Urban form and daily mobility: methodological aspects and empirical study in the case of Bordeaux

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Abstract

The influence of land use on daily mobility patterns can be described by the two dimensions of urban form: the first is quantitative, that is density, and the second is qualitative, that is land use mix. Empirical studies usually add control variables such as sociodemographic characteristics. They suppose that urban form factors and sociodemographic factors have a separate influence on travel patterns.

In this paper, we first show the possibility of a causal relationship between urban form and sociodemographic characteristics. Thus previous results, which suppose that these two kinds of factors are separated, may be biased. It describes systematic relationships between urban form, socio-demographic characteristics, and daily mobility. As a consequence, we have to use specific econometric methods to test the motives of mobility. We develop a new tool: the “typological regressions”. Travel patterns in the metropolitan area of Bordeaux are then analyzed. Results allow to disentangle the interaction between land use patterns and travel behaviours.

Keywords: Compact city; Urban density; Urban form; Mobility; Land use patterns.

1. Introduction

Sustainable development constitutes a normative framework for thinking as much as for action (Hart, 2002), which sets the necessity for a control of the negative externalities of economic growth. As such, the question of daily travel proves to be crucial. The objective of “sustainable mobility” consists in protecting both environment and health without decreasing the need for travel¹. As cities stand as a pertinent scale for the application of sustainable policies (Camagni et al., 1998), reaching the goal of

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¹ This formulation stems from a french national law, the LAURE of 1996, an equivalent of the american Clean Air Act.
sustainable mobility supposes that the share of the automobile in urban daily travels is reduced.

Beyond measures intending to reduce emissions or traffic, like car-sharing or incentives to use “soft” travel modes (walking or transit), an overall thought emerges, based on the interaction between urban form and travel patterns (Pouyanne, 2005). In the French city of Bordeaux, the P.D.U.² seeks to “act on the evolution of the urban morphology [to] limit automobile use and its foreseeable growth” (Cub, 2001: 31). The main goal is to control for urban sprawl, as it is supposed an interaction between automobile use and low-density settlement patterns.

- On one’s hand, automobile use has allowed to push back the boundaries of the city. The so-called Zahavi Law, which enounces that travel times are constant over time (Zahavi and Ryan, 1980; Gordon, Richardson and Jun, 1991; Levinson and Kumar, 1997), can be interpreted as follow: speed gains linked to automobile use were traded against an increase of the amount of liveable space through a more peripheric location (Dupuy, 1999; Gordon and Richardson, 1997). An Automobile City is shaped, which not only extends the urbanized area, but also fills in the empty spaces produced by the «fingerglove» structure of the Transit City (Newman and Kenworthy, 1998).

- On the other hand, the dispersed and low density urban form, which is a characteristic of sprawl, creates low levels of accessibility, and thus favours automobile use. Some authors talk about automobile dependence, stating that “use of an automobile became not so much a choice but a necessity in the Auto City” (Newman and Kenworthy, 1998: 31).

Thus automobile use has increased sprawl, as much as sprawl has expanded automobile use. That is why urban planification is oriented towards a control of urban sprawl, by means of bringing up to date urban revitalization (Breheny, 1995), or adopting “urban growth boundaries” measures (Dawkins and Nelson, 2002). The underlying model is the one of the “Compact City”.

The model of the Compact City is first based on empirical results. The well-known Newman and Kenworthy’s curve sets up, for thirty-two global cities, an inverse relationship between gasoline consumption per capita and net urban density (Newman and Kenworthy, 1989). Numerous studies confirm such a relationship, at an inter-urban scale (Naess, 1996; Cameron et al., 2003; Giuliano and Narayan, 2003; Cirilli and Veneri, 2008) as much as at an intra-urban scale (e.g. Fouchier, 1997; Cervero and Kockelman, 1997; Frank and Pivo, 1994).

Second, these converging results can be justified on a theoretical basis. Indeed, high densities allow:

- To improve overall accessibility. All other things being equal, more destinations are available at a given distance, which means shorter trip lengths (Fouchier, 1997). As a consequence, modal split is facilitated (Burton, 2000);

- An increase in congestion levels. What could be a drawback of density may be in fact an advantage: congestion decreases the comparative duration advantage of the

² Plan des Déplacements Urbains, a forecast planning document which focuses on the 5-years evolution of individual mobility and tries to plan it.
car in the denser parts of the city, and so incitates to the use of “soft” travel modes\(^3\);
- To increase the use of transit (Emangard, 1994; Iglesias, 2007), and to improve their economic efficiency (Kenworthy and Laube, 1999).

Nevertheless, the comparative advantages of the Compact City have been discussed (Pouyanne, 2004a: 9)\(^4\), sometimes vehemently. Densification measures are seen as “undesirable” (Breheny, 1997), as they go against the desire of a detached home (Gordon and Richardson, 1997), and because of the risks of crowding (Knight, 1996). Furthermore, a contradiction of the Compact City is due to the fact that people who pollute more are the ones which suffer less from emissions (Nicolas et al., 2001). At last, the raise in land values due to densification measures leads to the fear of a “compact city within a doughnut of decay” (Smyth, 1996).

