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Ecological Economics xx (2005) xxx–xxx
ECOLOGICAL ECONOMICS
www.elsevier.com/locate/ecolecon

ANALYSIS

Urban form and the ecological footprint of commuting. The case of Barcelona

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Received 12 May 2003; received in revised form 29 April 2004; accepted 14 December 2004

Abstract

One of the most controversial ideas in the debate on urban sustainability is that urban sprawl causes problems of ecological stress. This widespread assumption has been tested by measuring the ecological footprint left by commuters in the 163 municipalities of the Barcelona Metropolitan Region (BMR). This paper explores the determinants of the ecological footprint of commuting municipal variability by using the following regressors: population density, accessibility, average household income, and job ratio. The results confirm that urban form appears as the main determinant of ecological footprint variation among the municipalities of BMR.

Keywords: Ecological footprint; Suburbanization; Urban form; Commuting

1. Introduction

The location of jobs, residences, and other facilities within the city affects transport demand by conditioning the number and length of trips as well as the modal split. Over recent decades, many large European cities have grown in a scattered way. The current trend towards a decentralization of population and employment has led to longer trips and an increasing dependence on cars, exerting great pressure on the environment. In 1999, the energy consumed by the transport sector added up to 40% of total energy consumption and accounted for more than 40% of greenhouse gas emissions in Catalonia. Of this energy consumption, 54% corresponded to car use, and 50% occurred in the urban environment (ICAEN, 2002).

The environmental, economic, and social problems associated with urban mobility patterns represent the core of the debate on the possible influence of urban form on mobility patterns. This article follows the literature that focuses on this issue, although the authors would like to highlight that this is not the only causal relationship between urban form and mobility patterns, as it would also depend on the time period under consideration. If a short-term analysis is made, transport patterns (volume and means) will show to be a

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doi:10.1016/j.ecolecon.2004.12.008

consequence of population and employment geographical distribution. Conversely, if we focus on the long term, transport will turn out to be an important factor in determining urban form (Miralles, 1997).

Barcelona has often been described as a stylized paradigm of compacity and sustainability (Rogers and Gumuchdjian, 2000; Rogers and Power, 2000). The municipality of Barcelona has certainly been transformed by considering potential social and environmental impacts. Nonetheless, when we analyze Barcelona under a larger spatial scale (the metropolitan region), it presents stress problems related to urban sprawl and unsustainable mobility.

Much research on the influence of urban form on mobility has been done using indicators of travel patterns such as travel distance and modal choice. Some authors have nonetheless used a more interesting indicator, energy consumption, a composite measure of travel distance, modal choice, and journey frequency. However, when we calculate the impact of mobility on global warming, CO_2 emissions or ecological footprint appears as preferable measures. Accordingly, this paper uses ecological footprint as its main indicator. The eco-footprint does not only account for direct CO_2 emissions but also for indirect emissions and occupied land, combined in just one measure. This indicator better captures the global ecological impact of an activity, although there is still some controversy on the convenience of such an indicator. This paper seeks to contribute to a deeper understanding on the global environmental effects of transport by explaining how an appropriate urban form can reduce it by a causality analysis where the ecological footprint of commuting is taken as dependent variable. The research is also novel in offering the ecological footprint calculation for commuting in the Barcelona Metropolitan Region.

The paper's objectives are threefold: first, measuring the evolution of commuting trips within BMR (length and modal split); second, calculating the ecological footprint of commuting and its variation between 1986 and 1996; and third, determining the effect of urban form and other factors on commuting eco-footprint.

This document is organized in 6 sections, after this introductory section: Section 2 presents a brief survey of the literature concerning the relationship between transport and urban form, highlighting the main points of the debate. Section 3 describes the form and structure of BMR. Section 4 provides a calculation for the ecological footprint of commuting and its evolution during the 1986–1996 period. Section 5 explores the elements that explain the ecological footprint of commuting municipal variability (urban form, employment location, average household income). Finally, Section 6 summarizes the key findings and presents several conclusions.

2. Urban form and transport

Travel patterns in the metropolitan areas of most developed countries are increasingly car-dependent, and less subject to patterns characterized by trips from the periphery to the main center and/or subcenters. Car dependency has currently become a political priority for Western European governments (OECD, 1995) due, among other factors, to the environmental problems caused by this mobility pattern. The academic debate has mainly focused on the impact of urban spatial structure on travel patterns. However, it is not clear that causality works only in that direction. The influence of the transport system on land use characteristics requires a long-term analysis, which goes beyond the scope of this study. Following Banister (1998), the focus of this review is on empirical literature regarding the impact of land use characteristics on travel patterns. Additionally, this review highlights those studies that propose alternative socio-economic factors influencing travel patterns.

The debate on the relationship between intra-urban mobility (travel patterns) and urban form (land use characteristics) was reactivated by the publication of Newman and Kenworthy's (1989a,b) research. Using a sample of 32 cities in different countries and continents, they tested the influence of population density levels on the consumption of gasoline. Although Newman and Kenworthy's work does not constitute a new line of research, it is useful as a starting point due to its great popularity. Banister (1998) suggests that there are two important reasons why population density may reduce the ecological impact of mobility. First, higher density patterns reduce average distances between home and place of work; second, high densities may be more amenable to public transport supply.

2.1. Land use characteristics and other explanatory variables

2.1.1. Population density, accessibility, and suburbanization patterns

According to spatial economic Bid Rent models (Alonso, 1964; Muth, 1968; Mills, 1973), population density depends on accessibility.[1] It could then be argued that an analysis of urban form's impact on travel patterns should take accessibility, not density level, as its explanatory variable, inasmuch as it is a more fundamental factor. Nonetheless, the predictions of Bid Rent models on the relationship between distance to city center and density only apply to a hypothetical city, one solely built by market forces. This entails that neither history, nor planning is active players in defining urban form. This assumption appears to be much too restrictive, especially in the case of European cities, where urban planners have historically taken decisions on the intensity of land use of a particular area, regardless of its proximity to the city center. Accordingly, density is commonly included as explanatory variable, since it is not totally determined by accessibility.

