Urban Form and Travel Patterns: An Application to the Metropolitan Area of Bordeaux

G. Pouyanne
IERSO, IFReDE-GRES
Université Montesquieu-Bordeaux IV
33608 Pessac (France)

“Trips result from urban layout (...). The opposite is true too, i.e. urban layout results from the ‘conditions’ of mobility (...). We are in an interactive system where what is the most permanent – the constructed environment – and what is the most ephemeral – mobility – permanently shape each other, following a continually evolving process which is holistic (everything interacts on everything) and continuous (long term). This reciprocity (...) constructs the city itself.” (Translation by the author)

M. Wiel, Ville et Automobile, 2001

Introduction

Sustainable development is a normative framework which has justified bringing the negative externalities of economic growth under control, such as pollution due to transportation (Hart 2002). This concern has led to questioning the role of the automobile, as it is the most polluting mode of transportation. To date, various policies, ranging from interventions involving coercion to those involving incentives, have been implemented to reduce automobile use.

As the theorem of locality states, cities represent an efficient scale at which to promote sustainability policies (Camagni et al 1998: 109-110). Amongst these

* The author wishes to thank the two anonymous referees for their constructive comments on a previous version of this paper.
The underlying issue relates to the link between transportation and land use. If town planning is an appropriate tool to reduce the use of automobile in cities, then we must know how urban form affects travel patterns. Urban form reflects the way people use urban land: "the spatial locations of urban components seem like pawns which could form a shape on a chessboard but their meaning can only lie in the interrelationships that exist between them" (Wiel 2001: 22 – author's translation). Its outward sign is the spatial distribution of people and functions in the urban area. The way it is generally measured includes densities and degree of land use mix.

The purpose of this paper is to contribute to the debate on the interaction between urban form and travel patterns. The analysis of the determinants of travel behaviour combines two main sets of factors: urban form, and economic and demographic characteristics, usually regarded as independent. We suppose that these factors are interrelated, and we formulate an original conceptual framework for the analysis of urban form-travel pattern interactions, the so-called 'triangular interaction'. As a consequence, the analysis of the factors underlying travel behaviour must be completed by the analysis of the links between these factors.

The Interaction between Urban Form and Daily Travel

The Advantages of Urban Density

Past research findings

Numerous studies establish the impact of urban density on daily travel, at an intra-urban scale as well as an inter-urban scale. The link between density and automobile use at an inter-urban scale is illustrated by the Newman and Kenworthy's curve (Newman and Kenworthy 1989). They used a global comparative study of thirty-two cities to show a reverse relationship between urban density and gasoline use per capita. Numerous studies establish the impact of urban density on daily travel, at an intra-urban scale. The Newman and Kenworthy's curve (1989) points out the necessity of owning an automobile in recently urbanized, low density areas (Newman et al 1995). As a consequence of this interrelation, sprawl can be said to be an 'expensive form' of urban growth (Downs 1994).

The model of the 'compact city' aims at thwarting the city's tendency to spread out -- it is seen as a 'sustainable urban form' (Jenkins et al 1996). Measures to encourage compaction, such as urban containment, are supposed to be an efficient way to reduce automobile use, and hence pollution, in cities. The notion of the compact city has underlain the planning policies of numerous countries in Western Europe such as Netherlands (van der Walk 2002), Great Britain (Breheny 1995) and France (see the Law on a rational use of energy (LAURE) in 1996 and the SRU law in 1999). As illustrated in the case of London, numerous European cities have adopted special measures to combat automobile use. They include a strong commitment to land planning (2001 Plus 2002); in Bordeaux for example, the PDU (Urban travel plan) aims at "having an effect on the evolution of urban morphology so that automobile use and its foreseeable growth could be limited" (C.U.B 2000: 31, author's translation).

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Moreover, the link between density and energy use per capita seems to be valid at an intra-urban scale. Fouchier (1997) highlights the impact of different kinds of densities on daily energy consumption per capita in the cities in Ile-de-France (the region surrounding Paris), and Nicolas et al (2001) obtain similar conclusions regarding the metropolitan region of Lyon (France), noting important differences in polluting emissions between the traditional centre, the inner city and the outer city. Recent studies show that urban density has a negative impact on trip length or kilometres per capita (e.g. Cervero and Koedelmen 1997) for 50 households in the San Francisco Bay Area; Frank et al (2000) for 1,680 households in Seattle; and as well as on automobile use (e.g. Frank and Pivo 1994) for 1,680 house-
holds in Seattle; and Rajamani et al (2003) for 369 households in Portland, Or.).

Theoretical justifications

These empirical relationships need to be justified on a theoretical basis. The underlying idea is that high density settlements represent a 'hostile milieu' (using the words of A. J. Scott) for the automobile. It appears that high densities allow:

- Better accessibility and hence shorter trips (Fouchier 1997; Levinson and Kumar 1997), as there are more destinations available at a given distance from the origin of the trip.
- An easier modal split towards ‘soft’ ways of travelling such as transit and/or walking (Burton 2000; Frank and Pivo 1994).
- More efficient transit (see Emangard (1994) for an analysis of the larger French cities; and Kenworthy and Laube (1999) for a global cost comparison).