The controversy about drawbacks and advantages of high densities is an old one (e.g. Le Corbusier, 1933), and it seems that there cannot be any consensus. Consequently, we may be led to consider not only density, but other dimensions of urban form. What is interesting is not only the intensity in land use, but, more generally, the way a parcel of land is used. Thus, the underlying issue is the interaction between land use and travel patterns. An intra-urban analysis is needed, to characterize more precisely the urban form, among others by taking in account land use mix.

In this paper we want to understand the relationships between land use and travel patterns, through the proposition of a specific statistical method and an application to the metropolitan area of Bordeaux (France). We first describe previous results of the research as far as the land use-travel patterns interaction is concerned. Then, we point out some methodological problems, which lead us to build up our own method of analysis. This method implies the adoption of adapted econometric techniques, which will be tested in the case of the metropolitan area of Bordeaux.

2. The land use – travel pattern interaction: previous results

The issue of the interaction between land use and daily mobility has been of growing interest among researchers. R. Ewing and R. Cervero (2001) list more than fifty empirical studies on that subject during the 1990’s. Mobility variables usually considered are: trip length, number of trips, modal shares and the number of kilometres travelled per capita, which is a rough estimation of gasoline consumption per capita. Urban form is usually measured through the “3D’s”: Density, Diversity (of land use), and Design (Cervero and Kockelman, 1997), that is both quantitative (density) and qualitative (land use diversity and urban design) dimensions.

2.1. Density

The influence of density on travel patterns is now well-known. We have noticed above how convergent the results are, at an inter-urban scale as much as at an intra-

\(^3\) Such a reasoning is based on the converse of the well-known Mogridge Conjecture (Mogridge, 1980).
\(^4\) The controversy around the Compact City model is also related in the book of M. Jenks et al. (1996).
urban scale. The Newman and Kenworthy (1989)’s curve has been verified: residential density and employment density have a negative influence on vehicle-miles travelled (e.g. Frank and Pivo, 1994; Frank et al., 2000; Krizek, 2003; Cameron et al., 2003), which can be explained by shorter trip lengths and a modal shift towards “soft” travel modes (Meunié and Pouyanné, 2007; Cirilli and Veneri, 2008)\textsuperscript{5}.

2.2. Diversity of land use

The practice of zoning raises trip length by generating “tunnel effects» (OCDE, 1994). \textit{A contrario}, diversity of land use is supposed to bring the origin and the destination of the trip closer. What is meant by \textit{diversity} is the functional variety of land use. Differences in measuring diversity come from divergences in the functions taken in account by the authors.

The simplest measure of diversity is given by R. Camagni et al. (2002) in their study on the metropolitan area of Milan (Italy). Two functions are considered: to live and to work. Then land use mix is the jobs-housing ratio. The jobs-housing balance influences negatively the ecological impact of mobility\textsuperscript{6}, which indicates “a growing impact with […] an increase of the residential content of a zone” (Camagni et al., 2002: 126).

Travel behaviours may not be the same according to the purpose of the trip: home-work trips are usually distinguished from commercial or leisure trips. As a consequence, some studies make a difference between retail and others jobs; then, the measure of diversity is based on the sectoral distribution of jobs. For example, D. Chatman (2003) tries to explain mileage traveled for commercial purpose by the proportion of retail jobs in the area, but he does not find any significant relationship. M. G. Boarnett and S. Sarmiento (1998) make a joint test of retail jobs density and service jobs density to explain non-work trips. They don’t obtain any significant result. G. Pouyanné (2006) makes a joint test of functional and economic diversity, and finds they both have an effect on mobility patterns.

An entropy index can be used to measure the diversity of land uses. L. D. Frank and G. Pivo (1994) show that the more specialized an area is, the less people walk to their job. R. Cervero and K. Kockelman (1997) use a “dissimilarity index”: for each spatial unit, it measures the proportion of adjacent unit whose use is different. With an elasticity of 0.11, the dissimilarity index is positively associated with the car-sharing rate.

For a same density, some “trip generators” can produce more travel because of a specificity in land use. In San Francisco, R. Cervero and K.-L. Wu (1998) note that the biggest increase of VMT occured in the most remote and the most rapidly growing subcenters. Thus we’re led to consider not only the local accessibility of a zone, but also the regional accessibility. K. Krizek (2003) shows that the regional accessibility index is negatively associated with the variation of total VMT, individual VMT, and tours. For J. Rajamani et al. (2003), regional accessibility increases the number of leisure trips.

\textsuperscript{5} In cities that are still characterized by a monocentric structure, this relation may widely be due to the influence of the distance to the center: some studies on french middle-sized cities show that trip length and automobile use raise significantly with the distance to the CBD (e.g. Hivert, 1998).

