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

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## Introduction[*]

Together with technologies and consumption styles, the form of settlements and the way human activities are organised on geographical space represent crucial research fields – and sources of preoccupation – as far as ecological equilibria are concerned (Camagni, Capello, Nijkamp, 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

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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 losing this fundamental role as a result of the cumulative effect of decentralisation tendencies and standardisation and banalization in the use of space (Camagni, Gibelli, 1996 and 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 empirical analyses.

With reference to the metropolitan area of Milan, we have therefore examined the consumption of land in relation to different types of urban expansion at the level of the single municipalities, as well as the impact on mobility and the costs sustained by local authorities for the provision of transport services and infrastructure.

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 1); in the second and third parts we present the main findings of our empirical analyses carried out in the province of Milano. We define a number of archetypal forms of urban development (section 2.1), measure the associated consumption of land and the public costs for infrastructure (section 2.2) and then carry out a detailed analysis of the mobility generated and its environmental costs (section 3).

## 1. Development on the urban fringe: dynamics, interpretations and empirical analysis

### *1.1. Features of recent urban development*

In Europe, the areas surrounding most large cities have been radically transformed over the last ten to fifteen years. Not only there has 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 which 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.

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 tastes and lifestyle, 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.

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 retain that it is crucial to intervene, through the adoption of sectoral and town 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 represented in the European context by the “theoreticians” of the *ville emergente* (Dubois-Taine, Chalas, 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 high 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 liberty for people to design their own living 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 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 tendency of many industries to relocate near the residential suburbs; 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 centrally issued directives or instruments of 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 capital market (Gordon and Richardson, 1997).

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 built development in urban periphery. This approach necessarily includes a normative dimension, and the search for innovative policies and tools for governing the phenomenon of urban diffusion.

Given the strong propensity for intervention, and the legitimisation provided by the principles of sustainable development, the neo-reformist approach risks being assertive and oversimplified. There is, for example, a hiatus between empirical evidence (often not very strong, given the difficulty of finding suitable indicators) and the normative solutions proposed, and a tendency to adopt ideological metaphors and socially desirable buzz words, even though their practical effectiveness is only weakly proven. This is the case of the repeated emphasis in the documents and directives issued by the European Union or other supranational bodies on the advantages of the "compact city": this emphasis has been put in question by the contributions of certain urban analysts (Breheny, 1992; Banister, 1992; Blowers, 1993; Gibelli, 1998); but, above all, in concrete examples of *best practice* in planning (Hall and Landry, 1997).

### *1.2. 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 sustainable development.

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 *free-rider* behaviour, using the private car in the hope that most others will not do so – a sort of prisoner's dilemma which leads to non co-operative solutions, which are individually rational, but collectively inefficient (European Commission, 1995; Camagni, Gibelli, 1996).

In relation to the use of the private car, a further and apparently paradoxical problem concerns the fact that, contrary to rational 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.

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 this interesting research project (and also examined in the present investigation) was 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, 1997).

### *1.3 International empirical surveys of the costs of sprawl*

We now come to the central theme of our research programme on the community costs of “periurban” 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 thinner on the ground, due mainly to the objective difficulties of finding significant and reliable performance indicators. The specific results available relate to studies carried out prevalently 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 periurban 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 (Dougharty, 1975; Downing and Gustely, 1977). More recently, Robert Burchell and other researchers of the Center for Urban Policy Research, 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 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; Burchell and Listokin, 1995; Burchell, Dolphin and Moskowitz, 1995).

A research project financed by the Urban Land Institute, investigating the costs of road construction, public services and, in particular, schools, 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 investment costs (Frank, 1989). Similar results have been reached in numerous case studies (e.g. Duncan *et al*, 1989; Federal Home Mortgage Association, 1992, 1993, 1994).

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, Gent and Lock, 1993). The 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.

## 2. Social costs of different typologies of urban expansion: land consumption and public costs for infrastructure

### *2.1. Methodology of the empirical research on the Milano Province*

Following the general reflections outlined above, the purpose of our empirical survey, carried out in the province of Milano, was to identify the characteristics of urban development and the public and collective costs of the periurban expansion which occurred during the ten year period 1981-91. The variables examined include the consumption of land for housing development, the public costs for public utilities and roads resulting from the urbanisation process and the social costs of the mobility generated[1].

Using as a starting point the maps drawn up by Centro Studi PIM on land consumption in the Milano area in 1991 (Centro Studi PIM, 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 (B1),
extension (B2),
linear development (B3),
sprawl (B4), and
large scale projects (B5)[2].

All the combinations between these types were then identified and finally, by eliminating and re-assigning the least significant combinations, a selection of ten prevalent typologies was arrived at [3].

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. It is intended to make further refinements in future studies.

