Isère) and tram tracks in order to run a tram-train (Figure 7.5).

7.4. A two tool method: GIS and MCA

One of the objectives for public transport projects aims to serve the most potential users possible. Studying the trips made by individuals is therefore essential: it includes knowing the populations likely to be concerned, housing areas, route stops, places of study, busy public buildings (City Hall, hospitals), businesses, etc.

It is absolutely necessary to analyze the areas traveled through in order to determine the potential frequentation demand for the mode of transport, and to contribute to defining traffic supply. For this, the considered area must

generate stable and high alighting and boarding over time (on the scale of a day, as on the scale of a week or a month).

Thus, through the socio-economic study of the areas traveled through, the land use, commuter flows between the agglomeration and peri-urban zones, we then propose to develop a methodology to help make decisions for installing a tram-train, a peri-urban public transport with exclusive right of way, using both GIS and MCA methods.

7.4.1. Tools

The combination of multi-criteria and GIS methods is an important channel for solving problems related to infrastructure location.

7.4.1.1. Geographical Information Systems (GIS)

GIS software is a georeferenced (information storage) database management system (DBMS) which can be updated (data retrieval), where we can carry out requests (classic and spatial), apply topology rules, display, generate, simulate, model, handle and analyze spatial reference data (via the interface) in an aim to solve management and planning problems (display). Whether these are “raster” or “vector” problems, they provide the following functions: “acquire, archive, access, analyze, display” [DEN 97].

The spatial analysis operations which are available in GIS, such as *overlay* techniques, make it possible to combine and correlate different variables in order to provide thematic information. These variables are not sufficient for helping the decision maker because they are limited:

- *overlay* results which are difficult to understand when there are more than four or five factors involved;
- *overlays* do not take into account the unbalanced importance of the variables;

- when we input the variables for the *overlay* analyses, how are the used threshold values defined?
- using threshold values for charting continuous variables generates a loss in the quality of the information.

Using a GIS, in the strictest meaning of the term, to look for a potential site has its limitations. In fact, choosing a site for development will depend on the sites identified using the GIS's *overlay* procedures. These respond to the deterministic, digital criteria, but do not make it possible to indicate the best site, and are therefore limited with regard to being a decision making aid. The *overlay* techniques cannot identify solutions when the criteria are excluded from each other, if there is much research to carry out for the objectives, or if the decision's makers' preferences have to be considered...

7.4.1.2. *Multi-criteria analysis*

The multi-criteria analysis was able to be developed using questions of spatial analysis, where GIS ran into problems. The MCA can:

- take conflicting criteria into account;
- consider differing preferences and objectives;
- integrate non-spatial information;
- provide a result according to classification or choice;
- integrate value systems.

This tool is suitable for analyzing and assessing quantitative or qualitative effects relating to development projects. MCA also improve the decision making process which present different points of view. For these questions, GIS as a single analysis tool are not enough, whereas combining GIS and MCA can provide an answer to several spatial issues.

Amongst the existing MCA methods, we have taken the AHP (*Analytical Hierarchy Process*) although other methods are also suitable for transport problems (ELECTRE and PROMETHEE methods⁵). Developed by T. Saaty in 1980, the method combines different criteria (factors and constraints) in order to create the “best” solution for the problem raised. Integrating the AHP method into the GIS Idrisi enables us to visualize the results cartographically. Integrating the MCA and GIS is then suitable for studying decision making problems related to space, as strategic information is provided.

7.4.2. AHP method

The results are presented as a single classification. This method makes it possible to designate the best action (problematic of choice), good actions (problematic of sorting) and the best actions (problematic of sequencing). As opposed to other AMC methods, choosing the classification technique (choice, sorting, sequencing) may be determined *ex post*.

This method is a technique which makes it possible to develop a decision based on a hierarchical ordered structure.