\textsuperscript{6} Measured through a synthetic index of the environmental impact of travel on the environment.
2.3. Design

Some authors have pointed out the influence of urban design on travel patterns. For example, M. Boarnett and R. Crane (2001) show that a grid-shaped street pattern raises the modal share of the automobile for non-work trips. At the contrary, the number of culs-de-sac is inversely correlated to walking (Rajamani et al., 2003). Some other urban design characteristics, such as parking disponibility (Naess and Sandberg, 1996) or the density of bicycle paths (Cervero and Kockelman, 1997), also influence travel patterns.

Studies presented here bring a comprehensive view of the urban form – travel patterns interaction. However, some methodological issues related to this question must be stressed. They constitute a basis to formulate an original statistical method.

3. The urban form – travel patterns interaction: methodological issues

The necessity to take in account the sociodemographic individual characteristics in the study of the urban form-travel patterns interaction raises a problem of causality between explicative variables. Then the usual conceptual framework, which establishes a strict distinction between the two types of factors of urban daily mobility, must be complemented: we propose our own theoretical framework, the “triangular relationship”.

3.1. Taking in account sociodemographic individual characteristics

Individuals’ sociodemographic characteristics influence travel behaviour. Income, for example, has an effect on automobile possession and use (Jullien, 2002). Level of education, age, household size, etc. set up a “lifestyle” which determines specific travel behaviours (Kaufmann et al., 2001).

In the analysis of the urban form-travel pattern interactions, it is necessary to take the influence of sociodemographic characteristics in account. The underlying conceptual framework is the L. S. Frank and G. Pivo (1994)’s one: they suppose a strict distinction between urban form factors and non urban form factors - such as individuals’ characteristics (cf. Figure 1). Technically, the last are labelled “control variables”, and they are simply added to the model. Studies sometimes distinguish a base model (with only urban form variables) and a full model (e.g. Boarnett and Crane, 2001; Boarnett and Sarmiento, 1998; Rajamani et al., 2003).

Figure 1: The conceptual framework for the analysis of the factors of daily mobility.
This method puts forward non-urban form factors of daily mobility, such as: income (with a possible quadratic effect – Boarnett and Crane, 2001; Rajamani et al., 2003); household size (positively associated with the number of tours – Krizek, 2003); the level of education (in Netherlands, the highest level of education is, the lowest automobile use is – Dieleman et al., 2002); gender (Boarnett and Sarmiento, 1998), etc. As a consequence, the integration of sociodemographic characteristics in the analysis is essential. Nevertheless, we’re faced with two types of methodological problems: multicollinearity and causality.

3.2. The problem of multicollinearity

In a technical point of view, most of the empirical studies on the urban form-travel patterns interactions reviewed here are based on cross-sections data. This kind of data often produces multicollinearity problems. For example, urban density may include numerous distinct influences: “Density has often been used to proxy a large number of excluded urban form variables” (Rajamani et al., 2003). Inside each group of factors, some correlations between variables may stand out, which produce a bias in the results: in case of multicollinearity, the OLS estimator is inefficient (Greene, 2000, 6.7). If some variables are strongly correlated in the model, results may be difficult to interpret: according to R. Cervero and K. Kockelman (1997: 203): “it is questionable whether many built environment variables will show up as statistically significant. This is partly because of the linearity between factors like neighbourhood densities, mixed use levels and pedestrian amenities”.

It raises the problem of a pertinent use of urban density as an explicative variable. How to interpret the influence of urban density on mobility variables? Is there an effect “hidden” by density? R. Cervero and R. Ewing (2001: 100) summarize this dilemma in the following terms: “an unresolved issue is whether the impact of density on travel patterns is due to density itself or other variables with which density covaries (central location, good transit service, etc.). [S.] Handy puts this issue this way: ‘many studies focus on density, but is it density that matters? No, probably not. Probably what matters is what goes along with density’.”. As a consequence, it becomes necessary to explain density to understand “what goes along” with it: “the explanation for density is itself an important yet often neglected part of the story” (Boarnett and Crane, 2001: 825). Some previous work by the author was based on such an approach (Pouyanne, 2004b).

Technically, the multicollinearity can be overcome by testing several small models. However, another problem remains: the fact that urban form factors and non urban form factors can interact by means of causal links.

3.3. The problem of causality

The Gary and Pivo’s conceptual framework (cf. Figure 1) supposes that the non-urban form factors and the urban form factors are separated: they have a distinct influence on travel patterns. However, we may suppose an interaction between these two kinds of factors. As a consequence, it seems difficult to isolate the respective influence of each one. According to R. Dunphy and K. Fischer, “the patterns [of higher levels of transit use and lower automobile travel in higher density communities] is not as clear cut because of the intervening relationship between density and the demographic characteristics of certain households” (cited in Boarnett and Crane, 2001: 824-825).
Some causal links between variables may stand out between the two groups of factors of mobility. We would be faced with complex relationships between travel behaviours and sociodemographic and land use characteristics, which produce logical uncertainty. Usual quantitative techniques don’t allow to bring out clear causal relationships. We share the S. Handy’s statement, for whom studies on the urban form-travel patterns interaction “reveal correlations between the built environment and travel behaviour but do not prove causality” (Handy, 2002: 15).