### *2.2. Land consumption and public costs for infrastructure and transport*

#### *2.2.1. Land consumption*

As far as the analysis of land consumption was concerned, the first survey we carried out compared the land area developed for residential use[4] between 1981 and 1991 in each commune to the number of dwellings. Three main categories emerged (Fig. 1):

- the relatively "thrifty" types, where consumption was below 450 sq.m. per dwelling, which corresponded as expected to the categories "pure infilling" and "large 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 sq.m. per dwelling, plus "extension/linear" development with >550 sq.m.per dwelling;

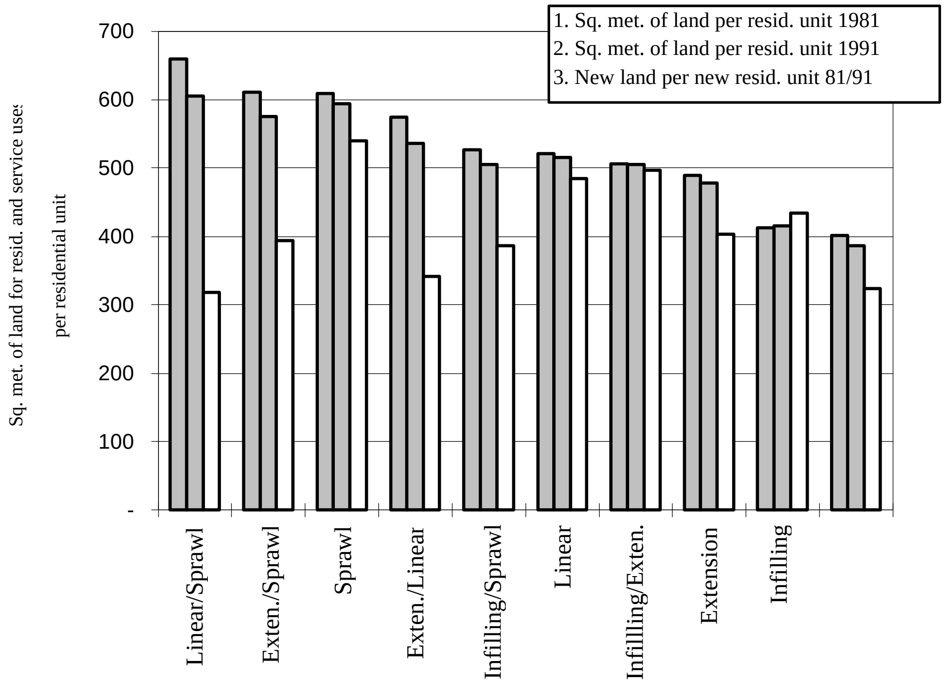
[1] For our empirical analyses we used the plans and calculations prepared by the Centro Studi PIM in 1991 as part of the research project *"Uso-consumo di suolo e dinamiche insediative dell'area metropolitana milanese"* undertaken for the Provincial Plan *(Piano Direttore Territoriale Provinciale*), the *"Certificati dei conti consuntivi 1996"* relating to the balance sheets for the districts of the Milano Province, ISTAT data concerning change of residence registered in the communes and Census data relating to mobility in 1991.

[2] Type B1 is characterised by situations in which the building growth occurs through the infilling of free spaces remaining within the existing urban area; B2 occurs in the immediately adjacent urban fringe; B3 is development which follows the main axes of the metropolitan transport infrastructure; B4 characterises the new scattered development lots; B5 concerns new lots of considerable size and independent of the existing built up urban area.

[3] These are: pure infilling (B1/B1), infilling/extension (B1/B2), infilling/sprawl (B1/B4), pure extension (B2/B2), extension/linear development (B2/B3), extension/sprawl (B2/B4), pure linear development (B3/B3), linear development/sprawl (B3/B4), pure sprawl (B4/B4), big projects (B5/B5).

[4] 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. The behaviour classes in the single years proved to be similar in the two cases.

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




- an intermediate group, which included the categories: infilling/extension, infilling/ sprawl, pure extension and pure linear development, with consumption around 500 sq.m. per dwelling.

If we observe the ratio between the new built 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 unitary consumption of land is slightly declining. This suggests that new urban development overall is relatively land-sparing compared with the past[5].

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 Milano is in general becoming less and not more "land greedy", probably due to the combination of rather strict development

[5] The regression analysis for single communes (% increase in the built-up area over % increase in number of dwellings) confirmed the result ($R^2 = 0.32$, Student T = 9.23). On average, a given percentage increase in dwellings corresponded to an increase in built-up area equal to about one quarter. This seemed to constitute a variable independent of the behaviour of the local authority, in that over ten year a certain increase occurred (9-10%) even in the absence of new residential construction (the value of the intercept of the straight line regression is 0.09).

control at the local level and of gradual exhaustion of land resources in the northern sector of the metropolitan area.

