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Urban mobility and urban form: the social and environmental costs of different patterns of urban expansion

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Abstract

The question of the environmental or social costs of urban form is increasingly attracting attention in spatial policy, but scientific debate in this field is often marred by prejudices and abstract visions; empirical analyses are very rare. The present study aims at establishing, in the metropolitan area of Milan, whether different patterns of urban expansion could be associated with specific environmental costs—in particular, for land consumption and mobility generation. Different typologies of urban expansion were defined, and an impact index weighting differently journey-to-work trips with reference to mode and time length was built at the municipality level. The statistical analysis confirmed the expected "wasteful" character of sprawling development patterns in terms of land consumption, though suggesting that recent urban development is becoming relatively 'virtuous' with respect to the past. With reference to the mobility generated, higher environmental impacts were proved to be associated with low densities, sprawling development, more recent urbanisation processes and residential specialisation of the single municipalities. Public transport seems to be strongly influenced, both in terms of efficiency and competitiveness, by the structural organisation of an urban area: the more dispersed and less structured the development, the lower its level of efficiency and competitiveness and consequently its share of the mobility market. On the contrary, trip times for private transport appear to be correlated not so much to urban dimension or density as to the presence of recent housing development, indicating the emergence of new models of lifestyle and mobility which are very different from those of the past.

Keywords: Urban expansion; Urban form; Urban sustainability; Public transport

1. Introduction

Together with technologies and consumption styles, the form of settlements and the way human activities are organised in geographical space represent crucial research fields—and sources of pre-

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occupation—as far as ecological equilibria are concerned (Camagni et al., 1998). In fact, in principle, the resource-efficiency of different settlement patterns is subject to wide variations with reference, at least, to two scarce natural resources: land resources (for residential uses) and energy resources (for mobility uses).

Land consumption depends directly on the relative compactness of human settlements and on residential density; energy consumption, on the other hand, depends indirectly on the same variables, via their linkage with mobility patterns: trip length and modal choice between private and public means.

The question of the relationship between different patterns of urban expansion and environmental or social costs is increasingly investigated, especially in the North American context, but it is now becoming an important issue in urban research also in Europe. The strong commitment by European governments to urban sustainability has encouraged experimentation with innovative planning policies in the widely shared conviction that the extensive building on the urban fringe not only consumes precious land resources, but is largely responsible for the high costs of infrastructure and energy, the congestion of transport networks, the increasing segregation and specialisation of land use, and also degradation of the environment: all elements which tend to draw the city away from the model of sustainable development, and undermine certain traditional features, such as its compactness and diversity. The European city, the very place of social interaction, innovation and exchange, risks weakening this fundamental role as a result of the cumulative effect of decentralisation tendencies, increasing specialisation of land uses and social segregation (Camagni and Gibelli, 1996, 1997).

Despite this renewed awareness, scientific debate is often marred by prejudices and abstract visions; empirical analyses on the environmental and social costs of different typologies of urban development are very rare (and in the case of Italy, practically non-existent). The aim of the present study is to tackle the issue explicitly, by developing innovative methods and carrying out some initial econometric analyses.

With reference to the metropolitan area of Milan, we have therefore examined the relationship between different types of urban expansion (at the level of the single municipalities) and:

- land consumption, and
- mobility patterns and their environmental impact.

Consequently, we were able to produce a statistical measure of the relevance of urban form in determining social and environmental costs, via land utilisation—or 'waste'—and the mobility patterns generated, differently linked to the private car use.

The study is divided into two main parts. In the first part we analyse the typical features of current urban development and look at the results of some recent international empirical analyses on the comparative costs of different typologies of urban development (Section 2); in the second part we present the main findings of our empirical analyses carried out in the province of Milan: we define a number of archetypal forms of urban development (Section 3.1), measure the associated consumption of land (Section 3.2) and then carry out a detailed analysis of the mobility generated and its environmental costs (Section 3.3).

2. Development at the urban fringe: dynamics, interpretations and empirical analysis

2.1. Emerging urban form and its relevance for sustainable development

In Europe, the areas surrounding most large cities have been radically transformed over the last 20 years. Not only has there been an increasing amount of built development, but this has spread extensively in forms which are very different from those characterising traditional suburbanisation, i.e. expansion that occurred around a dense urban nucleus, prevalently through extension and/or relatively compact development. Many urban areas, although demographically static, or at the most showing weak signs of population growth, have spread out and 'diluted' over space in a form of development whose features have been very effectively described with the

term *sprawl:* low density development, extending to the extreme edge of the metropolitan region and located in a random, 'leapfrog' fashion, segregated in specialised mono-functional land uses, and largely dependent on the car (May et al., 1998; OECD, 2000).

There are many closely interrelated reasons for the success of the 'diffused metropolis'. As far as residential location is concerned, the main reasons appear to be: the decline in environmental quality of the densely built city centre, due to traffic congestion, pollution, degradation of public spaces and reduction of safety; change in lifestyles, due in part to the increase in incomes, in favour of more spacious decentralised housing; the replacement of residential land use in the city centre by tertiary activities; the fact that housing improvement in the city centre costs more than new construction outside the city; and the housing supply strategies of real estate agents, which find less resistance in the more spacious out-of-town areas.

As far as economic activities are concerned, among the reasons for suburbanisation we can identify: lower development costs for activities which do not require accessibility to the centre (such as *back-office* activities), the difficulty of access to the city centre by car, the development of forms of out-of-town retailing based on the use of the car; and the suburbanisation of housing and hence of part of the consumer and labour market. Institutional factors, too, may encourage diffused forms of urban development: for example, the fragmentation of responsibility for town planning and an imbalance in local tax base (Camagni, 1999).

The interpretations of this phenomenon found in the literature can be reduced, in a highly simplified manner, to two main, but very different approaches: (A) an optimistic 'neo-free market' approach; and (B) a pessimistic 'neo-reformist' approach (Gibelli, 1999).

The former includes those analyses which adopt a fundamentally positive view, making optimistic assessment of the phenomenon of urban sprawl (and/or tending to take a neutral view): this approach naturally favours non-intervention, and non-interference through planning processes (or the most limited planning control at the local scale, concerned mainly with the layout of individual developments).