A critical view of the density-daily travel interaction

Indeed, density and accessibility can be seen as synonymous, which would explain the above results as well as provide a theoretical underpinning. However, defining accessibility as different from temporal proximity (as the Zahavi law suggests us to do), means accessibility and density are no longer equivalent (Emangard 1998).

Beyond such criticisms of the relationship between density and daily travels, other criticisms have been raised about the advantages of the Compact City as well as about the feasibility of compaction measures. The main argument is that urban sprawl is a consequence of specific consumers’ preferences: suburbanization has been caused by the desire for more liveable space (e.g. Gordon and Richardson 1997). From this perspective, the planning of greater urban density is in conflict with a spontaneous tendency to increase urban sprawl, and may be inefficient or even perverse (Breheny 1997).

Furthermore, compaction policies may not avoid the risk of crowding, which would decrease people’s well-being (Knight 1996). Finally, compaction measures raise the price of land (Dawkins and Nelson 2002), with negative social implications, such as the possible formation of ‘a compact city within a doughnut of decay’ (Smyth 1996).

The feasibility of compaction policies has been questioned as well. Gordon and Richardson (1997) notice the lack of efficiency of many policies of urban renewal. According to them, the objective is not to minimize gasoline consumption per capita, but to maximize social well-being. To reach that goal, they suggest that a system of prices which reflects the ‘real’ cost of resources would be more efficient than planning measures. The problem of the appropriate tools is crucial, since we do not know how to compact the city. For example, urban containment policies may lead to ‘leapfrog’ development, and therefore increase sprawl (Breheny 1997).

These criticisms necessitate one to go further than arguments based on the advantages and drawbacks of high densities, which has long been disputed in the history of urban planning without arriving at any convincing conclusion (Choay 1965). The underlying question is how urban form influences travel behaviour. A growing literature has been devoted to this subject at an intra-urban scale. It requires determining the contribution of land use characteristics to the whole set of factors underlying daily mobility.

A Search for the Factors of Urban Mobility

The characterization of urban form and its link with urban mobility

The exploration of the link between travel and urban form has been the subject of more than fifty recent empirical studies (Ewing and Cervero 2001), demonstrating urban researchers’ great interest in this field. The need to go beyond the opposition between high and low densities has led to characterizing urban form more precisely. New variables have been introduced, such as:

- The degree of land use mix between dwellings and workplaces: It has been suggested that zoning generates ‘tunnel effects’ which increase trip lengths (OCDE 1994). A contrario, mixed land use patterns should bring residential location closer to the workplaces (Wiel 2001).
- Number and type of jobs: The aim here is to distinguish retail jobs from service or manufacturing jobs, as it is generally assumed they do not have the same influence on travel behaviour. Yet Bournett and Sarmiento (1998) find no significant relationship between retail density or service density and number of non-work automobile trips. Nevertheless, it seems that this kind of analysis is quite rare, and results are still awaited.

The interaction between land use and mobility is biased by different kinds of ‘trip generators’, most notably employment sub-centres. In their study of the San Francisco Bay Area, Cervero and Wu (1998) find that the largest increase in VMT (vehicle-miles travelled) occurred in the fastest growing and most remote sub-centres.

These studies show that - more than the criticisms of the validity of global

4. Which measures the environmental impact of daily travel
comparisons of cities, which state the logical impossibility of comparing cities from different countries (Gordon and Richardson 1989; Gomez-Ibáñez 1991) - the need for more precise characterization of urban form has led to a reduction of the pertinent scale of analysis (e.g. it seems difficult to measure the degree of land use mix at a metropolitan scale). It is generally assumed that 'within a relatively homogenous area (...), the local differences in mobility patterns can, at least to a lesser extent, be attributed to the form in which urban growth has occurred' (Camagni et al 2002: 206). Thus, the interaction between urban form and travel is generally analyzed at the intra-urban scale.

The New Urbanism movement tends to be inspired by these results to design neighbourhoods that reduce automobile use and improve quality of life. This can be achieved by planning 'compact, pedestrian-friendly and mixed-use neighbourhoods', with 'interconnected street network', and 'concentrations of civic, institutional, and commercial activities (...) embedded in neighbourhoods and districts' (C.N.U. 2001). As such, New Urbanism is situated in the continuity of European urban planning principles which founded the ideal of the 'compact city'.

The exploration of the link between mobility and urban form has been enhanced not only by characterizing the urban form more precisely at an intra-urban level, but also by accounting for socio-economic characteristics that may have an impact on travel behaviour.

Taking in account individuals' characteristics:
A conceptual framework to understand the determinants of daily travel

Individual economic and demographic characteristics have long been recognized as influencing travel behaviour. Despite the democratization of the automobile in Western Countries, income is still a key factor in being able to afford and use an automobile (Jullien 2002; Dieleman et al 2002). Moreover, differences in automobile use (and, more generally, in travel patterns) across characteristics such as gender, level of education and age have been observed many times (e.g. Kauffman et al 2001).