*2.2.2. Public costs for infrastructure and transport*

The second stage of the analysis involved the examination of the accounts for the year 1996 of the 186 municipal authorities in the province of Milano, excluding the city of Milano itself, in order to discover whether any significant relationship existed between the form of urban development and the public costs for public utilities, transport and road construction.

The attempt to use data from local authority budgets to undertake a comparative analysis and also management and strategic *benchmarking* analyses is relatively new in Italy and, in fact, met with serious difficulties. Despite the official standardisation of municipal accounts and their subheadings, the content and economic significance of the single items still varies considerably[6].

As far as the statistical significance of the results is concerned, the preceding considerations naturally mean that these were invalidated. However, assuming that, given the large number of communes analysed, the different types of administrative/management/financial behaviour are distributed uniformly across the different types of commune identified above, it would seem legitimate to make some first comparative analyses on the costs of alternative typologies of urban development.

The first result concerns the expenses for infrastructure and public services per inhabitant (obviously a rough indicator giving only an approximate estimate). This indicates that among the “pure” types of urban development, the least expensive for the public were the following: infilling (63,000 liras per capita), extension (81,000), and large projects (89,000), together with extension/sprawl, whereas the most expensive were the following: sprawl (104.000), and linear development (102.000), plus infilling/ sprawl.

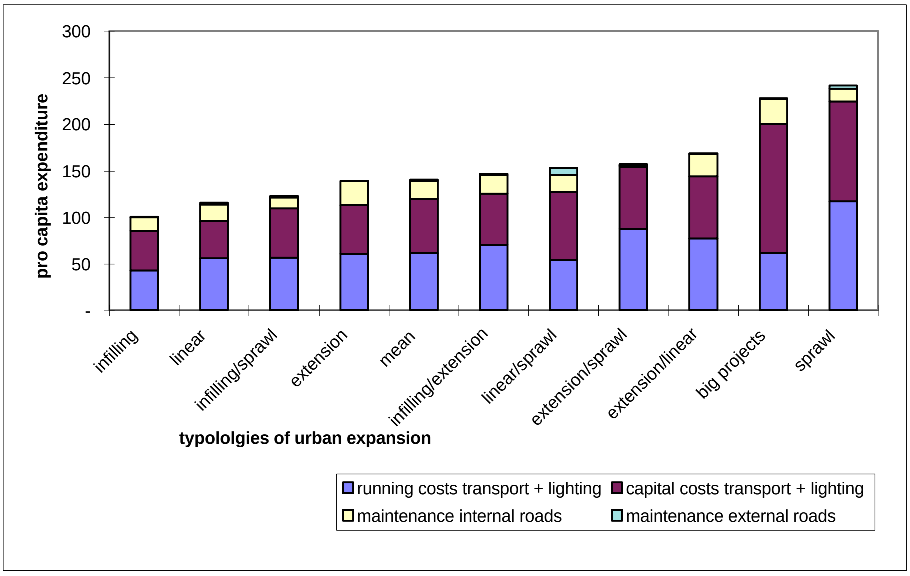
The second result concerns the transport costs per inhabitant, which were divided into four categories:

- transport, communications, roads and lighting: running costs,
- transport, communications, roads and lighting: capital costs,
- maintenance of internal roads,
- maintenance of external roads.

In this case, the public costs involved for both sprawl and large projects were high (over 230,000 liras per capita for all four transport cost categories and over 100,000 liras for the capital costs only). For the former this represented a confirmation of expectations, for the latter the opposite of the previous situation, i.e. medium costs for infrastructure but high costs for transport, partly because of the lack of integration with the metropolitan transport system. Relatively low transport costs were incurred by infilling, linear development and infilling/sprawl (under 130,000 liras per capita in total and less than 50,000 liras for capital costs), while extension and infilling/extension seemed to be around the mean (about 150,000 liras per capita in total) (Fig. 2).

[6] The reason is that the different sectors are managed through different organisational forms (some directly, some through independent agencies and companies) and hence the possibility that the infrastructure investment costs are sometimes financed by private bodies (i.e. works exclude urbanisation costs, which are not included in the budget). One of the indirect, but important outcomes of our research was the demonstration of the advantages which could result from a complete standardisation of the criteria adopted in local authority accounting systems.

*Figure 2 – Public expenditure for transport by typology of urban expansion*




## 3. Social-environmental costs of different typologies of urban expansion: the demand for mobility

### *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 1. For this reason, in the present study it was decided to establish whether it was possible to identify significant differences of behaviour within the study area as far as mobility was concerned and, if so, to ascertain whether there was any significant correlation between these differences and variables describing the form of development. The intention was to provide a basis for orienting planning policies.

The working hypothesis was 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 consumption of mobility 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.