Those who take the second approach maintain that it is crucial to intervene, through the adoption of sectoral and spatial planning policies, to contain urban sprawl. They consider the current, and above all, the probable future costs undesirable, maintaining that these are likely to grow exponentially in the absence of corrective measures. The emergence of the theme of urban sustainability is an element which, in recent years, has strengthened this second view, stimulating a variety of reflections and also operative indications.

(A) The first approach is well represented in the European context by the 'theoreticians' of the *ville émergente* (Chalas and Dubois-Taine, 1997), convinced opponents of any large scale planning aimed at controlling urban sprawl or restricting the mobility and location preferences of individuals or economic activities. They argue that it is impossible (due to the growing complexity of the spatial interactions permitted by car mobility), pointless (as new technologies will allow increasing freedom of location), but above all socially undesirable since the '*ville à la carte*', or the '*ville aux choix*' will offer an increasing freedom for people to design their own 'life-spaces' and interpersonal relations, a process in which it is not acceptable to interfere.

Even more radical is the view of the North American free-marketeers, who claim that the problems caused by extensive suburbanisation are overestimated, emphasising that the new information technologies are set to accelerate the dispersion of population and jobs until physical proximity will become irrelevant. They argue (Gordon and Richardson, 1997):

- that only unacceptable policies of 'command and control' could consider interfering with the evident individual preference for low density housing;
- that the relationship between urban densification and reduction of energy consumption is not scientifically proved;

- that spontaneous processes of self-correction are possible in the short to medium term to reduce the home-to-work distance, as shown by the edge-city phenomenon;
- that the efficiency of more compact suburban development has yet to be demonstrated, both in terms of costs and social re-equilibrium;
- and finally that top-down, large scale planning would risk taking away responsibility from local authorities in a period of globalisation and growing competition between cities in which any planning error is immediately punished by the market.

(B) The second approach, which represents the main current of thought, underlines the risks and contradictions of the emerging tendencies, emphasising, through empirical analyses and case studies, the negative economic, social and environmental impact of extensive suburbanisation (European Commission, 1990; Owens, 1992; OECD, 1995, 2000; Camagni and Gibelli, 1997; Sueur, 1998; CSD, 1999). This approach necessarily includes a normative dimension,[1] and the search for innovative policies and tools for governing the phenomenon of urban diffusion. The metaphor used is the "compact city" metaphor, implemented through urban infilling and densification.

This metaphor has been put in question by some scholars as too broad, generic and ideological (Breheny, 1992; Banister, 1992; Jenks et al., 1996). In particular, the urban scale to which it should apply remains uncertain and, beyond certain levels of density and size, it could produce 'town cramming' and scale diseconomies which are among the main causes of present suburbanisation tendencies (Elkin et al., 1991; Fouchier, 1998). A sufficient agreement exists, though, about the desirability of a polycentric urban structure, organised on small and medium-sized, compact centres, well connected through an efficient network of public transport (Breheny and Rookwood, 1993; Blowers, 1993; Breheny, 1996; Hall and Landry, 1997), we sometimes called a 'wisely compact' urban structure (Camagni and Gibelli, 1996).

2.2. Demand for mobility and its relationship with the form of city expansion

The demand for mobility, and in particular the growing dependence on private vehicles for intra-metropolitan trips, is currently a crucial component in the debate on sustainable urban development, given the economic, social and environmental impact for which it is responsible.

A diffused pattern of urban development, almost by definition, cannot be adequately served by the public transport infrastructure since the demand density is low, the scattering of the demand over the territory is high and the dispersion of destinations is also growing because of the suburbanisation of jobs. This is the reason why so many analyses of the social, economic and environmental costs of urban expansion have concentrated on the pervasive presence of the automobile: a technology capable of 'bringing places nearer' by providing access to the increasingly dispersed and specialised urban functions (Cervero, 1998; Newman and Kenworthy, 1999). The subject has already been widely investigated in North America, and is now becoming the focus of debate in Europe, too, given the emergence of the phenomenon of sprawling urban development and its incompatibility with the objectives of sustainability.

There are several factors which weigh in favour of the car: from its intrinsic flexibility to the fact that, unlike public transport, the capital investment and running costs have fallen in real terms. The choice of transport mode raises for the individual the alternative between adopting co-operative behaviour, helping to reduce overall congestion by using public transport, and non-co-operative behaviour, using the private car in the hope that most others will not do so—a sort of prisoner's dilemma which leads to solutions that are individually rational, but collec-

[1] Indirectly, approach A appears just as normative, as far as it assumes that the current trend is 'good'.

tively inefficient (European Commission, 1996; Camagni and Gibelli, 1996).[2]

Another factor to be borne in mind is the high consumption of land for road infrastructure: 25% of the total urban area in Europe and 30% in the United States (40% in Los Angeles!). Even more alarming evidence is obtained if we measure the impact on the consumption of land in space/time terms (land consumption in square metres per hour). Research carried out in the Paris region showed that the private car, which accounts for 33% of total trips, consumes 94% of road space/hour; while the bus, with 19% of total trips consumes only 2.3%: in other words, a bus in movement consumes 24 times less space per passenger than a single car (Servant, 1996).

One question posed by many researchers, and also examined in the present investigation, is whether it is possible to demonstrate a significant relationship between mobility consumption and the morphology of urban development. In this connection, it is interesting that an empirical analysis undertaken recently in the Paris metropolitan area shows a direct relationship between the rate of car ownership and distance of the area of residence from the centre, and also an indirect relationship between the demographic density of the area of residence and variables such as the rate of car ownership, the distance travelled each day and the per capita consumption of petrol (Fouchier, 1998).

2.3. The costs of sprawl in international surveys: land consumption and public costs

We now come to the central theme of our research programme on the community costs of suburban development, in order to underline immediately a difficulty that our analysis shares with other investigations at the international level. Although good evidence has already been provided of the economic, social and environmental costs, findings relating to the public costs of sprawl are modest, due mainly to the objective difficulties of finding significant and reliable performance indicators. The specific results available relate to studies carried out predominantly in North America and therefore refer to rather different suburbanisation patterns and a very different institutional/administrative context. Nevertheless, it is significant that the findings reveal a significant correlation between different forms of urban growth and public costs.

