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Long-term energy consumptions of urban transportation: A prospective simulation of “transport–land uses” policies in Bangalore ☆

Benoit Lefèvre *

Center for Energy, Marine Transportation and Public Policy (CEMTPP), Urban Energy Program, School of International and Public Affairs (SIPA), Columbia University, Mail code 3366, 420 West 118th Street, Room 1105, New York, NY 10027, USA

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ABSTRACT

The current trends of urban dynamics in the Third World are alarming with regard to climate change, because they are giving an increasingly important role to cars—to the detriment of public and non-motorized transportation. Yet this is the type of energy consumption that is expected to grow the fastest, in business-as-usual scenarios. How can these market-based urban trends be influenced? What level of emissions reduction can be achieved? This article shows that first, there is a relevant and urgent need to tackle the urban dynamics of cities in developing countries focusing on the “transport–land uses” couple, and second, that existing transport technologies and decision-helping tools are already available to take up the climate change challenge. Through the application of an integrated “transport–land uses” model, TRANUS, this study demonstrates that transit technologies affordable to an emerging city like Bangalore can significantly curb the trajectories of energy consumption and the ensuing carbon dioxide emissions, if and only if they are implemented in the framework of appropriate urban planning. Furthermore, this study establishes that there are tools which are available to facilitate the necessary policy-making processes. These tools allow stakeholders to discuss different political alternatives integrating energy issues, based on quantitative assessments.

The urban explosion in the Third World is undoubtedly one of the main environmental challenges of the century. By 2030, almost all of the global demographic growth will be occurring in Southern cities, with the total population of these cities doubling from 2 to 4 billion people (UN, 2000). Accommodating 2 billion inhabitants in urban areas means building the equivalent of seven new 10-million-person cities each year, which would be seven times Shanghai or Jakarta, or ten times London. The speed of this urban growth is unprecedented in history: it took London 130 years to grow from 1 million to nearly 8 million inhabitants. It only took Bangkok 45 years, Dhaka 37 and Seoul 25 to achieve the same demographic leap (PNUH, 2004).

Sustainable development has become widely recognized, but the challenge is now to translate the concept into action in the field, and especially in cities.

The current trends of urban dynamics in the Third World are alarming with regard to climate change, because they are giving an increasingly important role to cars—to the detriment of public and non-motorized transportation. Yet this is the type of energy consumption that is expected to grow the fastest, in business-as-usual scenarios.

Considering the life span of urban structures, the type of urban growth that cities of the South will experience in the next three decades will determine the level of their energy consumption and greenhouse gas emissions in the second half of the century.

How can these alarming urban trends be influenced? What level of emissions reductions can be achieved within cities in developing countries? The total activity (A), mode share (S), fuel intensity (I), and fuel type (F) (ASIF) framework (Schipper et al., 2000) is the world recognized methodology to break down the influence of urban policies on transportation energy consumption drivers. Transportation energy use is a function of ASIF. However this function is not as simple as it looks: Zegras (2007) shows how “multiple factors influence each of the ASIF components with many affecting more than one component.”

There is a general consensus that a prompt emergence and deployment of new green individual transport technologies is not to be expected (Pridmore, 2002; Cabal and Gatignol, 2004; Assmann and Sieber, 2005). Technology improvement (targeting the I and F components) will not be the hoped-for “silver bullet”, especially for poor and fast-growing cities. Heywood et al. (2003), assessing credible passenger vehicle technological improvements

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* Tel.: +1 212 854 0602; fax: +1 212 854 0603.
E-mail address: bl2321@columbia.edu

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in USA over the next 30 years, comes to the "sobering overall conclusion" (Zegras, 2007) that both technology improvements and demand growth management will be required to reduce transportation energy consumption. A further sobering fact is that, concerning cities in developing countries, these new 'green' vehicles will take even more time to be affordable in the local market and represent a significant share of the total fleet. Assmann and Sieber (2005) estimated that the additional time needed for a well-established technology in developed countries to penetrate the market in developing countries is around 10 years. Consequently, a new 'green' car, launched today in the developed world, will take 40–45 years to reach a significant share of the market in poor countries (Cabal and Gatignol, 2004).

In other words, we will likely have to work on all A.S.I.F. components in order to avert the business-as-usual scenario. Therefore, in the context of rapid and massive urbanization processes, it appears particularly relevant to act on the first two drivers of urban transportation emissions: the level of activity and the modal shares. But there are many doubts on the feasibility of influencing these essentially behavioral drivers through public policies. On the other hand, discussions also revolve around the efficiency of urban policies tackling the A and S drivers, thereby curbing the long-term energy and emissions trajectories. These two crucial issues were largely discussed in the debate among partisans and opponents of the compact city (see for example: Breheny, 1994, 1995; Owens, 1995). The dispute is still very lively (see for example: Haugton and Hunter, 1996; Newman and Kenworthy, 1999; Camagni et al., 2002). Proponents of the New Urbanism[1] promoted an alternative with the concept of "decentralized concentration" (Talen, 2005; Frey, 1999; Beatley, 2000; Dutton, 2001; Duany et al., 2003) but did not put an end to the debate (Vandermotten et al., 2005). Similarly, there is no consensus on what type of transport policies or/and land uses regulations are most efficient to achieve the targeted urban structure (Tang and Lo, 2008; Hensher, 2008a, b) and how to incorporate transport energy into urban planning (Saunders et al., 2008).

The article shows that first, there is a relevant and urgent need to tackle the urban dynamics of cities in developing countries focusing on the relation between transportation and urbanism, and second, that the existing transport technologies and decision-helping tools are already adequate to take up the climate change challenges. This study demonstrates that the transportation technologies affordable to an emerging city like Bangalore can significantly curb the trajectories of energy consumption and of the ensuing carbon dioxide emissions, if, and only if they are implemented in the framework of appropriate urban planning. Furthermore, it establishes that there are tools which are available to ease policy-making processes. These tools allow stakeholders to discuss different political alternatives integrating energy issues, based on quantitative assessments.

The article addresses these issues through a case study of Bangalore, India. This booming city illustrates what spontaneous urban dynamics can generate in a context of rapid and massive urbanization. For Bangalore, this accelerated urbanization came with the development of the city as the "Asian Silicon Valley". But the success story of the last two decades is threatened by the spread, fragmentation and congestion of the urban machine. Because of the tricky balance between an economical success obtained without any strong urban development planning and intervention, and the need to intervene in urban dynamics in order to avoid the collapse of this economic success, Bangalore, like most of the cities in developing countries, is facing one of the most critical moment of its history.

Section 1 discusses the challenges to sustainability that Bangalore is currently facing due to its economic boom. It shows to what extent these challenges are inter-related and need to be tackled with a systemic approach. Section 2 presents the urban prospective model, TRANUS, used to test the capacity of different combinations of land-uses and transport policies to reduce the long-term energy consumption of urban transportation. It describes the different existing models, explaining the choice of TRANUS. Section 3 explains the different steps faced in order to implement and to calibrate TRANUS, the difficulties faced and the choices made. Section 4 presents the three scenarios tested: Business-as-usual, construction of a metro, land use and economic policies integrated to the construction of a metro. Section 5 analyzes the results of the simulations. Finally conclusions are drawn from this research.

1. Bangalore (India): challenges to the sustainability of the economic boom

Over the past 15 years, Bangalore has experienced profound economic, social and spatial mutations linked to the boom in information technology (IT). But these transformations and their speed jeopardize the city's urban management capacity. The sustainability of urban development, especially its environmental component, is particularly at risk. The city with its dense and radial-concentric structure is confronted by high-speed demographic growth and urban sprawl,[2] and risks becoming congested, leading to an unmanageable situation.

Bangalore used to be called the "garden city" thanks to its fresh air and beautiful parks—which were clearly among the reasons why it became the Asian IT hub (Heitzman, 2004). Today, Bangalore has reached a critical point where spontaneous development endangers the traditional urban amenities. Like many cities in developing countries, Bangalore is caught in a pincer between a rapid and massive urban development, and a lack of funds and institutions to orient the market dynamics.