In summary, an indicator of accessibility can be a reasonable alternative to the use of population density as a land use indicator, since density is partially determined by accessibility. We do not mean that population density cannot be used as an explanatory variable of travel patterns. As a matter of fact, accessibility does not totally explain density, insofar as density at any given point of the city can be determined by other factors, such as the presence of previous settlements and planning decisions. From a theoretical perspective based on Bid Rent models, distance to the city center and population density must not be taken simultaneously as explanatory variables of travel patterns because both variables are, at least theoretically, correlated. Nevertheless, each one provides substantial information on the impact of urban form on mobility patterns. A solution might be to include each variable in different regressions.

One of the most generally used measures of accessibility is distance to the Central Business District (CBD), where most employment is concentrated according to Bid Rent models. However, air distance from the CBD is a limited measure of accessibility, since two points located at the same CBD distance may present different accessibility levels if they are located at different distances from the transport axes. The shorter the distance to the transport axis, the greater the accessibility. In single-city case studies, one way to solve this problem is to use two indicators of accessibility simultaneously in order to characterize each sector of the city: distance to the city center and distance to the nearest axis, as proposed by Steen (1986).

Many authors have examined the impact of population density on travel patterns before and after the publication of Newman's and Kenworthy (1989a,b) research (ECOTEC, 1993; Hillman and Whaley, 1983; Gordon et al., 1989; Banister, 1997; Camagni et al., 2002; and Kahn, 2000, among others). There is also a substantial body of research in which distance to city center has been used as a determinant of travel patterns (Spence and Frost, 1995; Curtis, 1995; Mogridge, 1985; and Gordon et al., 1989), but this is not the case for distance to transport axes. According to Banister (1998), the expected effect should be negative if what is tested is the impact of distance to the nearest metropolitan highway over the proportion of car trips. This effect could be counteracted because areas near to metropolitan highways offer greater accessibility, which implies a higher bid for land. In turn, this increases the intensity of land use (density) enabling the supply of public transport. Moreover, highways reinforce the radiality of train lines in many cases. This hypothesis must be tested without assuming a predetermined sign on its coefficient.

Some research has linked the impact of intensity of land use on travel patterns to population suburbanization trends. Suburban sprawl is believed to have significantly contributed to the increase in vehicle use (Kahn, 2000). A diffused pattern of urban growth on the edge of the metropolitan region cannot be adequately served by public transport since population

[1] According to the Bid Rent Model, or Monocentric City Model, population density declines with distance to the city center because bid rent declines to compensate for commuting costs. The population density gradient measures the proportional decline in population density per unit of distance. The lower the gradient, the higher the suburbanization. The standard population density exponential function is $\mathrm{DEN}(x)=D_0e^{-\gamma x}$ where $\mathrm{DEN}(x)$ is population density at distance x from the city center, D_0 is the theoretical density in the central district, and γ the population density gradient (Muñiz et al., 2003).

density (and spatial demand for transport) is low. The problem of suburban sprawl has been investigated in North America for more than 40 years, whereas in many European countries, the debate is now starting, given the widespread emergence of this phenomenon. As Camagni et al. (2002) point out, areas surrounding most large cities in Europe have been radically transformed, adopting urban forms that are very different from the typical compact development occurring around dense urban centers.

2.1.2. Socio-economic factors

One of the criticisms to Newman and Kenworthy's work (1989a) is that they do not include explanatory socio-economic variables in their model. According to Breheny et al. (1996), average household income and employment location do more to explain the variability of petrol consumption observed in the sample of cities used by Newman and Kenworthy than average population density. Using the same sample of cities as Newman and Kenworthy, Breheny and Gordon (1997) demonstrated that the density coefficient and its statistical significance decreases when petrol, and income are included as explanatory variables. Empirical evidence recommends including the average household income in the model, despite the problems related to a possible strong correlation with density levels[2] in the case of single city studies.

When the number of jobs per capita (*job ratio*) is included as an explanatory variable that reflects the mixture of land uses, the results obtained seem more controversial. Using a sample of six English cities, Banister et al. (1997) found a statistically significant relation between the proportion of employment per resident and energy consumed in transport in only one city. Ewing et al. (1996) and Cervero (1989) found similar results in North America. Therefore, evidence seems to indicate that the energy-saving potential when population and activity are mixed may not stand insofar as decisions regarding residential location are increasingly disconnected from employment location. Nevertheless, defenders of compacity argue that land specialization affects the physical separation of activities, augmenting the demand for travel (Rueda, 2002; Rogers and Gumuchdjian, 2000; EC, 1990). The inclusion of the job ratio as dependent variable can be used to test whether mixing of land uses reduces travel demand, a reasonable assumption that empirical research has not supported in the case of British and American cities.

[2] Urban filtering models and other population location models suggest that families choose their location by taking into account average density levels and social proximity with neighbours (King and Mieszkowski, 1973; Mieszkowski and Mills, 1993).

2.2. From energy consumption to global sustainability

Energy consumed in transport, the independent variable used by Newman and Kenworthy (1989a,b), is a good indicator of energy efficiency and local pollution. There are two possible energy measures: on one hand, primary energy consumption measured in MJ by mode, distance, and passenger; on the other hand, petrol consumption or petrol sales within the urban area. Limitations on data sources will determine the choice of energy measures, although the preferred unit tends to be primary energy consumption expressed in MJ (Banister, 1998).

Energy consumption in transport is a travel pattern composite measure of trip distance, frequency, and mode (Banister, 1998). It summarizes all that information in one single measure, which indicates the energy needed to satisfy the demand of transport in a city. However, if what we are seeking is the contribution of urban mobility on global sustainability, we should use more suitable indicators. Energy consumption cannot appropriately capture CO_2 emissions because a fixed level of consumed energy can generate different levels of CO_2 emissions depending on the energy source. Accordingly, transport CO_2 emissions better reflects the direct effect of transport on global warming. If direct and indirect impacts are to be captured, the ecological footprint appears as a more suitable choice, since it includes direct CO_2 emissions, indirect energy used for modes of transport supply and land occupied by transport infrastructures.