In the literature, the problem of the interactions between sociodemographic variables and urban form characteristics is only mentioned, without any attempt to overcome it. Yet it is essential to ensure the robustness of the results. The transfer from an empirically noticed correlation to a causal relationship must be made cautiously, as there could be a tierce factor intervening between the two terms of the correlation. That’s why the possibility of a causal link between urban form and sociodemographic characteristics is so important in studying the factors of daily mobility.

The Figure 2 shows the possibility of statistically significant noticed correlations between variables (bold type arrows) that could be explained by different causal relationships (normal type arrows). The link between individuals’ characteristics and urban form can be either a direct or an indirect relationship, that may allow us to complement the Gary and Pivo’s scheme (cf. Figure 1).

We illustrate these two kinds of causality thanks to the example of Bordeaux, a 801,309 inhabitants French metropolitan area. Data we use here is from the HTS (Household Travel Study) of 1998. This study has been conducted on 4,239 households. The study area was divided in 66 zones of different size, for which we had mobility data, sociodemographic data and land use data.

3.4. Direct causal links between sociodemographic characteristics and urban form

Individuals’ characteristics can determine the location in a specific environment. A direct causal relationship between sociodemographic characteristics and urban form can be described in the following way: (1) individuals’ characteristics determine their location in a particular urban form; afterwards, (2) such a location determine their travel behaviour, by virtue of the link between urban form and daily mobility.

The strong correlation between familial composition and travel behaviour seems to be of particular interest to illustrate the direct relationship between sociodemographic characteristics and urban form. Previous studies underline the influence of the number of children on modal shares (Rajamani et al., 2003), the influence of age on individual gasoline consumption (van Diepen and Voogd, 2001), the influence of number of employed people per household on modal shares (Dieleman et al., 2002), etc.
The noticed correlation between household size and travel patterns is usually interpreted this way: an increase in the number of children brings about an increase in the household’s mobility needs, possibly in the number of tours, an incentive to automobile use. Without denying the strong power of explanation of such an interpretation, we must put it into context: we can suppose that household size causes a location in a specific urban form, which in turns influences daily mobility patterns.

In the case of Bordeaux, we can notice that larger households are much more numerous in the peripheral, low density parts of the urban area. Inversely, the household size is smaller in the central, high density parts of the city. As a consequence, we can suppose a “location effect” on households’ travel behaviours. The Figure 3 shows a positive correlation between household size and the number of cars per household, and how sensitive to the values of human density this relationship is.

This “location effect” can be explained through two possible ways:

- **An amenity-based interpretation.** An increase in the household size may provoke a “flight from the center” behaviour, to protect one’s children from negative externalities traditionally associated with the CBD (pollution, lack of security, etc.) or to benefit from the positive amenities of the périphery. More generally, an increase of the age of the head of the household, which usually corresponds to an increase in income, may correspond to a peripheral location.

- **A real estate availability explanation.** Small flats appear to be more prevalent in central, high-density zones, while large-size homes (such as detached ones) are much more numerous in peripheral, low-density ones. Thus, small-size households will locate in the first ones, as large-size households will settle in second ones.

Thus the correlation between household size and mobility can either be a direct causal link, or an indirect one. In this last hypothesis, such a correlation comes from location behaviour of the household. We’re faced with a logical uncertainty, which means the impossibility to separate the cause and the effect: we can’t settle the “visible” causal link and the “hidden” one. We’re just able to notice a complex relationship between mobility variables and sociodemographic or urban form variables.

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7 Human density is the sum of residential density and employment density. It is used here, because it provides a good measure of the intensity of urban land use by human activities (Fouchier, 1997).

8 For this last type of explanation, we refer the reader to the « flight from blight hypothesis » literature (e.g. Carlino & Mills, 1987; Mills and Price, 1984).

9 Such an explanation supposes a specific structure of preference, which highlights detached houses in peripheral location. This hypothesis is usually of good help to explain american suburbanization (Mills & Lubuele, 1997), even if some studies try to go against this statement (Schlay, 1986). This structure of preference is less obvious in European cities (Brueckner et al., 1999).

10 R. F. Muth (1969) had already noticed such a phenomenon. It can be due to the dissociation between the density gradient and the rent gradient. While rent increases continuously, the rise in densities is affected by the durability of buildings: in European cities, some parts of the central city are protected of destruction because of their historical and aesthetic value. As a consequence, densities cannot adapt to the rise of the rent.
3.5. Indirect causal links between sociodemographic characteristics and urban form

The direct relationship between sociodemographic characteristics and urban form will be illustrated with the concept of self-selection, which “questions the direction of the causal relationship between urban form and travel” (Krizek, 2003: 268). The usual link between urban form and mobility is reversed: travel patterns determine location in a specific urban form. Choosing a specific environment to live would be partly due to individuals’ preferences on travel patterns: those who prefer walking, for example, may settle in dense, mixed-use locations because more destinations are available at walking distance. Thus, a wide selection of travel modes is an important criterion in the selection of the residential location: as suburban settlements are supposed “car-dependent” (Newman and Kenworthy, 1998), having a modal choice implies to live in dense, well-desserved areas.