Though the dynamics of Bangalore's urban development underwent an abrupt change during the 1990s linked to the boom of IT activities, the realities that urban planners must work with do not exactly fit with the idyllic image of an "Indian Silicon Valley". The IT sector has become an essential motor of urban prosperity,[3] but even so, it has not dramatically changed the

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[1] The New Urbanism is an urban design and planning movement—begun in the 1980s—that incorporates neo-traditional concepts to promote livability, pedestrian-friendliness, public transport, recreational space, dense developments instead of sprawl, environmental balance, social integration, and a true sense of community. Calthorpe, Duany, Moule, Plater-Zyberk, Polyzoides, and Solomon founded the Chicago-based Congress for the New Urbanism in 1993 (Congress for the New Urbanism, 1996).

[2] The *population* of Bangalore has tripled in 30 years. It increased from 4.13 to 5.68 million inhabitants between 1991 and 2001, growing the fastest of all Indian cities, apart from Delhi. Bangalore is now the fifth biggest city in the country. Though its growth rate has decreased slightly (from 3.52% between 1981 and 1991, down to 3.25% between 1991 and 2001), it could reach 10 million inhabitants by 2020. The *urban sprawl* of Bangalore is even more impressive: the annual growth rate of its urban area is 5.4% (which corresponds to 2200 extra hectares, or nearly 8.5 square miles every year). In 2005, the city's surface area was 540 km^2 (nearly 208.5 square miles), up from 284 km^2 in 1990, and 202 in 1983. (SCE-CREOCEAN, 2004 and 2005).

[3] From 1997 to 2001, overall job growth amounted to approximately 5,00,000 jobs; 94,000 companies were also created, of which 93,845 were small businesses (less than 10 employees), mostly informal (SCE-CREOCEAN, 2004 and 2005). This growth partially corresponds to the many cases of production off shoring that Bangalore benefited from in recent years. They also led to significant increases in induced employment in more traditional sectors of activity, especially services. However, though the turnover of IT companies increased rapidly, the rate of this

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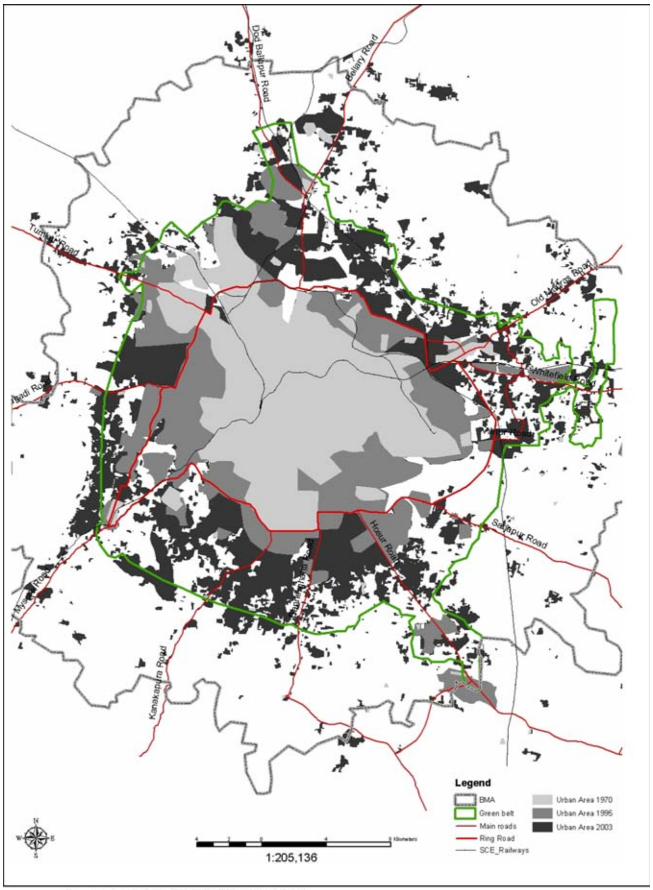
distribution of employment in the city,[4] or improved living conditions for the population as a whole. The IT dynamic contributed to the demographic explosion and the exacerbation of social inequalities. Alongside the glittering image of the “IT City”, it would be wise to consider the risks of fragmentation incurred by urban society because of the digital revolution: the disparity ratio of incomes between the first and the last quintile has changed in 10 years from 4.9 in 1991 to 13.6 in 2001, a significant jump that implies a profound change in the equilibrium of the city. While inequalities were until recently moderate, the city is now about to pass to a new form of society, marked by inequality tensions: the richest 20% of the city’s inhabitants benefit from over half the city’s income, whereas the poorest 20% only see a negligible amount–3.8% of the total (SCE-CREOCEAN, 2004 and 2005).

The question of the development of IT activities is often misapprehended. A review of the factors that have allowed their expansion would be valuable. Indeed, the different sectors of Bangalore’s economy are well interconnected, and so interdependent. Some sectors are more visible than others and have earned the city its national and international reputation, but they are all part of a network of strong mutual relations. The fulfillment of Bangalore’s aspirations to a world-megacity status will probably depend on finding an additional set of superior economic services, that have strong investment capacities, that are less volatile than IT, and that are less dependant on external factors (Heitzman, 2004). However, it would be wise to counterbalance the current headlong rush toward tertiary sector growth with an assessment of local development, and to base economic analysis primarily on the components of supply, rather than just on external demand (SCE-CREOCEAN, 2004 and 2005). This would mean considering a series of local elements, such as the quality of factors of production, cross-sector synergies, agglomeration and urbanization economies,[5] and innovation capacity, as the real parameters of long-term development of the metropolitan area (Heitzman, 2004; SCE-CREOCEAN, 2005).

The demographic and economic booms of the 1990s led to fundamental changes in the dynamics structuring the urban space and a dislocation of the traditionally dense and concentric urban structure. As shown in Fig. 1, in the absence of geographical constraints, Bangalore is now spreading in all directions, especially along major roads. These roads attract industries and commercial activities far from the city center, and the residential development is following. The passage from urban growth in concentric circles, which produced the dense fabric of the earlier city, to this linear and divergent expansion, has led to an imbalance between the different zones of the urban area. As one can see in Fig. 1, the intensity of urban development is not identical in all directions. It continues to sprawl massively to the north-east and to the South, whereas along Whitefield Road to the east and Hosur Road to the south-east, it is resolutely linear.



Source : SCE-CREOCEAN, 2005

Fig. 1. Urban sprawl of Bangalore 1970–2003.

The new pattern of mobility and the increasing congestion reinforce the unsustainable urban trends that Bangalore is facing. Today, Bangalore and Delhi share the highest motorization ratio in India: 32 vehicles for every 100 persons (SCE-CREOCEAN, 2004 and 2005). Though there is more and more congestion at rush hour, travel time remained on average around 33 min per trip in 2001 (SCE-CREOCEAN, 2004). But this situation is not likely to last. In 2005, 12.3% of the households owned a car and 44.5% a motorcycle. These modes represent, respectively, 4.5% and 30.4% of the modal share. On the other hand, 38.4% of the households do not own any vehicle, and walking and bus constitute, respectively, 16.2% and 41.3% of the distribution of trips by mode. Between 1991 and 2005, the number of vehicles registered in Bangalore increased by over 200% (from 6,80,000 to 2,200,000), which corresponds to an annual growth of the number of cars and motorcycles that is three times greater than that of the population (10.8% for car and 9.5% for two-wheelers, compared to 3.25% for the population) (RITES, 2003; SCE-CREOCEAN, 2004 and 2005). In view of the fact that rising household income leads to increasing private motor-vehicle ownership, and considering also the imminent entry into the market of the world cheapest Tata company’s car, the Nano, one can anticipate a dramatic growth in vehicle traffic and extensive gridlock to appear within the next few years. Moreover, Bangalore is in danger of entering into a vicious cycle in which the present dynamics of dispersion of housing schemes in peripheral areas leads to increase the use of private car. Increasing motorization will in return push for more dispersion of housing schemes. Traffic congestion, increasing transportation times, and the deterioration of the quality of life

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(*footnote continued*)
exceptional growth slowed significantly year by year, from 70% (2000–2001) to 33% (2001–2002), then to 25% (2002–2003) (SCE-CREOCEAN, 2004 and 2005).

[4] Out of a total working population of 2.4 million, only 3,60,000 are employed by IT companies. It is estimated that the non-organized sector employs about 1 million persons in Bangalore, which is over 40% of all jobs! Some experts even claim that the correct proportion is around 75% (SCE-CREOCEAN, 2004 and 2005).

[5] Economists identify three factors to explain the accumulation of productive activities in cities: economies of scale, which are internal to companies; localization economies, which are external to companies but internal to the relevant industrial sector; and urbanization economies, which are external to companies and to the industrial sector, and which proceed from the presence of public infrastructures and strong interaction between multiple activities (Camagni, 1996).