Three types of independent variables were adopted:

- geographical variables: the location of each commune with respect to Milano (inner and outer suburbs and the main axes);
- socio-economic variables: population density, size and dynamics, age of the buildings, ratio of jobs to population;
- morphology: i.e. the typologies of urban development previously described.

As far as mobility is concerned, 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 according to mode (6 categories)[7] and, within each mode, the time taken: up to 30 mins; 31-60 mins; over 60 mins [8].

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.

### *3.2. An operational definition of environmental impact of mobility*

From the data on travel modes and the time length of commuter trips, we endeavoured to obtain one or more indicators of the environmental cost of mobility. It is evident that the 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 took the following form (where the value 100 was arbitrarily assigned to the 45 min. trip by car):

*Weights by travel time and travel mode*

| | Weights for modes | Time | | |
|---|---|---|---|---|
| Classes of trip time | | 0'-30' | 31'-60' | > 60' |
| Average trip time | | 15' | 45' | 75' |
| Weight per time unit | | 1.20 | 1.00 | 0.80 |
| Equivalent trip time | | 18' | 45' | 60' |
| Walking or other means | 0.00 | 0 | 0 | 0 |
| Bus | 0.33 | 13 | 33 | 44 |
| Private car (driver) | 1.00 | 40 | **100** | 133 |
| Motorcycle | 0.33 | 13 | 33 | 44 |
| Private car (passenger) | 0.00 | 0 | 0 | 0 |
| Train, tram, underground | 0.20 | 8 | 20 | 27 |

It was assumed that:

- for any given mode, the impact of a trip per unit of time decreased 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.);

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

[8] 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', 20% in 31'-60' 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.

- for any given duration, the weight of the various modes, put conventionally at 1.00 per passenger x minute in the 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 retained 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 which can be assigned to every commuter trip made[9]. 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.

### *3.3 The variables*

In this introductory section, we briefly present 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 (Map 1);

*Mobility Influence*: index of influence of mobility, calculated as the ratio between the EIC and the resident population;

*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 per cent growth rate of population between 1981 and 1991;

*Gross and Net Density*: respectively, the density [*inhabitants/km*$^2$] over the whole land area (sq. Km.) 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;

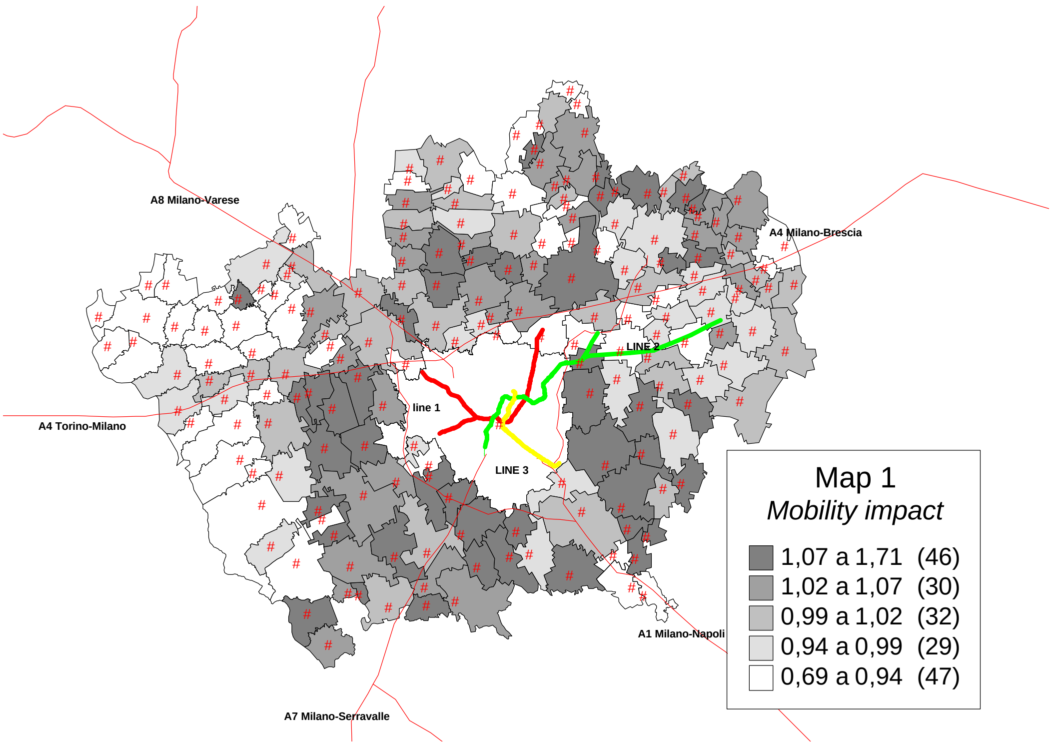
*Private Time*: average trip time [*min*] for private transport trips;

*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

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

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 |
| Big projects | Big Projects |



*3.4 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.