There are three essential steps needed in order to get a good result:

- 1) breaking down and then structuring the problem into hierarchical order according to the objective(s) to be reached, the criteria chosen and the alternative solution(s);

⁵ For more details, see work by N. STATHOPOULOS, *Performance territoriale des réseaux de transport*, Presses ENPC, Paris, 1997 and the thesis by N. MOLINES, *Méthodes et outils pour la planification des grandes infrastructures linéaires et leur évaluation environnementale*, PhD Thesis, University of Saint-Etienne, 2003.

2) determining the relative weight of the criteria which may be quantitative or qualitative. The measures are expressed according to a ratio scale:

- *for the quantitative criteria*, there are two techniques at our disposal. First of all, the direct inputting of the measures and their standardization as a ratio, followed by the pair-wise comparison matrix, both reciprocal and positive. It is also used for qualitative criteria,

- *for quantitative criteria*, we must use a scale of measurement in order to generate the pair-wise comparison matrix for the criteria. The one proposed by Saaty takes values spread over a scale from 1/9 to 9 [1/9 (extreme), 1/7 (stronger), 1/5 (strong), 1/3 (moderate), 1 (equal), 3 (moderate), 5 (strong), 7 (stronger) and 9 (extreme)]. The criteria are assessed in relation to each other in order to obtain the pair-wise comparison matrix. The coherence in assessing the weight of the criteria in relation to each other is ensured by the global coherence index. It “assesses that probability of the weightings being assigned in a random way” [EAS 95]. The main eigenvector of the pair-wise comparison matrix is used in order to create the best adjustment for the set of weights. To calculate this vector, the weighting coefficients are standardized so that their sum is equal to 1, in order to carry out a weighted linear combination. If the coherence index value is strictly higher than 0.10, then it is necessary to reassess the pair-wise weighting factors. This matrix also makes it possible to conduct sensitivity (determining criteria with a large influence over the outcomes) and robustness tests (testing the obtained result’s capacity to resist modification);

3) aggregating the contributions into one single criterion. The factors are weighted and combined in a linear way, then the stresses are applied by using a Boolean multiplication in order to eliminate pixels which contain values of zero.

As the AHP method is integrated into a raster GIS, then the outcome of combining criteria will produce a map which describes each pixel's ability to answer the question raised in the area studied.

7.4.3. Application of the AHP method

For this application we will present the three steps illustrated previously.

7.4.3.1. First step: defining the hierarchy

Faced with the legal jargon surrounding the definition of an organizational authority for transport responsible for the tram-train, the decision-making process which considers the skilled services in charge of transit is not modeled. For the method, we have chosen only high traffic areas.

Creating a public transport with exclusive right of way infrastructure is advantageous if the zones which generate incoming or outgoing traffic, such as dense residential areas, zones of activity, etc., are served and irrigated by transport in a high-quality, high-performing, attractive way. As the tram-train runs over the pre-existing rail infrastructure, we are looking for potential areas for installing new stops. The work grid resolution has a 10 m x 10 m pixel.

7.4.3.2. Second step: criteria choice

Integrating the AHP method in the Idrisi GIS enables an instantaneous cartographical visualization of the results obtained. The interface contains spatial data and the multi-criteria algorithm parameters.

The said algorithm which was generated for the Idrisi software is coded into the GIS software language. This analysis function can be used in the same way as the other analysis functions [LAA 00].

We decided to choose this software because the GIS/AMC integration is complete. The AHP method is based on combining criteria (factors and constraints), with a view to single out the “best” solution for the problem raised.

By going back to the available spatial database, we can translate certain aspects of the identified problem into factors and constraints. Each factor and constraints gives rise to a new map, maps which are aggregated to each other in order to define a solution.

7.4.3.2.1. Factors

There are seven georeferenced factors (Table 7.1).

