BUILT FORM, TRAVEL BEHAVIOUR AND LOW CARBON DEVELOPMENT IN AHMEDABAD, INDIA

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DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the Rector Magnificus,
prof.dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
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by

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born on 5th October, 1971

in Ahmedabad, India

This thesis is approved by
Prof.dr.ir. M.F.A.M. van Maarseveen, promoter
Dr. M.H.P. Zuidgeest, assistant promoter

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1. Introduction

The manner in which cities will develop and grow in the future is considered crucial in the context of air pollution, as it is believed that future spatial developments in the built form will be essential from the perspective of achieving development with low carbon emissions. Consequently, this thesis deals with the relation between built form and transport, and looks at this relationship from the policy perspective by performing scenario-based analysis in the context of fast developing metropolitan cities in India. The term 'built form', as a broad concept, implies the spatial pattern or arrangement of individual urban elements such as buildings, streets and land use collectively and is also referred to as the built environment (Bourne, 1982). 'Transport', in this context, is the travel behaviour of residents and is measured as distances travelled by individuals in a day and the modes they prefer to use for travel. Achieving Low-Carbon Transport Development means achieving growth and development targets using a low-carbon trajectory.

The purpose of developing the above-stated relation is to identify and represent the influence of built form on travel behaviour, and to use it to help in strategic urban planning that has as its ultimate objective the reduction of carbon emissions resulting from passenger transport in the city. The developed relation should therefore be able to help in analysing, evaluating, forecasting and simulating urban systems to support decision-making.

1.1 Built form, transport and local carbon development

In cities around the world, integrated land use and transport development is high on the agenda of state and local governments (Bertolini et al., 2009) and long-term plans that facilitate a positive modal shift to public transport and non-motorized transport are formed around built form interventions, which are derived from a large body of empirical research. For example, the relation is taken up in US cities as a way to counter sprawl (Cervero, 1998b, Dittmar and Ohland, 2004, Dunphy et al., 2004). In Australia, national policy seeks 'land use transport integration' as a means to achieve sustainable travel outcomes (Curtis, 2008, Curtis, 2011).The first empirical evidence in literature looking at the land use and transport relation is the study by Mitchell and Rapkin (1954). This study subsequently led to several other research studies and development of principles, which relate to the built components of land use and transport (also termed as built form) with travel behaviour (Cervero and Landis, 1991, Cervero, 1998a, Cervero and Kockelman, 1997, Frank, 2000, Kitamura et al., 1997, Frank and Pivo, 1994, Stead, 2001, Gim, 2012).

This large body of empirical work has also led to urban development principles and concepts described using terms such as 'New Urbanism', 'Smart Growth', 'Location Efficient Development' and 'Low-Carbon Development' or 'Low-

Carbon Mobility'. .New Urbanism, also called 'Neo-Traditional Planning', advocates returning to pre-World War II town planning principles, with major emphasis on design that provides mixed land use, narrow streets laid out in a closely-knit grid mesh, decreased setbacks, and reduced parking. 'Smart Growth' principles draw further from the New Urbanism principles of planning, the common thread among the concepts is development that revitalizes central cities and older suburbs, supports enhanced public transport use, and preserves open spaces and agricultural land. 'Smart Growth' principles generally call for higher densities, transit-supporting development where the emphasis is placed on providing a balance of housing, jobs, and shopping within a community. 'Low-Carbon Mobility' plans work on strategies that are aimed towards low-carbon development, wherein growth and development targets are achieved using a low-carbon trajectory or even through a 'carbon neutral' pathway. Carbon neutrality, or having a net zero carbon footprint of transport, refers to achieving net zero carbon emissions by balancing a measured amount of carbon released with an equivalent amount sequestered or offset, or by buying enough carbon credits to make up the difference.

The above-stated debate on the need to use built form and its relation with transport to reduce transport energy consumption is well recognized in India. The National Urban Transport Policy (MOUD, 2006) and The National Mission for Sustainable Habitat (MOUD, 2010) in India stress the relevance and the need to study the built form and travel behaviour and to demonstrate how this relation can be used to achieve Low-Carbon Development. However, the empirical evidence on the built form and travel relation as well as application of the stated principles is largely from the United States of America and Western Europe, as summarized by Ewing and Cevero (2001, 2010), Stead and Marshall (2001) and others (Cao et al. (2009),McMillan (2005), Gim (2012)). There are some recent studies in the context of China (Wang and Chen, 2009, Cao et al., 2006, Chao and Qing, 2011) and a few examples validating these relations cities in other developing countries (Zegras, 2007, Dissanayake and Morikawa, 2008, Estupiñán and Rodríguez, 2008). There is a lack of substantial evidence on the relation in the Indian context; only (Srinivasan and Rogers, 2005, Adhvaryu and Echenique, 2012)) have studied the relation to some extent, with limited use of built form measures. The relation between built form and transport energy consumption and emissions is not very conclusive, therefore Anderson et al. (1996) called for more empirical work on the subject. Even though, there is a significant amount of empirical research on the subject starting from the study by Newman and Kenworthy (1989a,b) who looked at the relation between population density and transport energy consumption per capita, to some more recent studies (Glaeser and Kahn, 2008, Stone Jr et al., 2007, Susilo and Stead, 2008, Brownstone and Golob, 2009, Chao and Qing, 2011) that have also looked at the effects of urban form on CO2 emissions or energy consumption. Given this background, this PhD research is empirical and looks at relations between built form and travel behaviour, and at environmental externalities of transport in the context of metropolitan Indian cities. This study provides empirical evidence on how built form influences travel behaviour in the Indian context. Moreover, it is also able to demonstrate that this relation can be used to guide urban development. The outcomes of this research can, therefore, contribute significantly to urban planning practice in India, especially for the urban development organizations.

The next section is an introduction to the concepts of built form, travel behaviour and low-carbon transport development.

1.2 Key indicators of built form, transport and environment

In the context of this research, the understanding of built form as a physical concept and its relation with travel behaviour is important. To develop this understanding, built form is defined and its relation with travel behaviour is reviewed. Table 1-1 presents the built form indicators that are used in empirical studies on built form and travel behaviour as mentioned in Ewing and Cervero (2010). The built form variables are grouped into six categories, referred to as the six D's. These indicators are Density, Diversity, Design, Destination accessibility, Distance to transit (transit access), and Demand management.

Table 1-1: Travel behaviour and built form Indicators

Travel Behaviour Indicator	Built Form Indicator	#
Vehicle Distance Travelled	Density	31
	Destination Accessibility	24
	Diversity	23
	Design	22
	Transit Access	7
	Neighbourhood Type	5
Transit Mode Choice	Design	18
	Diversity	15
	Accessibility to Destination	7
	Transit Access	5
	Neighbourhood Type	1
Walk Choice	Density	55
	Design	30
	Diversity	25
	Destination Accessibility	9
	Neighbourhood Type	7
	Transit Access	6

* Source:(Ewing and Cervero, 2010)
# = No of times the variable has been used in built form-travel behaviour analysis

Intensity of the red colour in the last column (#) in Table 1-1 indicates frequency of use of the particular indicator, the most frequently used built form indicators in relation with Vehicle Kilometres Travelled (VKT) are density, diversity, destination accessibility and design. Likewise, design, diversity and density are more frequently studied in relation to mode choice of transit and walk modes. In the next section built form indicators and measures used to operationalize these indicators are discussed, this is followed by a discussion on the relation between built form and transport.

1.2.1 Travel behaviour indicators

The most common travel outcomes modelled in relation with built form are trip frequency, trip length, mode choice and vehicle distance travelled (Ewing and Cervero, 2010). The measures used to represent travel behaviour variables are presented in Table 1-2. Vehicle distance travelled is most commonly measured as vehicle miles travelled (VMT) or vehicle kilometres travelled (VKT), expressed per household or per person per day. Some studies disaggregate distance travelled by purpose of trip or by modal use, for example, distance travelled for shopping trips, distance travelled by car, etc.

Mode choice is quantified in a binary format for all-purpose trips or by trip purpose, and is studied at either the household or the individual level. When higher aggregation levels like traffic analysis zones are used, the proportion of trips by mode is also used as a measure. To establish the relation of transit choice with built form, boarding at station is also used as a measure to relate with built-form variables. Walk and bicycle choice is at times studied as a combined choice or separately for both modes. Walk or bike (bicycle), and walk and bike trip rates are also used as a measure.

Table 1-2: Travel behaviour measures

Vehicle Miles/Kilometers	**Transit Mode Choice**	**Walk Mode Choice**
VHT/ VMT per Household/Person	Transit mode choice per Trip Purpose	Walk trips per Household/Person
Nonwork VMT per person	Transit mode choice/(Household or Person)	Walk mode choice/Trip purpose
VMT per Trip purpose	Proportion of transit trips	Walk/bike trips per Household/Peron
VMT per Mode use	Weekday boardings per station	Walk trips for perpose per Household/Person
		Non-private vehicle choice for nonwork trips
		Walk/ bike mode choice
		Walk/bike mode choice for Trip Purpose
More frequently used measure		Walk mode choice
		Weekday travel distance by walk/bike per
		Fraction walk/bike trips
Less frequently used measure		Pedestrians per hour

* Source:(Ewing and Cervero, 2010)

1.2.2 Built-form indicators

Density

Density is considered as an important urban-form indicator as concentration of growth in general is believed to reduce travel distances and encourage the use of non-motorized travel. Concentrating most growth and development around transit stops is believed to encourage walking to public transit stops and the use of public transit. The measures used to quantify density are presented in Batty (2009), who has defined density as mass of some entity, in case of urban areas this could be population, employment or any other collection like buildings etc., described by its size and normalized by some measure of area that the entity occupies. As can be seen from

Table 1-3 Built-form measures

Density	**Design**
Population or Household or Residence density	Intersection density/proportion
Job density	Sidewalk characterstics
Retail floor area ratio/job density	Plaza or Block Characterstics
Population and employment density	Street connectivity/density
Employment within walking distance/mile	Path directness
Parcel density	Pedestrian environment factor
Population per road mile or walking distance	Proportion front and side parking
Commercial or Business density	Bicycle lane density
Number of retail parcels	Space Syntax Parameters
Diversity	**Neighbourhood type**
Land use mix (entropy index)	New Urbanist Neighbourhood
Job-housing/population imbalance	Neighbourhood with retail
Distance to closest commercial use or grocery stores	Urban Neighbourhood
Land use dissimilarity	Traditional Neighbourhood
Business types in neighborhood	Transit-oriented Neighbourhood
Proportion of population within 1/4 mile of stores	Neighbourhood with retial and park
Proportion vertical mix	**Destination Accessibility**
Distance to nearest park	Job accessibility by Auto and /or Transit
Non-retail job-housing balance	Distance to CBD
Retail job-housing balance	Population centrality
Retail store count	Accessibility to shopping or retail
Walk opportunities within 1/2 mile of home	Household accessibility by auto
Transit Access	Job accessibility by walking
Distance to transit/bus stop	/ Indicates either or measures
% within walking distance of transit/bus stop	More frequently used measure
Transit/bus stop density	
Walk minutes to transit/bus stop	Less frequently used measure

* Source: (Ewing and Cervero, 2010)

Table 1-3, the density measure in an urban situation can take several annotations depending upon different considerations. The most common expression used to represent the density indicator is using population/household/residence density and job densities. These measures are quantified as net (density of total developed area) or gross (density of total area) densities. In built environments in countries like India where density values are expected to be high, considering other uses in the density computation can distort the density values. Therefore, in this situation density of development is computed as net residential and net job density. Formulation of both density values are shown in Equation 1-1 and Equation 1-2.

The connotations of densities in this study are similar to those used by Frank and Engelke (2005), Newling (1969).

Net Residential Density = $D_r = \frac{P_r}{A_r}$ ....Equation 1-1

Where: D_r= Net Residential Density (10000 persons/square kilometre), P_r = Residential Population (No of persons/10000), A_r = Area under residential land use in the grid cell (square kilometre)

Net Employment Density = $D_e = \frac{J}{A_{ea}}$ ....Equation 1-2

Where: D_e = Net Employment Density (10000 Jobs/square kilometre) , J = Total jobs available in the area(No of Jobs/10000), A_{ea} = area under economic activities in the grid cell (square kilometre)

Diversity

The land-use diversity measure describes the degree to which types of land use (e.g., residential, commercial, institutional, entertainment, etc.) are located in close proximity of each other. A higher mixing of compatible land use is said to increase the opportunities that are available to an individual in close proximity, and thus makes it easier for people to access the associated functions by walking or by other non-motorized modes. Like density, a good mix of activities around transit stops increases the number of opportunities accessible to people using public transit, and thereby the possibility of increased public transit use. A proper mix of land use can also help generate demand for transit (Frank and Pivo, 1994). This can happen not only during peak traffic periods but also during the off-peak times as proper mixing of land use ensures that activities like shopping, social and religious facilities are also available near transit stops or residences. The most commonly used variable to measure diversity is land-use mix or land-use entropy. Cervero and Kockelman (1997) have developed the following concept of 'Entropy'.