Ecological footprint is an adaptation of the carrying capacity indicator frequently used by ecologists to determine the area that requires a certain animal population to obtain resources and assimilate their wastes. The estimation of ecological footprints enables us to solve the problem of trade, which has been the main difficulty in calculating the carrying capacity of humans, given that, contrary to all other species, humans consume products and services from very distant places. Ecological footprint solves this problem under the assumption that every energy category, material consumption, and waste discharge requires a finite area of land (or water). Summing up land requirements for all categories of consumption, the total area represents the ecological footprint of that population on Earth, regardless of whether this area coincides with the population's natural region or not (in terms of Patrick Geddes' analytical tool for regional planning) (Rees and Wackernagel, 1996a, pp. 51).

One of the advantages in using ecological footprint as an indicator is that it translates all consumption into a single measurement unit (hectares per capita), which in turn can be compared to a reference threshold, namely the world's productive ecological land per capita.

The methodology proposed by Rees and Wackernagel (1996a,b) has been critically reviewed by Ayres (2000), Constanza (2000), Levett (1998), and Lenzen and Murray (2001), among others. The main criticisms are in relation to (a) the difficulty of assigning a surface area associated to the resources coming from the sea; (b) the use, in some cases inappropriately, of average global productivities instead of real productivities; (c) the omission of the possibility that a single land surface provides different resources; and (d) the assumption of a constant technology in time. Research critical of Rees and Wackernagel's proposal typically suggests diverse indicators as an alternative. Although this option allows for a more rigorous study of each impact on the ecosystems, it does not establish a global frame of reference, which is the main virtue of the method devised by Rees and Wackernagel.

One of the most controversial elements in the Rees and Wackernagel proposal is how they translate fossil energy consumption, the most important consumption in transport, into a corresponding land area. They outline three possibilities. The first consists of calculating the land required to produce a biologically substitute for liquid fossil fuel such as ethanol or methanol. The second consists of calculating the forest land area needed to sequester CO_2 emissions. The third method estimates the land area required to rebuild natural capital at the same rate that fossil fuel is being consumed. The authors choose the second method, given that this approach enjoys the highest public acceptance (Rees and Wackernagel, 1996a, pp. 73/74).

In summary, recent research suggests the inclusion of other explanatory variables besides population density to explain intra-metropolitan travel patterns variability, such as job ratio and household income. There is a rather long list of alternative indicators of travel patterns that includes average travel distance, the proportion of trips made by car, energy consumption, CO_2 emissions, and ecological footprint. Nevertheless, with the aim of examining the impact of urban transport on global sustainability, ecological footprint provides the richest indicator.

3. The Barcelona Metropolitan Region

The delimitation of metropolitan regions in each European Union country corresponds to administrative, statistical, or planning units. The Barcelona Metropolitan Region (BMR) was defined in 1987 for the purposes of regional planning and extended by the *Pla General Territorial de Catalunya*. The BMR includes seven *comarques* (*counties*) and 163 municipalities. The BMR ranks sixth within the European Union in terms of urban population (after Greater London, the Paris agglomeration, Netherland's Randstad, Germany's Ruhr agglomeration, and Madrid's metropolitan region), it ranks third in terms of gross population density (after Paris and Milan) (AMB, 1995).

BMR is a conurbation with a large, diverse, and compact center (the municipality of Barcelona), an extremely dense inner ring (A1) urbanized by massive housing blocks, discontinuities in the form of agricultural land and metropolitan parks, seven satellite cities, and an extensive area that combines rural and low-density residential uses. Its transport network is radial, and its subcenters communicate with the center through different railway lines. Metropolitan highways have reinforced the radial shape, even though it has been partially corrected by means of the transverse axes construction. BMR is a complex, diverse, discontinuous, polycentric,[3] and also partially disperse metro-

[3] Muñiz et al. (2003) examine BMR polycentricity by comparing the explanatory capacity of two alternative population density functions, the traditional exponential, and the cubic spline function. The cubic spline function fitted better than the exponential function. According to Muñiz et al. (2003), this is an expected result because in the BMR, the presence of density craters in city centers, dense peripheries, satellite cities, and green belts cannot be correctly captured by an exponential function.

politan region; a city of cities and towns that occupies almost 4000 km^2 in a maximum radius of 70 km.

3.1. Metropolitan integration between 1986 and 1996

The delimitation of the BMR used in this research corresponds to a planning unit. Obviously, this sort of delimitation does not fit exactly with alternative delimitation procedures based on functional relationships. Clusa and Roca Cladera (1997) and CPSV (1998) have calculated the functional region of Barcelona by applying an adaptation of the methodology proposed by the United States Bureau of Census. Their results indicate that in 1986, the functional agglomeration around Barcelona was composed of 94 municipalities and 3.7 million habitants; 145 municipalities and 4.2 million habitants in 1991, and 217 municipalities and 4.3 million habitants in 1996. Therefore, during this 10-year period, BMR has become increasingly integrated, measuring functional integration in terms of commuting flows. In 1996, the functional agglomeration of Barcelona clearly exceeded the limits of the Barcelona Metropolitan Region.

3.2. Suburbanization

Somewhat lagging behind the dynamics of large European and North American cities, in the last 10 years, BMR has seen an intense process of suburbanization, which has involved a remarkable growth of population in the municipalities around satellite cities and in metropolitan corridors, that is to say, in the furthest and more dispersed areas of the urban region. Since the total region's population has remained constant throughout the considered period, the municipality of Barcelona and municipalities pertaining to BMR's first ring have experienced remarkable population decreases, 193,000 inhabitants and 111,000 inhabitants, respectively (Table 1).

According to Nel.Lo (1995), suburbanization has been driven by improvements in transport infrastructure. Nel.lo also claims that mobility is less subject to a radial pattern, as it dramatically increases multidirectional commuting flows. Folch and Paris (1998) examine the public transport supply in BMR and they conclude that 80% of garden cities do not have a reliable public transport infrastructure. In more recent research, Miralles and Cebollada (2002) found out that distance traveled by people who live in suburban low-density municipalities is longer than in the case of people living in city centers. Rueda (2002) analyzed the increase in energy consumed in transport, concluding that it was mainly due to the spatial segregation of urban functions. In summary, previous studies suggest that suburbanization is accompanied by an unsustainable mobility pattern leading to a dramatic increase in transport energy consumed in transport, and probably also CO_2 emissions and the resulting ecological footprint. The following sections would test these hypotheses.