Factors	Zones of economic activity in each district (CLC data refined by IGN maps, 1/25 000)
	Housing zones (1) in each district (net population density [PUM 98]) (INSEE data, CLC data refined by IGN maps 1/25 000).
	City Halls for each district (IGN maps, 1/25 000)
	Station for each district (IGN maps, 1/25 000)
	Schools for each district (IGN maps, 1/25 000) and number of pupils (Education Authority data)
	High schools for each district (IGN maps 1/25 000) and number of students (Education Authority data)
	Commuting boarding and alighting (2) at the intersections between the transport corridors (county roads, national roads and highways). INSEE data (RGP 1999) for home based work flows and IGN maps, 1/25 000.
<p>(1) For each district, we calculated the number of residents in km² in relation to built up areas. The “brute density” [PUM 98] of the population per district therefore was not been chosen, specifically because it only takes into account the total surface area of the district.</p> <p>(2) See section 7.2.2. Traffic problems</p>	

Table 7.1. Databases, 7 factors

The list is not exhaustive as it reflects the data we have at hand. For example, we know the limits of the zones of activity, but we do not know the income of the employees related to these zones of employment on an *infra* communal level.

These factors characterize zones where installation a transportation stop is indeed possible (but is this relevant?) The limitations of the validity of these factors are progressive. According to the weighting combinations for each factor, the final outcomes will be different.

7.4.3.2.2. Constraints

Here there are five Boolean constraints. They indicate the zones where the installation of new stops has been considered as impossible.

Constraints	Slopes higher than 10 % (DTM ⁽¹⁾ for the Isère region)
	Rivers (CLC data ⁽²⁾ , refined by IGN maps, 1/25 000)
	Sheets of water (CLC data, refined by IGN maps, 1/25 000)
	Airfield (CLC data, refined by IGN maps, 1/25 000)
	Highway 41 (CLC data, refined by IGN maps, 1/25 000)
(1) Digital Terrain Model.	
(2) <i>Corine Land Cover</i> .	

Table 7.2. *Databases, 5 constraints*

These constraints are not exhaustive. For example, the zones with high flood risks are not considered because their perimeters are currently being redefined.

The choice of installation zone will come as the result of simulation, or a compromise between several simulations (as each simulation is the result of different factor weightings).

7.4.3.2.3. Creating an eigenvector

The step prior to developing the eigenvector is generating the factor comparison matrix.

Table 7.3 shows the results of this process.

Factors	School	Station	Intersection	High school	City Hall	Urban	Zones of activity
School	1						
Station	1	1					
Intersection	5	3	1				
High school	1	1	1	1			
City Hall	1	1	1	1	1		
Urban	3	3	3	3	3	1	
Zones of activity	3	3	3	3	3	3	1

Table 7.3. *Pair-wise comparison matrix*

The quantitative and qualitative factors are standardized using this matrix. As illustrated in Table 7.3, the weightings highlight the “intersection”, “urban”, and “zones of activity” factors.

Here it is a matter of identifying potential transport stop zones for individuals making trips between their home and work place via the road network.

The eigenvector is illustrated by Table 7.4 and the global coherence index is equal to 0.06.

Factors	Weightings
School	0.0701
Station	0.0726
Intersection	0.1423
High school	0.0853
City Hall	0.0853
Urban	0.2276
Zones of activity	0.3169

Table 7.4. *Factor weighting*

This table shows the weighting for each criterion, after an assessment of the criteria pair-wise matrix.

Our scenario favors locating stations within the vicinity of the “intersection”, “urban” and “zones of activity” factors.

7.4.3.3. *Third step: outcomes*

The solution, shown in map form, is obtained by aggregating the factors and constraints into a single criterion. Figure 7.6 is the cartographic expression of the obtained outcome for this example. This scenario assesses the land according to the areas traveled through by commuters.

In this example, the weightings for the set of factors deliver results which are expressed on a standardized scale from 0 to 175. Each zone of installation is represented, but the degree of relevance of installing a transport stop varies with regard to factor weightings.

Unfortunately there is an imbalance between the qualitative and quantitative factors in this method. The outcomes depend on the quantitative factors. A size effect

biases the results because the factors with high volumes, in fact, influence the end results.