$Entropy = \sum_j \frac{Pj \times \ln Pj}{\ln J}$..Equation 1-3

Where Pj is the proportion of developed land in the jth use type in a census tract, J is the number of distinct land uses

This construct as per (Kockelman, 1991) is normalized with the natural log of a number of distinct land uses, and therefore varies between zero and one (with one signifying a perfect balance of distinct uses considered). In Equation 1-3, the total land is considered, and this equation is further improved by using only proportions of developed land so that areas, which have been assigned a use but are not fully developed get properly represented. Another common diversity measure used to represent land-use mix is job - housing balance or imbalance, which is generally represented as jobs per household as in Ewing et al. (1994) and Barnes (2001).

$Dissimilarity\ Index = Mix\ Index = \sum_j^k \sum_i^8 (\frac{X_i}{8})/\mathrm{K}$.........................Equation 1-4

Where K = number of actively developed hectares in a tract and Xi = 1 if central active hectares use type differs from that of neighbouring hectare (Xi = 0 otherwise)

Kockelman (1997) argues that while entropy can be used to understand the balance of land use, the degree to which these land uses come into contact with one another is also important. For example, if the land uses are uniform clusters, they are likely to encourage less number of small distance trips and thus a lower demand for walking trips. Kockelman (1997) and Cervero and Kockelman (1997) propose the concept of 'dissimilarity index' which is explained in Equation 1-4. Thus if all the land uses in immediate contact of the hectare grid cell under consideration are the same, then the diversity value will be 0; if all are different, the value will be 1.Land-use diversity measures are studied in relation to vehicle miles travelled (Kockelman, 1997, Cervero and Kockelman, 1997) and non-personal mode choice (Cervero and Kockelman, 1997). Other measures such as retail store count, retail job - housing ratio, retail job-housing balance, distance to nearest grocery store/park etc. have also been used to represent the land use diversity.

Design

The design quality of the street environment, neighbourhood blocks and plazas can influence the transport mode choice and the distance that individuals travel. A fine-grained street network with many connections and good infrastructure for non-motorized modes provides more non-motorized travel options to individuals. The design measures considered relevant for this study are related to supply of transport, represented by Kernel density (described later in the section) of infrastructure, and second, by how individuals perceive distance from an origin to a destination represented by Space Syntax parameters.

The design aspect has been part of several studies and is mainly computed as the difference in the design of transport infrastructure (street, pedestrian and cycling provision, number of cul-de-sacs, T and X junctions, etc.). The most common use is to compute density of intersections or proportion of T and Y junctions in an area. Tracy et al. (2011) have used kernel density of a network, network junctions and public transport stops to represent design elements of the network. They operationalized these measures using spatial kernel density. To compute this value the study area is overlaid using a raster grid. The kernel value of each grid cell is computed as the summation of all overlapping kernel function values, which is defined using a kernel radius function. For example, for computing kernel density of intersections, each intersection is assigned a kernel function and a kernel radius.

Kernel density of a point = $K\,(1-\left(\frac{r}{R}\right)^2)^2$……………………………...Equation 1-5

Where r is the distance of the location from the point,, R is the search radium parameter entered, K is the scaling factor to give total volume = 1 or the population field

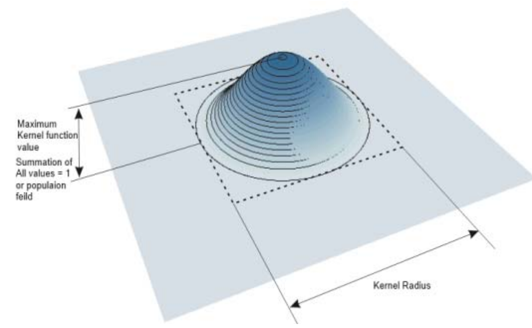


Figure 1-1: Illustration of Point Kernel Density Computation

Further adapted from http://forums.esri.com/Attachments/6701.gif accessed on 19th November 2011

The value of the kernel function is highest at the point, and diminishes with increasing distance from the point, reaching zero at the search radius of the point. The volume kernel value under this circular neighbourhood of the point is either equal to the population value defined by kernel function or is equal to 1 if no population field is used. As can be seen in Figure 1-1, the output is computed as a raster layer and the density of each output raster cell is computed by adding the values of all the kernel surfaces where they overlay each raster cell. This kernel function is based on quadric kernel function explained in (Silverman, 1986), and can be expressed using the algorithm in Equation 1-5. Design is also measured as characteristics of blocks defined by average block sizes, proportion of buildings having parking on the front side, path directness (e.g., whether curving or straight) and other physical variables that differentiate pedestrian-oriented environments from auto-oriented environments(Ewing and Cervero, 2010).

How individuals perceive the distance between origin and destination can also influence the person's travel distance and mode choice (Jayasinghe and Munshi, 2011). In literature, space syntax values are studied in relation with land-use density (Kim and Sohn, 2002), urban structure and personal travel behaviour (Jiang et al., 2000, Lee and Kim, 2009), and transit demand (Jayasinghe and Munshi, 2011). In addition, Matthews (2006) and Matthews and Turnbull (2007) studied the effect of space syntax values on land and property price, and found that space syntax values actually explain the formation of land price.

This perceived or imagined space is studied using the concept of Space Syntax, developed at the Unit of Architecture Studies, University College, London (Read, 1999). The Space Syntax concept looks at the spatial arrangement of networks in topological space. The concept proposes that the influence of network on travel behaviour is explained from the point of view of topological distance, and is measured as a change in direction needed to move from one space to another, and not via the metric distance that typically forms the basis of spatial analysis (Read, 1999). The approach is based upon principles of natural movement and the theory of movement economy (Hillier, 2007, Hillier et al., 1993), which forms the basis for space syntax's theory of spatial configuration. Essentially, space syntax focuses on free space and decomposes the entire urban space into small pieces of free space that allow the movement of people. Each space is defined by what can be perceived from a single vantage point and is represented as a so-called axial line.

Initially Space Syntax was used at a very small scale, for example, to understand movement patterns inside a building such as a museum or a hall. Recently, it has been developed further with the integration of GIS and is now being used to study many urban phenomena at larger scales (Jiang et al., 2000, Jun et al., 2007, Lee and Kim, 2009). For urban morphological analysis, space syntax provides a range of spatial properties derived from the connectivity graph of the axial map. (Jiang et al., 2000).The key measures or variables produced are identified as connectivity, depth, mean depth, relative asymmetry, real relative asymmetry, global integration, local integration and intelligibility (explained in (Manum et al., 2005, Hillier, 1996, Hillier, 2007). Space Syntax parameters, Connectivity and Depth explain the relative accessibility to other lines in the system. Relative Asymmetry (RA) and Real Relative Asymmetry (RRA) describe the integration of a node by a value between 0 and 1, where a low value describes high integration. Global integration is given by the reciprocal of RRA. It shows the integration of a particular line with the rest of the lines in the system. Values more than 1 indicate high integration while lower values indicate segregation from the rest of the lines in the system. Local integration is the integration value of a line with the lines, which are only three steps away from it. It is also called radius-3 integration. Intelligibility is the co-efficiency of correlation between local parameters and global parameters. Local parameters like connectivity, control and local integration thus can be correlated with global integration to see the intelligibility of the system. A local area is said to be more intelligible if the local integration is higher than the global integration values (Hillier, 2007).The notion of relative nearness can be analysed through variables of global and local integration. Thus, if a street shows a high global integration it means that it has better connectivity to the whole system than do other streets. If a street shows high local integration it means that the street is better connected to its immediate neighbouring streets. The axial representation and the measures derived from it have been researched and found successful in the study of the social and cultural roles of space, particularly for the evaluation of the impact of spatial configuration on pedestrian and vehicular movement patterns and also for evaluation of design proposals (Figueiredo and Amorim, 2005).

Destination and access to destination

Brotchie et al. (1996) studied the effect of technology on urban structures and especially on activity node formation. The opposite can also be considered true, that access to destination by different modes (transport technology) and characteristics of these activity nodes can be considered to influence mode choice. Access to destination by different modes is the most commonly used built-form variable. Destination accessibility is a measure of the effort required for access to trip destination. This measure, as stated in Ewing and Cervero (2010), can be regional or local as in Handy (1993). The most frequently used access to destination measure is defined by job accessibility by auto or transit as presented in Table 1-3. This is a cumulative accessibility measure (Geurs and Ritsema van Eck, 2001) giving the total number of jobs that can be accessed from a location by a particular mode within a given travel time. The regional accessibility is often measured as the effort required to reach the central business district, measured as network or Euclidian distance.

Distance to transit

Distance of a location from transit stops determines the access and egress distance an individual has to travel to access public transit and destinations from public transit. The longer the distance individuals have to walk or travel to or from transit stops, the lower the chance of using public transit. The most commonly used measure is distance to bus/transit stop; other variables used are population living within walking distance of a bus stop, and stop/transit density.

Demand (Travel demand management)

Built form is linked with travel behaviour, and change in built form is engineered by changing the land use. However, it is observed that change in the built form is not sufficient by itself to significantly alter travel behaviour in a city (Wegener, 2001). The desired shift from privately-owned vehicles to non-motorized and public transport can also be engineered by introducing mechanisms that increase the cost of using a privately-owned vehicle relative to walking, cycling and transit.

Table 1-4: TDM measures varying from push and pull factors

TDM Measures	
Taxation of cars and fuel	Teleworking
Closure of city centres for car traffic	Land-use planning encouraging shorter travel distances
Road pricing	Traffic management reallocating space between modes and vehicles
Parking control	
Decreasing speed limits	Park and ride schemes
Avoiding major new road infrastructure	Improved infrastructure for walking and biking

sourced from Gärling et al. (2002)

The travel demand management measures (Table 1-4), according to Gärling et al. (2002), can be classified as pull and push measures, push to discourage car use and pull to encourage non-motorized and public transit modes of travel (Steg and Vlek, 1997). The most common demand measure is parking supply and cost (Ewing and Cervero, 2010).

1.2.3 Low-carbon transport development

In India, transport is a major contributor of polluting gases and, as a result, poor ambient air quality. Transport contributes in the range of 70 to 90 per cent of carbon monoxide in the air, more than 60 per cent carbon oxides, almost all the hydrocarbon and about 10 per cent of particulate matter in the air (GoI, 2002). This underlines the need for reducing energy consumption by the transport sector in India to achieve reduction in these pollution loads.

For successful implementation of development plans, the urban development decisions should be acceptable to the urban residents. Accessibility to jobs, food, shops, health and social services along with access to family and friends are key measures of a good quality of life. Accessibility to jobs and places of employment are a necessity for economic functioning of the society. Therefore, if the process and decision restricts economic growth and the residents' access to economic, social and recreational opportunities, the urban development plans might not be accepted by the residents and will be difficult to implement or justify.

In December 2007, the 'Bali Action Plan', agreed at the United Nations Climate Change Conference in Bali, recognized the need for developing countries to fully participate in global emission reduction goals. The Plan recommended Nationally Appropriate Mitigation Actions (NAMAs) voluntary country engagement proposals to the United Nations Framework Convention on Climate Change (UNFCCC), which should ideally include every possible activity aimed at reducing or limiting GHG emissions (Bockel et al., no date). The second step is to move towards comprehensive Low-Carbon Development Strategies (LCDS). For India, according to Höhne et al. (2008), transport is one of the three key sectors where potential of NAMAs could be realized. An additional climate change measure suggested in the transport sector (ibid), is research in sustainable transport systems. The proposed urban development plans would therefore also be aimed at low carbon emission, one way of achieving which, as stated earlier, would be to use the land use and travel behaviour relation to guide the plans.

Even though there is no agreed definition of Low Carbon Development (LCD), the view of using 'less carbon for growth' is considered as the common denominator, as pointed out by UK's Department for International Development (DFID) (Mulugetta and Urban, 2010). Similarly, Islam (2010) considered low-carbon development in Europe and Asia as focused on reducing CO2 emissions while ensuring economic growth. Thus, the idea is to effectively reduce CO2 emissions without compromising on economic growth. Yuan et al. (2011) summarized the concepts related to low-carbon development and identified three stages of LCD. Low-carbon economy is the early phase in which achieving economic development with lower CO2 emissions is the main aim. The second phase is the low-carbon society phase, where government promotes low-carbon lifestyles and consumption. The third stage is the low-carbon world, achieved when many cities in the world adopt low-carbon development strategies.