If the location in a specific urban form depends on individuals’ preferences on travel patterns, then residential location is the result of a choice. But it can also be a constraint, due to economic and/or demographic characteristics: G. Dupuy (1999, 2002) has been underlying a tendency for populations who can’t afford an automobile (like students or unemployed people) to concentrate in the denser parts of the metropolitan area, where a modal choice is possible, to reach usual, dispersed destinations. A central location is constrained by the necessity to avoid automobile dependence.

Thus individuals’ characteristics have an effect on travel behaviours, which in turn influence the location in a specific urban form. We illustrate such a gregarious effect” in the case of Bordeaux. Populations who have a limited access to automobile are mainly unemployed people, students and retired people. The Figure 4 shows that the proportion of these populations is positively associated with the number of cars per

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11 This is consistent with the hypothesis of a «consumer city» where speed is one out of four «vital amenities» (Glaeser et al., 2000).

12 What is called the «gregarious effect» (Dupuy, 2002). Then we find usual results of the N.U.E, where a central location is wanted so as to minimize transport costs (and is counterbalanced by higher rents). Yet the justification is not the same, as for the N.U.E jobs are concentrated in the CBD. Here, jobs can be relatively dispersed in the metropolitan area, and what makes the center attractive is the fact that it is a transport node.
person, and negatively associated with human density. Furthermore, it exists an obvious negative relationship between human density and number of cars per person. Anew, we’re faced with a “systematic interaction” between mobility variables, and sociodemographic and urban form variables: it seems impossible to reveal causal relationships.

![Figure 4: The «gregarious effect» (the size of the circles is proportional to human density). Source: HTS 1998, treated by the author.]

3.6. The “triangular interaction”

We have brought to the fore two possible causal relationships between individuals’ characteristics and urban form: a direct one, and an indirect one. Our belief is that the Gary and Pivo’s conceptual framework of analysis of the determinants of mobility (cf. Figure 1), which separates urban form factors from non urban form factors, could be completed.

In order to determine the part of urban form in the whole set of factors of daily mobility, we propose to adopt an alternative conceptual framework, which is called the “triangular relationship” (cf. Figure 5). It takes in account the possibility of a systematic interaction between sociodemographic characteristics and urban form. The use of double arrows reflects our uncertainty as regards the direction of causality. Thus the three types of variables are linked by complex interactions. The “triangular relationship” is a kind of circuit for which, by definition, there is no causal theory (Mouchot, 2003: 172).

The adoption of the “triangular relationship” as a theoretical framework makes the analysis more complex, as if it is imposed by intellectual honesty. Thus, an empirical study only allows us to reveal interactions, not causal links. The solution to this problem is given by the “statistical control”: the objective is to control for one type of factor of the “triangular relationship”, so as to be able to isolate the effect of one type of factor on travel patterns. According to R. Cervero and K. Kockelman (1997: 201), “since complete statistical control is never fully introduced, any relationships that are uncovered are necessarily associative rather than causal.” In order to realize this statistical control, we built a specific statistical method which is presented in the following section. An application of this method to the metropolitan area of Bordeaux allows us to submit some results as far as the urban form-travel patterns interaction is concerned.
4. The urban form – travel patterns interaction: empirical results from an application to the metropolitan area of Bordeaux, France

4.1. Methodological insights: the “typological regressions” technique

**Sampling**. The first step of the “typological regression” technique is to sample the statistical population in homogeneous groups. The criterion we chose to make these group homogeneous is residential density. As density is recognized to have a strong influence on travel behaviours, our aim is to understand “what goes along with density”. The population of geographical areas was divided in three groups, labelled low density, medium density, and high density (see map).

**Constrained regressions**. We adapted a standard econometrical method to our subject: the constrained regressions technique. The same variables are used to build a constrained model (CM, where the coefficients are the same whatever the group) and a non-constrained model (NM, where the coefficients are different for each group):

\[ y_i = \sum_{k=1}^{66} \sum_{h=1}^{3} \alpha_{h,k} \cdot z_{i,h,k} + \varepsilon_i \]

**NM**:
\[ y_i = \sum_{k=1}^{66} \sum_{h=1}^{3} \alpha_{h,k} \cdot z_{i,h,k} + \varepsilon_i \]

**CM**:
\[ y_i = \sum_{k=1}^{66} \sum_{h=1}^{3} \alpha_{h,k} \cdot z_{i,h,k} + \sum_{k=1}^{66} \sum_{h=1}^{3} \alpha_k \cdot z_{i,h,k} + \varepsilon_i \]

Where \( y_i \) is the explained variable, \( \alpha_{h,k} \) is a coefficient vector indexed in \( h \), the density category, \( z_{i,h,k} \) the matrix of the \( k \) explicative variables. The \( \varepsilon_i \) are the error terms, with the usual properties. Linear restrictions are imposed on the explicative variables indexed in \( l \).

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13 As the number of observations was very low, we made an exogenous partition: each group has roughly the same number of observations, so as their size is sufficient to produce significant results.
We test the significativity of the constraints:

\[ H_0: \alpha_{h,k} = \alpha_k \]

either for every k, nor for some values of k.