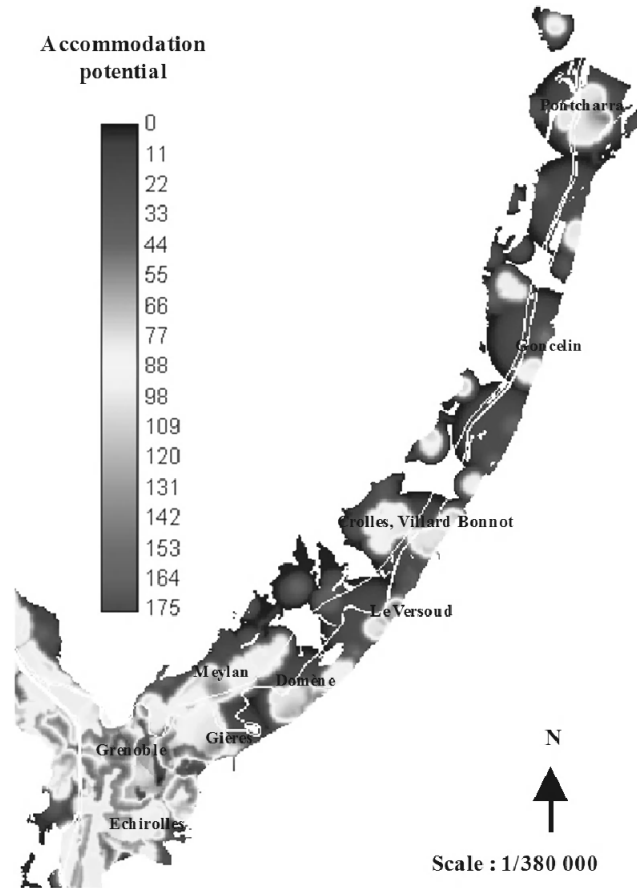


Figure 7.6. AMC outcome for first simulation (for color version see www.iste.co.uk/banos/GIS.zip)

7.5. Result analysis

In order to comment on the different outcomes, we will present two simulations. The previous example corresponds to the first simulation, and the second simulation will soon be presented.

7.5.1. *The second simulation*

We will briefly describe steps 2 and 3 of this method in order to develop this second simulation. The quantitative and qualitative factors have been standardized using the pair-wise comparison matrix, with the following results.

Factors	School	Station	Intersection	High school	City Hall	Urban	Zones of activity
School	1						
Station	1	1					
Intersection	9	3	1				
High school	1	1	1/3	1			
City Hall	1	1	1/2	1/2	1		
Urban	1	2	1/2	3	3	1	
Zones of activity	1	2	1/2	3	3	1/2	1

Table 7.5. *Pair-wise comparison matrix*

As Table 7.6 shows, the weightings highlight the “intersection” factor in relation to the other factors. Here it is a question of identifying potential stopping zones for individuals making trips in individual vehicles on the road network. The eigenvector is illustrated by Table 7.4 and the global coherence index is equal to 0.07.

This table presents the weightings for each criterion, after assessing the pair-wise matrix for the criteria.

Factors	Weightings
School	0.0937
Station	0.0812
Intersection	0.3304
High school	0.0838
City Hall	0.0755
Urban	0.1839
Zones of activity	0.1516

Table 7.6. Factor weightings

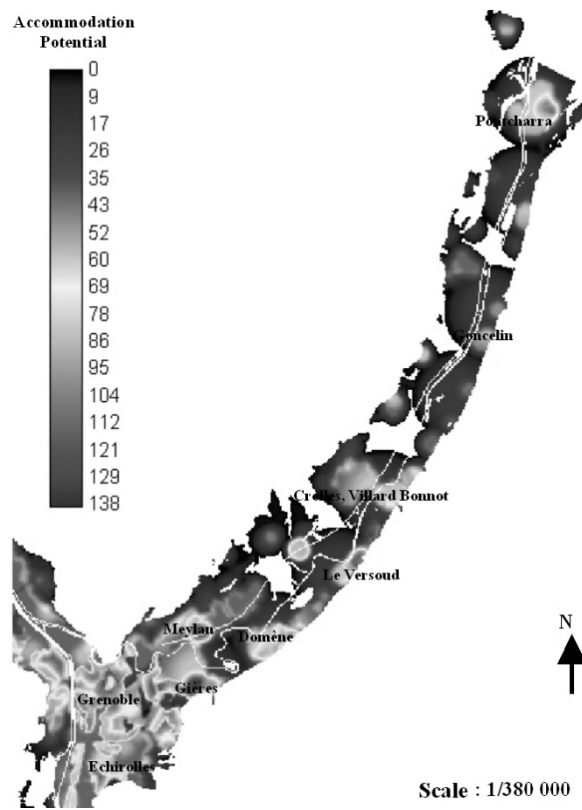


Figure 7.7. AMC result for the second simulation (for color version see www.iste.co.uk/banos/GIS.zip)