Studies of the link between urban form and mobility must take these influences into account. Thus, economic and demographic variables are simply added to the model (Boarnett and Crane 2001; Boarnett and Sarmiento 1998; Frank and Pivo 1994). The underlying conceptual framework has been proposed by Frank and Pivo (1994) (see Figure 1). Here, the 'non-urban form factors' include economic and demographic characteristics as well as individual preferences.

It seems logical that economic and demographic variables are important in explaining mobility patterns. Income is obvious but there is also other variables. The size of households is important. Krizek (2003) found the number of children had a positive influence on the number of trips in Puget Sound. Also, Boarnett and Crane (2001) found the same for non-work automobile trip frequency in San Diego. The level of education and gender have also been found significant. In the Netherlands, Dieleman et al (2002) show that people with higher education levels tend to have lower car use. And, Boarnett and Sarmiento (1998) found the proportion of women in the population has a positive influence on the number of non-work automobile trips.

Nevertheless, such a conceptual framework does not account for the possible interactions between variables in two ways:

- **Inside** each group of factors, we are faced with a problem of multicollinearity. Urban density, which is a synthetic indicator, interacts with other urban form variables. As Ewing and Cervero (2001: 100) write, '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 is difficult to know which variable has the strongest explanatory power. It is possible to overcome this problem by testing several explanatory models (Krizek 2003; Dieleman et al 2002), as carried out below.

- **Between** each group of factors, we are faced with the difficulty of identifying explicit causal links. We cannot override the fact that location in the metropolitan area is determined by economic (such as income) or demographic (such as household size) characteristics of the inhabitants, which interact with individual preferences. So, a problem of interpretation arises. Even if we accept a relationship between urban form and mobility, how can we know that the underlying causes of this relationship are not based on economic and/or demographic characteristics? It is only possible to 'reveal correlations between the built environment and travel behaviour but not [to] prove causality' (Handy 2002: 15). The solution is to understand the interaction between economic and demographic characteristics and urban form: 'The explanation for density is itself an important yet often neglected part of the story' (Boarnett and Crane 2001: 825).
Thus, travel patterns at an intra-urban level are the result of both urban form factors and economic and/or demographic factors, just as economic and/or demographic characteristics interact with urban form. These complex interactions form a 'triangular relationship' (Figure 2), which is an adaptation of the Gary and Pivo's framework (Figure 1). The 'triangular relationship' is a kind of circuit, where everything interacts with everything. Note the systematic use of double arrows, showing the uncertainty about the direction of the causal links.

This framework constitutes a basis for our empirical method. It is useful in understanding urban daily mobility. We have investigated this issue within the context of the metropolitan area of Bordeaux (France), a medium size city of about 800,000 inhabitants. The work reported is original in that, in addition to testing the usual factors of travel patterns (the two oblique arrows in Figure 2), we try to take account of 'what goes along with density' by testing interactions between urban form and economic and/or demographic characteristics (the horizontal arrow in Figure 2).

**Data and Methodology**

The Household Travel Study (HTS) is a survey conducted on the metropolitan area of Bordeaux and is aimed at gathering detailed data on inhabitants' travel habits. It was conducted in 1998 by the Regional Direction of INSEE (The Institut national de la statistique et des études économiques - French Statistics' Office), and involved 4,869 households.

The metropolitan area of Bordeaux consists of 170,547 ha, 95 communes (a municipality), and 801,309 inhabitants in 1998 who lived in 343,406 households and held 266,013 jobs that were provided by 50,279 firms. The study area was divided in 66 zones of various sizes.

We grouped variables into three categories: transportation, economic & demographic, and land use (see table A1 in the Appendix for details).

**Transportation Variables**

The four key transportation variables are: trip frequencies (rates of making trips); trip lengths (in distance); modal split; and the individual number of kilometres travelled per capita, which is a product of the first three. We distinguished between home-work travel (first purpose) and commercial and leisure travel (second purpose). We added car ownership to this set, and per household variables (for trip frequencies and car ownership only), because the comparison between per capita and per household variables allowed us to take into account the influence of the size of household.

To avoid multicollinearity problems (see above), we tested several separate models, built on the basis of the 5% significance levels of the Pearson correlation coefficient.

**Land Use Variables**

The land use variables were divided into two 'land use models':

- A general 'urban form model', which includes density, a mix of uses and jobs distribution indices. Population and firm densities were tested. Following Frank and Pivo (1994), the regressions use residential density (RESDEN) for kilometres travelled from the trip origin zone, and firm density (FIRM­DEN) for the kilometres travelled towards the trip destination zone. To measure the degree of land use mix, we calculated a khi-index (KHITOT, which corresponds to Gary and Pivo's approach mentioned above) and the jobs/housing ratio (JHBAL, which conforms with Camagni et al's approach mentioned above). We added a 'functional mix index' (FUNCMI) calculated on the ground of the jobs-housing ratio (see Appendix for detailed calculation). We distinguished two types of jobs: retail (proximity) and service/manufacturing (others), on the ground of their ability to induce trips, and calculated a khi-index (KHIPROX and KHIOTHER) to evaluate their distribution in a given zone compared to the overall distribution.
- A 'housing type model', which includes the proportion of the four types of housing in total housing (detached isolated houses, clustered houses, low-rise buildings and high-rise buildings), and an indicator of crowding (PEOPRO-
Economic and demographic Variables

The economic and demographic variables formed three models. Each of which were tested:

- a 'lifecycle model': this combines age (AGE, in years), the level of income (INCOME, in thousands of francs), and the level of education (COLLEDUC, the proportion of highly educated people);
- a 'type of population model': this combines rates of unemployed and retired people (respectively UNEMPL and RETIRED), minors (MINOR), students (STUDENT) and women (SEX) in the total population;
- a 'size model': this includes household size (HHSIZE, people per household), firm size (JOBFIRM, number of employees per firm), the total population in the zone (POP) and the floorspace per capita (SURFPEOP, in m²).