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can all have a direct impact on the economic dynamism of the city.

These observations underline some alarming tendencies: the spread, fragmentation and congestion of the urban machine, which endanger the sustainability of Bangalore's development. The economic pillar is affected through the fragmentation of traditional cohesion among the different economic sectors, the social pillar is affected through increasing social inequalities (the incomes' disparity ratio increase from 4.9 to 13.6 in 10 years), and the environmental pillar is affected through the dramatic rise in energy consumption and, hence, of local and global pollution. The Air Quality Index (AQI)-which ranged between 140 and 310 in Bangalore, despite the fact that air is considered "heavily polluted" for an AQI above 76-showed the air quality along every main traffic corridor is rated as "highly polluted" (EIA Studies, 2003). In view of these booming dynamics, is there a sustainable urban development path? If so, how can it be reached?.

The improvement of mobility is locally debated, according to two opposite conceptions of the city: a car-centered approach, with a proactive development of bypass roads, or on the contrary, a denser conception of urban fabric, adapted to public transportation. The answer to the future demand for land in a city in process of growing from 6 to 10 million inhabitants requires a global vision of its future (SCE-CREOCEAN, 2005). Considering Bangalore's present morphology, it is not inevitably reduced to the car-centered approach, even though the latter is already affecting the city and causing congestion. The dispersion of built-up areas is limited, and the structure of the city is still suitable to a mass transportation system. The overall density of population is 130 inhabitants/hectare (SCE-CREOCEAN, 2005), a relatively low figure which is explained by a strong occupancy rate in settlement areas and by the size of the big vacant public sites within the city. When limited to the residential surface, the semi-net density is close to 300 inhabitants/hectare (SCE-CREOCEAN, 2005). Specific pockets of very high concentrations of population are seen in old industrial sectors[6] and along the main roads and the rail tracks, with a peak of 800 inhabitants/hectare along some parts of Tumkur road (towards the North-East) (SCE-CREOCEAN, 2005). On the other hand, vacant lands (land without urbanization) inside the Outer Ring Road represent 130 km^2 (SCE-CREOCEAN, 2005). Thus the potential for development of a rapid mass transit system, along heavy traffic corridors, is intact.

2. TRANUS, an integrated "transport–land use" model

The objective here is to measure the effects of several urban policy alternatives on energy consumption and carbon dioxide emissions that are associated to urban transportation. However, first, because the interrelations between drivers of spatial organization process within a city, predicting empirically the impacts of various combinations of transport and land uses policies is a difficult task. Second, it is necessary to find a way to quantitatively assess the results on energy consumption and GHG emissions.

There are principally three methods to predict the systemic relations between the transport system and the land uses system (Wegener, 1994). The first, the "stated preference" method, consists of asking people how they would change their residential location and/or mobility pattern according to possible changes, such as transport costs, spatial distribution of urban amenities, etc. The second, the "revealed preference" method, consists of observing behaviors of people under different contexts and drawing conclusions on how people would react to possible changes. The third method is to simulate human behavior in mathematical models.

Wegener (1994) shows that all three methods have their advantages and disadvantages. The "stated preference" method can reveal subjective factors of location and mobility decisions, however, their respondents can only make conjectures about how they would behave in still unknown situations, and the validity of such conjectures is uncertain. The "revealed preference" method produces detailed and reliable results; these, however, are valid only for existing situations and are therefore not suited for the assessment of novel yet untested policies. Wegener (1994) adds that "it is usually not possible to associate the observed changes of behavior unequivocally with specific causes, because in reality several determining factors change at the same time". Mathematical models are also based on empirical surveys and observations. The differences with respect to the two other methods are first, that mathematical simulation allows transferring the observed behavior to unknown situations, and second, the conclusions to be drawn are quantified. Wegener (1994) adds that "mathematical models are the only method by which the effects of individual determining factors can be analyzed by keeping all other factors fixed".

Within the mathematical simulation method, Wegener and Fürst (1999) distinguished three major theoretical approaches analyzing the interrelationship between land uses and transport in urban area.

The first one is produced by geographers and sociologists. Since the development of the Chicago urban sociologist school, between the wars, this approach is based on an adaptation of Darwin's theories of evolution. It analyzes processes of social change at the neighborhood and urban levels (Wegener and Fürst, 1999). Cities are interpreted as a multi-species ecosystem, in which social and economic groups fight for "ecological positions" (Park, 1936; Park et al., 1925). These concepts were empirically testable. A number of qualitative theories of urban development were put forward, notably to explain the spatial expansion of American cities (see for example: Burgess et al., 1925; Hoyt, 1939; Harris and Ullman, 1945). This approach is highly informative for understanding eco-socio-spatial urban dynamics. But this approach presents two majors inconveniences for my purpose: it does not simulate interaction between transport and land uses systems; and these models give only qualitative results.

The second major theoretical approach focuses on the micro-economic foundations of urban dynamics. This approach is rotten in von Thünen's works (1826), and has since evolved in many ways. Probably the most influential examples of micro-economic models are the Alonso's model of the urban land market (1964) and more recently the Fujita's one (1989). This approach allows drawing critical conclusions on mechanisms of the interrelations between transport and land uses systems. However, even in more advanced variations of the Alonso model, when restrictive assumptions such as perfect competition and complete information or the mono-centric city have been relaxed (see for example: Richardson, 1977; Anas, 1983; Goffette-Nagot, 1994), its lack of real accurate representation of the city does not allow me to adopt it. These models, and particularly the operational ones, do not account the complexity of specific characteristics of each zone within the urban area. Rather, they view the space as homogeneous and generally mono-centric.

The third major approach was developed after World War II. It aims to help engineers and urban planners to accommodate the explosion of mobility. Thus, these models have clearly practical goals (Masson, 2000). One characteristic of this approach is to

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[6] For example, Cottonpet (620 inhabitants/hectare) and Chickpet (560 inhabitants/hectare) in the South-East center, Rajajinagar (440 inhabitants/hectare) in the West center, and Kaval Byrasandra in the North-East (400 inhabitants/hectare).

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mobilize different techniques of simulation resulting form sciences, like economic, physics and chemistry (Masson, 2000). Since its beginning, this third approach has operational purposes and therefore is not dependent on one specific theory. Clement (1996) distinguished three families of models within this third approach: the "Urban Transportation Modeling System" (UTMS)-also named "Conventional four steps model"—the "Discrete choice model" (DCM) and the Land Use and Transport Model" (LUTM).

UTMS were the first model used in practice (Masson, 2000). Their objective is to predict the number of trips made by purpose of the trip, time of day, origin-destination zones, and the mode of travel used to make these trips (Clement, 1996). UTMS use a four stages procedure, corresponding to a sequential decision process, in which people decide to make trip (generation), decide where to go (distribution), decide what mode to take (modal split), and decide what route to choose (assignment). As such, UTMS represents an "equilibrium" procedure in which the demand for transportation (represented by Origin/Destination zones flows and by mode) is assigned to the modal networks constituting the transportation system as a function of these network's characteristics (supply) (de la Barra, 1989). de la Barra (1998) precised that the data of population, employment and land use are given inputs in vector form. From these vectors the number of trips produced and attracted in each zone is calculated, also in vector form. In turn these are used to estimate matrices of trips. Each cell of these matrices is then split by mode (private and public) and assigned to the respective networks. The output of UTMS is a predicted set of modal flows. These models are criticized mainly for two reasons:

- UTMS do not give a behavioral representation of trip making (Domencich and McFadden, 1975). They represent a pragmatic approach to reducing an extremely complex phenomenon, but the decision to make a trip is hardly independent from the destination choice, the modal preferences and even the itinerary.
- Since these models are needed for runs into future, they must take into account the interactions between the transport system and the land-uses system.

The DCM, based on the discrete choice theories developed originally by McFadden (1973) and Ben-Akiva (1973), aim to answer the first limit of UTMS. These models are used for the analysis and the prediction of trip behavior for short and middle term. However, they are not relevant for long-term analysis because they are not taking into account the effects of changes in accessibility due to changes in the transport system (Clement, 1996).

The main objectives of the transport–land uses integrated models (LUTM) was to improve the UTMS scheme by modeling internally the inputs vectors of population, employment and land uses.