The following linear model was selected, as it seemed satisfactory with respect to both its empirical fit and the theoretical interpretation of its parameters:[10]

$$\begin{aligned}(Mobility\ Impact)_i = b_0 + b_1 \cdot (Distance\ from\ Milan)_i + b_2 \cdot \log(Net\ Density)_i + \\ + b_3 \cdot (Growth\ Rate\ of\ \ Residents)_i + b_4 \cdot \log(Age)_i + b_5 \cdot \log(Emp/Res)_i + e_i\end{aligned} \tag{3.1}$$

In order to estimate the unknown parameters of the model, [12] the error term was first assumed to have constant variance across observations and to be uncorrelated in the space:

$$\begin{aligned} Var(e_i) &= s^2 \qquad \forall\ i \\ Cov(e_i e_j) &= 0 \qquad \forall\ i, j \end{aligned}$$

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,[13] 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 (see the Annex).

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 1). Therefore, it is possible to say that the inference based on the *OLS* estimators, while not completely accurate (above all as far as the standard deviation of the estimators is concerned), is not misleading.[14] For this reason, in the following of the paper only *OLS* estimators will be displayed, even though we acknowledge that more efficient estimators could be found.

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[10] It's 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:

$$\frac{\partial(Mobility\ Impact)}{\partial(Net\ Density)} = b_2 \cdot \frac{1}{Net\ Density}.$$

[11] Notice that Table 1 presents the estimate of a version of the model also including group effects relating to the types of development. In fact, three dummy variables were added to allow the intercept shift.

[12] Notice that Table 1 presents the estimate of a version of the model also including group effects relating to the types of development. In fact, three dummy variables were added to allow the intercept shift.

[13] 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.

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

*Table 1 – Regression analysis of the model (3.1)*

| *Dependent variable*: MOBILITY IMPACT | | | | |
|---|---|---|---|---|
| | *Ordinary Least Squares OLS* | | *Weighted Least Squares WLS* | |
| *Independent variables* | *b* | *T-Stat* | *b* | *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 |
| *N of observations* | 184 | | 184 | |
| $R^2$ | 0,49 | | * | |

* the $R^2$ of the *WLS* estimation is not displayed since it is not comparable with the $R^2$ of the *OLS* estimation and can not be interpreted as the degree of variation explained

The outcome is summarised briefly as follows (see *Table 1*):

- a significant 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[15];
- the coefficient relating to the distance from the centre of Milan is small in terms of

[15] There is a second way of using the EIC that involves referring to the resident population instead of the number of commuters ("Mobility Influence"). Repeating the analysis with this indicator, we obtained results similar to those illustrated above. In the following Table we display the OLS and WLS estimations of a model where only one variable, the average age of building, enter in a non linear way. This estimation doesn't allow for any violation from the classic assumption of homoscedasticity and of lack of autocorrelation of the error. Taking into account such deviations (for example by means of weighted least squares, assuming the variance to be proportional to the inverse of the square root of resident population or by allowing for a spatially autocorrelated error) doesn't anyway result in notably different inference. As it happens in the case of the impact index model, the estimates of the coefficients are only slightly different and the statistical significance of the corresponding variables tends to drop slightly. The multiple regression analysis gave results, which were interesting with respect to both the degree of variation explained, and the significance of the variables.

| *Dependent variable*: MOBILITY INFLUENCE | *OLS* | | *WLS* | |
|---|---|---|---|---|
| *Independent variables* | *b* | *T-Stat* | *b* | *T-Stat* |
| Constant | 2,032 | 16,248 | 2,084 | 15,843 |
| Distance from Milan | -0,008 | -5,592 | -0,008 | -5,187 |
| log (Age) | -0,246 | -6,139 | -0,264 | -6,032 |
| Growth Rate of residents | 0,063 | 5,466 | 0,064 | 3,862 |
| Gross Density | -2,991E-05 | -5,733 | -2,70E-05 | -6,811 |
| *N of observations* | 184 | | 184 | |
| $R^2$ | 0,65 | | * | |

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";[16]

- 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, big projects;
- 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.