Important Issues and Preliminary Observations

Based on the general problem outlined earlier, we seek to determine the factors underlying daily travel patterns. The method is to test separately the two land use models and the three economic and demographic characteristics models. The technique we used is OLS regression.

When the dependent variable is the set of modal shares, the appropriate technique is a multinomial logit model, as modal shares are the result of a choice (DePalma and Thille 1987). Such a model rests on the hypothesis of a perfect substitutability among travel modes. However, there are cases when substitutability does not hold. For example, in areas where there is no transit supply, or from a given distance threshold (Salomon 2001). Multinominal models require a reference dependent variable, which in this study is the modal share of the car. The coefficients themselves have no meaning, only their sign is significant (Thomas 2000). The regression results are shown in Tables 1 to 4.

An important issue in this research is to account for the interaction between the location in a specific urban form and the economic and demographic characteristics, as it constitutes an 'unresolved issue' in this field (see citation above). We

5. We used the White correction to avoid problems of heteroscedasticity (see Greene 1999: 547-549).
TABLE 2 Multinomial Logit Model of Modal Choice for Urban Form – Mobility Interaction

<table>
<thead>
<tr>
<th></th>
<th>CARSHARE</th>
<th>TRANSIT</th>
<th>WALK</th>
<th>BICYCLE</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.334</td>
<td>-1.341</td>
<td>-2.580</td>
<td>-2.304</td>
<td>-1.733</td>
</tr>
<tr>
<td>(12.363)</td>
<td>(13.002)</td>
<td>(-18.107)</td>
<td>(-16.706)</td>
<td>(-17.528)</td>
<td>(-13.957)</td>
</tr>
<tr>
<td>RESDENS</td>
<td>-0.765**</td>
<td>-0.002</td>
<td>0.014</td>
<td>-0.017</td>
<td>-0.065</td>
</tr>
<tr>
<td>(0.508)</td>
<td>(9.545)</td>
<td>(15.819)</td>
<td>(3.014)</td>
<td>(3.002)</td>
<td></td>
</tr>
<tr>
<td>FIRMRESDENS</td>
<td>-0.002</td>
<td>0.095</td>
<td>-0.118</td>
<td>-0.064</td>
<td>-0.163</td>
</tr>
<tr>
<td>(0.129)</td>
<td>(8.458)</td>
<td>(13.398)</td>
<td>(3.979)</td>
<td>(-2.582)</td>
<td></td>
</tr>
<tr>
<td>JHHAL</td>
<td>0.026</td>
<td>0.016</td>
<td>-0.011</td>
<td>0.181</td>
<td>-0.014</td>
</tr>
<tr>
<td>(0.842)</td>
<td>(0.569)</td>
<td>(3.718)</td>
<td>(7.267)</td>
<td>(-5.055)</td>
<td></td>
</tr>
<tr>
<td>KHHJOB</td>
<td>0.234</td>
<td>0.234</td>
<td>-0.247</td>
<td>0.336</td>
<td>-0.474</td>
</tr>
<tr>
<td>(0.639)</td>
<td>(0.645)</td>
<td>(-0.520)</td>
<td>(0.700)</td>
<td>(-1.428)</td>
<td></td>
</tr>
<tr>
<td>Pseudo-R²</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>N</td>
<td>4329</td>
<td>4329</td>
<td>4329</td>
<td>4329</td>
<td>4329</td>
</tr>
</tbody>
</table>

| Intercept        | 1.875    | -2.463  | -2.545 | -2.816  | -2.299 |
| (11.430)         | (-16.183) | (-17.956) | (-13.818) | (-11.063) |
| INDCLUS          | 0.085    | 1.975   | 1.800  | 0.570   | 0.368 |
| (0.241)          | (4.059)  | (5.404)  | (0.961) | (-1.066) |
| LOWBUILD         | 0.135    | 2.899   | 3.829  | 1.490   | 2.379 |
| (0.380)          | (6.828)  | (13.330) | (2.533) | (-1.871) |
| HIBUILD          | -0.077   | 2.286   | 2.068  | -0.083  | -1.603 |
| (0.099)          | (6.496)  | (8.488)  | (-0.183) | (-2.414) |
| Pseudo-R²        | 0.04     | 0.04    | 0.04  | 0.04    | 0.04  |
| N                | 4329     | 4329    | 4329  | 4329    | 4329  |

Note: Coefficients in bold are significant at a 5% level.