Table 1
Evolution of the average trip distance (km), 1986–1996

Metropolitan rings	1986	1991	1996	Growth rate 1986–1996
Barcelona	3.2	3.8	4.4	0.37
First ring (A1)	5.2	5.9	6.8	0.30
Second ring (A2)	6.3	7.1	8.1	0.28
Satellite cities	4.2	5.3	6.5	0.52
Satellite city commuting area	7.0	8.5	10.1	0.44
Metropolitan corridors	6.8	8.6	10.6	0.54
Total BMR	4.6	5.5	6.7	0.45

4. The ecological footprint of commuting

4.1. The evolution of commuting trips in BMR

In order to characterize transport patterns, two basic dimensions of transport are measured, trip length and modal split. Trip length is measured by the average trip distance per municipality, and the modal split by the proportion of trips made by car. Both variables are calculated from the origin–destination matrix of daily required mobility[4], obtained from the Census and Statistics of Population (IDESCAT, 1987, 1992, 1997). The origin–destination matrix provides infor-

[4] The required mobility refers to the trips made for work and study purposes. We are aware of the limitations involved in considering only commuting trips. In the case of BMR, the required mobility represents approximately 30% of all trips (ATM, 1997), and those commuting trips tend to cover longer distances than trips for other purposes; but, at the same time, it is the most reliable source of information on modal split and trip length.

mation on the number of commuters for each municipality, destination municipality of each commuter, and the mode of transport. Each trip is associated to the distance needed to cover the route between the origin and destination municipalities. By crossing the origin–destination matrix with the network distances (km) between the region's municipalities, we find the total distance traveled in each municipality. Dividing it by the number of commuters in each municipality, we obtain the average trip distance per municipality. Taking the information on the modal split of trips made by each municipality's residents, the proportion of trips made by car over the total of trips per municipality has also been calculated.

Table 2 shows that the average trip distance for all the municipalities of BMR increased between 1986 and 1996 from 4.6 km to 6.7 km, a 45% growth rate. The municipality of Barcelona has the lowest average distance whereas metropolitan corridors have the highest. Corridors and satellite cities are the metropolitan areas where distance increased at the highest rate.

Spatial differences in the evolution of the proportion of trips made by car are reported in Table 3. For the whole region, this mode of transport was used in 22% of total trips in 1986. In 1996, the proportion increased until it accounted for 35% of all trips. Hence, the use of the car in commuting trips has increased by 62%.[5]

Table 2
Evolution of the proportion of trips made by car, 1986–1996

Metropolitan rings	1986	1991	1996	Growth rate 1986–1996
Barcelona	0.19	0.22	0.24	0.25
First ring (A1)	0.19	0.25	0.30	0.59
Second ring (A2)	0.24	0.35	0.44	0.82
Satellite cities	0.26	0.36	0.42	0.57
Satellite city commuting area	0.36	0.50	0.58	0.60
Metropolitan corridors	0.29	0.42	0.51	0.75
Total BMR	0.22	0.29	0.35	0.62

4.2. The ecological footprint calculation

In order to measure the global ecological impact of transport patterns, the ecological footprint of commuting has been calculated as a global sustainability indicator. The approach taken here is a 'component-based' footprinting, which is based on the calculation of the eco-footprint for certain activities using data appropriate to the region under consideration (Wackernagel, 2002; Simmons et al., 2000). The activity under consideration here is intra-metropolitan commuting.

4.2.1. Estimation methodology and data sources

The eco-footprint of commuting includes the energy used in traction, vehicle manufacturing (cars, motorbikes, trains, busses, etc.), and the construction and maintenance of transport infrastructures (roads, railways...), in addition to the land occupied by the transport infrastructures. In eco-footprint calculation only trips made by car, bus, motorbike, train, underground, and bicycle are considered. Walking is not included since its impact can be considered negligible.

The equation used for the calculation of annual ecological footprint of the required mobility in municipality i is:

$$\mathrm{E.F.}_{i} = \sum_{z}\left[\left[\sum_{j}\mathrm{EC}_{z}\mathrm{EL}_{z}\mathrm{D}_{ij}\mathrm{Trip}_{ij,z}\right] + \mathrm{L}_{z}\right] \tag{1}$$

where $\mathrm{E.F.}_i$ is the annual ecological footprint of trips made by municipality i residents; EC_z is the energy consumption of mode of transport z per kilometer and passenger (Gj/km); EL_z is the ecological land per Gj in mode of transport z (ha/Gj); D_{ij} is the network distance between municipalities i and j; $\mathrm{Trip}_{ij,z}$ are the annual trips made by residents from the municipality i[6] towards municipality j made by mode of transport z; L_z is the land area corresponding to the infrastructure space used by mode of transport z (ha).

Energy consumption (EC_z). The assumed energy consumption per each mode of transport follows the standards for Spain established by Estevan and Sanz (1996), who calculated the 'Energetic balance for the integral cycle of transport' from real data on

[5] The municipality of Barcelona presents the lowest proportion, while the municipalities surrounding satellite cities have the highest proportion. The proportion of trips made by car increased at a higher rate in the second ring and the corridors.

[6] The annual trips per municipality are the total amount of trips made by commuters from the municipality in 1 year. As we only have information on the number of commuters per municipality, the annual number of trips per commuter for the required mobility was calculated by assuming a constant frequency: 460 trips per year (230 workdays per year, 2 trips per working day).

Table 3
Footprint of direct and indirect energy

Mode of transport	Energy consumption (Gj/passenger—km) (a)	Energy-to-land ratio (ha/Gj) (b)	(a x b) Fooprint[a] (ha/passenger—km)
Car	0.00259	0.01	2.59×10^{-5}
Bus	0.00061	0.01	6.1×10^{-6}
Motorbike	0.00129	0.01	1.29×10^{-5}
Train	0.0013	0.0085	1.1×10^{-5}
Underground	0.0013	0.0085	1.1×10^{-5}
Bicycle	–	–	2.6×10^{-6}*

[a] It does not include the land area taken by the infrastructures of transport.