1.3 Research problem

From the discussion in the preceding sections it is clear that from the perspective of low-carbon transport development, cities in India cannot continue to grow in the manner they have in the past. There is a need to intervene in a manner that the long-term plans facilitate people to travel less and encourage them to use non-motorized and public transport modes for travel. This need is also recognized by the National Urban Transport Policy (MOUD, 2006), the National Mission on Sustainable Habitat (MOUD, 2010) and the Working Group on Urban Transport for the 12th Five-Year Plan set up by the Planning Commission, Government of India (2012). As described earlier, empirical research coming mainly from the Western countries shows that the driver for the desired changes, that is, the manner in which residents of an urban area travel, is the built form of the city. These empirical findings might not have direct application in the Indian context. This is because most Indian cities tend to have migration-led urban development (Adhvaryu, 2011), poor development control and regulatory mechanisms, and poor or inadequate transport infrastructure (Alan, 1992, Dimitriou, 2006a, Adhvaryu, 2009).Therefore, in India, the strength and direction of the relation between built form and travel behaviour could be different from or similar to what has been found in the context of Western cities. Indian urban policies on the spatial pattern of built form in cities will therefore have to depend upon empirically-derived information on the relation in Indian cities, which has been lacking so far and sets the need to conduct this research. The information thus derived can be used for framing policies, which can be translated into strategies that lead to urban development scenarios that promote the desired travel behaviour changes leading to a reduction in the total carbon emissions in a city. From the low-carbon transport development perspective, these polices should not have negative repercussions on societal benefits for the city residents.

Thus, in a country where cities are typified by fast urban growth coupled with even faster economic development, and by individuals aspiring to own motorized modes of transport, the future spatial development of built form in cities will be crucial for achieving development that is carbon neutral or low carbon, thus the core hypothesis of this research is as follows.

1.3.1 Research hypothesis

In rapidly growing cities in India, like Ahmedabad, future spatial developments in built form that encourage lower travel distance and higher use of public transit and non-motorized modes for travel are crucial from the perspective of achieving low-carbon transport development.

1.3.2 Research objectives

The objectives of this research are to quantify the relation between built form, transport, and environmental externalities of transport for a fast-developing metropolitan city in India, and to derive urban policy recommendations towards low-carbon transport development.

1.3.3 Research questions

To achieve the above-stated objectives the research questions to be answered are

- What is built form and what is its relation with transport, and what indicators are used to represent the built form of a city?
- What is the urban development reality in metropolitan cities in India, and what built-form measures can be used in the context?
- What data and methods can be used to operationalize built form in a metropolitan city in India, and what is the pattern of built form in the case city of Ahmedabad?
- What methods can be used to derive the built form - travel behaviour relation, and what are the policy implications of this relation for Ahmedabad?
- What is Low-Carbon Transport Development, and how can built form-transport relation help in achieving future scenarios that are Low-Carbon Transport Development?
- What is an appropriate method to model future urban development, and from the policy perspective, does built form and transport relation help in achieving future development that is Low Carbon Transport Development?

1.3.4 Scope of work

This thesis has been operationalized taking Ahmedabad city in India as a case. The city is located in the state of Gujarat in western India. Ahmedabad is considered a typical Indian city, which is classified in the second tier of cities in India. This means that it is not as large as Mumbai or Delhi, however, it manifests problems that are typical of cities in India. The recent government initiative, interest and investment in a mass transit system in the city also make Ahmedabad an interesting case for empirical research.
India is also a region where access to spatial data is subject to much restriction, and data of any kind is not easily shared. However, in order to develop, illustrate and test the built form, travel behaviour and environment relation, data has been mined from different sources. Geographic scales at which different datasets are available differ, so for certain data requirements geo-statistical methods have been used to generate data, which is accompanied with inherent marginal inaccuracies and errors.

Lastly, an ecological footprint map has been developed to be used as a decision-support tool. It is assumed that the local government will be sensitive to the environment, and its actions will be governed by the local carbon agenda. Reducing pollution levels through changes in travel practices is also one of objectives of the National Urban Transport Policy in India (MOUD, 2006), which too should guide the local government policies and actions.

1.4 Research design and outline of the thesis content

Figure 1-2 presents the conceptual framework of the study. From the earlier discussion in this chapter, it is assumed that planning decisions influence transport supply, and transport supply and planning decisions together influence activity location decisions. The configuration of activities and transport infrastructure constitute the built form, which influences individual travel behaviour and consequently its impact on the environment.

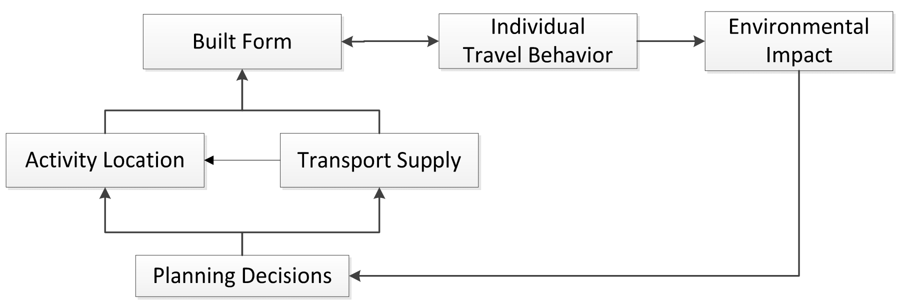


Figure 1-2: Conceptual Framework

This research is composed of several inter-related stages. Figure 1-3 presents the main stages and research design of this thesis. Theory, methods and application constitute the three major sections of this research. Chapter 2 provides the theoretical background, Chapter 3 and 4 deal with built form - travel behaviour relation and Chapters 5 and 6 deal with the application of these methods to help in making urban planning decisions.

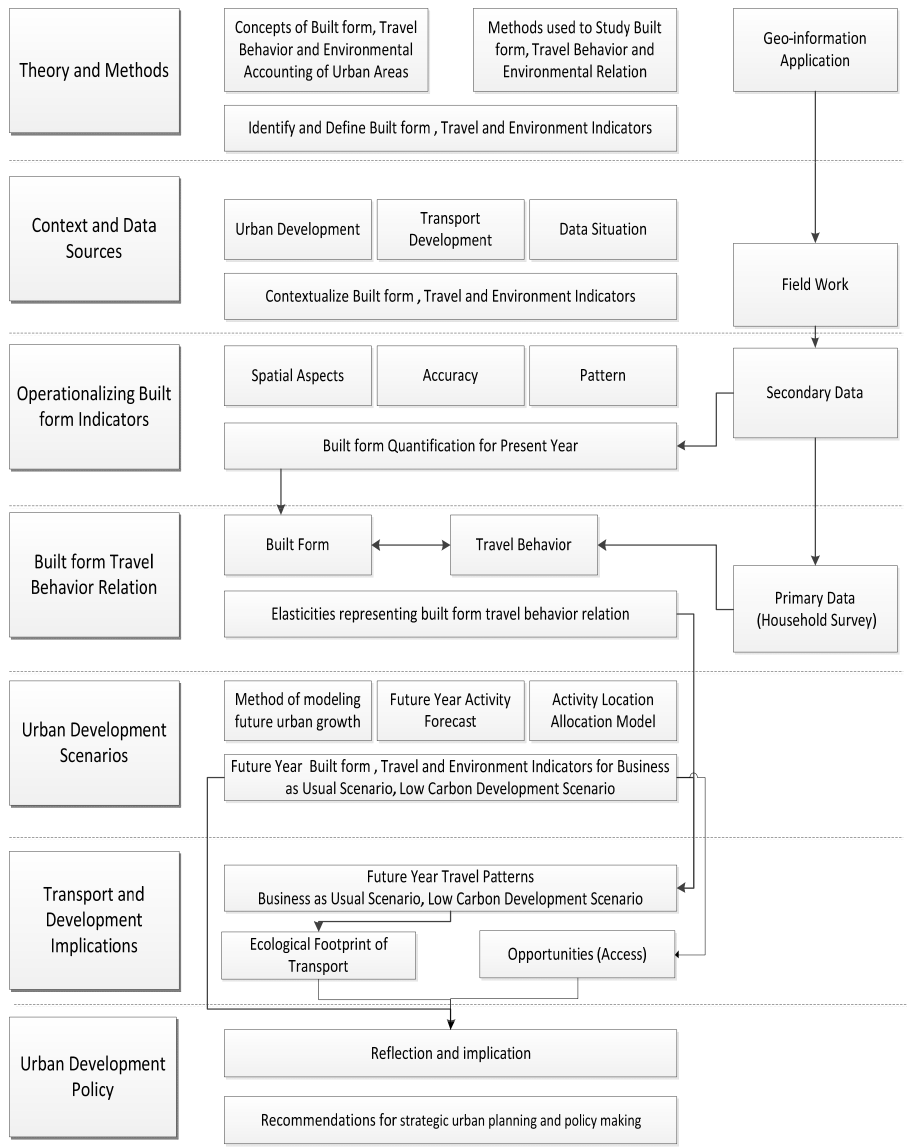


Figure 1-3: Main stages of this thesis and the research design

Chapter 1 provides an overview of the research, with a general background and the research problem. This chapter also offers a theoretical and methodological discussion, and poses and briefly answers the research questions: what is built form, how is it related to transport, what indicators represent built form and how are these defined? It also discusses empirical research on built form, travel behaviour and environment research, including aspects of spatial data representation. Built form, travel and environmental measures used in literature are identified, defined and their relationship described. The conceptual framework discussed earlier in this section is the result of this evaluation.

Chapter 2 looks at the reality of urban development in India with a focus on built form and transport using available data. Given these realities in Ahmedabad, the chapter reflects on the relevance of built-form indicators described in Chapter 1.

Chapter 3 answers two core research questions: 1) What data and methods can be used to operationalize built form variables, taking Ahmedabad as the case for study? and 2) What are the patterns of the quantified built-form measures? The first section of the chapter discusses quantification of input data required to quantify built form data, which includes technological aspects such as the use of remote sensing data and census data, and the use of spatial data modelling to generate input data. In the second section of the chapter, built form variables are contextually defined and operationalized. The last section of this chapter discusses the accuracy of quantified indicators and their statistical and spatial distribution patterns and properties.

In Chapter 4, relations between built form variables and travel behaviour are developed. Relations are developed between signatures of urban form at a particular location and travel behaviour of the individuals who reside at the same location. The derived regression models show the relation between travel behaviour (choice of mode of transport and total distance travelled in a day for work and non-work travel) with urban form variable and choice of destination. The applied approach has several steps: conceptualizing the method used to study the relation, spatial mapping of household survey data, relating urban form signature at the surveyed household location with travel behaviour of the individuals, and lastly, drawing inferences from the developed relation. This chapter discusses how the information derived from the built form - travel behaviour relation can be used in urban policy making, and also the key pointers for policy making. These pointers are translated into urban policies for which strategies for urban development and related actions are derived.

The focus of Chapter 5 is on defining Low-Carbon Transport Development, and on describing the methods that will be used to test and apply built form and transport relation from future policy perspective to achieve low-carbon transport development. The methods to operationalize the approach to analyse the impact of urban policies are discussed and formulated. This chapter also discusses methods to simulate future urban development and growth, to evaluate impact of urban development on the environment and to compute economic and societal benefits for the urban residents.

In Chapter6, the methods developed in Chapter 5 are operationalized to simulate urban development and growth for a future development scenario and to study the impacts of these scenarios on the environment and on economic and societal benefits. Thereby this chapter demonstrates the benefits of implementing built-form strategies that lead to lower travel distance and higher public transit and non-motorized mode choice on two essential indicators of low-carbon transport development, namely, carbon emissions and societal benefits. The main themes and outcomes of this research are synthesized and discussed in chapter 7. Chapter 7 also outlines future scope of work.

2 Urban Development in India and the Case City of Ahmedabad

2.1 Introduction

This chapter first discusses urbanization and the transport sector in India, which helps in understanding the relevance of this study and how it can help in the planning of Indian cities. It also draws conclusions on why the focus on metropolitan cities in India is important. Section 2 of this chapter gives a background to the urban and transport practices in India and to the associated problems. Section 3 introduces the city of Ahmedabad, which is used as a case to demonstrate how built form and travel behaviour relation can be used to make sustainable urban-planning decisions. This is followed by a discussion on the availability of data and issues related to quantification of data for this study, and to the identification of built-form measures that are relevant for the case of Ahmedabad.

Thus, the overall aim of this chapter is to give a background to the urban and transport planning problems in India and describe the case city of Ahmedabad. The chapter also reviews the available data, and identifies relevant built form variables for the city of Ahmedabad. Thereby this chapter addresses two core research questions. The first is regarding the reality of urban development, with a focus on built form and transport in Indian cities. The second question considered is regarding what indicators can be used to suitably represent built form in metropolitan cities in India, taking the city of Ahmedabad as a case.