We build a \( F \)-statistic which follows a Fischer-Snedecor law. This test is about the same as the structural stability ones (the so-called “Chow” tests). The difference is that we seek to analyze spatial stability instead of temporal one. \( F \) is defined as follow:

\[
F(a,b) = \frac{\left( \sum_{i=1}^{66} (\varepsilon_{i,MC})^2 - \sum_{i=1}^{66} (\varepsilon_{i,MNC})^2 \right) / a}{\sum_{i=1}^{66} (\varepsilon_{i,MNC})^2 / b} \rightarrow F(a,b)
\]

where \( \varepsilon_{i,MC} \) are the constrained model errors, \( \varepsilon_{i,MNC} \) are the non-constrained model errors (with usual properties), \( a \) is the number of linear constraints, et \( b \) the number of degrees of freedom of the model.

According to the value of \( F \), we will reject or not the hypothesis of a differentiated effect of the explicative variable on the explained variable, according to the group of density. As different models are in competition according to the number of linear constraints, the choice of the final model is based upon the quality of the adjustment, that is the level of the adjusted-\( R^2 \) and the Akaike criterion.

4.2. An empirical study of the metropolitan area of Bordeaux

In the urban form – travel pattern literature, four mobility variables are usually explained: number of travels per day per person; trip length (in km); modal share; and VKT (Vehicle-kilometers travelled) per capita, which we consider here as a proxy for the gasoline consumption per capita. As the latter variable is the outcome of the other ones, some comments will explain VKT per capita by the number of travels and the trip
length. We excluded the modal shares, because their analysis need the formulation of a
 discrete choice model (de Palma and Thisse, 1987), for which the typological
 regressions technique is unsuited. We added the number of cars per person. We
distinguished between home-work trips and non home-work trips, as they’re supposed
to stand out from distinct travel behaviours.

To avoid multicollinearity between explicative variables, we built separate models. The “urban form model” includes residential density, the standard error of the
residential density, and two land-use mix variables: the jobs-housing balance, and a
sectoral mix khi-square index. The “size model” includes total population, average
size of the firms, liveable surface per person, household size. The “income model”
comprises medium income, age, and proportion of college graduates in the population.
The last one is the “type of population” model (unemployment rate, proportion of
retired people, people under 18, students, and women in the population). The results of
the regressions are presented in the Table at the end of the paper.

The “Urban Form” Model

As far as home-work trips are concerned, the usual hypothesis of a negative impact of
residential density on gasoline consumption per capita is corroborated in the low- and
medium-density zones. In low-density zones, it can be explained by a lower number of
trips per person, and by shorter trip lengths (cf. Table). In the medium-density zones,
this impact is explained by a modal share in favour of “soft” modes. In the high-density
zones, residential density has no significant influence on the individual gasoline
consumption, nor the trip length, nor the number of trips: in the central parts of the city,
density has no influence on travel patterns.

The influence of density is more often significant for home-work trips than for non
home-work trips. Indeed, home-work trips are more scheduled, and a modal shift can be
made easier; commercial and leisure trips usually represent more complex travel
patterns, like multi-purpose ones, for which the flexibility of the automobile is more
adapted.

Whatever the motive of the trip is, the influence of the distribution of residential
density on gasoline consumption is only significant for low-density zones. Surprisingly,
the sign of the coefficient is inversed according to the motive of the trip. The
interpretation may be as follow:

For home-work trips, the more the distribution of residential density is homogenous, the lower
individual gasoline consumption is. An homogenous distribution of residential density may
make the co-location of homes and workplaces easier;
For non home-work trips, the more the distribution of residential density is heterogenous, the
lower individual gasoline consumption is. This result is in line with usual arguments about the
drawbacks of a diffuse pattern of housing – or the advantages of the “polycentric network
city” (Camagni and Gibelli, 1997). Such a model indicates that relevant planning places exist
for transit, by standing bus lines against the peripheral concentrations of housing, following
the principles of Transit-Oriented Development (Laliberté, 2002).

The different models were built on two criterions: the 5% significativity of the Pearson coefficients,
and a Tolerance superior to 0.3.

Built upon the 36 sectors division made by the INSEE (National Institute of Statistic and Economic
Studies).
As far as the land use mix is concerned, we’ll notice two main results. First, the jobs-housing balance has a positive influence on gasoline consumption per capita (which is contrary to Camagni et al. (2002)’s results). A high jobs-housing balance in a given zone may raise individual number of trips, as there are more opportunities around home (see the sign of the coefficient); as a consequence, a high jobs-housing balance may influence the gasoline consumption via the number of trips per person, and not via trip length, as some authors have suggested (Cervero and Wu, 1998; OCDE, 1994).\(^{16}\)

Furthermore, the more residential a zone is, the higher car owning is. This result is in line with usual comments about residential use, which prompts people to use a car, as destinations (jobs) are further away. The coefficient is the same whatever the group of density is, which means that the effect of residential specialization on the number of cars is not differentiated along with the category of density, when number of studies on car-dependent land use patterns usually point out a high automobile dependence in peripheral, low density zones, where detached housing is predominant.