(Figure 7.10) of a GIS providing non-preferential potential zones with the results from Figures 7.6 and 7.7 which show the benefit of using the MCA. Reflective of the relative importance of each criterion, the MCA provides strategic information, helps the decision-maker...in short, it offers a basis for discussion.

Once the MCA is conducted, the results are exported into a GIS vector, namely Geoconcept in this case.

7.5.3. Line route

The development of peri-urbanization and economic dynamism in the Grésivaudan valley over these last thirty years has led us to restrict our research of potential zones in districts located between Gières/Meylan and Villard Bonnot/Crolles. The results in this part of the valley concern a 4 to 7 km wide, longitudinal band, cut through the middle by the River Isère.

The districts in the Gières/Crolles area present a much higher installation potential than those towards the North of the valley. The interconnection between the two rail networks is indeed possible around the Gières district, by means of the Grenoble-Gières-Université train station.

This location was selected as a point of network interconnection in order to provide a peri-urban service in the Grésivaudan valley by the rail track located on the left bank of the River Isère.

Figures 7.9 and 7.10 respectively represent simulations 1 and 2. They are the result of Figures 7.6 and 7.7 in Geoconcept, created in the raster GIS "Isrisi". This is a matter of extending the Gières/Crolles area.

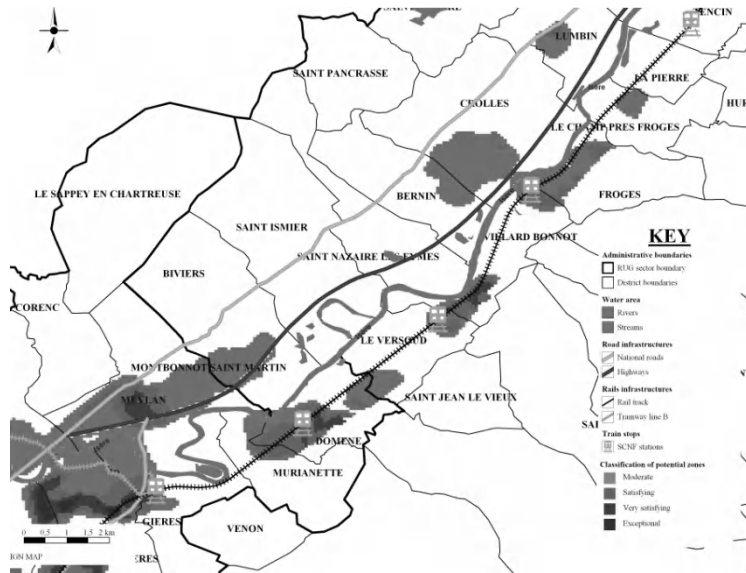


Figure 7.9. Simulation 1 (for color version see www.iste.co.uk/banos/GIS.zip)