2.2 Urban development and transport in India

Thirty per cent of India's 1.21 billion people live in urban areas. India's population is likely to grow at a rate of 1.5 to 1.8 per annum till 2030, and by then around 40 per cent of India will reside in urban areas. Table presents the classification of Indian cities according to their population size, which is adopted from Wilbur Smith Associates' (2008) study for the Ministry of Urban Development, Government of India, and Tiwari (2011). At present, about 24 per cent population resides in medium -sized cities (or metropolitan cities (Revi et al., 2012)), that is, cities that have a population greater than one million and are not classified as mega cities (more than 8 million population). Therefore, planning of urban areas and using appropriate methods to plan cities in India are essential for sustainable growth of these areas.

By and large, Indian cities have a mixed and heterogeneous land-use structure, which is at times organic (not planned) and a result of poor implementation of development control regulations (Pucher et al., 2005). Indian cities also have substantial informal settlements, with about 15 to 60 per cent of the population, depending upon the size of the city, living in slums; in larger cities about half the population lives in slums. A large section of the slum dwellers are not able to afford motorized modes of transport, including shared modes. The share of walking trips in all Indian cities, irrespective of their size, is therefore high. The per capita trip rates in Indian cities are, however, low compared to cities in Latin America, Africa and other parts of Asia(UITP, 2006). The lower number of trips is also a reflection of the social structure in India, as in smaller towns in India only a few women work, but this percentage increases as the size of the city increases. Likewise, the trips lengths also increase with an increase in the size of the town but the average journey speed decreases, which indicates congested streets and sprawl-type development.

Table 2-1: Classification of Indian cities by population size and travel characteristics

Category	Population (million)	% of total population in cities	% Mode Share (Walking + Bicycle +Public Transit)	Per Capita Trip Rates (PCTR)	Average Trip Length (Km)	Average Journey Speeds (Kmph)
1	< 0.5	52	43(34+3+5)	0.76	2.4	26
2	0.5 – 1.0	10	61(32+20+9)	0.81-1.02	3.5	22
3	1.0 – 2.0	10	56(24+19+13)	0.98 – 1.25	4.7	18
4	2.0 – 4.0	6	53(25+18+10)	1.20-1.29	5.7	22
5	4.0 – 8.0	8	58(25+11+21)	1.30-1.50	7.2	19
6	> 8.0	14	76(22+8+44)	1.41-1.67	10.4	17

Source: Wilbur Smith Associates (2008)

The overall values of mode share, per capita trip rates (PCTR) and average trip length look better in Indian cities in comparison to similar size towns in the Western countries, which for example in the United States of America was 3.79 PCTR (Santos et al., 2009). However, as stated in Tiwari (2011), more than 60 per cent of public transit and non-motorized choice is because of lack of choice arising from poor affordability. Also given the poor status of transport services, these individual who use public transit and non-motorized transport modes for the above reason, aspire to own a personalized mode to travel. It has been observed that as soon as they can afford to own a motorized mode for travel, they shift towards self-owned motorized modes. The per-capita income in India is expected to increase by about four times in the next twenty years (Sankhe et al., 2010) and car ownership is likely to grow by more than four to five times the present level in the same period. Thus, the overall transport situation in urban areas in the country does not look good from sustainable transport development point of view. In this light Dimitriou (2006a) believes that medium-size cities provide opportunities for meaningful interventions, as most mega cities are already developed beyond a level where structural changes can be made. The Ministry of Urban Development in India considers cities in the population range between 4 and 8 million as medium-sized cities in India (classified as metropolitan cities (Revi et al., 2012)). This classification is slightly different from Dimitriou (2006a) definition but still relevant as cities like Ahmedabad, Kanpur or Surat could face problems faced by Delhi or

Mumbai if the current developments in these cities are allowed to continue in the business-as-usual manner. In the next section, typical urban planning methods followed in India are reviewed.

2.2.1 Urban planning and development

In India, the Ministry of Urban Development, the Ministry of Housing and Urban Poverty Alleviation, and the Planning Commission of the Government of India are the main agencies dealing with the subject of urban planning and development. Their role is to lay down policies, legislations and programs, and provide monetary assistance for the states and local bodies to implement these programs and policies. The state governments also have a town planning department, which is governed by the state Town Planning Act established in most states in the country. Although the role of the town planning departments may vary from state to state, in general they are responsible for the preparation of regional plans, master/development plans and small area plans like town planning schemes and zone plans(Gurumukhi, 2003).

The Development Plan (DP) generally drives planning of towns in India. The DP is prepared for a 20-year period and is revised every 10 years in accordance with the Town Planning Act prevailing in the particular state. The DP generally outlines the land-use zones in which uses like residential, commercial, industrial, etc. are specified. Although the Development Plan is a statutory plan, it does not have a financial plan attached to it, and therefore can be difficult to implement (Mahadevia and Joshi, 2009). The government mandates the cities to prepare City Development Plans (CDP's) in addition to the Development Plans. These CDP's are prepared with the aim of prioritizing development in line with the medium and long-term vision for the future and are supported by financial resources. The DP is supported financially by the City Development Plan. CDPs take a more strategic view of the development of a city and align infrastructure development and service delivery to the vision of the city. But, the general observation is that CDPs are prepared independently of the city's Development Plan or the Master Plan (Mahadevia and Joshi, 2009). The DP, which is a strategic document, is implemented at a micro level (small area plans of about 100 hectares) (Ilhamdaniah et al., 2005), by a 'land pooling method' or the land 'readjustment method' where land is pooled from the owners and the pool of land is subsequently planned to implement the development plan and other transport and infrastructure facilities. The ownership of the plot remains with the original owner; a portion of the land is taken from all the pooled plots (30-40 per cent) and used for providing roads and other social infrastructure (Ballaney and Patel, 2008). Thus, the configuration of land use is dependent upon the macro-level DP, the CDP and the micro-level local area plan (town planning schemes).

The General Development Control Regulations (GDCR) of the city are specified to help the urban government to implement the development plan and the town planning schemes. GDCRs regulate the size and margins of individual buildings. The GDCRs set guidelines on parking requirement, setbacks, and how much a plot can be developed. The intensity of use of land is controlled by the Floor Space Index (FSI) guidelines, FSI being the ratio of the total built-up floor area to the area of land.

2.2.2 Transport planning in India

The working group on urban transport setup by the Planning Commission, Government of India, acknowledges that at present no organisation is responsible for urban transport planning in India and there is, in general, a lack of transport planning skills (Working Group on Urban Transport for 12th Five Year Plan, Government of India, 2012). In the development planning exercise also, transport is viewed as one of the infrastructure facilities alongside sewerage and water supply networks that need to be provided in the city. The transport aspect of the DP includes the future city-level network along with road widening proposals for existing roads and tentative proposals for development of new roads with suggestions of total road widths (Ballaney and Patel, 2008, Adhvaryu, 2009).

However, the history of urban transport planning in India dates back to the early 1960s when comprehensive traffic and transport planning exercises were carried out for Mumbai, Kolkata and Bengaluru. Traffic and transport studies conducted in Indian cities so far have utilized the standard/traditional transport planning process developed in the United States in the early 1950s and 1960s. However, these studies, and many studies that were conducted later on in other cities, are either one-off affairs or are conducted to study feasibility of a transport proposal like Metro Rail etc. As these surveys are done to serve the purpose of a particular capital project, they are often not representative of the traffic situation of the entire city (Pucher et al., 2007) nor do they reflect the relation between traffic flows and built form. As such, India does not have a national survey or even any systematic record of travel behaviour that covers the entire country or even a part of it.

Under the Jawaharlal Nehru National Urban Renewal Mission (JNNURM), like CDP, City Mobility Plans (CMPs) are used as a mechanism to finance transport infrastructure. The preparation of CMPs and the process of transport planning in India, in general, has an inherent limitation of conditional forecasting wherein a suitable transport plan is developed for a fixed land use, using the transport plan developed for the base year (CRRI, 1998). Therefore, the accuracy of these forecasts and consequently of the CMPs or transport plans is dependent upon the accuracy of the land use and transport plan developed for the base year. Thus, most of the transport studies are carried out independent of the urban development planning process and not as an iterative process. Therefore, they lack integration. Moreover, as stated earlier, the Development Plan itself might only represent about 50 per cent of the ground reality of the land use, which along with population, is used to compute the demand for urban transport using the conventional four-step urban transport model in most studies.

To reiterate, the way transport plans are prepared for capital projects, they are deficient in providing a complete picture of the overall transport problem in the city. Secondly, because transport planning is not institutionalized, every time a new study is initiated, the entire exercise is repeated and, therefore, in most cases lacks depth and the motivation to solve the overall transport problem in the city.

The discussed realities of urban and transport development in India have obvious implications on the built form in the cities, which are discussed in the next section.

2.2.3 Built form in Indian cities

As presented in Figure 2-1, the current built form in typical metropolitan Indian cities are a result of several reasons, most of which relate to the above-mentioned practice of urban planning in India. As a result, metropolitan cities in India are subject to wide intra-city spatial variation in built form characteristics. Most cities include a congested core area, characterized by narrow streets, commercial and trade activities and largely unregulated land-use mix. As these cities expand, it has been observed that mobility and accessibility levels have declined rapidly (Gakenheimer, 1999). In addition, because the development regulations are not inclusive and control is poor, informal activity development is rampant.

As the poor cannot afford to pay high rent/price for locations with better access to opportunities, they settle in the unplanned areas of the city. Consequently, slums and squatter settlements can be found within the city limits and beyond. Thus large variations, both in socio-demographic and physical (built form), can be observed (Tiwari, 2001). Rising household income, combined with population and economic growth, and other factors have resulted in rise in motor vehicle ownership, which has created conditions of transport demand that far exceed the capacity of the available infrastructure(Dimitriou, 2006a, Gakenheimer, 1999). Despite the economic growth and increased individual income of a select section of the population, there still exists increased marginalization of the urban poor who are also growing in number.

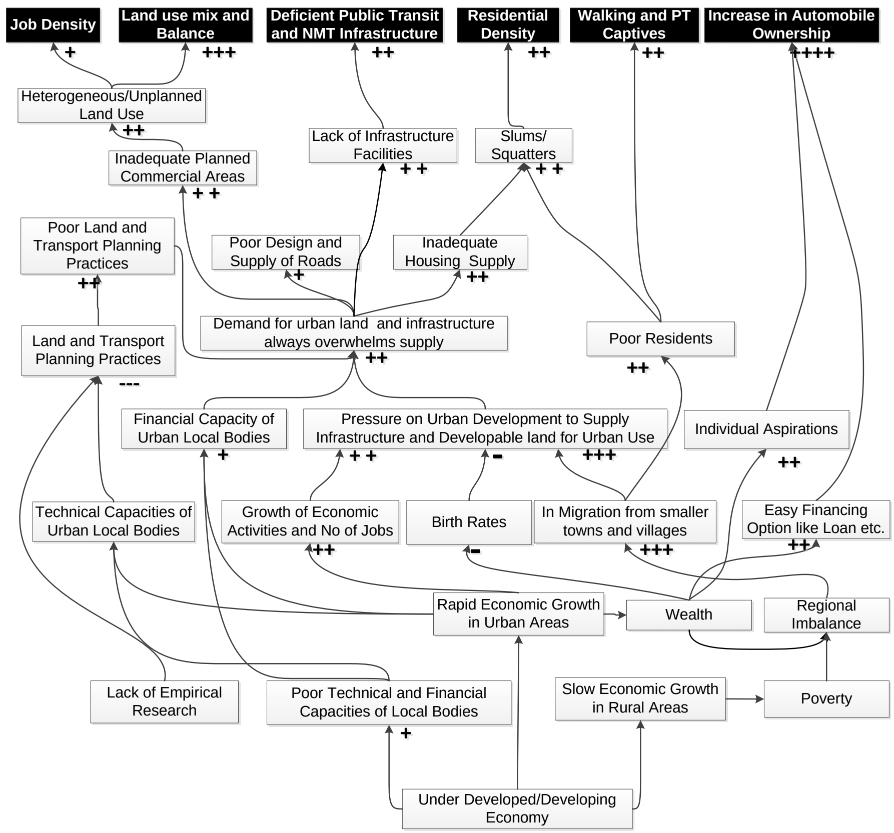


Figure 2-1: Urban Planning Problems in India

+ Denotes a positive relation, more + means higher positive relation, - Denotes negative relation.