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TABLE 3 OLS Regressions for the Interaction between Mobility and Economic and Demographic Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Adjusted R²</th>
<th>SEX</th>
<th>AGE</th>
<th>INCOME</th>
<th>COLLEGE</th>
<th>TRIP</th>
<th>INCOTAMP</th>
<th>TRIP</th>
<th>INCOTAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.772</td>
<td>0.079</td>
<td>-0.157</td>
<td>0.034</td>
<td>-0.412</td>
<td>0.177</td>
<td>-0.412</td>
<td>0.177</td>
<td>-0.412</td>
</tr>
<tr>
<td>N</td>
<td>163 919</td>
<td>0.156</td>
<td>0.157</td>
<td>0.034</td>
<td>0.412</td>
<td>0.177</td>
<td>0.412</td>
<td>0.177</td>
<td>0.412</td>
</tr>
</tbody>
</table>

Note: Coefficients in bold are significant at a 5% level.
undertook an OLS regression on the regressors, linking the two models of urban form and the three models of individuals' characteristics (Table 5). These results help contextualize our main results regarding the factors of urban daily mobility.
Specifically, they help us understand the structure of land use in the metropolitan area of Bordeaux. We graphed the exponential form of the density gradients for both jobs and people (Figure 3), and the distribution of two different types of housing according to the distance to the centre (Figure 4): isolated detached houses (INDISOL) and flats in low- or high-rise buildings (BUILD). These graphs show the strong explanatory power of distance to the centre. Like most European cities of this size, Bordeaux still has a monocentric structure. That is, densities decrease almost uninterrupted with distance from the center.

Furthermore, the structure of the building stock is obviously linked to distance to the centre because both the share of detached homes in the total housing stock increases and the share of buildings decreases as distance increases. In this paper, we may contrast low/high-density as well as centre/periphery areas or detached homes/buildings.

Results:
Motives of Mobility in the Metropolitan Area of Bordeaux

The application of the above mentioned conceptual framework to the metropolitan area of Bordeaux provides two sets of results. First, we examine the 'pure' effect of land use variables on travel behaviour. Numerous indicators of density as well as land use mix have been tested, and we present the most relevant results. In particular, we are able to confirm the traditional role of density on travel patterns. The case of land use mix is not so clear; its impact is only significant for diversity of activities. Second, we show the existence of a 'location effect' which reveals the strong interactions between economic and demographic effects and location in a specific urban form, with effects on travel behaviours. As a consequence, the impact of economic and demographic variables on travel patterns may be misunderstood if not replaced into its spatial context.

The Interaction between Urban Form and Mobility: The Effect of Density and Land Use Mix on Travel Patterns

The land use model allows us to confirm the traditional role of density in travel patterns. Residential density as well as firm density have a significant negative impact on kilometres travelled per capita, trip length and car ownership (Table 1). And, it is positively associated with the use of walking and transit compared to automobile use (Table 2). Here, the impact of density tends to confirm previous results such as high density settlement is associated with shorter trip length, lower automobile ownership and use, and a modal shift towards 'soft modes'.

Differences in land use characteristics do not explain differences in individual trip frequencies (see the weakness of the $R^2$, Table 1). This is in line with expectations as trip frequencies are an indicator of the demand for travel, which theoretically does not depend on urban form or accessibility but rather on economic and demographic characteristics (Quinet 1998; Ewing and Cervero 2001).

We observe that the degree of land use mix (MIXFUNC), whichever definition we adopted, as well as the khi indices for the distribution of jobs (KHIPROX and KHIOTHER), have no influence on travel variables.6

The regressions do not show any outstanding difference between the two purposes of trips, contrary to what was expected. Travel behaviour may depend on the location in a specific urban form more than on the purpose of the trip, such as the influence of urban form is roughly the same whatever the purpose of the trip.

The jobs-housing ratio (JHBAL) has a significant positive impact on kilo-

6. This is why they were not included in the result tables.
metres travelled per capita for work trips — contrary to previous results (Camagni et al 2002) — and a negative impact on car ownership (Table 1). This impact is neither due to an increase in trip length, nor to a modal sharing in favour of the car (Tables 1 and 2). On the contrary, walking and transit are more common in areas with high jobs-housing ratios (Table 2).

This result must be linked to the significance of KHIJOB, which measures the degree of economic specialization of a zone. Table 1 shows a significant positive relationship between economic specialization and kilometres travelled per capita for work trips. That is, the more numerous the jobs are compared to the number of inhabitants in a given area, and the more this area is economically specialized, the higher the kilometres travelled per capita for work trips. This type of zone corresponds to the developing employment sub-centres situated around the cloche (ring-road) (Gaschet 2001). One could surmise that this situation implies longer trips, but neither JHBAL nor KHIJOB are significant for trip length variables. So we are obliged to suppose a kind of 'structural effect', which simply makes kilometres travelled per capita higher because of the scarcity of the population in these employment sub-centres. This hypothesis is supported by the sign of the population variable in Tables 3 and 4 (when significant).