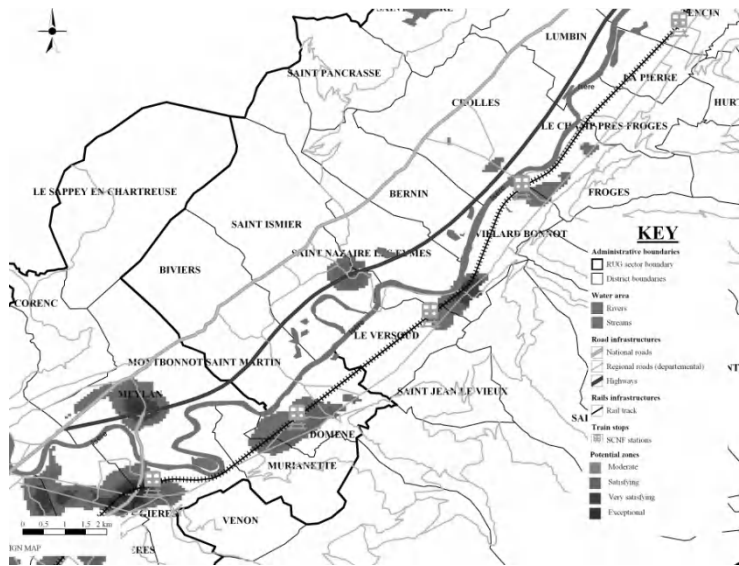


Figure 7.10. Simulation 2 (for color version see www.iste.co.uk/banos/GIS.zip)

The potential zones are classified into 7 categories, all of equal ability. As Table 7.7 shows for each scenario, the 4 best classes have been selected. The correspondence between Idrisi and Geoconcept for both simulations is presented in the following table.

Values in Idrisi S1	76/100	101/125	126/150	151/175
Values in Idrisi S2	60/79	80/99	100/119	120/138
Geoconcept categories	Moderate	Satisfactory	Exceptional	Very satisfactory

Table 7.7. *Factor weightings*

Both simulations give different strategic information (Figures 7.9 and 7.10). The intersection factor is over represented in both simulations, which explains the recurring zones as with districts Gières, Murianette, Domène, Le Versoud and Villard Bonnot for the left bank, and Meylan and Crolles on the right bank (Table 7.8).

Factors	S1 Weightings	S2 Weightings
School	0.0701	0.0937
Station	0.0726	0.0812
Intersection	0.1423	0.3304
High School	0.0853	0.0838
City Hall	0.0853	0.0755
Urban	0.2276	0.1839
Zones of activity	0.03169	0.1516

Table 7.8. *Factor weighting*

At a first glance, the outcomes for both simulations show zones which can accommodate tram-train stations (as well as the necessary land developments: loop line, interchange station, etc.). The location of the potential zones reveals that, even though the rail track is located on the left bank of the Isère, there are possibilities for a potential zone on the right bank. The tram-train line could therefore, using construction works and project phasing, serve the districts on the left and right banks between Gières and Crolles.

The districts on the right bank of the Isère have high potential in terms of zones for installing new stops. The results show that it is possible to serve the right bank. By respecting certain conditions, the MCA results for the zone between Gières and Crolles justifies why we are interested in services for the right bank districts.

The main constraint with regard to the districts on the right bank of the Isère boils down to the construction of rail tracks. The decision to run the tram-train over this bank involves constructing an uncoupling ramp, and station stops in order to serve it. The method shows that only a single tram-train running over the left bank track is not the only possible solution.

In order to assess the potential zones for each district, we have combined them with the databases for objects belonging to the solution (built-up areas, employment zones, other zones). In order to compare the different districts which present potential zones, but also different simulations between them, we have disaggregated the information taken from the RGP INSEE 1999: disaggregation in terms of residential zones, and disaggregation of assets over the district in terms of zones of employment.

The number of residents and employed people is calculated pro rata over the area of the residential or employment zone in one district out of all the residential or

employment zones from this district. This simplified reality is the outcome of constraints concerning access to costly databases. In fact:

- as we do not have access to information on the nature of the housing on an *infracommunal* scale, we have supposed a uniform distribution of the residents in the residential zones without taking into account the nature of the housing (dense or low-rise);

- with the lack of information on employment on an *infracommunal* scale, we have considered a uniform distribution of the employment over the “employment housing” zones (Industrial zones, zones of activity).

Thus, by crossing the potential zones with land-use databases (using topological examinations), we were able to quantitatively estimate the following, for each district and each simulation:

- the area size of the potential zones;
- the population concerned according to the type of land-use (net densities of inhabitants and workers).

7.5.4. Transport stop locations

The selected zones involve four districts on the left bank of the Isère, and six zones of the right bank.