Pioneer research was carried out in this field in 1974 by the Real Estate Research Corporation of the US Government in order to estimate the economic and environmental costs of different types of urban development and different forms of growth on the urban fringe. The empirical analyses consider the public costs relating to the construction and maintenance of schools, housing, green space, roads and shopping centres, and estimate the costs to the community in terms of the negative environmental effects (land consumption, air, water and noise pollution) and social effects (car journey time, accidents, psychological and social costs). The main result of this research was the identification of urban density as the fundamental variable of the overall costs sustained by the community (Real Estate Research Corporation, 1974), though these conclusions did not go unchallenged: see, among others, Altshuler (1977) and Windsor (1979).

Later research undertaken to evaluate the comparative costs of 'leapfrog' development using greenfield sites and the extension of existing built up areas reached similar conclusions (Downing and Gustely, 1977). More recently, Robert Burchell and others, using a similar approach to that of the RERC, have analysed the infrastructure costs of two alternative forms of development: market-guided suburbanisation, and planned development (subject to *growth management* policies and wiser planning and design) in

[2] In relation to the use of the private car, a further and apparently paradoxical problem concerns the fact that, contrary to common sense expectations, a growing percentage of car trips involve short and very short distances: 57% of journeys in Great Britain are less than 8 km; 50% of trips in France are less than 3 km; and in Spain 25% of trips cover less than 2 km. In the Paris region 72% of trips are under 4 km and, in 22% of cases, under the record threshold of 1.25 km. (Servant, 1996). The main reason for this is the lack of eco-compatible alternatives (protected pedestrian routes and cycle tracks) especially for the intra-suburban trips, where the risks and inconvenience for the pedestrian and cyclist are highest.

three different localities. The aim was to evaluate the savings achieved by the latter in terms of land consumption and infrastructure costs (assuming stability of housing costs and the local tax base). The results revealed that the planned form of development saved around 20–45% of land resources, 15–25% of the costs for providing local roads, and 7–15% for water and drains (Burchell et al., 1992).

Finally, a research project investigating the costs of road construction, public services and, in particular, school management and investment, also arrived at the conclusion that the lower the density of development and the greater the distance from the centre of the metropolis, the higher the public costs (Frank, 1989). Similar results have been reached in numerous case studies, investigated in depth in a recent study (TCRP, 1998), which revisits and updates the RERC Report 20 years later.

In the European context, despite the fact that the phenomenon of sprawl is now highly evident, both from the quantitative and qualitative point of view, there has so far been little research on its public costs. A comparative evaluation of the advantages and risks of different patterns of urban development, commissioned by the British Department of the Environment, has been carried out recently on the wave of the growing government commitment towards sustainable urban development (Breheny et al., 1993).

This research, which made use of statistical analyses, case studies and surveys of local authorities, examines five types of development: the densification of the city through re-use and infill, urban extension, key village extension, multiple village extension, and new settlement. The advantages and disadvantages of each type were assessed in terms of the economic, social and environmental costs, both public and private, with the aim of formulating recommendations and suggestions for action aimed at various administrative levels with responsibility for town and country planning. The authors themselves declare the findings to be largely inconclusive as to the preferable model.

3. Social costs of different typologies of urban expansion: land consumption and mobility patterns

3.1. Typologies of urban expansion

Following the general reflections outlined above, the purpose of our empirical analysis, carried out in the province of Milano, was to identify the characteristics of urban development and the social costs of the urban expansion which occurred during the ten-year period 1981–91. The variables examined include the consumption of land for housing development and the social costs of the mobility generated.[3]

Using as a starting point the maps drawn up by Centro Studi PIM on land consumption in the Milano area in 1991, the patterns of residential development over the period 1981–91 in each of the 186 communes within the province were analysed using a descriptive/intuitive approach. At the macro level, it was possible to distinguish five types of urban expansion:

- *infilling* (T1),
- *extension* (T2),
- *linear development* (T3),
- *sprawl* (T4), and
- *large-scale projects* (T5).

Type T1 is characterised by situations in which the building growth occurs through the infilling of free spaces remaining within the existing urban area; T2 occurs in the immediately adjacent urban fringe; T3 is development which follows the main axes of the metropolitan transport infrastructure; T4 characterises the new scattered development lots; T5 concerns new lots of considerable size and independent of the existing built up urban area.

All the combinations among these types were then identified and, finally, by eliminating and re-assigning the least significant combinations, a selection of 10 prevalent typologies was arrived

[3] For our empirical analyses we used the plans and calculations prepared by the Centro Studi PIM in 1991 as part of the research project '*Uso-consumo di suolo e dinamiche insediative dell'area metropolitana milanese*' undertaken for the Provincial Plan (*Piano Direttore Territoriale Provinciale*), ISTAT data concerning resident population in the communes and Census data relating to mobility for working reasons in 1991.

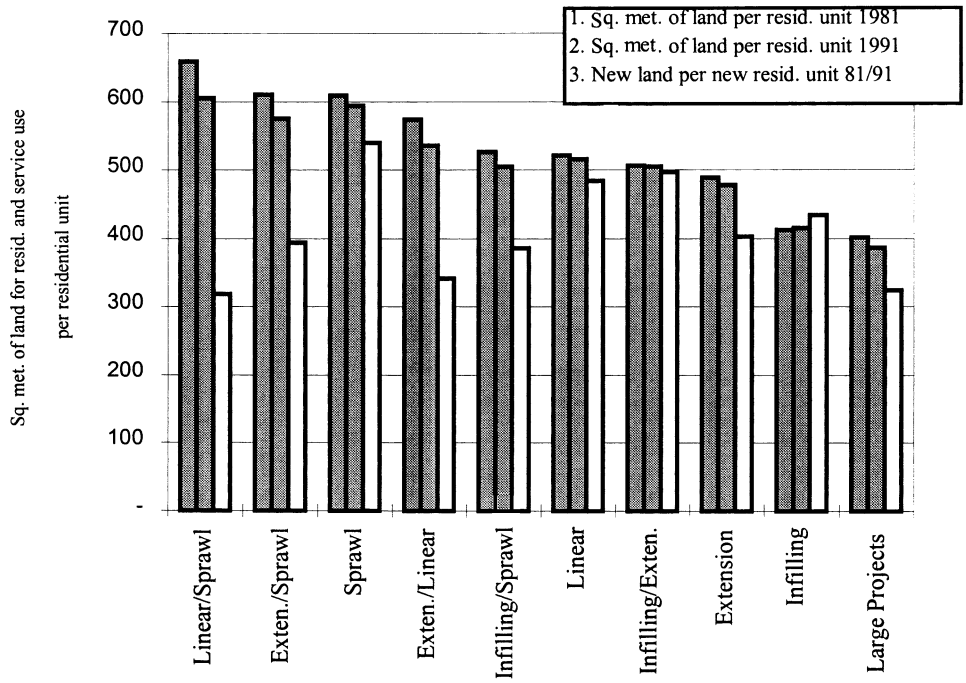

Fig. 1. Land consumption by typologies of urban expansion.