The housing type model shows a strong positive impact of the isolated detached houses variable (the reference category') on trip length as well as on car ownership (because of the negative impact of all other types of housing — Table 1), and on the shares of transit and walking modes (Table 2). Interpreting this relationship needs careful attention to what is 'hidden' behind type of housing: it seems difficult to justify that the percentage of isolated detached houses has an influence by itself on travel behaviour and car ownership. In fact, the type of housing has the same effect on travel patterns as density. A significant effect of the type of housing on density is observed: the higher the densities, the higher the percentage of high and low buildings in the total housing stock, and the more are numerous retail firms compared to others (Table 5). On the other hand, isolated detached homes are the most numerous in low density, outlying areas. This leads us to the results shown on Figure 3, which tend to confirm the usual statements as far as automobile dependency is concerned: low density, residential areas that are mainly composed of isolated detached houses strongly encourage ownership of an automobile and its use (Newman et al 1993). Furthermore, the outer location of these areas can explain the positive impact of isolated detached houses on trip length.

One may notice the negative impact of the share of high-rise building flats on kilometres per capita, whatever the purpose of the trip (Table 1). These are central areas, or planned areas with an excellent transit supply: as average household income and level of car ownership are low, planners have wanted these areas to be well-served (Bidou 1994). The effect of the percentage of low-rise buildings on individual kilometres travelled may be significant as well, as this type of housing is frequent in central areas, but these are also areas with higher trip frequencies, which counterbalances the expected effect of shorter distances travelled and/or a modal shift at the expense of the car.

The Interaction between Mobility and Economic and Demographic Characteristics

In this section, we analyze the interaction between travel patterns and economic and/or demographic characteristics. Our comments take into account the interaction between these last characteristics and urban form characteristics.

Income and travel patterns: the low density effect

The 'lifecycle model' shows an insignificant effect of income on trip frequencies and kilometres per capita. However, income has a strong positive impact on car ownership, as expected. This influence is strengthened by the results of the 'type of population model', as low income populations (unemployed and students) proved to be significantly related to car ownership (Table 3). The results in Table 4 provide further support to this, as modal shares of transit and walking depend negatively on income.

Thus, income seems to be related to travel behaviour by favouring car ownership and use. One could interpret this result suggesting that 'rising incomes may be the root cause of much of the growth in auto dependence' (Gomez-Ibáñez 1991: 377). This author is interested in a distinction between 'direct effects [of high incomes] on auto use' (people buy more mobility as income rises) and 'indirect effects on density' (people buy more space as income rises). The direct effect seems obvious in view of the above results; the indirect effect is confirmed by Table 5, in which income is negatively related to density, and positively related to isolated detached housing.

Gender and travel patterns: an interaction with urban form?

The 'type of population model' shows a significant negative impact of the share of women in the population on kilometres per capita. This is rather paradoxical, as a higher percentage of women is associated with higher trip frequencies (Table 3). The explanation lies in shorter trips (Table 3) as well as on a higher share of walking (Table 4) — i.e., shorter distances between trip origin and destination.

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7. It was essential to set a reference category to avoid perfect multicollinearity in this model.
8. Which can be understood from a 'market area' perspective: all things equal, the higher the density, the more profitable retail firms are.
allows for a modal shift.

Various interpretations of these results are available, with none of them prevailing:

- Higher trip frequencies may be due to a greater number of purposes, like shopping and school service. As a consequence, women attach a greater value to the location of the home and seek to settle closer to their usual destinations;
- A kind of aversion to the use of an automobile;
- An interaction with urban form: the heads of family for single-parent households are mainly women. This may explain that the SEX variable is significant for individual trip frequencies and not for household trip frequencies. Single-parent households are often poorer than other households (Djider and Ravel 2004) and hence may not have access to car ownership. Furthermore, the head of the family has to manage both domestic and non-domestic activities. As a consequence, single-parent households may locate in central, well-served parts of the city in order to shorten distances travelled, and to have a wider modal choice. This statement is confirmed by the relationship between the proportion of single-parent households and density (Figure 5).

This last explanation raises the question whether there are any differences in mobility according to the type of population.

FIGURE 5 Percentage of Single-Parent and Bi-Active Households (zones ordered by increasing density)
Source: HTS (1998), analysis by the author

Type of population and travel patterns: a question of self-selection

The unemployment rate proves to be significantly related to "soft modes" use compared to car use, while the percentage of retired people and the percentage of students is significantly related to transit use compared to car use (Table 4). Such results are no surprise, as these kinds of population have a lower degree of access to automobile ownership (Table 3) and may shift towards other modes.

The concept of self-selection can help us to interpret these results. It questions the direction of the causal relationship between urban form and travel (Krizek 2003: 268). Urban form may determine travel patterns as much as travel patterns determine the location in a specific urban form. Choosing a specific environment to live in would be partly due to individuals’ preferences for a particular travel pattern: those who prefer walking, for example, may settle in dense, mixed-use locations because more destinations are available at walking distance. We can generalize this statement by arguing that a wide selection of travel modes is an important criterion in the selection of the residential location: as suburban, low density settlements are supposedly "car-dependent", having a modal choice implies living in dense, well-served areas.

If location in a specific urban form depends on individuals’ preferences for 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: Dupuy (1995, 2002) has highlighted a tendency in populations who cannot 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 their usual, dispersed destinations. This location is constrained by the necessity of avoiding automobile dependence.