There are around twenty-integrated models (EPA, 2000). There are significant variations among the models as concerns overall structure, comprehensiveness, theoretical foundations, modeling techniques, data requirements and model calibration process.[7] TRANUS is the one which offers the appropriate balance between theoretical relevance and operational requirements for my research project (Lefèvre, 2007). TRANUS is an integrated transport–land use model, which de la Barra and Perez have been developing since 1982 (de la Barra et al., 1984; de la Barra, 1989, 1998). It is the most widely applied integrated model (EPA, 2000). It has been implemented both in Northern cities (Baltimore, Sacramento, Osaka, Brussels, etc.) and in Southern cities (Sao Paulo, Mexico, Caracas, Bogota, etc.). Moreover, as reported in Miller et al. (1998), de la Barra showed through an application on Baltimore that TRANUS is able to simulate urban dynamics already observed, in a retrospective way. This success in an ex-post simulation-which is considered as the most significant test for a prospective model's relevance (Masson, 2000)—proves its operationality. In addition to that, theoretical and practical arguments achieved to convince me that TRANUS was the most appropriate model for the objectives and the context of my research.

TRANUS adopts the main concepts of spatial economics, location, land use, and the generation of land rent, developed by Von Thünen in 1826, and refined by Wingo and Alonso in 1964. The works on gravity and entropy models developed by Hansen (1959) and Lowry (1964), and completed by Wilson (1970) are also an important component of TRANUS. Finally, TRANUS uses the input–output accounting framework developed by Leontief (1936), since it includes a complete input–output model to represent the economy of a spatial system and the formation of prices. In TRANUS the original input–output model has been generalized to all sectors participating in urban dynamics, like land, activities, population and transport operators. Thus, the spatial dimension has also been added and integrated with the transport system. TRANUS is also rooted in the DCMs and random utility theory (McFadden, 1973). In TRANUS the discrete choice approach is applied to all components of the land use and transport system, from trip generation to mode choice, path choice, location choice and land use choice. de la Barra (2004) presents TRANUS as "a long chain of linked discrete choice models". Finally TRANUS has drawn heavily from conventional four steps transport models, such as graph theory, queuing theory, minimum path search as originally proposed by Dijkstra in the 1950s (de la Barra, 1989).

Among different theoretical features, the original matrix-to-matrix structure deserves to be presented here because it improves significantly the consistency of TRANUS. de la Barra (2004) explains that the first integrated transport–land use models (LUTM) that attempted to feed back the results of the transport model into the land use calculations preserved the vector structure of the data. The resulting structure is shown in Fig. 2(left). The vectors of activities estimated by the land use model are fed into the transport model, from which trip flows are calculated. The trip distribution model calculates trip matrices from such trip ends, and from this point the calculations become matrix-based. Each cell in the trips matrix is split by mode and then assigned to the corresponding networks. After capacity constraint procedures, the model estimates for each cell travel cost and time contributing to generalized cost, and the resulting matrices are fed back into the land use model. Because the land use model is based on a vector structure, the matrices of generalized cost must be aggregated from matrix-to-vectors, becoming vectors of accessibility, affecting the location of activities. A transformation in the transport system at some points changes the corresponding cells in the matrices of generalized cost, and eventually the vectors of accessibility, thus affecting the location of activities.

de la Barra (2004) suggests that there are two important problems in this scheme. The first come up from the matrix-to-vector transformation when generalized cost is fed back into the land use model because there is no satisfactory method to aggregate matrices of generalized cost into vectors of

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[7] It is not the purpose of this article to discuss in a detailed manner all these differences, but rather to explain how TRANUS fit into the various approaches. For a comprehensive analysis see for example: Wegener (2000); Simmonds et al. (1999); Masson (2000); EPA (2000) and Waddell (2001).

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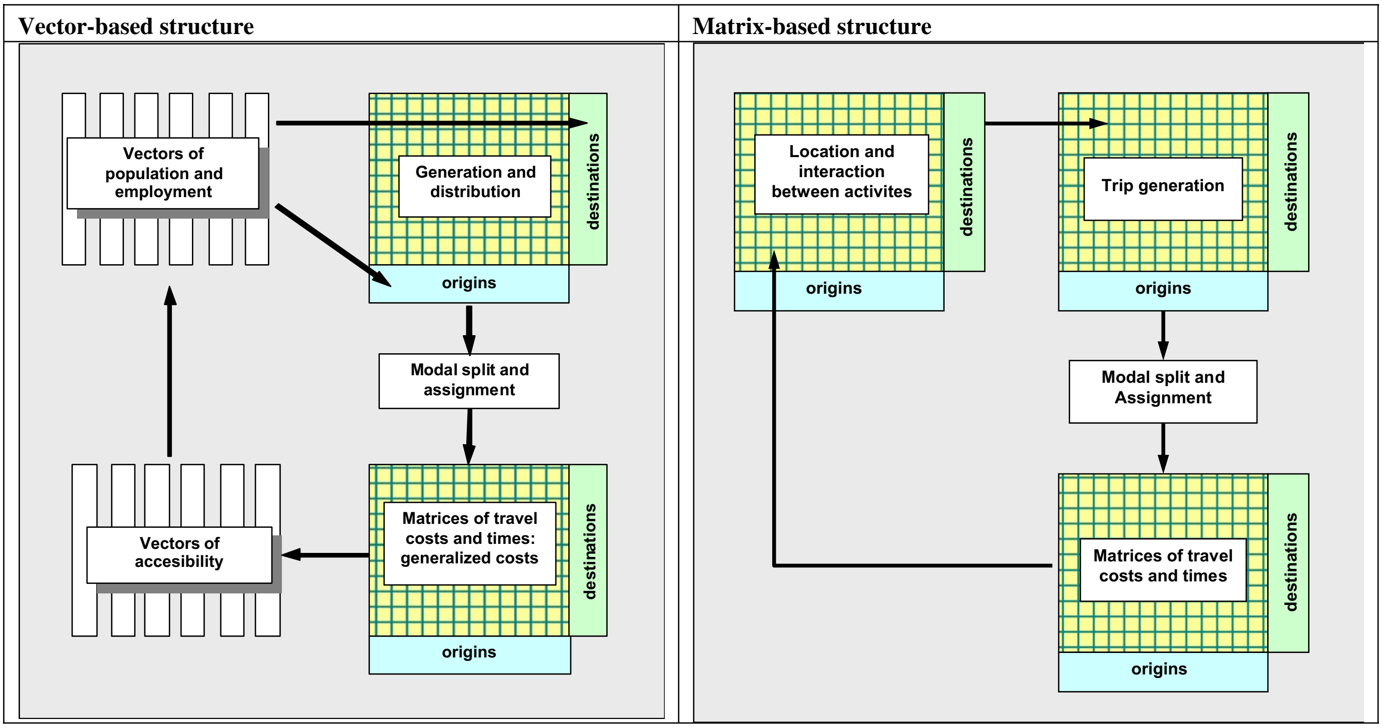

Source: de la Barra, 2004.

Fig. 2. Structures in integrated land use and transport models.

accessibility.[8] A transport change that, for example, improves a specific origin-destination link but not others, might get completely diluted in the aggregation process, perhaps becoming worthless and producing similar results in terms of population and employment in the with and without-project scenarios. The second problems identified by de la Barra (2004) occurs in the vector-to-matrix transformation when the results of the land use model are fed into the transport model, because there is no guarantee of consistency between how the relationships between activities are simulated in the trip distribution model and in the land use model (through accessibility vectors). They may have contradictory results. In the previous example, a gain in accessibility between two-specific zones may not show in the vectors of population and employment used by the land use model, but the distribution model, because it is matrix-based, will reflect the change, resulting in an increase in the number of trips.

To solve these problems, de la Barra adopted in TRANUS a matrix-based structure, as shown in Fig. 2(right). The land use model estimates both the location of and interaction between activities, generating matrices of flows. On a cell-by-cell basis, trip generation functions transform the matrices of flows into trip matrices, divided by mode, and are assigned to the network. After capacity restriction the process ends with transportation cost and time matrices, which are fed back into the land use model. The entire process is carried out on matrices, without the need for aggregations. Also, if there is a local transport improvement affecting only a couple of cells, as in the previous example, it is followed throughout the process without loss due to aggregation.

On the practical point of view, TRANUS presents key advantages. The TRANUS system is programmed to run on standard PCs operating under Windows. All programs and documentation may be downloaded freely.[9] Finally, the TRANUS user's interface provides useful flexibility and ease of use for setting up a database, importing/exporting data to and from other applications, running the models and presenting results.