### *3.5 Components of the mobility impact: transport mode and trip time*

As we have seen in section *3.2*, 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. 3). On the one hand, we have:

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;

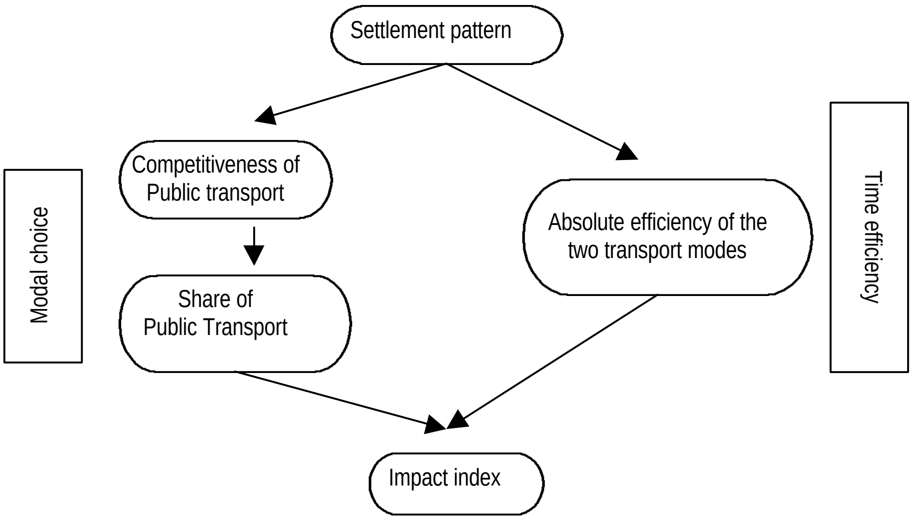
on the other:

Settlements of relatively compact structure → greater efficiency of both public and private transport → lower commuting time → lower mobility impact.

Before moving towards the econometric results, 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.

[16] 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 (see Map *1*); the inclusion of these effects in the model (*3.1*) is nevertheless disturbed by problems of multi-collinearity.

*Figure 3 – Causal chains in the explanation of mobility impact*




*3.5.1. The relative competitiveness of the two transport modes*

As far as the modal split is concerned, distinguishing simply between public transport (road and rail) and private transport (car and motorbike), we can analyse the relationship between the share of trips for each mode and a competitiveness indicator for public transport, given by the average time taken for trips made by private transport in comparison with public transport.

From Table *2* 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 *2a*);
- there is an evident connection between this competitiveness indicator and the modal split (Table *2b*);
- the market share of public transport has a significant influence on the mobility impact index (Table *2c*). In order to study this relationship, a slightly different equation from the model (*3.1*) was estimated, since problems of multicollinearity due to the high correlation among 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 confirmed in the estimate of the second model.

Figure 4 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[17] - do trips by public transport take less than 150% of the time taken by

[17] 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.

*Table 2– Mobility impact index and share of public transport*

| *Dependent variable:* | *a* | | *b* | | *c* | |
|---|---|---|---|---|---|---|
| | *COMPETITIVENESS PUBLIC TRANS.* | | *SHARE PUBLIC TRANS.* | | *MOBILITY IMPACT* | |
| *Independent variables:* | *b* | *T-Stat* | *b* | *T-Stat* | *b* | *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 |
| *N. of observations* | 184 | | 184 | | 184 | |
| $R^2$ | 0,42 | | 0,47 | | 0,41 | |

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:[19]

$$\log(\mathit{Share\ Public\ Trans.})_i = b_0 + b_1 \cdot \log(\mathit{Competitiveness\ Private\ Trans.})_i + e_i\,, \qquad (3.2)$$

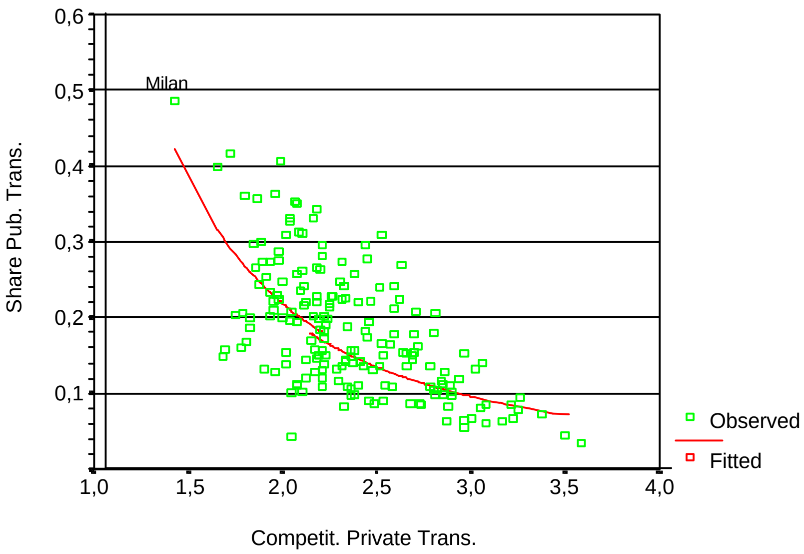
where $b_1$ represents the elasticity of the market share of public transport with respect to the relative competitiveness of the private transport. In the following table the *OLS* estimation of the model is displayed:

| Dependent variable: | *LOG (SHARE PUBLIC TRANS.)* | |
|---|---|---|
| Independent variables: | *b* | *T-Stat* |
| Constant | -0,287 | -2,142 |
| log (Competitiveness Private Trans.) | -1,874 | -11,660 |
| *N. of observations* | 185 | |
| $R^2$ | 0,42 | |

[18] 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.