Second, the positive influence of sectoral specialization on gasoline consumption per capita (for home-work trips only) is in line with the hypothesis of a link between land use mix and travel patterns (cf. supra): the more economically specialized a zone is, the higher individual trip length by car is. This effect is undifferentiated according to the group of density, which means that we can’t rely this result to an economic specialization of the peripheral zones.\(^{17}\) Some elements on the differentiated impact of the type of specialization on travel patterns can be found in G. Pouyanne (2006).

**The “size model”**

As far as firm size is concerned, there is a positive relationship between firm size and gasoline consumption per capita in low-density zones. It can be explained by greater trip lengths. Here, the analysis of travel patterns is in line with the fact that the larger firms have a strong tendency to suburbanize first, because they have greater needs in space, which is more affordable in peripheral zones (Fujita and Ogawa, 1982).\(^{18}\)

In the overall model, household size has a positive influence on gasoline consumption. But as soon as we sample according to density, such an influence becomes insignificant. This result corroborates strongly the above hypothesis of an interaction between density and household size, for reasons linked to the size of the homes and their spatial repartition. Density and household size covary, and traditional methods can’t distinguish which has the strongest influence on travel patterns. Here, our method of typological regressions seems to reach its goal: the statistical control of density allows to establish that household size doesn’t have an influence by itself on travel patterns – its influence “goes along with density”.

\(^{16}\) Nevertheless, it is difficult to linken jobs-housing balance to the degree of land-use mix, as this variable is used most of the time to detect peripheral job centers (Cervero, 1989).

\(^{17}\) Furthermore, in the case of the metropolitan area of Bordeaux, F. Gaschet (2001) has showed that economic specialization is valid for peripheral zones as well as for central ones.

\(^{18}\) If there is a transport infrastructure to provide a good accessibility to these firms, and that these firms don’t need complex interactions (as face-à-face ones), like back-office or industrial activities. Otherwise, they may stay in the CBD (Ota & Fujita, 1993).
The “income model”

Income has a negative influence on gasoline consumption per capita for non home-work trips, which can be interpreted by the potential, for richer people, to settle near natural amenities. Furthermore, income has a negative influence on trip length, which corroborates the co-location hypothesis: richer people, thanks to their stronger bidding power, have the potential to locate near their workplace (Gordon *et al.*, 1991; Krizek, 2003).

The influence of median age is negative on trip length as well as on number of travels per capita. It may have two possible explanations. First, a “location effect”: as age increases, people may have a tendency to use less their automobile, and to locate nearer from places they go to. Second, an “urbanization effect”: home-owners, as age increases, are more and more in a central location, because the city expands.

The hypothesis of a specific structure of preference is tested thanks to the proportion of College graduates in the population. We note that its negative influence on VKT per capita (home-work trips), trip length and number of cars per person is not significative after having controlled for density. It means there is a mediation of urban form on this influence: college graduates have a tendency to concentrate in denser parts of the city, but don’t have a specific mobility behaviour.

The “type of population model”

Thanks to the “type of population” model, we try to test the validity of the “gregarious effect” hypothesis, which supposes that people who don’t have access to an automobile (such as retired people, students, poorest people…) may locate in the denser parts of the city, because it’s easier to use an alternative travel mode, such as transit or walking (see above). Our results confirm a weaker access of such populations to the car, as the coefficients for number of cars per person are all negative. But we cannot confirm a gregarious effect in terms of trip length, number of travels (except for retired people), or gasoline consumption. That is, if the type of population has an effect on car possession, it doesn’t have an effect on car use.

5. Conclusion

The debate on the model of Compact City, following the very controversial P. Newman and J. Kenworthy (1989)’s book, *Cities and Automobile Dependence*, has quickly ended up at a very general controversy about the advantages and the drawbacks of urban densities. This long-time questioning seems to be condemned to slip towards a confrontation of value judgement, as we don’t (and we will probably never) know if cities must be built vertically or not (Breheny, 1997). As such, the debate is in the deadlock.

However, a problem without solution may be a badly formulated problem: the debate has turned to an investigation of the interaction between land use and travel patterns. The copious literature on this subject has allowed to make some progress, on the ground of the method as well as on the ground of empirical results. Numerous urbanistic
realizations or urban plans, aiming at reducing automobile use, were based on the progress made by this kind of literature.

This paper is based on the idea of a systematic interaction between the factors on daily mobility: There are complex interactions between the individual (sociodemographic characteristics), its environment (urban form characteristics), and its behaviour (the travel patterns). This framework presses to the use of a specific quantitative method. As was noted in other contributions (Cervero and Kockelman, 1997; Handy, 2002), progress can’t be made without “statistical control”. We built an econometric method, the “typological regressions”, which allows to control for a factor by sampling the population according to a specific factor. Here, the objective is to control for density, so as to understand the influences that “goes along with density”.