* The ha/passenger—km required for bicycle is derived from annual footprint for bicycle for an individual who commutes 10 km each day proposed by Rees and Wackernagel (1996a, pp. 106) which is 0.0122 ha/(10 km×230 workdays×2 trips)=0.0000026).

the energy used, units of transport produced, and level of occupancy of public transport. Their data include the energy used for traction, vehicle manufacturing, construction, and maintenance of the infrastructure. For example, in the case of cars, the indirect energy needed for manufacturing and road maintenance represents around 30% of the energy consumed in traction, while this percentage is much higher in the case of trains and underground (50% of the energy needed for traction). The values for EC_z are provided in the first column of Table 4. This calculation methodology is subject to two essential assumptions, given the limitation of data sources: (a) technology is constant in time, and (b) vehicle occupancy level is constant in time. The first assumption is actually less restrictive than it seems for automobiles—as Estevan and Sanz (1996) point out—given that the engine's greater energetic efficiency (lower fuel consumption per kilometer) obtained in the 80s and 90s was counteracted by a greater use of capacity, acceleration and speed.

Energy-to-land ratio (EL_z). In Spain an important share of electricity production (around 18%) is obtained from renewable sources (hydraulic, wind power, and photovoltaic), the ecological productivity of which is about 10 times higher, and thus conversion factor for modes of transport that use electricity has been proportionally adapted.

Land taken by transport infrastructures (L_z). This dimension of ecological footprint has been added to the footprint of direct and indirect energy. Here we input the share of road space used by motor vehicle taking the information from traffic flows by mode of transport (ATM, 2000). Car uses 79% of road space, busses 10%, and motorbikes 6%. Following Rees and Wackernagel (1996a), road space used by bicycles is considered to be negligible. These percentages of use are applied to the total area occupied by highways, motorways, and streets in 1986 and 1996. Regarding railway space, it has been considered that 75% of train infrastructure is used for traveler transport. This percentage has been extrapolated from Estevan and Sanz (1996) data on energy consumed in freight and traveler transport.

4.2.2. Eco-footprint estimation and its evolution

Results shown in Table 5 indicate that the total ecological footprint of commuting increased from 65,226 ha in 1986, to 127,239 ha in 1996, which means a growth rate of 95%. The municipality of Barcelona presents the lowest increase, caused by its loss of population (see Table 1), while satellite city commuting area and the metropolitan corridors have the highest growth rate. The outcome referring to the evolution of per capita ecological footprint offsets the effect of demographic changes.

BMR administrative boundaries contain an area of 325,000 ha. The proportion of land occupied by urban uses is only 15% (12% housing and services, and 3% industrial parks and transportation infrastructures). Cropland and forestry land represent 85% of the territory (85,200 ha and 197,700 ha, respectively). The ecological footprint of commuting estimated in

Table 4
Evolution of the ecological footprint of commuting (ha), 1986–1996

Metropolitan rings	1986	1991	1996	Growth rate 1986–1996
Barcelona	16,891	22,742	25,799	0.52
First ring (A1)	14,467	20,283	23,288	0.60
Second ring (A2)	10,776	17,028	22,415	1.08
Satellite cities	8303	12,990	17,290	1.08
Satellite city commuting area	2347	4003	6111	1.60
Metropolitan corridors	12,441	20,655	32,333	1.59
Total BMR	65,226	97,703	127,239	0.95

Table 5
BMR population evolution, 1986–1996

Metropolitan rings	1986	1991	1996	Growth rate 1986–1996	Number of municipalities
Barcelona	1,701,812	1,643,542	1,508,805	−0.11	1
First ring (A1)	933,183	919,957	882,307	−0.05	10
Second ring (A2)	491,432	519,661	535,652	0.09	24
Satellite cities	581,788	591,185	596,983	0.03	7
Satellite city commuting area	78,703	91,253	107,824	0.37	20
Metropolitan corridors	442,609	498,824	579,419	0.31	101
Total BMR	4,229,527	4,264,422	4,210,990	−0.004	163

1996 is 127,239 ha. The energy land required to absorb the direct and indirect CO_2 emissions is 122,900 ha. Considering that commuting is about one-third of total mobility, it seems clear that the total impact of mobility exceeds the total capability of the region to absorb CO_2 emissions of transport. Therefore, BMR exports CO_2 that must be absorbed by other regions, otherwise it might be contributing in net terms to global warming.

The outcome of Table 6 shows that the per capita ecological footprint was 0.015 ha on average for the whole BMR in 1986 and 0.030 ha in 1996, which means an increase of 94%.[7] The metropolitan rings with the lowest and highest per capita ecological footprint are the municipality of Barcelona and the satellite city commuting areas, respectively.

One interesting result from Table 6 is that the increase in per capita ecological footprint was greater in the central city than in the inner ring (A1). One possible reason for this unexpected finding could be that the increase in household income has actually been more intense in Barcelona city than in BMR's inner ring, possibly leading to a higher increase in car use. However, a simple visual inspection of Table 3 questions this hypothesis. Surprisingly enough, the increase in the proportion of trips made by car between 1986 and 1996 was greater in the inner ring than in Barcelona. Therefore, the reason must be related to the other component implicitly included in the calculation of ecological footprint: travel distance. The results shown in Table 2 confirm that hypothesis. The growth rate of per capita eco-footprint was higher in Barcelona city than in BMR's inner ring mainly because average trip distance increased more in Barcelona than in the inner ring.

Another finding from Tables 5 and 6 worth considering is that the range between the different settings is much narrower per capita than for the total measurement. This pattern is mainly due to the effect of population suburbanization. The decrease in population in central areas (Barcelona and the inner ring), and the increase in peripheral areas (A2, the commuting satellite cities area, and in the metropolitan corridors), makes those differences in the per capita ecological footprint increase to the extent that they are lower than in the case of those not indexed by population ecological footprint values.