at.[4] These typologies were used in the statistical analysis on land consumption; in the subsequent econometric analysis they were reduced to four main typologies and used as independent dummy variables, together with other variables referring to settlement structure, in the interpretation of the environmental impact of mobility.

Before going any further, we should specify an important caveat. Given the level of subjectivity inherent in the attribution of the various communes to the different categories, the results which we now analyse must be taken as a preliminary approximation.

3.2. Land consumption

As far as the analysis of land consumption is concerned, the first survey we carried out compares the land area developed for residential and service use between 1981 and 1991 in each commune to the number of dwellings. This indicator was preferred to the per capita consumption of land because the latter may increase in cases where the population of a commune declines, giving a false indication. Three main categories emerged (Fig. 1):

- the relatively 'thrifty' types, where consumption was below 450 m^2 per dwelling, which corresponded as expected to the categories 'pure infilling' and 'large scale projects';
- the relatively 'land-greedy' types, which belonged, again as expected, to the categories 'pure sprawl', 'linear development-sprawl', and 'extension-sprawl', where consumption was above 600 m^2 per dwelling, plus 'extension-linear' development with > 550 m^2 per dwelling;
- an intermediate group, which included the categories: infilling-extension, infilling-sprawl, pure extension and pure linear development, with consumption around 500 m^2 per dwelling.

If we observe the ratio between the new built

[4] These are: pure infilling (T1/T1), infilling-extension (T1/T2), infilling-sprawl (T1/T4), pure extension (T2/T2), extension-linear development (T2/T3), extension-sprawl (T2/T4), pure linear development (T3/T3), linear development-sprawl (T3/T4), pure sprawl (T4/T4), large scale projects (T5/T5).

up area and new dwellings in time (1981 vs. 1991), an unexpectedly positive trend emerges. In fact, for all types of development (except infilling), the consumption of land per dwelling is slightly declining in time. This suggests that new urban development overall is relatively land-sparing compared with the past.

The regression analysis on single communes (% increase in the built-up area over% increase in number of dwellings) confirmed the result ($R^2 = 0.32$, Student's $t = 9.23$); on average, a given percentage increase in dwellings corresponded to an increase in built-up area equal to about one quarter.

In conclusion, the results obtained so far confirm the standard hypothesis which suggests that less land is consumed by the more compact types of development, in particular 'infilling' and large-scale projects. However, the expectations concerning the change of behaviour over the last ten years was overturned, since it emerged that new development in the metropolitan area of Milan is in general becoming less and not more 'land greedy', probably due to the combination of rather strict development control at the local level and of gradual exhaustion of land resources in the northern sector of the metropolitan area.

3.3. The demand for mobility and its social costs

3.3.1. Methodology

It emerges clearly from the literature that the demand for mobility is an important component of the environmental impact of urban development, as illustrated in Section 2. For this reason, in the present study it was decided to establish whether it is possible to identify significant differences of behaviour within the study area as far as mobility was concerned and, if so, to ascertain whether there is any significant correlation between these differences and variables describing the form of development. The intention is to provide a basis for orienting planning policies.

The working hypothesis is that within a relatively homogeneous area (in terms of income level and general socio-economic conditions), such as the province of Milano, the local differences in the mobility patterns (time and mode) can, at least to a certain extent, be attributed to the form in which urban growth has occurred. Mobility therefore has the role of dependent variable, while the form of development and its dynamics represent the independent variables.

Four types of independent variables were adopted (see Appendix A for statistical details and definition of variables):

- geographical variables: distance from Milan;
- socio-economic variables: population density, size and dynamics, age of buildings, ratio of jobs to resident population (Emp/Res);
- morphology: i.e. the typologies of urban development previously described, reduced to four classes: infilling-extension; extension-linear; sprawl; large-scale projects (see Appendix A);
- accessibility and transport efficiency: competitiveness of public transport, share of public transport, average trip time for public transport trips (*Public time*) and private transport trips (*Private time*).

As far as mobility is concerned—our dependent variable—we used the only data available on a homogeneous basis at the local (commune) level, that is the journey-to-work data recorded in the 1991 Census for each active resident, disaggregated by mode (6 categories)[5] and, within each mode, by the time taken: up to 30, 31–60, over 60 min.[6]

A limitation of the analysis derives from the impossibility of linking trip duration and length, thus distinguishing between the effect of distance and that of vehicle speed and traffic conditions. Other limitations concern the nature of the data, which account for only one segment (commuting), ignoring all the non-systematic aspects of mobility. These limitations were serious, but did not prevent us, as will be seen, from extracting significant indications from the analysis.

From the data on travel modes and the time length of commuter trips, we endeavoured to

[5] Walking or other soft means; bus; car (driver); motorcycle; car (passenger); train, tram or underground.

[6] The classification of trip length applied by ISTAT (National Statistics Institute) is unfortunate. In fact, as far as the province of Milano is concerned, 74% of trips fall in the lowest class below 30 min, 20% in 31–60 min and only 5% in the highest class. It is evident that such a subdivision, which has little correspondence with the actual range of values, reduces the sensitivity of this extremely important indicator.

Table 1
Weights by travel time and travel mode

	Weights for modes	Time		
Classes of trip time		0–30 min	31–60 min	>60 min
Average trip time		15 min	45′	75 min
Weight per time unit		1.20	1.00	0.80
Equivalent trip time		18 min	45 min	60 min
Walking or other soft means	0.00	0.00	0.00	0.00
Bus	0.33	0.13	0.33	0.44
Private car (driver)	1.00	0.40	**1.00**	1.33
Motorcycle	0.33	0.13	0.33	0.44
Private car (passenger)	0.00	0.00	0.00	0.00
Train, tram, underground	0.20	0.08	0.20	0.27

obtain an indicator of the environmental cost of mobility. It is evident that the environmental impact of a trip depends on the combination of mode and time: a weighted index of impact was therefore defined for the 18 combinations of mode and time which could be obtained from the available data.