As slums and squatter locations develop fast, growth in population is faster than urban expansion (Alan, 1992).Thus population and job densities are usually high, with an evident sprawl of jobs. An indirect benefit of poor land-use control is that land-use development tends to be organic, and so the land-use mix tends to be naturally high. Public transit provision is deficient, and thereby access to destinations (jobs) by transit is poor. Infrastructure for pedestrians and bicyclists is either absent or inadequate. Thus of the six Ds, density and diversity values are expected to be high, access to and by transit, and urban and street design are likely to be poor, with very few demand management initiatives. Given the constrained travel budgets of individuals, the influence of discomfort or externalities of transport (for example travel cost) are likely to be higher for a large section of the population. Thus, the land use and transport relation is expected to be stronger in this context (Gakenheimer, 1999).

While deciding on the built-form variables and the measures to operationalize these variables, the above-stated realities will need important consideration. To further the discussion on built form and transport relation, in the next section urban and transport developments in the case city of Ahmedabad are reviewed. Aspects related to growth of the city, land use and transport developments, and availability of data are discussed, which help in formulating and identifying the candidate list of built form indicators and transport indicators.

2.3 The case city of Ahmedabad

The history of Ahmedabad can be divided into three distinct periods, first, its establishment during the Sultanate rule and the pre-colonial period; second, the British rule; and third, the post-colonial period. The city was founded on the banks of river Sabarmati in 1411 A.D. in the State of Gujarat located in the western part of India. King Sultan Ahmed Shah of Muzaffarid dynasty established the city, and it got its name 'Ahmed' from the king's name and 'Abad', which means founded by, or populated. The king also invited merchants and traders to the newly founded city, and the city developed as a commercial, industrial and trading centre. In 1580, the grandson of Ahmed Shah fortified the city with an outer wall, 10 kilometres in circumference (Pandya, 2002).

As depicted in Figure 2-2, the initial growth and development of the city was on the principles of town planning in Islamic regions of central Asia (Pandya, 2002). The city establishment included social, religious and economic institutions. The early development in the city occurred around these institutions.

The primary elements, with respect to which the city grew, include the palace complex and the Friday mosque (*Jumma Masjid*) and the elements between them that constituted the central spine. This central spine was connected with radials, extending out of the city through its well laid out 12 gates. The second-order roads, including the radials, divided the city into '*Chaklas*'; and *Chaklas* were further divided into '*Pols*'. The urban character at this stage was a dense fabric resulting from a wall-to-wall construction of buildings each of which had an internal courtyard. A pol consisted of approximately 500 such houses (Pandya, 2002). The British East India Company took over the city in 1818. A municipal government was formed in 1858, and the rail link between Ahmedabad and Bombay (now Mumbai) was established in 1864. The railway station was located on the eastern periphery of the walled city. The new British textile machinery was supported by the mercantile class in the city, which resulted in a flourishing textile industry to an extent that Ahmedabad was called 'The Manchester of India'. The industrial activity developed near the railway station, towards the east. The advent of the municipal government and of educational institutions strengthened the institutional structure of the city. The colonial period also saw the expansion of the city beyond the fort walls.

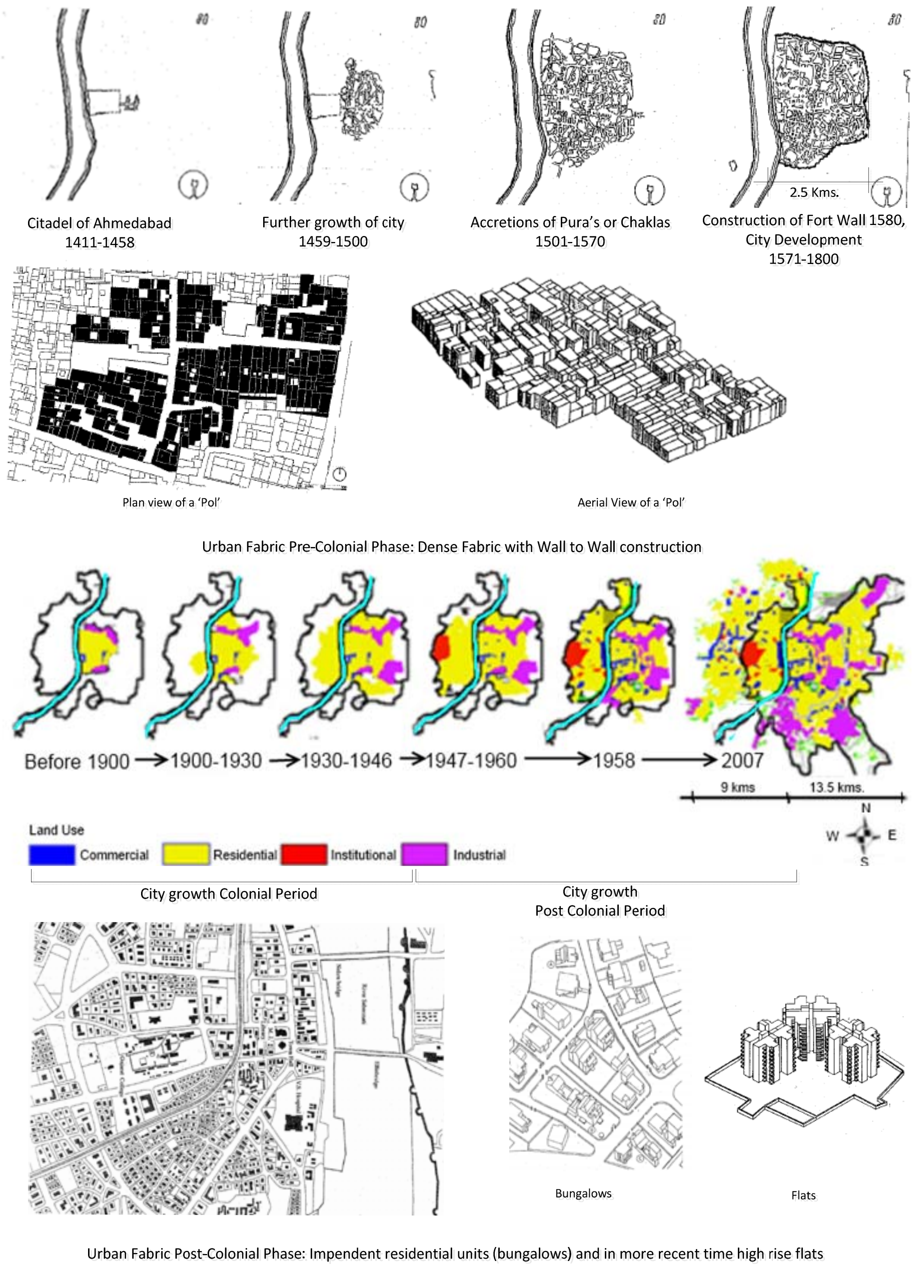


Figure 2-2: Ahmedabad: Urban Growth and Development

* Adapted from Pandya (2002), **

** The period 1570 – 1800 represents growth which was contained within the walled area. The wall around the development was constructed in 1580.

The development started spilling out towards areas northeast and southeast of the walled city. Construction of the bridge (Ellis Bridge) in 1875 facilitated residential development across the western side of the river Sabarmati. The colonial period also resulted in a total reversal of the urban fabric in the newly developed areas, with the introduction of British planning norms. The new fabric was now fragmented, as buildings (bungalows) were set in their individual compounds (Pandya, 2002). Thus, two distinct built-form fabrics emerged. In the post-British era, economic activities and business in Ahmedabad were still concentrated around the cotton textile industry, and Ahmedabad was the second largest producer of cotton textiles after Mumbai (Spodek, 2001). The textile base in Ahmedabad collapsed during the late 1980's, which led to decentralization of employment into small-scale factories. By 2001 almost all the spinning and weaving mills in Ahmedabad had closed down. Although the closing of textile mills had negative effects on employment in Ahmedabad, it also had some positive effects as a result of the diversification of the economic sector in the city (Spodek, 2001).

Today the city still maintains it status as one of the major trade, commerce and industrial centres in the country and in the state of Gujarat. It accounts for 19 per cent of the total urban workers in the state, and hosts several key textile, chemical, engineering and pharmaceutical industries. During the post-colonial period, urban development in the western part of the city gained momentum. Two new bridges were constructed across the river, one in 1962 and the second in 1973. These developments also coincided with the development of other major streets. Currently there are about 20 radials; 12 in the west and eight in the east, and a north-south radial running parallel to the river on it western side. As the need to connect these roads to facilitate cross mobility arose, a series of rings / orbitals were added to form ring roads.

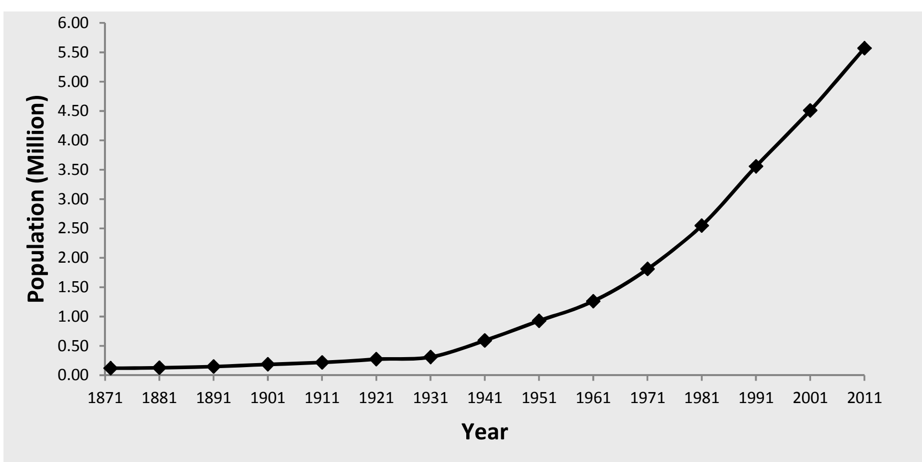


Figure 2-3: Ahmedabad Population Growth

Figure 2-3 shows that in 1881 the population was very small, around 110,000; it grew quite steadily until the pre-World War II period. The most rapid increase in population was observed after independence and post liberalization of the economy in the 1990s.The development of the city areas in the post-colonial period has been piecemeal and has lacked vision of balanced development of the metropolis (Pandya, 2002). Moreover, urban planning policies and methods have not been able to supply residences to all sections of the population; thus, a large section of the population in the city of Ahmedabad resides in slums and squatter settlements. The 2001 Census estimated the slum population of the city to be 4.39 lakhs, which was 13.46 per cent of the city's population; a survey done by Self Employed Women Association (SEWA) in Ahmedabad estimated the slum population of the city to be 25.77 per cent (Mahadevia et al., 2012). Therefore, the process of development and the archetypical problems are not different from those discussed in section 2.2. The built-form pattern is marked by lopsided and heterogeneous development. The population density ranges from 2293 persons/hectare at certain locations in the walled city area to densities of 150 to 370 persons/hectare in the western part of the city. Likewise, a wide variation in income groups can also be found; poor residents live near the industrial areas in the east, whereas the western part of the city is predominantly inhabited by high and middle-income groups. Because of poor implementation of the General Development Control Regulations, commercial land use can be observed across the city, but the distribution and supply and distribution of institutional land use including education, medical etc. is poor (Ilhamdaniah et al., 2005). Design wise, Town Planning Schemes have been able to achieve regular plot sizes and connectivity via roads, but proper road hierarchy and infrastructure for non-motorized transport is absent. There are two mass-transit modes in the city, Ahmedabad Municipal Transport Service with around 540 buses and routes oriented mostly to serve the central portions of the city; and a Bus Rapid Transit System, which now runs on the connecting radial.

The present mean trip lengths in Ahmedabad are low compared to the other metropolitan cities, namely, Bengaluru, Hyderabad and Pune (Pai, 2008). But the city is developing fast and is facing rapid rise in motorized vehicles. These are matters of concern from a low-carbon transport point of view. The modal shares of public transit and non-motorized modes have declined. The reason why mean trip length in Ahmedabad and in similar Indian cities are low, is because large sections of the population residing in the city are captive walking and bicycle-mode users. They reside close to their work place, mostly in illegal settlements (Tiwari, 2001, Mahadevia et al., 2012).

From a carbon footprint point of view, these changes in mode choice from public transit and non-motorized modes towards self-owned motorized vehicles (SOMV) are definitely not desired. Transport and urban planning in the city needs to ensure that the undesired mode shift is arrested and that future urban expansion does not result in increase in the distances that city residents have to travel. Moreover, with the stated estimates of growth in per-capita income in India, the aspirations of the poor population are also likely to rise, and it is likely that in a business-as-usual scenario, they will shift to privately(self) owned motorized vehicles as soon as they can afford them. The incentive for these captives to continue using their present modes of transport would include not only technological changes but also planning and policy initiatives, including policies related to planning of the built form.