5. The impact of urban form on the ecological footprint of commuting

5.1. Urban form and socio-economic variables

The characterization of urban form is based on intensity of land used for residential purposes

Table 6
Evolution of the per capita ecological footprint of commuting (ha/cap), 1986–1996

Metropolitan rings	1986	1991	1996	Growth rate 1986–1996
Barcelona	0.010	0.014	0.017	0.72
First ring (A1)	0.015	0.022	0.026	0.70
Second ring (A2)	0.022	0.033	0.041	0.87
Satellite cities	0.014	0.022	0.029	1.02
Satellite city commuting area	0.030	0.044	0.057	0.91
Metropolitan corridors	0.028	0.041	0.056	0.99
Total BMR	0.015	0.023	0.030	0.94

[7] This coincidence of growth rate with total ecological footprint could be explained in terms of a zero net increase of population for the whole region.

(population density), and accessibility (distance to the center and distance to the transport axis).

Net population density (DEN)

Municipal population divided by hectares of residential land. Municipal population is provided by the Census of Population (INE, 1987, 1992, 1997) and the municipal residential land, from the map of land uses (PIM, 2000).

Distance to the center (DC)

The distance to the center (km) consists of the network distance from the geographical center of each municipality towards the center of Barcelona (CBD).

Distance to the transport axis (DA)

This distance (km) is the distance from the geographical center of each municipality to the nearest transport axis.

In characterizing social and economic factors, two indicators have been used: average household income and job ratio.

Average household income (INC)

It is the average declared income per municipality coming from fiscal information (PIM, 2000). This variable has some relevant limitations[8] but remains useful in the characterization of the predominant social composition of each municipality.

Job ratio (JOB)

This economic indicator gives information on the per capita employment in each municipality, that is, the ratio of number of jobs and residents. This ratio basically refers to the dimension of the economic sector in reference to the inhabitants of one municipality. It gives us an idea of the potential for self-containment of the municipal labor market if all the municipality's active population worked there.

Table 7 summarizes average urban form and socio-economic indicators per metropolitan settings. In 1996, the area with the greatest population net density was the inner ring. The value is even higher than that corresponding to the municipality of Barcelona. Dense inner ring peripheries are fairly common in cities of Mediterranean countries, such as Marseille, Lyon, and Milan, as well as in cities of post-communist countries. The evolution of average density per spatial setting confirms the existence of a population suburbanization process, leading to a decrease in the central area (Barcelona and A1), and an increase in the rest of the metropolitan area (Table 7).

Barcelona and its satellite cities commuting areas are the spatial areas with the highest average household income. The lowest average household income is found in A1, satellite cities and corridors. Two observations must be taken into account. First, inside Barcelona neighborhoods coexist with very different average household incomes; and second, the inner ring continues to be the urban area where poverty is more concentrated. Looking at the variation rate, the settings where average income increases most dramatically are A2, the satellite cities commuting areas, and the metropolitan corridors. These areas have grown from lower values in 1986, so that suburbanization has led average income to converge, leaving the inner ring as an exception to this pattern (Table 7).

Barcelona and its satellite cities unsurprisingly have the highest job ratio levels. Decentralization of employment and new job opportunities have led to a substantial increase in the job ratio in areas that previously departed from lower levels, such as A1 and A2. In A1, the process has been reinforced by a decrease in the denominator (population) (Table 7). More relevant than a global increase in the job ratio is that the standard deviation has substantially increased between

[8] First, we are aware that this income measurement surely underestimates the real income. Given the possibility of using proxies of average household income (education level or car ownership), we have chosen the income variable because alternative measurements can generate econometric problems regarding the relation of causality with other explanatory variables used in the regression. The second relevant limitation is the lack of information about the different income levels (and hence of the expected travel patterns) among the neighborhoods from the municipality of Barcelona. However, the other municipalities that make up BMR (163) do not have such diversity within their administrative boundaries. Therefore, we believe this indicator captures the difference between them rather accurately.

Table 7
Evolution of the household income, job ratio, and residential density, 1986–1996

Metropolitan rings	Household income			Job ratio			Residential density		
	1986	1996	Growth rate 1986–1996	1986	1996	Growth rate 1986–1996	1986	1996	Growth rate 1986–1996
Barcelona	2001	2904	0.31	0.39	0.42	0.10	413.2	366.4	−0.113
First ring (A1)	1438	2154	0.33	0.19	0.26	0.35	402.5	380.5	−0.055
Second ring (A2)	1558	2431	0.36	0.23	0.31	0.34	219.5	239.3	0.090
Satellite cities	1530	2211	0.31	0.32	0.36	0.11	164.9	169.2	0.026
Satellite city commuting area	1612	2522	0.36	0.27	0.34	0.24	40.9	56.0	0.370
Metropolitan corridors	1547	2390	0.35	0.32	0.35	0.07	52.2	68.3	0.309
Total BMR	1706	2508	0.32	0.31	0.35	0.15	187.1	186.2	−0.004

Measure units: household income—thousands of pesetas; job ratio—jobs/cap; residential density—inhabitants/ha.

1986 and 1996.[9] This implies that the differences between low, middle, and high job ratio municipalities are more remarkable in 1996 than in 1986, possibly leading to a larger demand for mobility for workers living in low job ratios municipalities towards high job ratio municipalities. This hypothesis is tested in the next section by the regression analysis.

5.2. Determinants of the ecological footprint of commuting

The aim of this section is to test the effects of two different types of factors: (a) urban form (population density, distance to city center, and distance to nearest transport axis), and (b) socio-economic factors (average household income and job ratio) on eco-footprint.