Three important results can be taken from this empirical investigation on the metropolitan area of Bordeaux. First, the influence of urban form. The influence of density on travel patterns is corroborated, which confirms the traditional advantage of the “Compact City” model. What’s more, the influence of the distribution of densities in a given zone shows the relevance of the Polycentric Network City. Thus, urban policies may tend to raise densities and to follow the principals of the Transit Oriented Development. Second, our results corroborate some important hypotheses in the literature, such as the “gregarious effect”, and the “co-location hypothesis”. However, the hypothesis of the impact of land use mix on travel behaviour needs further investigation. Third, on a methodological ground, the analysis of household size shows that the method of “typological regressions” is particularly well fitted to disentangle urban form and sociodemographic factors of daily travel. As such, we hope that such methodological and technical considerations will be more taken in account in the literature, as, for example, Lin and Yang (2009) has recently tried to do.

References

Cervero, R. (1989) America’s suburban centers. The land-use transportation link, Boston, Unwin Hyman.


### Table 1: Results of the typological regressions for the metropolitan area of Bordeaux.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Overall Model</th>
<th>Low-density zones</th>
<th>Medium-density zones</th>
<th>High-density zones</th>
<th>Overall Model</th>
<th>Low-density zones</th>
<th>Medium-density zones</th>
<th>High-density zones</th>
<th>Overall Model</th>
<th>Low-density zones</th>
<th>Medium-density zones</th>
<th>High-density zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>VKT (gasoline consumption) per capita (purpose: home-work)</td>
<td>3.574</td>
<td>8.419</td>
<td>5.596</td>
<td>3.588</td>
<td></td>
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<tr>
<td></td>
<td>5.929</td>
<td>8.055</td>
<td>4.754</td>
<td>3.277</td>
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<tr>
<td>Residual density</td>
<td>-0.029</td>
<td>-1.844</td>
<td>-0.163</td>
<td>-0.012</td>
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<tr>
<td></td>
<td>-6.407</td>
<td>-4.930</td>
<td>-2.506</td>
<td>-1.206</td>
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<tr>
<td>s.e. of density (non-normalized)</td>
<td>-0.006</td>
<td>0.177</td>
<td>0.030</td>
<td>-0.008</td>
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<td>-0.018</td>
<td>2.226</td>
<td>1.586</td>
<td>0.558</td>
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<tr>
<td>Jobs-housing Balance</td>
<td>1.431</td>
<td>1.523</td>
<td>0.659</td>
<td>0.297</td>
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<tr>
<td></td>
<td>5.799</td>
<td>4.574</td>
<td>2.263</td>
<td>1.513</td>
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<tr>
<td>Sectorial Specialization</td>
<td>7.198</td>
<td>3.957</td>
<td>3.957</td>
<td>3.957</td>
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<td></td>
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<td></td>
<td>3.845</td>
<td>2.697</td>
<td>2.639</td>
<td>2.639</td>
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<tr>
<td>Adj. – R² (Akaike)</td>
<td>0.645</td>
<td>0.795 (4.215)</td>
<td>0.532</td>
<td>0.746 (5.620)</td>
<td>0.185</td>
<td>0.709 (3.907)</td>
<td></td>
<td></td>
<td>0.049</td>
<td>0.2804 (1.077)</td>
<td>0.589</td>
<td>0.668 (2.251)</td>
</tr>
<tr>
<td>N</td>
<td>66</td>
<td>22</td>
<td>23</td>
<td>1</td>
<td>66</td>
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</tbody>
</table>

Note: The t-ratios are in italics; significant coefficients (at a 5% level) are in bold type.
### Table 2: Results of the typological regressions for the metropolitan area of Bordeaux (to be continued).

<table>
<thead>
<tr>
<th></th>
<th>VKT (gasoline consumption) per capita (purpose: home-work)</th>
<th>VKT (gasoline consumption) per capita (purpose: residential, leisure)</th>
<th>Trip length (km)</th>
<th>Number of travels per day per capita</th>
<th>Number of cars per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overall Model</td>
<td>Low-density zones</td>
<td>Medium-density zones</td>
<td>High-density zones</td>
<td>Overall Model</td>
</tr>
<tr>
<td>Intercept</td>
<td>50,552</td>
<td>14,665</td>
<td>4,447</td>
<td>-0.090</td>
<td>19,138</td>
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<td>Income (1000s)</td>
<td>2.017</td>
<td>1.377</td>
<td>0.344</td>
<td>-0.011</td>
<td>1.956</td>
</tr>
<tr>
<td>Age</td>
<td>0.019</td>
<td>-0.011</td>
<td>-0.028</td>
<td>-0.012</td>
<td>0.025</td>
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<tr>
<td>College</td>
<td>-9.433</td>
<td>-0.038</td>
<td>0.125</td>
<td>0.111</td>
<td>-0.198</td>
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<tr>
<td>Graduate</td>
<td>-16.27</td>
<td>-18.04</td>
<td>5.023</td>
<td>5.328</td>
<td>-9.384</td>
</tr>
<tr>
<td>Adj. – R² (A)</td>
<td>0.177</td>
<td>0.167</td>
<td>0.563</td>
<td>0.011</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Note: the t-ratios are in italics; significant coefficients (at a 5% level) are in bold type.