In accord with de Palma et al. (2005), I agree that the most promising technique for transport–land uses modeling is certainly micro-simulation[10] which makes it possible to reproduce the complex spatial behavior of individuals. These models aim a more detailed representation of urban activities' diversity and of the trip decisions process. Up to now, this approach consists of associating a very detailed land-use model with a very detailed transport model.[11] However, first, these models still do not have a sufficient record of application and, second, they require a large amount of data that are not available nowadays in Bangalore.

Therefore, I selected TRANUS as the most appropriate model to satisfy my theoretical and operational requirements. As presented in the next section, I also added to TRANUS a module to translate urban structure's evolution in terms of energy consumption, according to specific characteristics of the vehicle park in Bangalore. I applied TRANUS to Bangalore and test a set of transport and land-uses policies, based on the current, voted or under-discussion urban policies in Bangalore.

3. The application of TRANUS to Bangalore

The required data were gathered through five main sources: SCE-CREOCEAN, the consulting office in charge of the elaboration of the master plan "Bangalore 2020" who welcome me during 6 months; RITES, the consulting office in charge of the development

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[8] Current methods use weighted averages or other simple formulas, resulting in a loss of richness in the information.

[9] From www.modelistica.com or www.tranus.com.

[10] Like IRPUD (Wegener, 1994), URBANSIM (Waddell, 2001), MASTER (Mackett, 1990), DELTA (Simmonds, 1998).

[11] For example, de Palma works on the connection between URBANSIM and METROPOLIS.

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Table 1
Application of TRANUS: sub-division of each urban sector and collect of data.

Sector	Category	Data	Sources of data
Activities	Traditional heavy industries Information technologies industries Administrative services Retail Educational services	Minimum and Maximum input demand by output unit, production, price By population's categories: % of total employment by zone: employment	• SCE-CREOCEAN • Reports form the local, state and national authorities • Literature on Bangalore • Interviews of experts
Land	Mixed-use land Residential land Industrial land	By zone: superficies, prices	• SCE-CREOCEAN
Population	Quintile 1 Quintile 2 Quintile 3 Quintile 4 Quintile 5	Average income, value of travel time, value of waiting time	• SCE-CREOCEAN • Census 2001 reports form the local, state and national authorities
Public transportation modes	Bus Metro Rickshaw	Equivalent PCU, frequency minimum and maximum, average waiting time, capacity, average occupancy, unit boarding and alight time, tariff, operation costs, free flow speed, flow at peak hours for major roads	• SCE-CREOCEAN • BMTC (local public bus company) • RITES • Interviews of experts
Private Transportation modes	Car Motorcycle Bicycle Walking		
Road network	Arterial Sub-arterial Main road Ring road Connect road Walking	Name, length, authorized modes, carrying capacity, free-flow speed, % speed reduction at volume/capacity = 1, V/C at Max speed reduction, etc.	• SCE-CREOCEAN • RITES • Reports form the local, state and national authorities

of the metro project; existing reports in the different local, state and national administrations; and interviews with experts. The existing transport data sets were completed with traffic surveys carried on at the key intersection of the road network by seven surveyors during the month of April 2004.

The urban area of Bangalore was divided into forty-seven zones. To determine their limits, I had to arbitrate between administrative boundaries, the data presentation format, and the homogeneity of territories. Based on various ward boundaries, existing physical features, and analysis of the existing development trends, SCE-CREOCEAN had divided the city of Bangalore into forty-seven planning districts and organized all their data set according to this division. Therefore, for convenience, I choose to adopt their division. Thus, the representation of the city comprises seven central zones, which constitute the historic center of Bangalore, and concentrate most jobs and commercial and administrative services, and therefore, commuter destinations. The whole network converges toward this center, which provokes congestion in the areas just beyond it. It also comprises nineteen peri-central zones, which have different profiles: some are being developed through the spontaneous concentration of activities linked to IT, while others are declining, especially former traditional craftsmanship centers. Finally, the representation of Bangalore also comprises twenty-two peripheral zones with a highway bypass crossing through them (the Outer Ring Road). These are socially diverse areas, including both under-developed zones and wealthy neighborhoods. The geographical coordinates of these forty-seven zones were provided by the Geographic Information System (GIS) developed by SCE-CREOCEAN, and directly entered in TRANUS.

Then I entered for each zone the set of data describing the different sectors, taking 2003 as the base year to calibrate the simulation. Each sector was divided into several categories as presented in Table 1. Table 1 also indicates the required data for each categories and the source where these data were found.

According to the base theory (Hoyt, 1954), activities were separated into "exporting activities" (traditional heavy industries, IT and administrative services), and "induced activities" (retail, educational services). Land was divided into three categories: mixed-use land (for homes, IT activities and retail), residential land, and industrial land (for traditional industries and IT activities). The population was divided up into five income groups. For each group of the population, two categories[12] of trips' purpose were defined, according to whether they are journeys from home to work, or from home to school. TRANUS consider the motorization ratio as "having access to a car or a motorcycle". TRANUS take that into account through penalty factors for each categories of population. Thus, the use of a car or a motorcycle depends both of these penalty factors, and the relative performance of each alternative mode of transport. These penalty factors for each category of population were determined during the calibration process, based on data provided by SCE-CREOCEAN (2005) and interviews with RITES experts in charge of the simulation done for the metro project.

Then I defined two modes of transportation (public and private) and five operators (bus, rickshaw, car, motorcycle,

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[12] These two categories of trips, respectively, represent 60% and 20% (RITES, 2003; Traffic surveys, 2004) of all trips (all types of purpose and mode) in the urban area. Given that trips that do not start from, or finish at, homes constitute 1.3% (RITES, 2003, 2004) of the total, and that Bangalore has a high level of functional mixed land uses, it seems that the trips which are not comprised in these two categories (from home to work and form home to school) can be neglected in terms of the distance covered.

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walking). Finally, using the GIS provided by SCE-CREOCEAN, I represented the road network: 1547 segments classified into five categories determined by their characteristics (carrying capacity, free-flow speed, etc.).

In TRANUS, the energy consumption of each type of vehicle is calculated with negative exponential functions:

$$\text{Conso } E = [(E_{\min} + E_{\max} - E_{\min})\exp(-\mu V)]$$

where Conso E is the energy consumption per distance unit per vehicle; $E_{\min}$ is the minimum consumption of energy per unit distance when a vehicle of operator o travels at free-flow speed; $E_{\max}$ is the maximum consumption of energy per unit distance when a vehicle travels at a speed close to zero; μ is the parameter regulating the steepness of the energy consumption curve; V is the speed of vehicle after capacity restriction.

This calculation is made on a link-by-link basis, because the speed is link-specific. TRANUS adopts a negative function in order to take into account the increase of energy consumption due to congestion. As TRANUS does not quest after taking into account the increase of energy consumption due to an excessive speed, it does not consider that the energy consumption raise beyond an optimal[13] speed (specific to each vehicle). Therefore, I preferred to adopt U-shaped curves that allow me to take into account both congestion and excessive speed. Thus, I calculated the energy consumption based on the functions provided by the Indian Road Congress (IRC, 1995) for each type of vehicle.

New technology car:

$$\text{Conso } E = 21.85 + (504.15/V) + 0.004957 \times V^2$$

Old technology car:

$$\text{Conso } E = 10.31 + (1675.52/V) + 0.0133 \times V^2$$

Motorcycle:

$$\text{Conso } E = 3.38 + (549.57/V) + 0.00436 \times V^2$$

Rickshaw:

$$\text{Conso } E = 4.13 + (549.57/V) + 0.00436 \times V^2$$

Bus:

$$\text{Conso } E = 32.97 + (3904.64/V) + 0.0207 \times V^2$$

where Conso E is the energy consumption per distance unit per vehicule; V is the speed of vehicle of operator o, after capacity restriction.

Based on the data provided by the Bangalore Transport Department (SCE-CREOCEAN, 2005), I considered that 90% of the cars in Bangalore are old technology cars and 10% are new technology cars.