The correlation matrix (Table 8) confirms that the greatest multicollinearity problems are concerned with the relationship between density and accessibility. Therefore, empirical data confirm what was previously pointed out from a theoretical perspective: density and accessibility variables must not be taken together as explanatory factors. It is worth highlighting that the correlation becomes stronger at the end of the period. In addition, the two accessibility indicators, distance to the center and distance to the nearest transport axis, are correlated. Such a correlation is not surprising because average distance to the axis increases with distance to city center (see Fig. 1). However, the correlation level is below the maximum level that is normally recommended so as not to have non-desirable effects on regression analysis. There is another pair of correlated variables, distance to the center and household income. Although the correlation is not strong compared to the other pair of variables considered, it is interesting to point out that it is negative. In Barcelona, average income is greater in the central city than in the periphery. Thus, these two variables perform like typical European and American East Coast cities, and much differently to Southern and Western American cities. However, if we look at the variation in the correlation index, we can see that the value decreased between 1986 and 1996, which implies that suburbanization is making average incomes to converge, a consistent result with previous analyses of average income evolution per metropolitan settings.

Columns 1 and 2 in Table 9 show that the explanatory capacity of density and accessibility measures have a similar effect. While density mainly affects the proportion of trips made by car, accessibility variables have a higher impact on trip distance (see columns 1 and 2 of Tables A1 and A2 in the Appendix, where maintaining the same regressors, the dependent variable is average distance traveled and the proportion of trips made by car respectively). Ecological footprint is calculated by incorporating both sources of information (modal split and trip distance). Therefore, both factors counteract, which results in similar effects

[9] The standard deviation of the job ratio was 0.15 in 1986 and 0.20 in 1996.

Table 8
Correlation between the explanatory variables (1986–1996)

	Job ratio	Household income	Distance to the transport axis	Distance to the center	Residential density
(A) 1986					
Residential density	−0.15	0.06	−0.45	−0.68	1.00
Distance to the center	−0.01	−0.35	0.49	1.00	
Distance to the transport axis	0.03	−0.14	1.00		
Household income	0.00	1.00			
Job ratio	1.00				
(B) 1996					
Residential density	0.05	0.07	−0.47	−0.73	1.00
Distance to the center	−0.15	−0.31	0.49	1.00	
Distance to the transport axis	−0.16	−0.08	1.00		
Household income	−0.08	1.00			
Job ratio	1.00				

on ecological footprint, suggesting that, in order to explain municipal eco-footprint variation, accessibility is as important as population density. Another relevant finding is that 1996 estimation has a higher goodness of fit than the correspondent does for 1986. This result implies that urban form variables influence increasingly the ecological impact of transport as time passes.

Average household income has a statistically significant positive effect on the value of footprint, as expected (in both years, 1986 and 1996). Comparing the estimated coefficient and its significance in Tables A1 and A2, it seems clear that the effect is basically associated to modal choice. Job ratio variable exerts a negative effect on eco-footprint, confirming the assumption that proximity to jobs reduces the transport impact. Comparing the results for 1986 and 1996, the estimated coefficient of job ratio has significantly increased, which seems to indicate that the tendency towards the job ratio dispersion among municipalities is pushing the demand for travel from municipalities with a low job ratio towards municipalities with a high job ratio. Although urban form variables determine the ecological footprint of commuting in a larger extent than socio-economic variables, it is also clear that changes over time in the job ratio and income spatial distribution are raising their relevance in explaining eco-footprint differentials.

It is worth pointing out that, comparing the 1986 and 1996 regressions, we observe a higher goodness of fit in regression corresponding to 1996; which means that observed travel patterns are better explained by the model's determinants. We believe that the main reason for the significant increase in the model's goodness of fit is that the metropolitan region has been more functionally integrated during that period. This should be stressed because this sort of analysis tends to consider a constant functional integration level, which is not the case

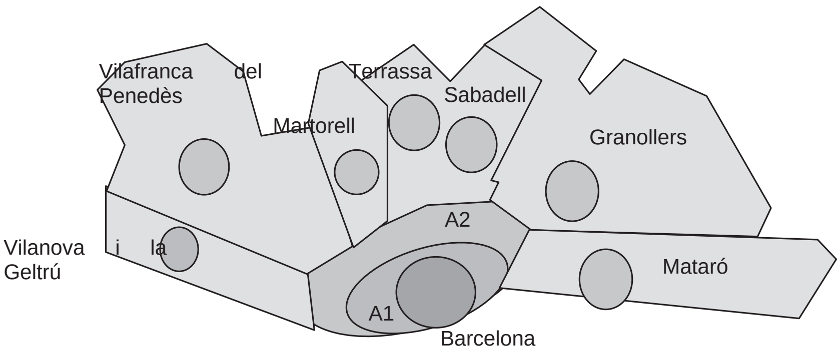

Fig. 1. The BMR urban structure.

Table 9
Determinants of the per capita ecological footprint

Variables	1		2		3		4		5	
	1986	1996	1986	1996	1986	1996	1986	1996	1986	1996
Constant	0.044*	0.081*	0.027*	0.040*	0.008	0.037*	0.018*	0.045*	−0.019*	−0.020
	(20.3)	(27.5)	(6.63)	(8.08)	(0.92)	(2.96)	(2.27)	(4.5)	(−2.01)	(−1.5)
DEN	-8.74×10^{-5}*	−0.0001*	–	–	–	–	-9.5×10^{-5}*	0.0001*	–	–
	(−5.9)	(−8.17)					(−6.7)	(−9)		
DC	–	–	2.6×10^{-5}	0.0003*	–	–	–	–	0.0002*	0.0005*
			(0.20)	(2.24)					(2.11)	(4.2)
DA	–	–	0.0027*	0.0040*	–	–	–	–	0.0027*	0.0031*
			(5.3)	(6.2)					(5.6)	(6.2)
INC	–	–	–	–	1.9×10^{-5}*	1.6×10^{-5}*	2.12×10^{-5}*	1.9×10^{-5}*	2.7×10^{-5}*	2.5×10^{-5}*
					(3.8)	(3.4)	(4.6)	(4.9)	(5.8)	(6.3)
JOB	–	–	–	–	−0.007	−0.036*	−0.018	−0.032*	−0.009	−0.018*
					(−0.67)	(−3.2)	(−1.8)	(−3.4)	(−0.9)	(−2.0)
R^2 adjusted	0.17	0.28	0.18	0.31	0.07	0.12	0.28	0.41	0.32	0.47
Schwarz	−4.83	−4.38	−4.82	−4.39	−4.69	−4.14	−4.91	−4.53	−5.06	−4.67
S.E.	0.020	0.026	0.020	0.025	0.022	0.029	0.019	0.023	0.018	0.022
Obs.	163	163	163	163	163	163	163	163	163	163

t values in parenthesis, R^2 adjusted—goodness of fit, S.E.—standard error of the regression, Schwarz—Schwarz statistic.
* Significant variable at 95%.

for BMR, where spatial integration is still in process.