The matrix of weights for time and mode, applied to each commuting trip in order to consider its different impact, took the following form (Table 1), where the value 1 was arbitrarily assigned to the 45 min. trip by car:

It was assumed that:

- for any given mode, the impact of a trip per unit of time decreases with the trip length (to take into account the higher pollution produced by a vehicle with catalytic converter at the start of the trip, the greater fluidity of traffic outside the urban area, the lower number of stops for trains on longer journeys, etc.);
- for any given duration, the weight of the various modes—put conventionally at 1.00 per passenger × minute the weight of the trip by car—is, respectively: 1/3 for motorcycle and bus; 1/5 for rail trips; zero for pedestrians or bicycle trips and transported passengers (this is justified by considering that the possible lengthening of a journey due to the presence of the passenger is already absorbed by the length of the journey travelled by the driver).

This weighting system is obviously only a rough indication and could be refined by carrying out specific analyses, but it was determined sufficient for the use to which it would be put in this study.

Using the above values, the commuters recorded in the Census were transformed into 'equivalent impact commuters' (EIC). At this point, having two values for each commune—'real' commuters and EICs—by comparing the two values it was possible to arrive at an 'impact intensity index' (or quality index) for each commune, measuring the average impact that can be assigned to every commuter trip made.[7] Referring the characteristic value for each commune to the mean value for the province, we obtained a normalised index, which could then be used in the following stages of the analysis.

The advantage of this index of mobility impact over other, more direct indices of environmental damage (emissions, congestion) resides in the fact that it refers to the mobility demand *generated in each municipality* (as a consequence of its settlement structure) and not to the mobility effects on each place, which could well derive from trips originating in other municipalities.

3.3.2. Factors determining the intensity of the mobility impact

The spatial distribution of the indices of impact intensity was examined using an econometric analysis to ascertain whether there was a significant correlation with any of the selected independent variables describing the characteristics of the urban form.

[7] In other words, a town with 100 commuters and 30 EIC, has an intensity index of 0.30 or 30%. In terms of dimension, it is a pure number (impact commuters/real commuters).

Table 2
Regression analysis of the model Eq. (1)

Dependent variable: MOBILITY IMPACT	Ordinary Least Squares (OLS)		Weighted Least Squares (WLS)	
Independent variables	β	T-Stat	β	T-Stat
Constant	2.539	9.436	2.257	8.941
Dummy Sprawl	−0.066	−1.617	−0.032	−0.931
Dummy Extension/Linear	−0.087	−2.107	−0.042	−1.209
Dummy Infilling/Extension	−0.103	−2.620	−0.061	−1.833
Distance from Milan	−0.006	−4.060	−0.006	−4.225
log (Net Density)	−0.113	−4.784	−0.079	−3.585
Growth Rate of Residents	0.047	2.661	0.054	3.162
log(Age)	−0.143	−3.176	−0.149	−3.328
log(Emp/Res)	−0.079	−4.211	−0.073	−3.851
No. of observations	184		184	
R^2	0.49		[a]	

[a] The R^2 of the *WLS* estimation is not displayed since it is not comparable with the R^2 of the OLS estimation and cannot be interpreted as the degree of variation explained.

The following linear model was selected, as it seemed satisfactory with respect to both its empirical fit and the theoretical interpretation of its parameters:[8]

$$\begin{aligned}&(\text{Mobility Impact})_i\\&=\beta_0+\beta_1\cdot(\text{Distance from Milan})_i\\&\quad+\beta_2\cdot\log(\text{Net Density})_i \qquad (1)\\&+\beta_3\cdot(\text{Growth rate of residents})_i+\beta_4\cdot\log(\text{Age})_i\\&+\beta_5\cdot\log(\text{Emp/Res})_i+\varepsilon_i\end{aligned}$$

In order to estimate the unknown parameters of the model,[9] the error term was first assumed to have constant variance across observations and to be uncorrelated in the space:

$$\text{Var}(\varepsilon_i)=\sigma^2 \quad \forall i$$

$$\text{Cov}(\varepsilon_i\varepsilon_j)=0 \quad \forall i,\ j$$

and consequently the model was estimated with the ordinary least squares (OLS) technique.

Next, the hypotheses of constant error variance (homoscedasticity) and of no spatial autocorrelation were tested. Since both hypotheses were rejected,[10] the model was estimated with other suitable techniques: the weighted least squares (WLS) to deal with heteroscedasticity (with a weight equal to the inverse of the square root of total area) and an iterative technique to deal with spatial autocorrelation.[11]

[8] It is easy to verify that the partial derivative of impact with respect to the variables entering the model in logarithm format is not constant, but rises with the value of the variable itself. For example, the partial derivative with respect to *Net Density* is:

$$\frac{\partial(\text{Mobility Impact})}{\partial(\text{Net Density})}=\beta_2\,\frac{1}{\text{Net Density}}.$$

[9] Notice that Table 2 presents the estimate of a version of the model also including group effects relating to the development typologies. In fact, three dummy variables were added to allow for the intercept shift.

[10] The deviations from the hypothesis of homoscedasticity and of no spatial autocorrelation were faced separately, as their joint treatment is very complex, going beyond the aim of this study.

[11] Assuming a neighbouring structure among the communes defined by a distance of less than 5 km., we obtained a level of spatial autocorrelation for the dependent variable sufficiently high (Moran's I index = 0.272). Using a suitable, iterative estimation technique for our model Eq. (1), we obtained coefficient estimates only slightly different from the OLS ones presented in Table 2, with a small decrease in the *t-statistics*. Presentation of these results goes beyond the scope of this paper.

It is important to note here that using these techniques instead of OLS did not involve, for our model and for our aims, big differences in the results (Table 2). Therefore, it is possible to say that the inference based on the simpler OLS estimators, while not completely accurate (above all as far as the standard deviation of the estimators is concerned), is not misleading.[12] For this reason, in the remainder of the paper only OLS estimators will be displayed, even though we acknowledge that more efficient estimators could be found, in particular if we were interested in testing hypotheses about the value of the parameters.