Because the existing traffic data was not sufficient to calibrate the application of TRANUS to Bangalore, I carried out a traffic survey with seven surveyors during the month of April 2004. The objectives were first to evaluate the volume and composition of the traffic circulating in both direction during morning and evening peak hours, and second to ask to a sample of drivers and passengers the purpose, origin, destination, and duration of their trips. The traffic survey has been carried out in two types of locations[14]: (i) at 6 locations beyond the Outer Ring Road, on the six main roads and (ii) at 12 locations inside the Outer Ring Road, beyond and on the Inner Ring Road.

Once the different sets of data were entered, it remained to calibrate the application of TRANUS to Bangalore. The process of calibration is iterative, with many parameters to control. In the activities and land-use model, the convergence in prices and production are evaluated at each iteration. Both are calculated for each zone and sector as the percentage variation with respect to the previous iteration:

$$Cp_j^{n,\tau} = \max_j \left| \frac{p_j^{n,\tau} - p_j^{n,\tau-1}}{p_j^{n,\tau-1}} \right|$$

$$CX_j^{n,\tau} = \max_j \left| \frac{X_j^{n,\tau} - X_j^{n,\tau-1}}{X_j^{n,\tau-1}} \right|$$

where $Cp_j^{n,\tau}$ is the price convergence indicator; $CX_j^{n,\tau}$ is the production convergence indicator; $p_j^{n,t-1}$ is the unit price of sector n in zone j in the previous iteration $t-1$; $p_j^{n,\tau}$ is the unit price of sector n in zone j in the current iteration τ; $X_j^{n,t-1}$ is the exogenous production of sector n in zone j for time period $t-1$; $X_j^{n,t}$ is the exogenous production of sector n in zone j for time period t.

These indicators are calculated separately for each sector, and adopt the value of the worst zone, that is, the zone that varies the most. The calibration process ends when convergence indicators are smaller than a pre-specified convergence criterion.

Similarly, in the transport model, convergence is checked for all links as the percentage variation between the current iteration and the previous one, considering two variables: operating speeds and traffic flows. The iterative process ends when such differences are both below a pre-defined convergence criterion.

According to the record of application of TRANUS, I adopted 0.001 as convergence criterion for both the activities and land uses model and the transport model.

4. Testing three urban policies scenarios

Next, I assessed the capacity and the better combinations of the three levers—investment in transport infrastructure, land-uses regulation and pricing policy—available to the municipality to reduce long-term energy consumption. I therefore compared a business-as-usual scenario with a "metro–" scenario and a "metro+" scenario articulated to the metro project which is under construction in Bangalore. The three scenarios main characteristics are presented in Table 2. It should be noted that this is not a fictional urban planning scenario: the policies involved in the three scenarios are being implemented or planned in Bangalore or in other developing cities.[15]

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[13] The optimality is considered here in terms of energy consumption per unit of distance.

[14] The survey were carried on: Bellary Road, beyond the Outer Ring Road, near Hebbal kere, beyond Kempapura Road; Magadi Road, beyond the Outer Ring Road, in front of Beggars Colony; Old Madras Road, before intersection of 100 Feet Road, near the Police Station; 100 Feet Road, before intersection of Old Madras Road; Airport Road, before the circle with Trinity Church road and Victoria Road; Inner Ring Road, before the intersection of Shinivagalu Main Road; Hosur Road, before intersection of Begur Main Road and 27 cross; Sarjapur Road, before the intersection of Outer Ring Road, near Amblipur; Outer Ring Road, before the intersection of Sarjapur Road; Hosur Road, between the intersection of Sarjapur Road and the intersection of Marigowda Road, near St. Anthony's Friary; Outer Ring Road, before the intersection with Banasvadi Main Road and Ramamurthi Nagar Main Road, near Vigneshwara Layaout; Bannerghatta Road, before the intersection of the Outer Ring Road, near Maratt Rubber; Karnakapura Road, before the intersection of the Outer Ring Road, near Creamline Food specialities; Mysore Road, before the intersection of Kenchenhalli Main Road, near KC's Club; Tumkur Road, before the intersection of Ring Road and Subbroto Mukherjee Road, near KBC; Old Madras Road, before the intersection of Davasandra Main Road, near the Police Stations, near Taluk Office; White field Road, after the intersection of Basavanna Nagar Main Road before the intersection of Hudi Main Road, near HUDI; Vartur Road, before the Rail way, Gandhi Nagar.

[15] A metro is currently under construction; transport oriented land use policies regulating the type of usages authorized, the level of mixed usages, etc. were implemented in Curitiba (Brazil), but also partially in Mumbai (India); density fuel tax and parking pricing were implemented in Bogota (Colombia) at the end of the 1990s.

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Table 2
Characteristics of the three scenarios tested with TRANUS.

Scenario name	Transport policies and investment	Land uses policies	Economic policies
Business as usual	• Construction of the central ring road (CRR) • Construction of the peripheral ring road (PRR) • Extension of bus lines as far as the PRR • Intervention at highly congested intersections (quality of road service equal or under G[a])	No new policies (only zoning rules)	No policies
Metro−	• Construction of two lines of metro, crossing at the city center	No new policies (only zoning rules)	No policies
Metro+	• Construction of two lines of metro, crossing at the city center (similar as "Metro−")	• *City center*: all the vacant lands are open to urbanization+Progressive conversion of industrial lands to mixed lands (5% per year) • *First belt*: all the vacant land are open to urbanization • *Second belt*: no lands are open to new urbanization+progressive conversion of residential lands to industrial lands (equivalent to the superficial changes in the city center)	• Increase of the operation costs of car: tax on fuel (100%) • Parking costs in the city center (equivalent to 30 min of the time value of quintile 5) and in the first belt (equivalent to 15 min of the time value of quintile 5)

[a] Quality of road service is evaluated according to "Transport Research Board (TRB), 2000, Highway Capacity Manual, National Research Council, Washington, DC."

The business-as-usual scenario is based on continuation of the tendencies observed in Bangalore over the past 15 years. Among these are the construction of two highway ring-roads that have already been voted on: a central one, 3–5 km[16] from the center and one further out (18–20 km[17] away). These trends also include the construction of bridges or underpasses at highly congested intersections, broadening roads, and converting two-way to one-way roads—temporarily for the rush hour, or permanently. Finally, the business-as-usual scenario also involves no control of urbanization and the extension of bus lines, particularly all the way to the outer highway bypass. Urbanization of vacant lands in the city center and in the first belt is not allowed. This is to simulate the continuation of the non-urbanization of these vacant lands by a real-estate business which has until now mainly focused on real-estate opportunities in the peripheries of Bangalore (SCE-CREOCEAN, 2004 and 2005).

The "metro−" scenario implies the construction of two metro lines intersecting in the city center, with the same land-uses and pricing policies as those in the business-as-usual scenario. The "metro+" scenario involves the two similar metro lines, but this time, the investment in the transport infrastructure is integrated with an adapted policy for densification (opening vacant lands for urbanization in the center and in the first belt), containment of urban sprawl (forbidding urbanization of vacant lands in the second belt), and functional diversification of the center and its immediate periphery. It also includes a pricing policy to discourage people from using their cars[18]: fuel taxes as well as parking charges in the center and in the first belt around it.

In all scenarios, the investment capacity of the municipality is capped by the budget currently devoted to the construction of the two metro lines today (US$ 1089 billion over 20 years). Moreover, these simulations were carried out *ceteris paribus*.[19]

5. Findings: a policy integrating transportation and urban planning can significantly lower the trajectories of energy consumption associated with urban transportation

Over the next 20 years, a business-as-usual scenario would mean that transport energy consumption and carbon dioxide emissions would increase by 70% compared to 2003 levels. These two parameters would increase by 51% in a "metro−" scenario. Conversely, if the politicy option selected is that of investment in a mass transportation system—two subway lines—along with appropriate land use regulations and pricing policies, then energy consumption and emissions of greenhouse-effect gases would only increase by 9% compared to 2003 levels (Table 3).

Two main conclusions can be drawn from these results. First, the answer to the initial question is "yes": with realistic[20] policies (building a subway network, encouraging higher density and mix of land-uses in zones of improved accessibility, and implementing economic instruments, like fuel taxes or parking pricing schemes), a stabilization of energy consumption and carbon dioxide emissions is possible. Second, the energy savings obtained from the integration of transport policies and land-use policies are significantly larger than those obtained from a transport investment alone.

What are the underlying processes shaping these results? Why and how is the integration of "transport–land uses" policies so successful? I analyzed the evolution of the spatial distribution of homes and jobs, as well as the growth in land consumption using GIS maps. These maps allow us to understand how the policies

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[16] or 2–3 miles.