The analysis of the data shows a weak confirmation of this hypothesis. The rate of unemployed people proves to be positively related to residential and firm densities, and negatively linked to the proportion of isolated detached houses (Table 5), but the proportion of students or retired people is not significant. This result converges with the above comments on the impact of income on travel behaviour and land use.

Household size and travel patterns: the "location effect"

The "size model" shows a strong impact of household size on travel patterns. Household size has a significant effect on per household trip frequency and per
household car ownership (Table 3), which seems reasonable. But what is really interesting is the significant positive relationship between household size and kilometres per capita. Therefore, as this last variable is a composite one, it can be explained as follows:

- Higher automobile ownership: greater household size encourages ownership of an automobile, as the household's needs in travels are higher (Table 3);
- Lower use of 'soft modes' compared to automobile use (Table 4), which goes along with car ownership;
- At an individual level, trip frequencies do not increase as household size increases, which is in keeping with the hypothesis presented above that there is a stability of travel needs amongst individuals. However, trip lengths increase with household size. This relationship could be due to the location factor, as detached houses are much more numerous in peripheral zones.

Such a hypothesis of a 'location factor' is confirmed by results in Table 5. It seems obvious that large households settle in specific zones, with low residential and firm densities, low rates of retail firms, and high rates of isolated detached houses. This description corresponds to low density, residential neighbourhoods, which are commonly described as 'auto-dependent' urban forms (Cervero 1998; Newman and Kenworthy 1998).

Thus, household size is linked to specific residential patterns and travel behaviours. To find a relevant explanation for these results requires exogenous elements that the researcher has to find based on experience and knowledge of the situation. Two possible explanations are suggested:

- An 'amenities' explanation. The denser parts of the city are associated with pollution and low levels of security. This is tolerable for certain adults (as negative amenities go along with positive ones) but constitutes a repulsive environment for children: parents with young children have a strong tendency to settle far from the centre, near natural amenities. However, this type of explanation is very difficult to corroborate because of a lack of available data for Bordeaux.
- A 'real estate availability' explanation. An increase in household size implies an increase in surface area needs. We have observed the stability in floor-space per capita across the whole metropolitan area (see the Appendix, where the standard error is less than 10 % of the mean). As a consequence, an increase in household size implies an increase in the size of the flat.

Now, small flats appear to be more prevalent in central, high-density zones, and large-size homes (such as detached ones) are much more numerous in peripheral, low-density ones. Thus, small-size households will locate in the former, and large-size households will settle in the latter (Figure 6). Thus, the distribution of households by size (and the travel patterns that ensue) is due to the availability of housings linked to their surface area needs.

It is not possible to ascertain whether this state of affairs is imposed on or chosen by households. Do large-size households settle in low-density zones because of the abundance of large-size housings, or are large-size houses numerous in low-density zones because large-size households settle there? It would be chosen if the real estate market adapts to their demand and needs, which is the common hypothesis. It would be imposed on them if households had to adapt to the real estate supply. Muth (1969: 96-99) has underlined the consequences of the gap between the durability of housing, which is measured in centuries, and the necessity to adapt buildings to quick changes in housing demand. He pointed out that there is an upper limit to residential density in older parts of the city, as most of the buildings are protected from destruction because of their aesthetic and historical value. The problem is that there is no limit to increases in rent. It may lead to a growing disconnection between the rent gradient and the density gradient, yet they are theoretically linked (Mills 1972: Chapter V). But 'durability affects primarily the exteriors of buildings' (Muth 1969: 97), and an increase in rent which does not go along with a rise in density leads to a multiplication of small-size, more rentable flats.

**Conclusion**

The study of the key factors determining daily travel is generally treated as a twofold relationship, with economic/demographic characteristics and urban form considered as the two main factors underlying travel patterns. We argue that such a conceptual framework needs to be completed, as there can be some interactions between urban form and economic and demographic characteristics. We adopted the 'triangular relationship' framework and specified the models in a way that takes these complex relationships into account. The analysis of 1998 transportation data for the metropolitan area of Bordeaux confirms the traditional role of density...
on travel patterns. The evidence for land use mix seems to be weak.

The three economic and demographic models showed some significant influences on travel patterns. The examples of income, gender, the type of population and household size reveal strong interactions between these variables and location in a specific urban form, with consequences on travel behaviour.

These results allow us to draw out some lessons for policy purposes. From a planning perspective, we must be aware of complex interactions between individuals (economic and demographic characteristics), their environment (the urban form), and their behaviour (the travel patterns). Compaction measures aim at increasing density to thwart urban sprawl and influence daily mobility patterns. But an increase in density may not be sufficient in itself to reduce automobile use, as economic and demographic characteristics interact with the distribution of densities. These kinds of policies may be more effective if they are reinforced by specific measures, for example real estate policies such as building large-size flats in the CBD to prompt families with children to go ‘back to the centre’.

The study of the key factors of urban daily travel shows very complex relationships, and one must be wary not to oversimplify such phenomena, notably for policy purposes.