6. Conclusions

The pattern of urban transport is responsible for a substantial part of a city's energy consumption, which has major global environmental consequences. In order to elucidate the impact of urban form on CO_2 emissions and the consumption of resources associated to the transport sector, it is necessary to measure the global environmental cost of transport, as well as using appropriate indicators of urban form and other control variables such as family income and job ratio. In this study, the ecological footprint of travel-to-work in the Metropolitan Region of Barcelona has been calculated. While there are certain inherent limitations with this indicator (e.g., technology and level of vehicle occupancy are not necessarily constant in time) in addition to the impossibility of tackling such an important aspect as non-required mobility, there were some interesting results. First, between 1986 and 1996, the total and per capita ecological footprint doubled, average trip distance increased by 45%, from 4.6 km to 6.7 km, and the proportion of trips made by car increased by 62%, from 22% to 35%. Within these average estimations, highly remarkable intra-metropolitan differences were found. It is important to consider the polycentric and discontinuous form of the Barcelona Metropolitan Region. Second, measures of urban form typically used (net population density and accessibility) have a greater capacity to explain municipal ecological footprints variability than other factors, such as average municipal family income and the job ratio, which leads the authors to conclude that urban form exercises a clear effect on the ecological footprint of transport. Third, Municipalities with low-density levels located in the outer periphery have a higher per capita ecological footprint of commuting than denser central areas. A suburbanization pattern driven by the occupancy of peripheral land with low densities implies important global ecological effects. The control variables estimates show that ecological footprint also increases with income and decreases with job ratio, which recently is becoming a more important determinant. In summary, results support compacity policies that allow for the supply of public transport and an appropriate mix of population and activity.

Appendix A

Table A1
Determinants of the average distance

Variables	1		2		3		4		5	
	1986	1996	1986	1996	1986	1996	1986	1996	1986	1996
Constant	9.75*	15.43*	5.91*	6.11*	6.14*	14.16*	7.81*	15.79*	0.30	1.70
	(25.4)	(29.9)	(8.41)	(7.57)	(3.8)	(6.21)	(5.3)	(8.3)	(0.17)	(0.79)
DEN	−0.014*	−0.027*	–	–	–	–	−0.016*	−0.027*	–	–
	(−5.72)	(−8.6)					(−6.3)	(−8.8)		
DC	–	–	0.032	0.121*	–	–	–	–	0.059*	0.14*
			(1.56)	(5.16)					(2.93)	(5.9)
DA	–	–	0.44*	0.64*	–	–	–	–	0.44*	0.59*
			(5.02)	(6.30)					(5.2)	(6.05)
INC	–	–	–	–	0.0019*	0.0003	0.0022*	0.0008	0.003*	0.0022*
					(2.12)	(0.41)	(2.73)	(1.19)	(4.33)	(3.3)
JOB	–	–	–	–	−2.68	−8.04*	−4.48*	−7.16*	−2.96	−4.41*
					(−1.3)	(−3.9)	(−2.44)	(−4.24)	(−1.73)	(2.88)
R^2 adjusted	0.16	0.31	0.21	0.44	0.026	0.07	0.22	0.37	0.30	0.50
Schwarz	5.50	5.92	5.46	5.74	5.68	6.24	5.48	5.87	5.39	5.67
S.E.	3.70	4.57	3.58	4.11	3.99	5.29	3.57	4.34	3.37	3.87
Obs.	163	163	163	163	163	163	163	163	163	163

t values in parenthesis, R^2 adjusted—goodness of fit, S.E.—standard error of the regression, Schwarz—Schwarz statistic.
* Significant variable at 95%.

Table A2
Determinants of the proportion of trips made by car

Variables	1		2		3		4		5	
	1986	1996	1986	1996	1986	1996	1986	1996	1986	1996
Constant	0.39*	0.66*	0.29*	0.46*	0.21*	0.38*	0.27*	0.43*	0.07	0.11
	(41.4)	(53.7)	(14.24)	(18.6)	(4.8)	(6.4)	(7.6)	(10)	(1.4)	(1.7)
DEN	−0.0005*	−0.0008*	–	–	–	–	−0.0005*	−0.0008*	–	–
	(−8.7)	(−10.9)					(−9.39)	(−12.2)		
DC	–	–	0.0005	0.0016*	–	–	–	–	0.0014*	0.003*
			(0.95)	(2.33)					(2.4)	(4.4)
DA	–	–	0.009*	0.014*	–	–	–	–	0.008*	0.012*
			(3.56)	(4.51)					(3.8)	(4.4)
INC	–	–	–	–	$7.5 \cdot 10^{-5}$*	$7.8 \cdot 10^{-5}$*	$8.5 \cdot 10^{-5}$*	$9.4 \cdot 10^{-5}$*	0.0001*	0.0001*
					(2.9)	(3.4)	(4.2)	(5.7)	(4.5)	(6.03)
JOB	–	–	–	–	0.044	−0.024	−0.021	0.003	0.03	0.05
					(0.79)	(−0.4)	(−0.04)	(0.09)	(0.7)	(1.2)
R^2 adjusted	0.32	0.42	0.11	0.22	0.04	0.06	0.38	0.51	0.20	0.36
Schwarz	−1.87	−1.53	−1.57	−1.21	−1.5	−1.02	−1.91	−1.66	−1.64	−1.36
S.E.	0.09	0.10	0.10	0.12	0.1	0.13	0.08	0.10	0.09	0.11
Obs.	163	163	163	163	163	163	163	163	163	163

t values in parenthesis, R^2 adjusted—goodness of fit, S.E.—standard error of the regression, Schwarz—Schwarz statistic.
* Significant variable at 95%.

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