The outcome is summarised briefly as follows (see Table 2):

- a significant inverse relationship was found between the index measuring the mobility impact and net population density (density of the built up area), in line with the expectations expressed in the international literature. Together with the size of the urban areas in terms of absolute population, density appears to have mainly an *indirect* effect on the mobility impact, through its influence on the average trip time of public transport and hence on the modal split of commuter trips in favour of public transport;
- a significant relationship also exists with the variables representing demographic growth rate and the average age of housing. In both cases, the impact index increased with the dynamism of the communes concerned: in other words, high values were associated with communes with a rapid growth of population over the ten year period 1981–1991 and also those with newer housing, i.e. areas of recent expansion;
- the coefficient relating to the distance from the centre of Milan is small in terms of absolute values (0.006 points per km), but is significantly less than zero, indicating the greater autonomy of the towns in the most external parts of the province and a spatial structure of settlements similar to that of a self-contained 'industrial district';[13]
- following the subdivision into groups proposed in the previous paragraph, three dummy variables were introduced to allow for intercept shift. The analysis of the relative coefficients makes it possible to establish the following ranking (in increasing order of impact): infill-extension, extension-linear development, sprawl, large-scale projects;[14]
- finally, an analysis was made of the role of the employment/residents ratio, a variable to which the literature attributes considerable importance in connection with mobility demand. This relationship can be considered an indicator of the level of functional diversification–integration–segregation, the 'functional mix' of each commune. A significant and negative relationship emerged in the multiple regression analysis, indicating that the mobility impact was higher when the proportion of employment was lower, i.e. in areas of specialised residential nature.

3.3.3. Components of the mobility impact: modal choice and trip time

As we have seen in Section 3.1 and Table 1, the mobility impact index is the result of two components: transport mode and trip time. These two components determine two distinct 'logical chains' through which it is possible to hypothesise a causal relationship between the physical structure of urban development and the social costs represented by the mobility impact (Fig. 2). On the one hand, we have:

[12] It should be noticed that the violation of the two hypotheses of homoscedasticity and of no spatial autocorrelation does not involve any problem of bias or of consistency, but only of efficiency.

[13] Signs of second order effects were also recorded (due to the fact that in the immediate suburbs of Milan the influence of distance on the mobility impact index seems to have the opposite sign; the inclusion of these effects in the model Eq. (1) is nevertheless disturbed by problems of multi-collinearity.

[14] Large-scale, suburban residential projects show a limited mobility through soft modes and, due to the location of most of them in the case of Milan, far from metro lines, low utilisation of public trasport.

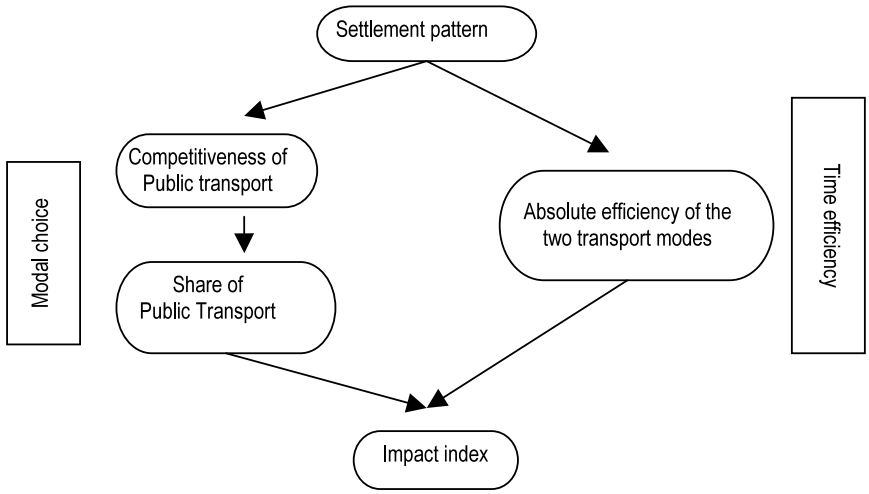

Fig. 2. Causal chains in the explanation of mobility impact.

- settlements of relatively compact structure → greater competitiveness of public transport (in terms of journey to work time) → greater use of public transport → lower mobility impact (left-hand logical chain in Fig. 2); on the other:
- settlements of relatively compact structure → greater efficiency of both public and private transport → lower commuting time → lower mobility impact (right-hand logical chain in Fig. 2).

Before moving towards the econometric analysis, it seems necessary to make a methodological point. A causal interpretation of the models presented in the following cannot be derived from a statistical estimation process, but can be maintained only on the basis of a priori theories or knowledge regarding the phenomenon under consideration. It then follows that all the estimates reported below can give only an idea of the strength of the causal connections between the involved variables and not of their direction.

3.3.3.1. The relative competitiveness of the two transport modes. As far as the first logical chain is concerned, distinguishing simply between public transport (road and rail) and private transport (car and motorbike), we can analyse the relationship between a competitiveness indicator for public transport—given by the average time taken for trips made by private transport in comparison with public transport—and the share of trips for each mode, which has a direct effect on the impact index. From Table 3 it is easy to see, in logical sequence, that:

- the relative competitiveness of public transport depends significantly on the form of urban development, and in particular on residential density (Table 3a);
- there is an evident connection between this competitiveness indicator and the modal split (Table 3b): as it is well known in the transportation literature (and close to common sense expectations), the share of public transport increases with its comparative efficiency *vis-à-vis* the other transport modes;
- the market share of public transport has a significant influence on the mobility impact index (Table 3c).

In order to study this last relationship, a slightly different equation from the model Eq. (1) was estimated in Table 3c, since problems of multicollinearity due to the high correlation between the variable *Share Public Trans* and the other variables included prevent inferences being made with respect to the variable *Share Public Trans* itself.