References


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13 As was done in the ZAC (concerted planning zone) of the Chartrons, in the historic centre of Bordeaux, where city authorities have planned with real estate promoters to mix small and large-size flats in a set of new buildings.
Appendix

TABLE A1 Definition of variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESDENS</td>
<td>32.298</td>
<td>39.18</td>
<td>0.69</td>
<td>150.83</td>
</tr>
<tr>
<td>Gross residential density (people/hectare)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIRMDENS</td>
<td>3.15</td>
<td>6.3</td>
<td>0.03</td>
<td>39.47</td>
</tr>
<tr>
<td>Gross density of finns (finns/hectare)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JHBAL</td>
<td>1.39</td>
<td>1.94</td>
<td>0.13</td>
<td>9.25</td>
</tr>
<tr>
<td>Jobs-housing balance (jobs/people) normalized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUNCMIX</td>
<td>0.56</td>
<td>0.25</td>
<td>0.08</td>
<td>0.98</td>
</tr>
<tr>
<td>Index of functional mix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KHIJOBS</td>
<td>0.29</td>
<td>0.15</td>
<td>0.08</td>
<td>0.87</td>
</tr>
<tr>
<td>Khi index for distribution of jobs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KHIROX</td>
<td>0.07</td>
<td>0.07</td>
<td>0.007</td>
<td>0.334</td>
</tr>
<tr>
<td>Ratio jobs of proximity/other jobs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INDRES</td>
<td>44%</td>
<td>0.31</td>
<td>0.0%</td>
<td>98%</td>
</tr>
<tr>
<td>% of detached isolated houses in total housing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INCLUS</td>
<td>22%</td>
<td>0.15</td>
<td>2%</td>
<td>58%</td>
</tr>
<tr>
<td>% of clustered houses in total housing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOWBUILD</td>
<td>14%</td>
<td>0.15</td>
<td>0.0%</td>
<td>68%</td>
</tr>
<tr>
<td>% of low-rise building (less than 4 levels) flats in total housing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIBUILD</td>
<td>22%</td>
<td>0.2</td>
<td>0.0%</td>
<td>83%</td>
</tr>
<tr>
<td>% of high-rise building (4 levels or more) flats in total housing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEOROOm</td>
<td>0.63</td>
<td>0.03</td>
<td>0.56</td>
<td>0.71</td>
</tr>
<tr>
<td>Average number of people per room</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKMT01</td>
<td>6.11</td>
<td>4.03</td>
<td>1.91</td>
<td>30.61</td>
</tr>
<tr>
<td>Kilometres travelled per capita from the origin zone for the first purpose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKMT01</td>
<td>6.11</td>
<td>4.03</td>
<td>1.91</td>
<td>30.61</td>
</tr>
<tr>
<td>Kilometres travelled per capita towards the destination zone for the first purpose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKMT02</td>
<td>13.51</td>
<td>7.31</td>
<td>5.06</td>
<td>43.37</td>
</tr>
<tr>
<td>Kilometres travelled per capita from the origin zone for the second purpose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PKMT02</td>
<td>13.51</td>
<td>7.31</td>
<td>5.06</td>
<td>43.37</td>
</tr>
<tr>
<td>Kilometres travelled per capita towards the destination zone for the second purpose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIPLENG</td>
<td>9.11</td>
<td>2.78</td>
<td>4.76</td>
<td>18.72</td>
</tr>
<tr>
<td>Average trip length (km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRIPFQ</td>
<td>3.76</td>
<td>0.46</td>
<td>2.62</td>
<td>4.67</td>
</tr>
<tr>
<td>Average trip frequency (trips per person)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTRIPFQ</td>
<td>8.58</td>
<td>1.75</td>
<td>2.34</td>
<td>13.32</td>
</tr>
<tr>
<td>Average trip frequency (trips per household)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAR</td>
<td>51%</td>
<td>0.13</td>
<td>19%</td>
<td>70%</td>
</tr>
<tr>
<td>% of trips made by car (driver)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CARSHAR</td>
<td>15%</td>
<td>0.04</td>
<td>5%</td>
<td>23%</td>
</tr>
<tr>
<td>% of trips made by car (passenger)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRANIT</td>
<td>7%</td>
<td>0.05</td>
<td>0%</td>
<td>24%</td>
</tr>
<tr>
<td>% of trips made by transit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Three type reference populations were used: total population, working population, number of households.
2. JHBAL is normalized, which means the value for a particular zone is divided by the value for the whole study area; a value of JHBAL equal to one means that the zone has exactly the same jobs/people ratio as the whole study area.
3. This index was built on the same basis as JHBAL (jobs/people), the shortcoming of JHBAL is that it only indicates the quantity of jobs compared to population. Functional mix is at its highest level for JHBAL=1 (equal proportion in the zone and in the whole area). For values superior to one, JHBAL increases whereas functional mixity decreases. This is why we inverted values superior to one to build FUNCMIX.
4. The Khi Index is a specialization index. The higher it is, the more specialized the zone, which means that the sectoral distribution of jobs is all the more different from that of the whole area (Laugier et al 1985).
5. Many studies have underlined the necessity of distinguishing the purpose of the trips, on a basis of its frequency and repetitivity (e.g. Dietlmania et al 2001). Purpose 1 is commuting (work trips), and purpose 2 is other (non-work trips, mainly shopping and leisure ones).