[19] Notice that a multivariate model could have been adopted as well (for example the model (*3.1*)) 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 *2b* 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.

*Figure 4 - Public transport mode: market share vs relative competitiveness*




On the basis of the estimation just carried out, in Table *3* we present some extrapolations, in order to give a general indication about the implied relationships between the two variables.[20]

*Table 3*
*Values of Share Public Trans. forecasted by the model* (*3.2*)

| 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% |

Some comments can follow:

- the condition which would allow public transport to gain the full market share of trips is when trips 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

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

competitiveness (the actual situation in many communes), there still remains a faithful 5% of commuters who used public transport [21].

From what has been indicated previously (Table *2b*), 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÷0,2% every *km*$^2$;
- increases with gross density, at the rate of 0,023% every 1000 *inhab/km*$^2$.

### *3.5.2. 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 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.[22]

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’ (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 seconds every 100 *inhab/Km*$^2$;
- increases with distance from Milano.

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’) 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 4 – Efficiency of public and private modes (average trip time)*

| *Dependent Variable*: | *PUBLIC TIME* | | *PRIVATE TIME* | |
|---|---|---|---|---|
| *Independent Variables:* | *b* | *T-Stat* | *b* | *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 |
| *N. of observations* | 184 | | 184 | |
| $R^2$ | 0,52 | | 0,47 | |

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

[22] 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 minutes, while the average trip time with respect to the individual transport is about 21 minutes. Such a sharp difference seems to confirm that the individual transport is used especially for short distances (see § 1.2), rather than being a clear evidence of the relative efficiency of the two modes of transport.

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 resources (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.

This theme is high on the agenda not only of urban researchers, but also of the strategic planning agencies in many countries and many cities in Europe, especially in France, the United Kingdom, Holland and Germany, and also in the United States.

It was in this context that the present empirical survey was developed, with the aim of establishing, in the metropolitan area of Milan, the public and collective costs associated with different patterns of urban expansion - in particular, land consumption, the public costs incurred in providing infrastructure and, above all, the effects on the ‘consumption’ of mobility.

As far as land consumption is concerned, three main categories emerged: a category of relatively ‘virtuous’ patterns (pure infill and big 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 unitary consumption of land decreased slightly for all development types, suggesting that recent urban development is in general relatively ‘virtuous’. Therefore, although these results confirm the standard hypothesis that compact types of development have a lower level of land consumption, the expectations relating to the last ten years are partially overturned. They appear to indicate that, in new urban expansion, greater attention is now paid than in the past to the question of land consumption. This is probably due to the progressive exhaustion of land resources in the Milan metropolitan area, but perhaps also due to greater awareness, expressed in the more recent local plans.

The analysis of the budgets of the local municipalities, in particular the expenditure for the provision of utilities and the transport and road infrastructure, confirmed what has already been indicated in many international studies: the more compact forms of urban development (infilling and extension) are less costly than the relatively diffused forms (sprawl and linear development).

Finally, with reference to the question of mobility, the results for the province of Milan underlined the strong influence of the form of urban development on collective costs deriving from mobility. Residential density and settlement size were variables which had significant impacts on mobility, both directly and indirectly, through their effect on the relative efficiency of public transport and its consequent market share (the modal split). It was shown in addition that the greatest impacts occurred in the areas of most recent development, which were those furthest from local centres of secondary level, from interchange nodes and the main transport routes.

As far as the transport modes and trip times are concerned, an interesting outcome of the analysis was the evidence that 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 the level of efficiency and competitiveness. On the contrary, trip times for private transport appear to be correlated not so much to 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 big projects), which show a very different behaviour with respect to the modal split. Sprawl is associated with the lowest share of public transport, while big projects have the lowest share of trips made on foot.

In conclusion, our results confirm the long-sightedness of the strategic guidances and innovations at the urban design level that aim towards a “judiciously compact” and polycentric model of urban development. They are oriented, on the one hand, to achieving better integration between new residential development and the metropolitan transport network, and on the other, to achieving greater functional diversification at the local scale (and in particular improving the jobs/housing balance) in order to recreate a “city effect” even in locations which are distant from the metropolitan core: two strategic objectives and fields of action which seem more than ever necessary, also in the context of the metropolitan area of Milan.

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*Annex*

*Spatial statistics considerations*
*by Federico Martellosio*

When regional data, typically observed on heterogeneous aggregate spatial units, are analysed by statistical models, it is often the case that the error term doesn't satisfy the classical assumptions. In this Annex we briefly discuss the consequences deriving from the violation of the hypothesis of lack of spatial autocorrelation.