7.5.4.1. Left bank of the Isère river

For both simulations presented previously (Figures 7.6 and 7.7), Table 7.9 shows the details of the outcomes for the potential zones in the left bank districts (Figures 7.9 and 7.10) according to the land-use types.

Left bank districts	Zone surface area (km ²)		Activity zone (km ²)		Residential zone (km ²)		Other (km ²)		Number of employed people		Number of inhabitants	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Domène	2.49	1.80	0.78	0.72	1.04	0.94	0.67	0.14	2,203	2,019	4,936	4,440
Le Versoud	1.20	0.43	0.25	0.09	0.39	0.14	0.56	0.20	594	218	1,358	476
Murianette	0.72	0.39	0.03	0.00	0.09	0.09	0.60	0.30	73	0	169	173
Villard Bonnot	1.39	1.11	0.16	0.14	0.90	0.80	0.33	0.17	1,305	1,156	3,564	3,164
All together	5.80	3.63	1.22	0.95	2.42	1.97	2.16	0.81	4,175	3,393	10,027	8,253

Table 7.9. Outcomes of first simulation for the left bank

The potential zones for all these districts cover a variable surface area according to the simulation:

– for S1, 5.8 km² of potential zones, out of which 2.4 km² are “inhabited zones”, 1.2 km² are “zones of activity” and 2.2 km² are “other zones”;

– for S2, the results are different. The surface area of the potential zones covers 63 km², out of which 1.97 km² are “inhabited zones”, 0.95 km² are “zones of activity”, and 0.81 km² are “other”.

For all these districts, the “residential zone” for S1 concerns around 10,000 residents, and nearly 4,200 assets for the “activity zone”. The population concerned for S2 is around 8,000 inhabitants in the “residential zone”, and nearly 4,000 workers for the “zone of activity”.

In spite of the changes in potential district surface areas from one simulation to other, the populations concerned remain relatively stable for important districts such as Domène and Villard Bonnot, as opposed to smaller districts such as Murianette and Le Versoud where the resident population is more dispersed.

Both simulations clearly indicate three zones (Figures 7.7 and 7.9). They form a quasi-continuous area of potential zones between: Murianette/Domène (S1 and S2), Domène/Le Versoud (S1), Le Versoud/Villard Bonnot (S1 and S2) and Villard Bonnot (S1 and S2). The importance of the zones concerned here in the districts of Domène and Villard Bonnet, and the recurrence in simulations could justify the creation of new stops on the lines. For the districts of Versoud and Murianette, it is more difficult to construct these stops because, according to the simulations, the potential may vary. The potential stops over these two districts depends on the “zones of activity” and “residential zones” factors. The importance of the “other zones” over

these districts enables us to contemplate the development of interchange stations.

As they have a larger population, the districts of Domène, Villard Bonnot and to a lesser extent, Versoud, they are more likely to accommodate interchange stations with car parks and other services than Murianette (which has a large surface area, however, in terms of “other zones”).

7.5.4.2. *Right bank of the Isère river*

For both simulations, Table 7.10 shows the detailed outcome for the potential zones in districts from the right bank of the Isère river (Figures 7.9 and 7.10) according to the land-use types.

According to the simulations, the surface area may vary and some districts are involved, and others are not. The districts of Bernin, Montbonnot Saint Martin, Saint Ismier, and Saint Nazaire les Eymes are involved in this situation. For the districts of Crolles and Meylan, the results are variable according to which simulation is used (S1 or S2), and they do not enable us to draw a clear consensus.

The potential zones for all these districts cover a surface area which varies according to the simulation. For S1, we have 2.76 km² of potential zones, out of which 0.6 km² are “inhabited zones”, 0.89 km² are “zones of activity” and 1.27 km² are “other zones”. The surface area of zones in S2 covers 8.46 km², out of which 2.39 km² are “inhabited zones”, 7.7 km² are “zones of activity” and 2.28 km² are “other zones”. For all these districts together the “residential zone” for S4 concerns more than 2,000 residents, and the “activity zones” concerns close to 6,000 employed people. For S2, the population concerned is around 9,000 residents in the “residential zone” and more than 18,000 workers in the “activity zones”. The populations concerned have seen large variations, whether it is a matter of S1 or S2, or the size of the districts.