It should be noted that the comments made in relation to the estimate of the first model are fully

Table 3
Mobility impact index and share of public transport

Dependent variable:	*a*		*b*		*c*	
	Competitiveness Public Trans		Share Public Trans		Mobility Impact	
Independent variables:	β	*T*-Stat	β	*T*-Stat	β	*T*-Stat
Constant	0.279	19.113	−0.050	−1.536	1.487	9.989
Competitiveness public trans.			0.561	7.585		
Gross density			2.33E−05	4.519		
Net density	2.5E−05	5.361				
Growth rate of residents			−0.022	−2.622	0.078	4.602
log(Growth rate of residents)	0.026	5.883				
Built up area			−1.34E−03	−3.402		
Emp/Res	0.07	3.857	−0.048	−2.265		
log(Emp/Res)					−0.043	−2.426
Share public trans.					−0.267	−2.572
log(Age)					−0.113	−2.425
Distance from Milan					−0.005	−3.328
No. of observations	184		184		184	
R^2	0.42		0.47		0.41	

confirmed in the estimate of the second model: the environmental impact of mobility lowers the higher the share of public transport, the older the building stock, the lower the recent demographic growth rate, the wider the mix of economic and residential activities.

Fig. 3 represents the relationship between relative competitiveness of private transport (which is just the inverse of the relative competitiveness of the public transport) and the share of trips on public transport. It shows that in only one commune—being Milan, for the first time included in the analysis, given its relevance in this relationship[15]—do trips by public transport take less than 150% of the time taken by private vehicles, giving rise to conditions of equilibrium between the two modes (50–50%).

The data are interpolated by means of the following model, with a forecasting purpose:[16]

$$\log(Share\ Public\ Trans)_i = \beta_0 + \beta_1 \cdot \log(Competitiveness\ Private\ Trans)_i + \varepsilon_i \quad (2)$$

where β_1 represents the elasticity of the market share of public transport with respect to the relative competitiveness of the private transport. In Table 4 the OLS estimation of the model is displayed.

On the basis of the estimation just carried out, in Table 5 we present some extrapolations, in order to give a general indication about the implied relationships between the two variables.[17]

Some comments can follow:

[15] It should, however, be pointed out that the inferential results reported below are sturdy with respect to the exclusion of the observation relating to Milan itself.

[16] Notice that a multivariate model could have been adopted as well (for example, the model Eq. (1)) in order to make forecasts concerning the variable *Share Public Trans*. This, although allowing greater detail, would have resulted in the need to establish the values of further exogenous variables that condition the forecasts. Following this multivariate approach, the variable *Share Public Trans* was forecasted by using the model presented in Table 3b and assigning the additional variables their sample mean: the results obtained in this way were not very different from those obtained with the univariate model.

[17] One main limitation of these extrapolations is the high forecast error connected with them, resulting from the relatively low fit of the monovariate model.

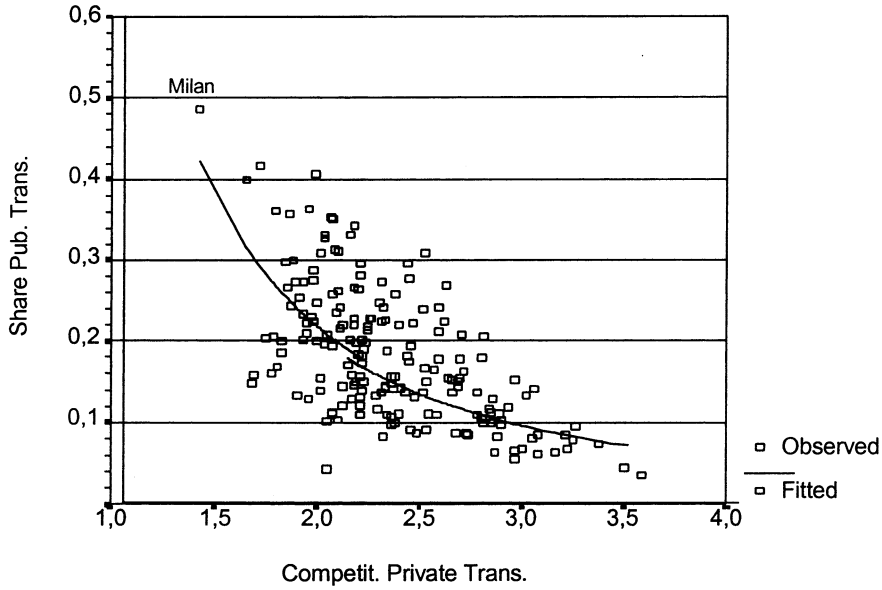

Fig. 3. Public transport mode: market share versus relative competitiveness.

- the condition which would allow public transport to gain the full market share of trips is when trip times are just under 85% of those on private transport;
- when trip times are the same, public transport can expect to achieve a 75% share;
- at a certain point, market share declines rapidly, falling to 20% when public transport trip times are the double of those on private transport, and 10% when they are triple; the curve then flattens out, and even in conditions of very poor competitiveness (the actual situation in many communes), there still remains a faithful 5% of commuters who used public transport.[18]

From what has been indicated previously (Table 3b), we can state in addition that the market share of public transport:

- decreases with the increase of the total built up area, at the rate of $0.1 \div 0.2\%$ every km^2;
- increases with gross density, at the rate of 2.3% every 1000 inhab/km^2.

3.3.3.2. The absolute efficiency of the two transport modes. In this paragraph the relation between urban expansion and the absolute efficiency of the two transport modes is studied (the second logical chain in Fig. 2). The absolute efficiency is measured by the average trip time; it is, in fact, clear that a typology of transport is more efficient in an absolute sense the shorter is the duration of the trips made with that mode.[19]

Table 4
Share of public transport and its relative competitiveness

Dependent variable:	Log (Share public trans.)	
Independent variables:	β	T-Stat
Constant	−0.287	−2.142
log (Competitiveness private trans.)	−1.874	−11.660
No. of observations	185	
R^2	0.42	

[18] It should be pointed out that the value of around 5% is that for many American metropolises.

[19] Before moving toward the estimation of a statistical model, it is worth taking into consideration the average values on the whole province: the average trip time with respect to the public transport is about 49 min, while the average trip time with respect to the individual transport is about 21 min. Such a sharp difference seems to confirm that the individual transport is used especially for short distances (see Section 2.2), rather than being a clear evidence of the relative efficiency of the two modes of transport.