Though similar to the temporal one, the concept of spatial autocorrelation displays some important differences. The first of them is connected with a less obvious directionality of dependence among observations: while in a temporal context the direction of dependence is clearly defined (usually going from past to present), in a general spatial context a more subjective choice is needed to establish a classification based on closeness between observations. It is furthermore intuitive that, moving from a mono-dimensional case, like the temporal one, toward a multi-dimensional case, like the spatial one, the complexity of the possible dependence structures increases.

Let's start bearing in mind that if the errors are correlated across observations, the *OLS* estimates of a given model are not the most efficient. There are two possible solutions to this problem: an attempt can be made either to model the phenomenon in such a way as to remove the error (for example, seeking not to omit relevant spatially-correlated variables), or to estimate the same model with ad hoc techniques.

In our analysis the inclusion of the variable 'Distance from Milan' in the model for the mobility impact belongs to the first category, and consists of an attempt to attenuate the spatial correlation of the non-modelled part of the Impact Index. The inclusion of an east-west coordinate, which makes it possible to include in the analysis cultural, historical and geographical differences not captured by other variables, serves a similar purpose. These differences are evident in a map of residuals obtained from the model without the east-west coordinate and probably are above all due to the different degree of accessibility to underground (see Map *1*) and highways between the east and the west area. It is possible to show that the autocorrelation of the error (measured with the Moran index) of a model including both the east-west and the north-south spatial coordinates is very low, and not significantly different form zero, due to the neighbourhood structure adopted and described below.[23]

As mentioned above, an alternative approach is to adopt suitable estimation techniques.

Let $y=Xb+e$ be our model written in matrix form. Let's assume that the error term follows the structure $e=rWe+u$, where $r$ is the autocorrelation parameter, $u$ is a spatial process not autocorrelated in the space and $W$ is a square spatial weights matrix of dimension equal to the number of communes, whose general term is:

$$w_{ij} = \begin{cases} \dfrac{1}{number\ of\ neighbours\ of\ commune\ i} & if\ \ i\ and\ \ j\ are\ neighbours \\ \\ 0 & otherwise \end{cases}$$

*i*th e *j*th communes being defined neighbours if their centroids are less far than 5 km.[24] Choosing this distance we obtain an average number of neighbours for commune of

[23] It should be recalled, to avoid misunderstandings, that the value of the spatial autocorrelation varies with the neighbourhood structure adopted.

[24] It should be noticed that the neighbourhood structure could have been defined in many other different ways. For example, we could have called neighbours two communes sharing a common boundary or two communes well linked up by the public or private transport infrastructure. Our choice, based on the geographical distance, seems to us sensible as well as simple.

6,75 and a level of spatial autocorrelation for the variable Mobility Impact high enough (0.272 for the Moran's *I*, see Fig. 5).

Having made such premises, our model may be written as:

$$(I - rW)y = (I - rW)Xb + u\,,$$

where $(I\text{-}rW)y$ and $(I\text{-}rW)X$ represent the vectors of the averages on the neighbours respectively for the variables $y$ and $X$. The estimation of parameters $b$ and $r$ may be carried out either jointly, by maximizing the likelihood, or iteratively, by implementing an algorithm that at each step estimates $b$ assigning $r$ at the value estimated from the *OLS* residuals obtained at the previous step.

In order to illustrate the differences involved by following this way, we show the estimates obtained with the iterative technique just mentioned. Next to it, we also show the *OLS* estimates of the model (*3.1*) (for the sake of simplicity without the group effects introduced with the dummy variables). A comparison between the results obtained with the two techniques shows, in line with the underlying statistical theory, that the coefficient estimates are only slightly different and that the *t-statistics* decrease a little.

| *Dependent variable*: MOBILITY IMPACT | | | | |
|---|---|---|---|---|
| | *Ordinary Least Squares OLS* | | *Iterative technique for spatially autocorrelated error Iteration n. 7* | |
| *Independent variables* | *b* | *T-Stat* | *b* | *T-Stat* |
| Constant | 2,440 | 9,486 | 0,201 | 9,109 |
| Distance from Milan | -0,006 | -4,299 | -0,006 | -4,075 |
| log (Net Density) | -0,112 | -4,739 | -0,079 | -3,585 |
| Growth Rate of Residents | 0,059 | 3,534 | 0,058 | 3,492 |
| log (Age) | -0,138 | -3,062 | -0,138 | -3,053 |
| log (Emp/Res) | -0,078 | -4,064 | -0,077 | -3,989 |
| *N. of observations* | 184 | | 184 | |
| $R^2$ | 0,46 | | 0,44 | |

*Figure 5 - Spatial autocorrelation correlogram of Mobility Impact and of the OLS residuals of the model estimated in Table 1*