Right bank districts	Surface area of the zone (km ²)		Activity zone (km ²)		Residential zone (km ²)		Other zone (km ²)		Number of employed people		Number of residents	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Bernin		0.44		0.16		0.13		0.16		427		230
Crolles	0.16	2.61	0.02	1.09	0.02	0.36	0.12	1.16	82	4,147	53	1,124
Meylan	1.76	3.81	0.87	1.87	0.48	1.76	0.40	0.17	5,683	12,222	1,996	7,304
Montbonnot Saint Martin		1.60		0.65		0.14		0.81		2,049		403
Saint Ismier	0.72		0.00		0.06		0.66		0		88	
Saint Nazaire les Eymes	0.12		0.00		0.03		0.09		0		49	
All together	2.76	8.46	0.89	3.77	0.59	2.39	1.27	2.28	5,765	18,845	2,186	9,061

Table 7.10. Scenario outcome for the right bank

The other zone category for Bernin, Crolles, Meylan and Montbonnot Saint Martin is indeed important, and shows an interest for developing the stops into interchange stations.

Both simulations show one zone over the Meylan district which is clearly distinguished (Figures 7.9 and 7.10). The zones which are identified as “other zone” out of these two simulations are not significant. The idea of serving Meyland by an uncoupling ramp cannot be overlooked, but these simulations do not make it possible for us to decide on the direction to be taken, the stops to be installed, etc. We must conduct other simulations, consulting the policies before discussing the chance of serving the right bank more than the left.

7.6. Conclusion

This study has allowed us to propose the problems which still need to be researched in more depth. Thus, the numerical results are still revealing, due to a work grid (the district) which is too large, a lack of specific data related to mobility, transport modes, etc. These results underline the importance of working with suitable data. The single solution at hand was disaggregating the information, but this led to approximations during work on a larger scale.

The results for the surface areas and populations are changeable between both simulations for districts on the right bank. As opposed to those for the right bank, the size of the district on the right bank is not a factor of stability in the simulation results. The changeability of the surface areas involved according to the simulations is related to the different geographic constraints on both banks. The low natural constraints on the right bank lead to a higher spatial distribution of employment and housing locations. On the other hand, these locations are concentrated on the left bank due to an area which is largely constrained by the River

Isère on the one hand, and the Belledonne mountain range on the other. These differences in density explain the variability in the results for both simulations. Carrying out other simulations would reinforce the results, or could make them weaker. In fact, the value analyzes are taken into account in the method for determining the relative weights of each criterion. With several simulations which offer different choices, the decision makers are not faced with a single solution, but with a set of acceptable solutions. The discussion process is then open to potentially relevant zones.

The installation solutions in the study do not resolve all the problems:

- running a tram-train is limited to pre-existing rail tracks. New tracks must be reliable, for obvious reasons to do with cost. In this case, the installation of new stops (and their accessibility) must be chosen with care, because it is the users which come to take the tram-train, and not the other way round;

- serving stops in peri-urban environments may vary from one service to another, just like the Parisian RER network. This transport policy must not lead to an exclusion of certain zones of mobility related to public transport.

Therefore, this chapter presented the potential of such a procedure. Let us now point out the limitations:

- the limited number of MCA methods built into a GIS makes it impossible to compare these results with other equivalent tools;

- the results are attributed to quantitative factors, via a size effect.

The method developed here may clearly be perfected (choices for other criteria, suitable data scale, etc.) but no less, it can be adapted to other tram-train line studies, and

more generally, to other public transport systems with exclusive right of way.

Nonetheless, with the tram-train, there is a renewed line of thinking with regard to managing mobility on behalf of public transport in agglomerations and their peri-urban zones. The question of serving these peri-urban zones still remains complete, because the car itself will partially help solve the problem of pollution, but will not answer questions regarding the saturation of transport corridors, or the need for mobility.

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