2.4 Built-form measures for Ahmedabad city

As discussed in Chapter 1, six indicators are used to represent built form, these are, density, design, diversity, destination accessibility, distance to transit stop (transit access) and demand management. In the case of Ahmedabad, management of on-street parking is practically non-existent and off-street parking is very poor (Barter, 2010). Other travel demand management measures like congestion pricing etc. are also absent in the city. Therefore, travel demand related measures will not be relevant for this study and are, therefore, not considered. However, it is believed that locations with high concentration of poor people could influence mode choice, thus 'Disparity', representing density of poor people, is considered as one of the indicators. Accordingly, six indicators, namely, density, diversity, design, distance to transit stop, destination access and disparity are considered relevant for this study. The measures that can be used to represent each of these indicators are mentioned below.

Density of development in Ahmedabad is expected to be high. Density of households, population and jobs are commonly used to represent the density indicators (see Table 1-3). These densities can be computed as gross densities (units/area) or net densities, for example, net residential density of a census ward is computed as total residents in the census ward/total residential area in the census ward. Considering the morphological diversity in the city as discussed earlier, for both residential and job densities, net density values are considered as appropriate measures to present the density variable.

In Ahmedabad, because of its developmental history, the land use is expected to be heterogeneous and mixed. For land-use diversity (mix), quantification based on majority use(given the heterogeneous land use) will not represent the ground reality, as a residential building can have retail shopping on the ground floor, which will not be represented if the vertical mix is not considered. Therefore, the built-form measure representing land-use balance (Entropy Index) needs to consider all land uses in the vertical space. Similarly, land-use mix measure (diversity index) should also be computed using the vertical space. Job - housing ratio is a measure similar to the entropy index, but it only considers the number of job opportunities available in the grid cell and households located within it. The measure represents the balance of jobs and households in the grid cell, and is considered alongside land-use balance and mixed built-form measures as relevant for Ahmedabad.

Access to destination is an important determinant of mode choice and travel distance. The three most commonly used indicators are job accessibility by auto (car), job accessibility by transit, and distance to the central business district (CBD). Access to jobs by car (or self-owned motorized vehicle) will represent overall efficiency of land use and the transport network, and likewise, access to job by transit will represent efficiency of land use with respect to the transit system, and are thus considered in this study.

For the design indicator, intersection density is the most commonly used measure. Intersection density can influence travel behaviour. It is also important to distinguish streets that are safe from the ones that are not, and study the influence of these streets on mode choice. In addition to intersection density, density of roads and local and regional connectivity of roads are important considerations. In other studies, availability and design of parking spaces and sidewalk have been used as a measure, but this might not have relevance in Ahmedabad's context. This is because even if sidewalks are theoretically present, these are not used because of private use of public land and poor design of sidewalks. So measures that represent density of intersection, density of road space, road safety, and local and regional connectivity of roads are considered appropriate design measures for Ahmedabad. Likewise, for distance to transit stop, density of public transport stops, density of transit routes and distance to the nearest bus-stop are considered relevant.

After Cervero and Kang-Li (1998), Brotchie (1984), Brotchie et al. (1996), Ma and Banister (2007), it is known that polycentric development can also influence mode choice and travel distance. Consequently, city centre and sub-centres are also considered important as urban form variables in the context of Ahmedabad city.

The quantification of these indicators and their quantities and spatial pattern is discussed in the subsequent chapter.

2.5 Discussion

The objective of this chapter is to give a background to the urban and transport planning practices in India. This chapter also describes the case city of Ahmedabad and looks at available data sources to identify the built-form measures relevant in the context. Opportunity presented by geo-information technology to quantify built-form indicators from the available data is also considered.

It is found that cities in India are growing rapidly resulting in sprawling cities with very little land use and transport integration at the stage of Development/Master Planning or even by other planning mechanisms. It is also observed that the cities that have grown more rapidly in the past two decades are cities in the second tier after the mega-cities. These cities pose the highest challenge of managing urban development, but also provide opportunities for meaningful interventions. One of the main drivers of urbanization and urban growth in India is in-migration from rural areas, mainly to escape poverty. This fact makes Indian cities atypically different from cities in the Western countries. Because of the pre-colonial, colonial and post-colonial history of urban development, cities in India also have a diverse morphology.

Conventionally, six indicators are used to represent built form in empirical literature: density, diversity, design, destination accessibility, distance to transit stop (transit access) and demand management. As there are no demand management related policies in India, travel demand management related measures will not be relevant for this study and are, therefore, not considered. However, it is believed that location with high concentration of poor people could influence mode choice, thus a 'Disparity' indicator representing density of poor people is considered as one of the indicators. Accordingly, six indicators, namely, density, diversity, design, distance to transit stop, destination access and disparity are considered relevant for this study. In addition to these six Ds, employment sub-centres that define macro-level built form can also influence travel pattern, therefore are considered as an additional indicator representing the destination end of the trip.

The planning and management of Indian cities has been poor, cities suffer as the response to substantial demand is an arbitrary decision-making process, development control is poor and there is no integration of transport planning process with the urban Development Plan or the Master Plan. Thus, Indian cities are likely to have built form that is dense, with mixed, heterogeneous but poorly distributed land use and a poor transport infrastructure. This has an obvious influence on the choice of indicators and measures used to operationalize these indictors.

The next chapter first discusses how the available datasets have been used to quantify built form, and then discusses the pattern of urban form in Ahmedabad.

3 Built-form measures: Ahmedabad city

3.1 Introduction

As discussed in chapters 1 and 2, in this research, following the work done by Ewing and Cervero (2010), Stead and Marshall (2001) and others, the first broad list of built-form measures includes the 'five Ds' Density, Diversity, Design, Destination accessibility and Distance to transit. In addition to these five, given the ground realities in India and following Estupiñán and Rodríguez (2008), a socio-demographic variable termed as Disparity (density of poor people in the neighbourhood) is used as a measure. As discussed in the previous chapter city centre and sub-centres are also used as macro level built form variables in this study. Two core research questions are answered in this chapter, first, what data and methods can be used to operationalize built-form variables? Second, what are the patterns of the quantified built-form measures?

This chapter is further divided into three main sections. The first section gives the contextual definitions of the built-form measures used in this research. This is followed by a description of the pattern of these variables, and in the last section, employment sub-centres are identified and their characteristics described.

3.2 Built-form measure quantification

3.2.1 Travel and built-form data

For this study, data on modes used for travel and on travel distance for work and non-work purpose travel is not available from any of the earlier transport studies. Therefore, it was decided to conduct a household survey. Travel behaviour is quantified as vehicle kilometres travelled by each individual per day for work and non-work purposes. Thus, the following variables are used to quantify different aspects of travel behaviour:

(1) Home-based daily Vehicle Kilometres Travelled (VKT) per person for work purpose travel;
(2) Home-based daily VKT per person for non-work travel;
(3) Public transport use for work purpose travel (trips made by public transit, Intermittent Public Transport (IPT) and shared IPT modes);
(4) Public transport use for non-work travel;
(5) Non-motorized mode use for work purpose travel (walking and bicycle);
(6) Non-motorized mode use for non-work purpose travel;
(7) Self-Owned Motorized Vehicle (SOMV--cars and two-wheel motor vehicles) use for work purpose travel, and
(8) SOMV use for non-work purpose travel

The total travel distance includes the return home trips. If multiple modes like walking and public transit are used for a single purpose, then both modes are considered as modes used for the purpose and distances are computed accordingly.

This data is spatially represented using points that are geo-referenced to the residential location of the surveyed household. After cleaning the dataset, 4,950 valid household samples are available that have travel behaviour information of 16,124 individuals (only individuals older than 16 years were considered for analysis) and 29,880 trips. Surveys were conducted over weekends so that the head or the main person in the household was available for the survey. The travel information was recorded in a tabulated format and spatially on the map of Ahmedabad city. For each trip, travel duration, and start and end addresses were recorded in the survey form as well as on the map.

The household survey was conducted during the period from December 2007 to February 2008. In Figure 3-1, residential locations of the household survey respondents are shown. Care was taken to distribute the sample according to the population density, so the inner core area has more samples in comparison to the outer areas.

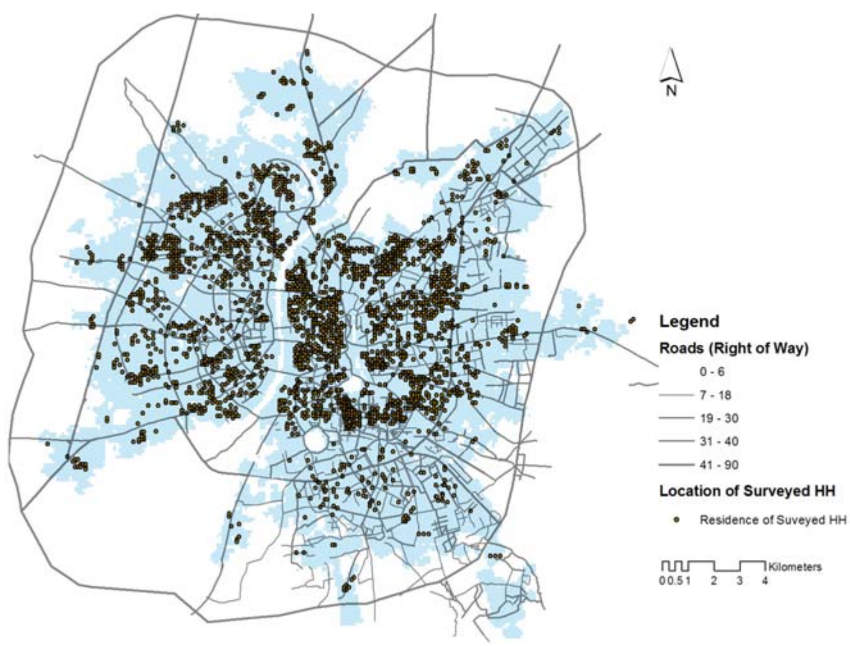


Figure 3-1: Household Survey Locations

Data regarding built form is available for Ahmedabad in four spatial units. Figure 3-2 displays spatial units of Traffic Analysis Zone (TAZ), census wards, census enumeration blocks and property tax enumeration blocks. The TAZ provides a good opportunity to relate built form with travel behaviour. Even though limited travel data is available from the previous transport studies, there is a possibility of using household survey data collected for this research after aggregating these to TAZ. However, because the spatial unit to which the data is aggregated is too large (from 0.2 sq. km. in the inner core areas to more than 10 sq. km. in the peripheral locations) to represent neighbourhood-level built form variations that are important to understand choices made for walking and bicycle (bike) trips. Therefore, it was decided that this dataset can be used in support of other data.