Table 5
Values of Share Public Trans forecasted by the model Eq. (2)

Trip time: public/private (%)	Forecasted market share of public transport (%)
85	101.72
90	91.39
100	75.01
150	35.08
200	20.46
250	13.47
300	9.57
350	7.17
400	5.58
450	4.44

As far as the absolute efficiency of the two transport modes is concerned, it was found that average trip time for public transport trips:

- decreases by about 10 min (20%) from the smallest communes to the largest ones;
- decreases with the increase of net density (inhabitants/built-up area), at the rate of 4.4 s every 100 inhab/km^2;
- increases with distance from Milan (Table 6).

Notice that also the variables 'demographic growth', with a direct effect on trip time, and the variable 'housing age' (with an unexpected positive sign, which in this context probably indicates a congestion effect) proved to be significant.

On the other hand, the trip time for journeys by private vehicles shows:

- perfect indifference to demographic size (with a horizontal regression line at the level 22 min) and substantial indifference to density;
- a negative relationship with the age of housing and positive relationship with the demographic growth, confirming the existence of a pattern of new urbanisation which relies heavily on long trips by private car (Table 6).

Here we have two interesting results: public transport is strongly affected, in terms of efficiency and competitiveness, by the form of urban development. In fact, both efficiency and competitiveness decline, as the form of development becomes more dispersed and unstructured. Trip times by private transport, on the other hand, do not react positively either to density or compactness of development, as the shorter distances are probably counterbalanced by greater congestion. However, there seems to be a dichotomy in behaviour between the older and the more recent residential settlements, the latter being linked to the acceptance of longer journeys to work by private car.

4. Conclusions

The wide dispersion of metropolitan population and the spread of settlement patterns with a high consumption of scarce or non-renewable re-

Table 6
Efficiency of public and private modes (average trip time)

Dependent variable:	Public time		Private time	
Independent variables:	β	T-Stat	β	T-Stat
Constant	40.328	19.021	26.394	34.789
Distance from Milan	0.363	5.538	−0.127	−4.538
Age	0.136	2.319	−0.081	−3.115
Growth rate of residents	1.461	2.541	1.391	5.452
Net density	−7.3E−04	−3.288		
Emp.	−9.8E−05	−1.707	−4.74E−05	−1.919
No of observations	184		184	
R^2	0.52		0.47	

sources (especially land and energy) are relatively recent phenomena in Europe. They have triggered debate, in new forms and with new policy options, of an issue already well rooted in the town planning tradition, that of urban containment. Neologisms such as '*ville éclatéé*', 'ville émergente', 'città diffusa', 'ubiquitous city' and so on, have all been used to express this renewed interest, though representing different analytical approaches and interpretations.

It was in this context that the present empirical analysis was developed, with the aim of establishing, in the metropolitan area of Milan, whether different patterns of urban expansion could be associated with different social and environmental costs—in particular, for land consumption, and, above all, mobility generation.

As far as land consumption is concerned, three main categories emerged: a category of relatively 'virtuous' patterns (pure infill and large-scale projects), an intermediate category (infill-extension, infill-sprawl, pure extension and pure linear development), and finally a 'wasteful' category of development (encompassing pure sprawl, linear development-sprawl, extension-sprawl, and extension-linear development). This was in line with expectations. An analysis of the dynamic aspects, however, revealed an unexpected trend: over the period 1981–91 the consumption of land per dwelling decreased slightly for all development types, suggesting that recent urban development is becoming relatively 'virtuous' with respect to the past.

Secondly, with reference to the question of mobility, an index of environmental impact of the mobility generated in each municipality was built, weighting differently the different modes and time lengths. Urban density, demographic growth rates, age of the building stock and functional mix (economic-residential balance) were proved to be statistically significant in explaining mobility impact. Higher impacts are associated with diffused, sprawling development, more recent urbanisation processes and residential specialisation of the single municipalities.

Public transport seems to be strongly influenced, both in terms of efficiency and competitiveness, by the structural organisation of an urban area: the more dispersed and less structured the development, the lower its level of efficiency and competitiveness and, consequently, its share of the mobility market. On the contrary, trip times for private transport appear to be correlated not so much to urban dimension or density as to the presence of recent housing development, indicating the emergence of new models of lifestyle and mobility which are very different from those of the past.

In terms of mobility, the least environmentally acceptable situations are represented by two opposite types of development (sprawl and 'large-scale projects'), which show a very different behaviour with respect to the modal split. Sprawl is associated with the lowest share of public transport, while large projects have the lowest share of trips made on foot.

In conclusion, our results confirm the farsightedness of the strategic guidances and innovations at the urban design level that aim towards a 'wisely compact' and polycentric pattern of urban development.

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Appendix A. The variables of the econometric models

We briefly present here the variables used in the econometric analysis and discuss the characteristics of the available data.

Mobility impact: index of the impact of mobility, calculated as the ratio between the EIC and the number of commuters recorded in the Census;

Distance from Milan: the distance [km] between the centroid of a commune and the centroid of Milan (according to Corine Land Cover);

Age: the average age of building [years];

Growth rate of residents: the percent growth rate of population between 1981 and 1991;

Gross and net density: respectively, the density [inhabitants/km^2] over the whole land area (km^2) and over the built up area;

Emp: total employment;

Emp/res: ratio between employment and number of residents;

Competitiveness public trans.: the relative competitiveness of public transport, calculated as the ratio between the average time taken for trips made with private transport and the average time for trips made by public vehicles.

Share public trans.: the market share of public transport, i.e. the percentage of all trips made by public transport;

Built up area: total area [km^2] classified as built up area by Corine Land Cover;

Public Time: average trip time [min] for public transport trips;

Private time: average trip time [min] for private transport trips;

Dummies for typology of urban expansion: to simplify the analysis, three dummy variables were considered, reducing the 10 development types defined above into four groups. The simplification involved aggregating the types according to their similarities, maintaining a sufficiently large sample for each group.

Typology of urban expansion	Associated dummy variable
Infilling/Extension	Infilling/Extension
Pure infilling	Infilling/Extension
Pure extension	Infilling/Extension
Extension/linear development	Extension/Linear
Pure linear	Extension/Linear
Extension/Sprawl	Sprawl
Linear development/Sprawl	Sprawl
Infilling/Sprawl	Sprawl
Pure sprawl	Sprawl
Large-scale projects	Large-scale Projects

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