[17] or 12–14 miles.

[18] The ownership ratio is endogenous in the model and is the result of the motor-vehicle attractiveness in comparison to other alternatives.

[19] In other words, we assumed that the social and economic structure of the city was not going to be modified, meaning that demographic growth would be identical (leading to 10 million inhabitants in 2020), that the ratio of the working population to the total population would remain constant, and that economic growth would be identical. This also entails that the technological characteristics of the vehicle park do not evolve, the input/output ratios of different activities remain constant, that income inequalities remain stable compared to the present situation, and that the distribution of workers between the different job categories linked to export remain the same, in terms of percentages of all jobs.

[20] Indeed the set of policies tested here are being implemented or planned in Bangalore or in other cities of developing countries: cf. footnote 16.

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Table 3
Projected mobility indicators and energy consumption.

Scenario	Inter-zone trips	Average distance (km)	Share of private mode (car+moto) (%)	Average time (decimal hour)	Energy consumption (L)
Base year	664,553	12.66	45	1.13	853,151
BAU	+65%	13.66	43	1.27	+70%
Metro−	+61%	13.08	36	1.63	+51%
Metro+	+59%	12.19	23	1.23	+9%

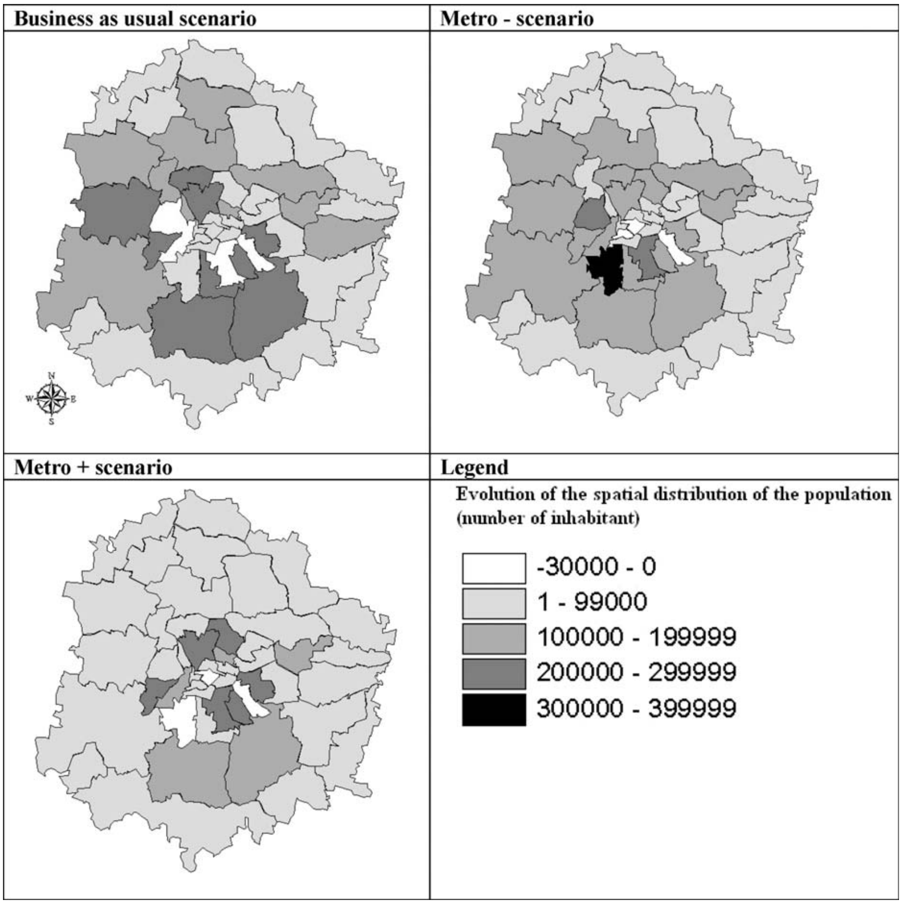

Fig. 3. Projected population distribution.

tested impact the location decisions. Then, I examined the impact of this urban structuring process on inter-zone mobility, characterized by number, distance, average duration and modal distribution of trips (Figs. 3–5).

In the business-as-usual scenario, phenomena of peri-urbanization and de-densification can be observed in the city center, whereas the localization of jobs remains stable. The localization of new jobs is homogenous throughout the territory of Bangalore.

In the "metro−" scenario, this centrifugal process is similarly observed, although in a less intensive way. Moreover, the peri-urbanization of the residences is in this case mostly oriented toward the first-ring suburbs. Meanwhile, the new employments are more concentrated in the catchment area of the metro, notably in the city center.

On the contrary, in the "metro+" scenario, the spatial distribution of new homes and jobs is concentrated in the inner-ring suburbs and in the South of the second-ring suburbs. The city center, at the intersection of the two subway lines, is still losing residents, but this time, it is clearly because the population is being driven out by jobs. The trend of job concentration in the city center increases real-estate prices, and the population that cannot pay leaves the center to find housing in peripheral areas that are accessible by metro.

To represent the phenomena of urban sprawl, or conversely, urban condensation, I choose the proxy of the evolution of land consumption—that is, the evolution of square meters occupied by residences and activities.

The evolution of land consumption[21] is very dissimilar in these three scenarios. In the "metro+" scenario, new real-estate consumption is concentrated in central zones and in the first-ring and second-ring suburbs accessible by metro. We observed that the amount of this real-estate consumption is relatively low, which indicates a process of densification of these zones. Real-estate consumption decreases in the other zones, especially the

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[21] This was the parameter chosen to represent the phenomena of urban sprawl or condensation.

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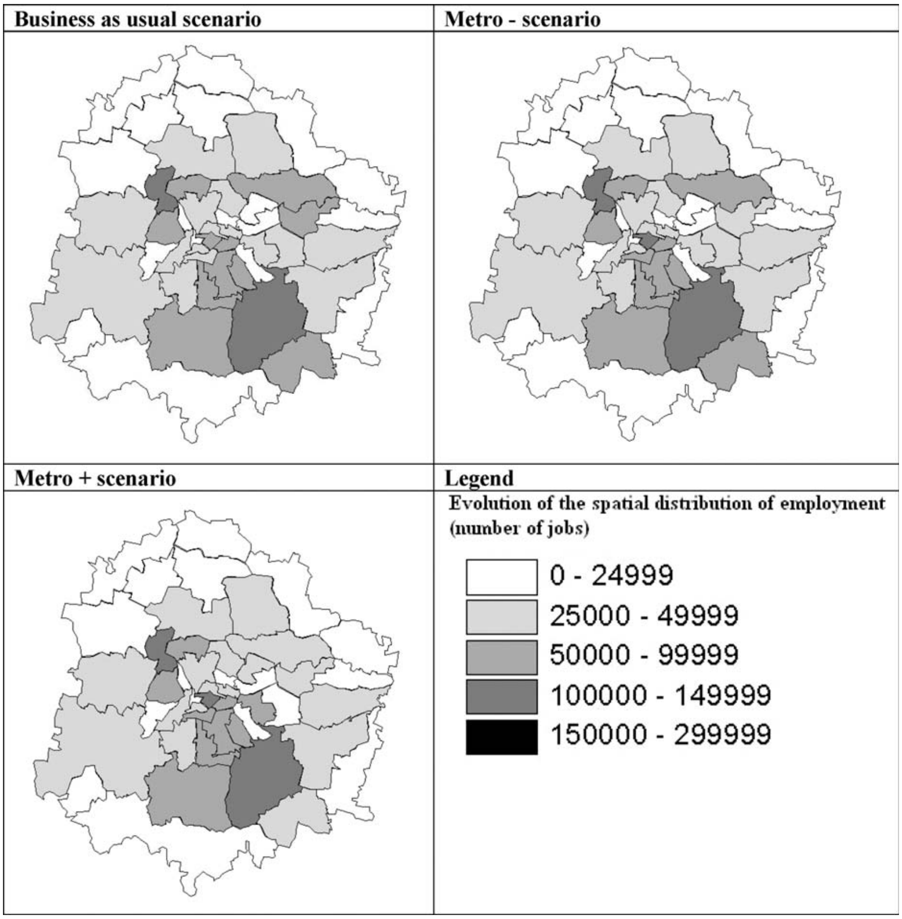

Fig. 4. Projected employment distribution.

more peripheral ones; this suggests a phenomenon of urban condensation. The evolution of land prices reflects these trends: residential and industrial land prices increase significantly in the city center and in the first belt. In these areas, the growth is more moderate for mixed-uses land. The decision to limit the amount of land open to urbanization in the peripheries, in order to fight against urban sprawl, generates a strong valorization of the peripheral lands.