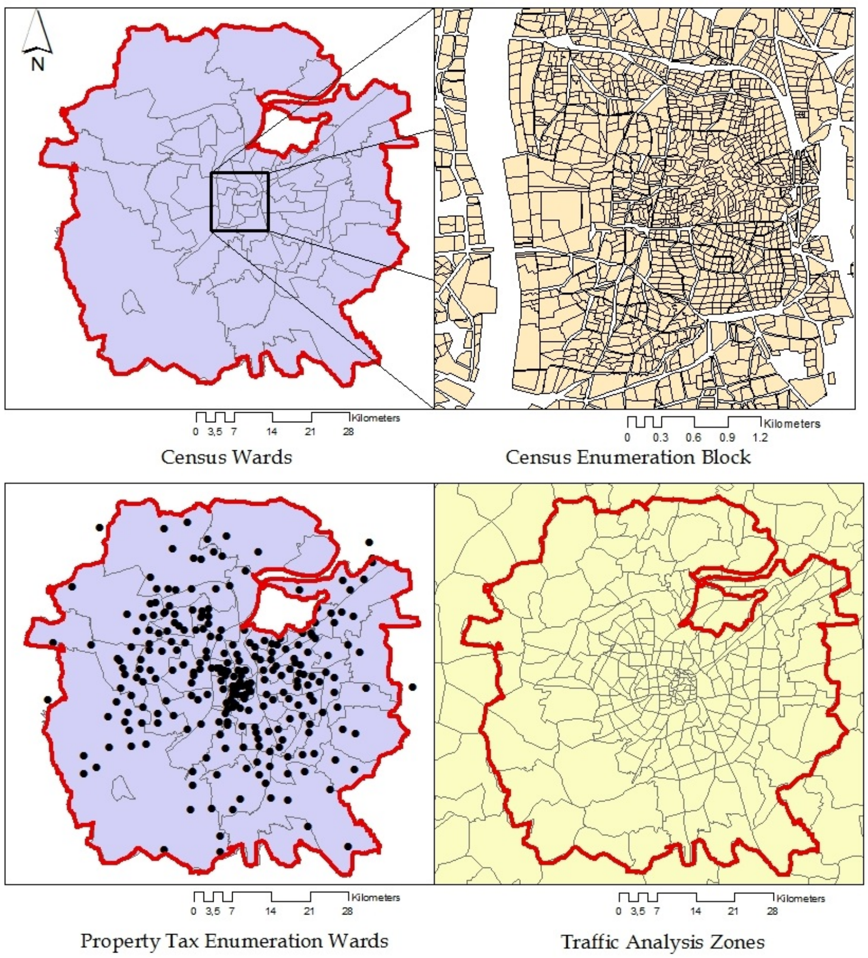


Figure 3-2: Spatial Aggregation Units/Source of Data

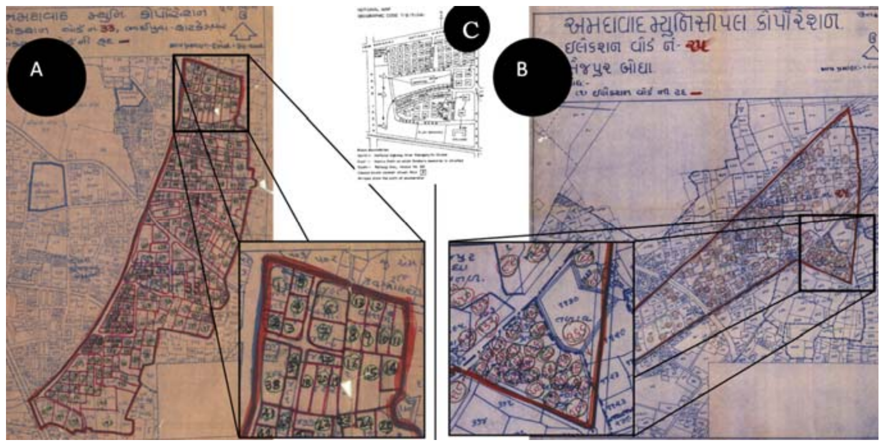


Figure 3-3 Enumeration Block Maps
* A = Enumeration block with boundaries marked, B= Enumeration block marked only as numbers, C = Enumeration block notional map

Enumeration Block (EB) data (Figure 3-3) contains data on building use, population and availability of amenities at the scale of 100-150 households, or around 0.01 to 1 sq. km. area. Considering that the mean trip length for walking mode is 1.3 kilometres in Ahmedabad, and mean household density is 58 households/hectare (580 household/km2), the spatial scale at which EB data is available is considered appropriate to represent neighbourhood characteristics. However, these are notional maps prepared by individuals drawn from various professions for the purpose of enumeration (e.g., municipal school-teachers), who may have no background or understanding of cartography. These maps thus suffer from problems of scale accuracies and lead to problems related to interoperability of data. Images A and B in Figure 3-3 are maps showing spatial representation of these units, image A has proper boundaries demarcating the EB whereas in image B, each EB location is marked as a point location. For Ahmedabad most Census wards had properly marked EB boundaries; out of 53 Census ward maps, only 15 maps did not have proper boundary representation, of which 10 were not part of Ahmedabad Municipal Corporation (AMC) during the 2001 Census. It was possible to demarcate these after overlaying the points shown in map B of Figure 3-3 on the land use and road network map. This was done with the help of staff from the drawing section in the AMC who had been involved in preparing the original maps. The second issue is that this dataset is for the 2001 Census, so it had to be extrapolated for the year 2007.

The third set of data that was available for this study was property tax enumeration data (Figure 3-4). This is an extensive dataset and contains recent data on use and age of different non-residential properties in the city. There are 262 property tax enumeration blocks in the city, so as in TAZ, the spatial aggregation is high; hence it offers limitations when used directly. However, this is the only dataset on location of activities at a disaggregated scale and offered the opportunity of being used in combination with other datasets like land use at a further disaggregate level, as described later in this chapter.

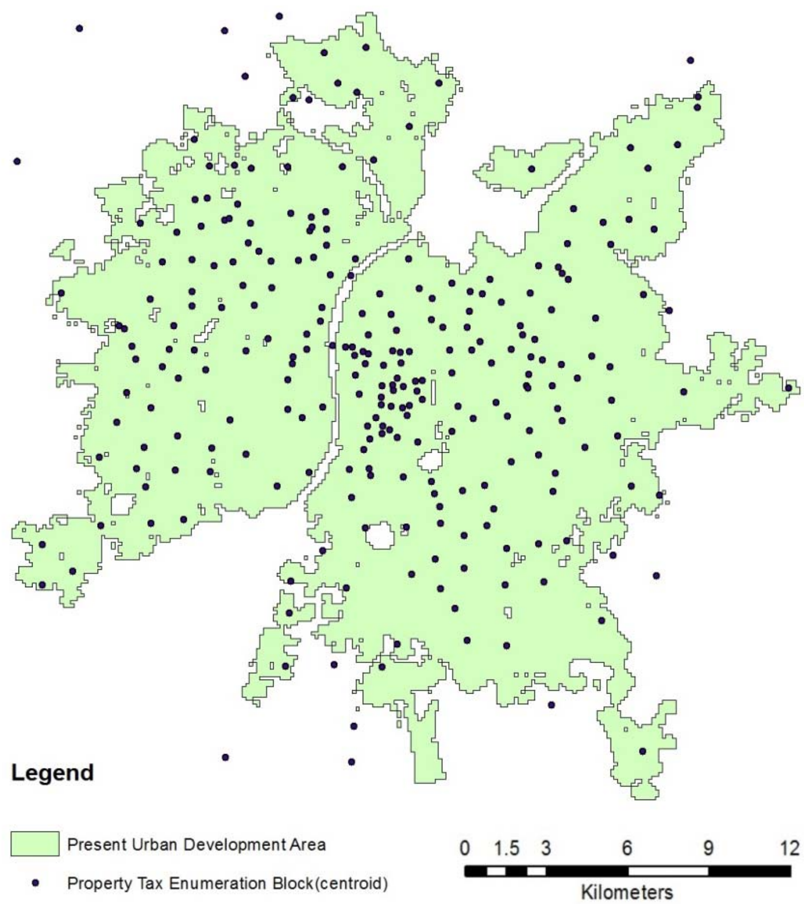


Figure 3-4: Property Tax Enumeration Blocks (Property Tax Zones)

Data acquired by remote sensing satellites has also been used. Indian Remote Sensing Satellite products, namely, a stereo Cartosat - 1 image having 2.5 metre (m.) resolution in panchromatic band, and a LISS-4 image having 5.6 m. multispectral resolution, were acquired from the National Remote Sensing Agency in India (these images were acquired in November 2007). The Cartosat data is used to derive a Digital Elevation Model of the city to compute height information for the built-up space. The multispectral image is used for the purpose of identifying urban features. Time series Landsat TM and Landsat ETM data were acquired in October 1990 and November2000 respectively from the free archives of the

Landsat satellite. Data from Landsat satellite was used to compute urban growth, which in turn was used to project population for the year 2008.

The most common source for land use data in India is the Development Plan or Master Plan map. However, concerns about poor development control in India are well established (Pucher et al., 2005, Dimitriou, 2006b, Alan, 1992), and these apply to Ahmedabad as well. Therefore, it will not be practical to use the same to quantify land use related built-form measures. The maps prepared by Anada (2007) offer a better representation of land use, which is used to prepare the land use map is presented in Figure 3-5. This data has a high accuracy level as it was based on data for each sub-plot in the city and therefore can be used further in quantifying land use related built-form variables.

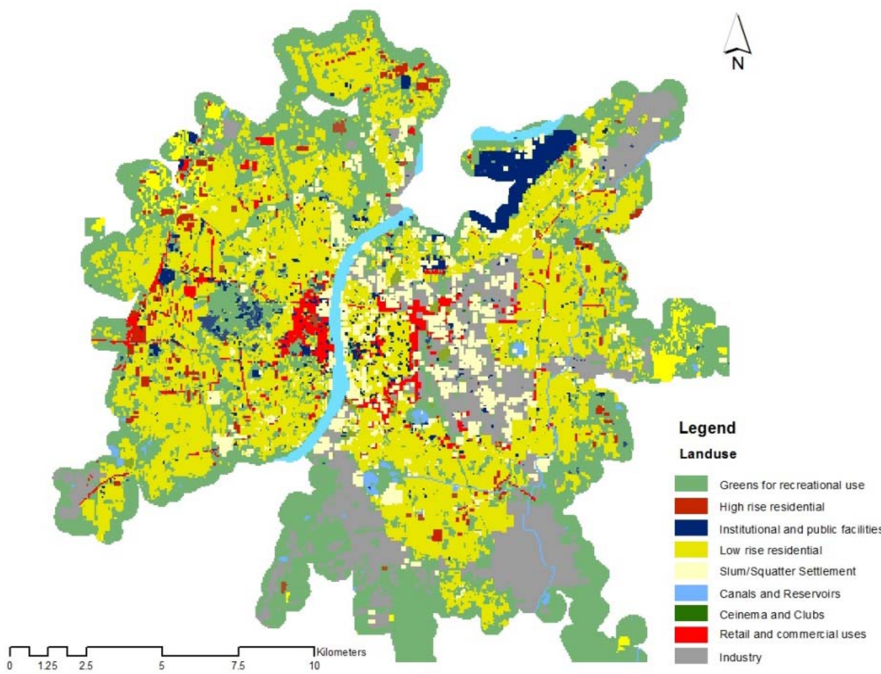


Figure 3-5: Land Use Map

*Based on (Anada, 2007), Colour coding as per http://www.gsd.harvard.edu/gis/manual/style/ColorConventions.pdf accessed on 17th October 2011

Thus, data to quantify built form has been derived from several sources, with different spatial and temporal resolutions. To operationalize built form measures from these sets of data, it was required that all the datasets have the same spatial and temporal resolution.

3.2.2 Data preparation

Barber (1988) identifies four key problems relevant to spatial data analysis: Boundary Problem, Scale Problem, Pattern Problem (also known as Spatial Autocorrelation) and Modifiable Aerial Unit Problem (MAUP). The concept of 'Ecological Fallacy' (Blalock, 1964) underlines that there are many possible grouping and regrouping strategies for a set of individually measured data. The correlations between variables increase as the level of aggregation increases and it is observed that values cluster towards the mean. The observed relationships in aggregated data do not necessarily apply at the individual level, which essentially means that correlations at the group level are not necessarily applied evenly at the individual level. This fallacy is closely linked to these aerial unit problems. In order to revisit the concept of 'Ecological Fallacy' for representing land use or built form so that it can be studied in relation to travel behaviour, a few important considerations have to be made. In line with the above discussion, it was found that the use of a regular grid representation in GIS facilitates spatial analysis. Moreover, it also facilitates a number of remote sensing applications that have shown the potential to map land use and other urban phenomena (Barnsley et al., 1993, Jensen and Cowen, 1999). The main advantages of data organization in GIS are the ease of data capture or data entry, data manipulation and visualization. Another important advantage is the possibility to co-process data stored in different data models (Wegener, 2001). With procedures of aggregation and disaggregation, it can associate data corresponding to different geographical scales in the same model (Wegener, 2001). Since the model developed here also attempts to handle several hierarchies of scales, raster-type grid model is considered as an appropriate representation as demonstrated in Figure 3-6.

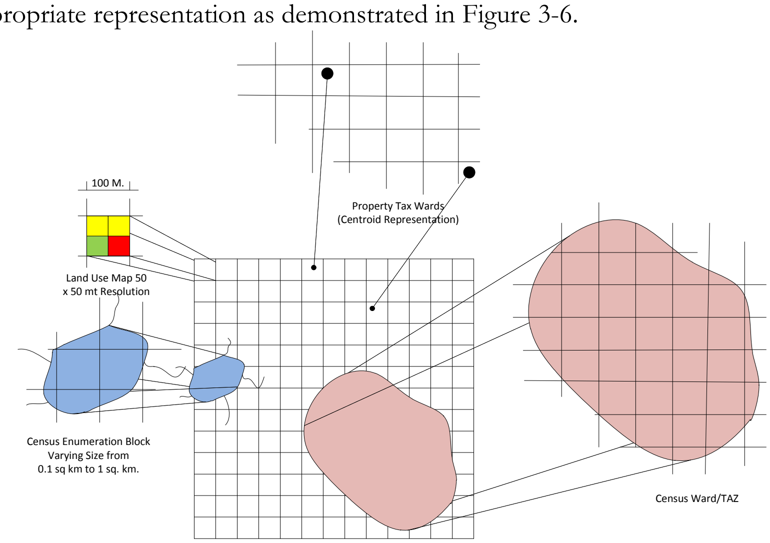


Figure 3-6: Grid Representation and Aerial Unit Problem

Converting data from different sources to uniform grid can lead to MAUP-related inaccuracies resulting from aggregation and disaggregation of data. Thus, unless disaggregation is based on weights derived from ground reality, it will not improve the quality of data. Therefore, the potential of using geo-spatial technologies is looked at from two points of view, first, for data disaggregation, and second, for improving the information base from remote sensing sources, where information is not available from conventional sources.