In contrast, in the business-as-usual scenario, the peripherization of homes and jobs, and the de-densification of the city center, induces high land consumption in the periphery and abandonment of land in certain central urban areas.

Again, the ''metro−'' scenario presents an intermediate situation characterized by less peripheral land consumption than in the business-as-usual one. The metro limits the urban sprawl and increase the attractiveness of the city centre, but alone it does not generate a process of urban condensation. That explains why the increase in land prices–for residential, mixed, and industrial usages—is rather similar to the one observed for the BAU scenario, and lesser than the one observed for the ''metro+'' scenario.

Thus, the subway alone channels urban development toward certain areas, but it needs to be integrated into appropriate urban planning in order to counterurban sprawl (Table 4).

How are these evolutions of the urban structure translated in terms of mobility? How do the differences between the evolutions of the urban structure under these three scenarios explain that the integration of land uses and transport policies (the scenario ''metro+'') allows larger transport-energy savings?

The least increase both in inter-zonal mobility and particularly in average distance of inter-zone trips can be observed in the ''metro+'' scenario. These two results reflect both the greater densification and the greater diversification of land usages in the ''metro+'' scenario than in the two other scenarios. Densification and mixed land usages lead to both fewer and shorter trips because it becomes easier to find a job or a shop near where one lives.

Likewise, I observed a decrease of the modal share of private transport modes: 43% for the ''BAU'' scenario, 36% for the ''metro−'' scenario and 23% for the ''metro+'' one. This is again due to the densification and the diversification of land usages, and, for the ''metro+'' scenario, to the pricing policies discouraging people from using their cars and motocycles. Densification, mixed land usages and pricing policies lead to fewer and shorter trips, and discourage the use of the car for these trips.

Finally, I observed the strongest congestion in the ''metro−'' scenario. This can be explained by the relatively high modal share of private vehicles and the little investment in road infrastructures characterizing this scenario. This stronger congestion in the ''metro−'' scenario generates a longer average duration of trips than in the ''metro+'' and even than the ''BAU'' scenario.

In conclusion, the differences in terms of average distance and time, and modal share, and the magnitude of these differences explain that the ''metro+'' scenario generates the greatest energy savings.

Additional analyses could have been interesting to pursue. For example, what pricing policies (fuel tax and parking pricing) would have to be implemented to achieve alone the same energy savings as in the ''metro+'' scenario? What energy consumption reduction could be achieved soley by land uses policies? What investments in vehicle technology improvements would have

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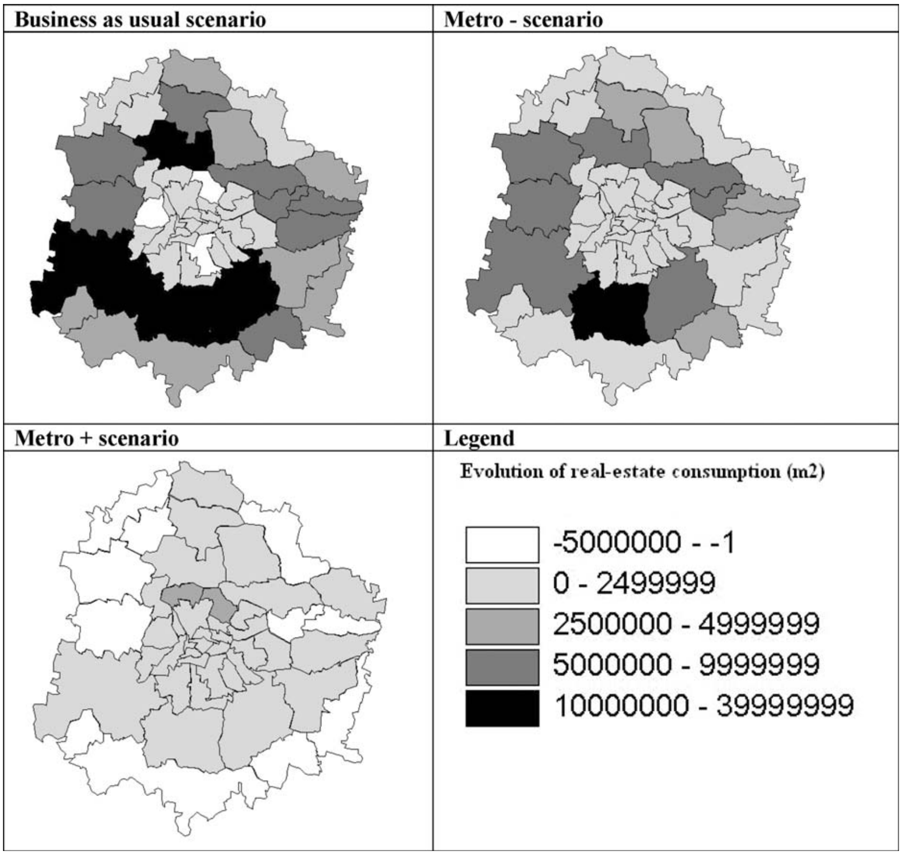

Fig. 5. Projected evolution of land consumption.

Table 4
Projected land prices.

	BAU (%)	Metro– (%)	Metro+ (%)
Residential land			
City center	+89	+76	+103
First belt	+84	+70	+99
Second belt	+3	0	+122
Mixed usages land			
City center	+81	+81	+84
First belt	+38	+36	+10
Second belt	0	0	+134
Industrial land			
City center	+26	+81	+125
First belt	+62	+36	+223
Second belt	0	0	+314

been necessary to achieve the same energy reductions? Would a Bus Rapid Transit system have had similar consequences as the metro?

Several shortcomings in my analysis also exist. For example, I considered only "one-shot" policies: the two lines of metro are constructed at one time, at the beginning of the 20 year period of simulation. What would have been the consequences of taking into account the timing of the implementation of these policies? Similarly, the issues of urban boundaries and potential leakage outside the limits of Bangalore have been ignored. The available data and the capabilities of TRANUS didn't allow taking this possibility into account. However, while these shortcomings influence the magnitude of the results, they do not influence the overall lessons.

6. Conclusions

Beyond the case of Bangalore, this research shows the significant influence of urban policies on transportation energy consumption drivers. Returning to the ASIF framework presented in the introduction of this article, this analysis shows that actions on total activity (A) and mode share (S) can significantly reduce transportation energy consumption. It shows that the effects of the "metro–" scenario on the total inter-zone trips—a parameter participating in the activity (A) component—are close to the effects generated in the "metro+" scenario: the growth of total inter-zone trips in the "metro–" scenario and the "metro+" scenario are, respectively, 61% and 59%. On the contrary, there are significant differences between these two scenarios in terms of average distance (respectively, 13.08 and 12.19 km), which is also part of the activity (A) component. There are also significant differences in terms of modal share, the (S) component of ASIF, and in terms of average time. This last parameter influences not only the (F) component (more fuel consumed for the same distance) but also indirectly the (S) component by changing the relative performance of each mode.

Moreover, these results demonstrate the relevance of focusing the urban governance of transportation energy planning on the interactions between transport system and land uses system: the savings obtained from the integration of transport and land use policies are much more important than the savings obtained from a transport investment alone. The transportation technologies affordable to an emerging city like Bangalore can significantly

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curb the trajectories of energy consumption, as well as the ensuing carbon dioxide emissions, if and only if they are implemented in the framework of appropriate urban planning.

This study also demonstrates that the existing transport technologies and decision-helping tools are already available to take up the challenges of climate change. The study establishes that there are tools which are available to facilitate the policy-making processes. These tools allow stakeholders to discuss different political alternatives integrating energy issues, based on quantitative assessments. TRANUS allows one to test different combinations of the three main policies available to urban planners: regulation of urban and peri-urban land uses, investment in transport infrastructure, and pricing policies.

In conclusion, this article shows that the urban developers, private and public, have effective levers of action in their hands. The main task is to first anticipate and secondly frame the market dynamics within an urban planning approach focusing on the "Transport–Land uses" couple. However, the land-uses policies and the transport policies are only means for achieving a more global objective. They need to be framed by a more general vision of "the city that citizens want".

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