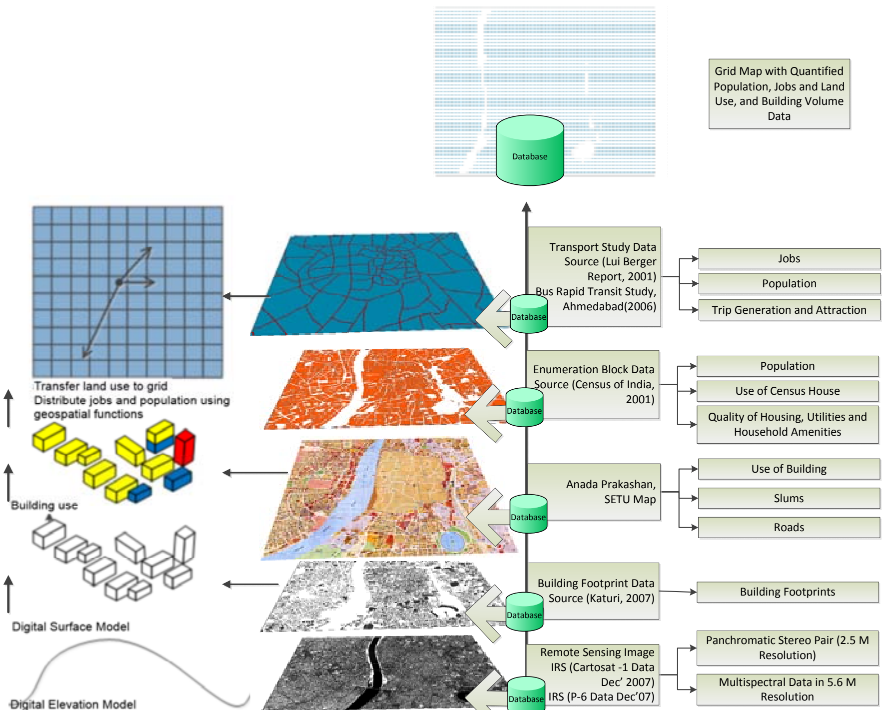


Figure 3-7: Remote Sensing and GIS Data Fusion

The data availability situation for the city of Ahmedabad required the combining of data provided by the different sources, GIS and remote sensing, sensibly and consistently to improve the quality and classification of the data. The data fusion in the context of Ahmedabad can be between GIS data with GIS data of multiple scales, and remote sensing inputs into GIS. The most optimum way to integrate remote sensing with GIS data is to convert interpreted remote sensing data into a layer like any other GIS data file, as observed by Gamba and Dell'Acqua (2007). Based on such integration, as presented in Figure 3-7, different objects for the available data were integrated to generate a dataset with a resolution of 100 m. x 100 m. grid cell. So remote sensing data has been used to create a Digital Elevation

Model (DEM). DEM extraction technique is used to convert DEM from raster to vector representation. Thus, all data was converted to vector representation.

Tomlin (1991) identified four basic functions in map algebra as local function, focal function, zonal function and incremental function, which were mainly relevant for raster operation but are also relevant in the present context for disaggregating data from higher aggregation level to lower aggregation level, using intelligence derived from remote sensing (elevation) and other datasets (land use). As mentioned in Ehlers (2007), Albrecht (1996) approach went a step further and classified GIS functions into six categories. These have been listed in Table 3-1. The more relevant operators in the case of Ahmedabad, given its data situation, would be location analysis, mainly buffer and overlay, the distribution and the spatial analysis functions.

Table 3-1: Universal high-level GIS operators (Source: (Albrecht, 1996, Ehlers, 2007)

	Function Group						
	Search	Location Analysis	Terrain Analysis	Distribution	Neigh'hood	Spatial Analysis	Measurement
(Sub) Functions	Thematic search	Buffer	Slope/ Aspect	Cost/ Diffusion/	Spread	Pattern/ Dispersion	Distance
	Spatial search	Corridor	Catchment/ Basin	Proximity		Centrality/ Connectivity	Area
	Interpolation	Overlay	Drainage/ Network	Nearest neighbour		Shape	
	(Re)classification	Thiessen/ Voronoi	Viewshed analysis			Multivariate analysis	

3.2.3 Methods

Presented in Table 3-1 are the built-form measures chosen and the base data that has been used to derive them. The data required to compute net residential density is a combination of data on residential population and the area under residential use. For net job densities, data on the number of jobs is required along with the area under economic activities. To compute land-use diversity, floor area per land use is required. Data on road network, transit network, and accidents is required for design measures, whereas road network and job location data is needed for calculating access to destination. Finally, for the disparity measure, the location of poor people is required. In Table 3-1, universal high-level GIS operators are shown; some of these operators have been used to populate the grid cells with the identified built-form indicators from the available data formats. In the following section, quantification of these indicators is discussed starting with quantification of population, followed by jobs, land use and network-based indicators.

Table 3-2: Built-form measures and base data used

Indicator	Variables	Base data use
Density	Net Population Density	Population from Census enumeration block data (2001); Land use data from (Kharche et al., 2009, Anada, 2007) (Data A); Digital Surface Model (DSM) from (Bock, 2008) using Indian Remote Sensing Satellite Cartosat -1 (2007) data (Data B); Change in built-up area using Landsat images (October 1990, November 2000) and Indian Remote Sensing Satellite LISS-4 data.
	Net Job Density	Job projections for year 2011(Gujarat Infrastructure Development Board (GIDB) , 2001); Data A; Data B.
Diversity	Job Housing Balance	Data A; Data B.; Floor space per activity from property tax enumeration data (2009). To compute Entropy Index five land uses are considered, that is, Residential, Commercial, Industrial, Recreational, Institutional
	Floor Space Dissimilarity Index (land use mix)	
	Floor Space Entropy Index (land use balance)	
Design	Road/Road Junction Kernel Density	Street network
	Public Transport Stops Kernel Density	Bus-stop location from (Munshi, 2003) updated with AMTS office for 2008.
	Space Syntax Parameters	Street network axial lines
Destination	Access to job by self-owned motorized vehicle	Street network; Jobs
	Access to job by transit network	Transit network from AMTS office 2008;
Distance from transit stop	Distance from transit stop	Bus stop location from (Munshi, 2003) updated with AMTS office for 2008; Street network
Poly Centric Development	Trip destination location	City centre and sub-centre locations
Disparity	Below poverty line population	Enumeration block data

Population

The year 2007 is considered as the base year for all computations in this research. Population data is available from Census data for the year 2001.Therefore, it has to be projected for the year 2007. This extrapolation of population is done by identifying locations that have developed during the period from 2000 to 2007, and during the period from 1991 to 2001, separately. To identify developed or built up area, Landsat TM images for October 1990, November 2000 and an IRS –P6 image for November 2007 were available, which, more or less, correspond to the census of 1991, 2001 and the projection year 2007 respectively. The built-up area for the corresponding years (presented in Figure 3-8) is estimated by computing the Normalized Difference Vegetation Index (NDVI). To compute the NDVI, red and infrared bands of the remote sensing image are indexed to identify the green/non-built-up areas and built-up areas in the city for the three years. For time series, 1991-2001 and 2001-2007 locations, which existed in 1991 and 2001, and areas that were newly-built locations during 1991 – 2001 and 2001 - 2007 are identified. When allocating population, the city is divided into three locations: the walled city area, the western part of the city (locations west of the river Sabarmati) and the eastern part of the city (locations east of the river Sabarmati). The maximum density value allowed (cut-off value) in each grid cell is computed. This value is the highest density value within these three locations respectively (slums and squatter settlements are not considered in computing the maximum density at these locations).

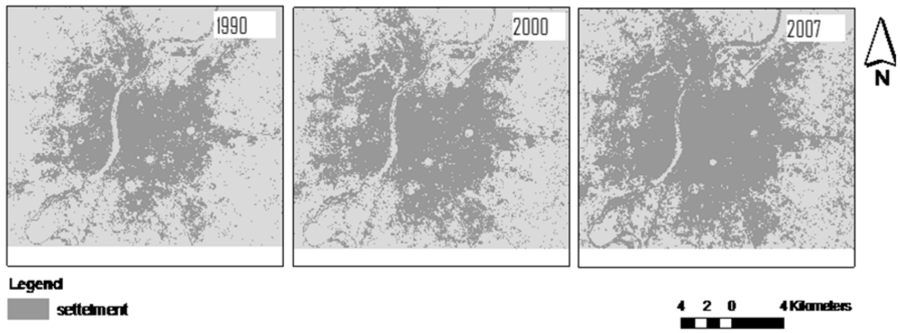


Figure 3-8: Urban Growth of Ahmedabad City (years 1990, 2000 and 2007)

For development that existed in 2001, first location are identified where the density of population is still below mean population density value for all developed grid cells, the 2007 population was computed using population growth rate between 1991 to 2001, with the mean density of developed areas as a cut off value. For locations that developed after 2001 the average function (population/land area) is used; therefore, the population is distributed based on quantity of new development and proportion of development in the grid cell under consideration.

Jobs

The input data for constructing the employment density grid includes data on building use and floor area of business establishments (from the property tax department) and data on jobs from two sources, namely, total numbers of jobs per traffic analysis zone from the Intermittent Public Transport Study (GIDB, 2001), and job classification data for the entire urban agglomeration area from the Census data. Data on land use and built-up volumes have been compiled from other studies in combination with data from Census sources. Figure 3-9 gives a plot of property tax ward locations and shows a Digital Elevation Model prepared using CartoSAT- 1 data of a portion of the city. It is clear that the central locations have relatively closely packed property tax wards, and as we move towards the peripheral areas, the size of property tax wards increases.

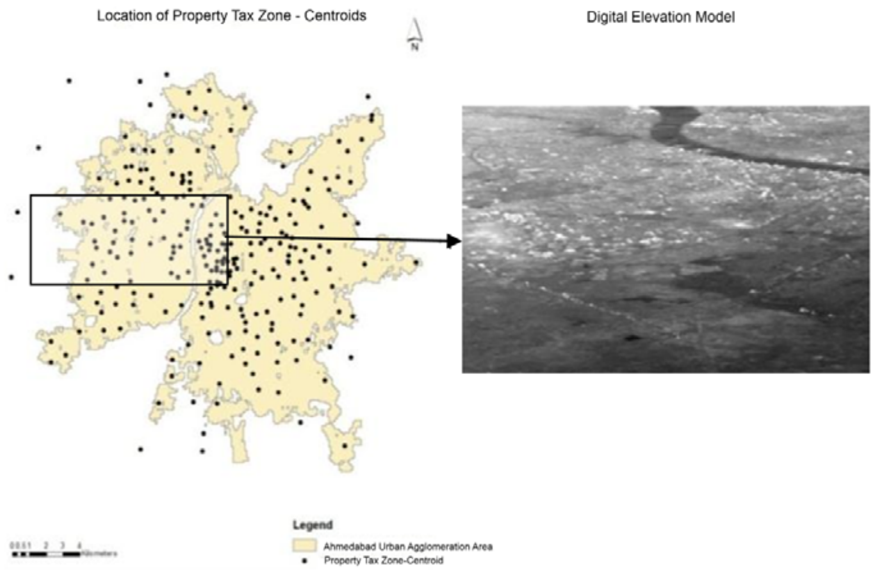
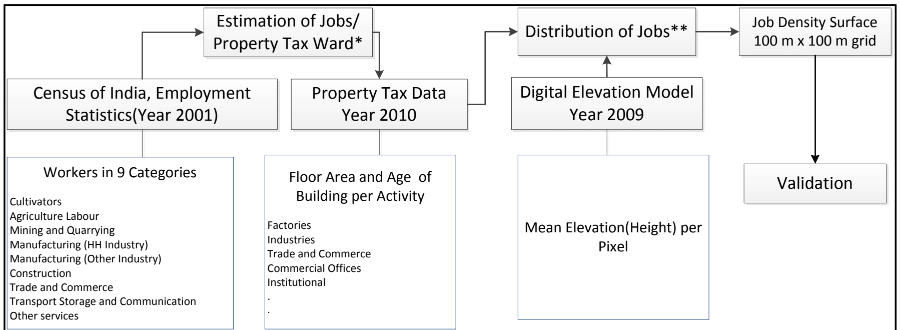


Figure 3-9: Ahmedabad: Property Tax Zone Centroids and Digital Elevation Data

These datasets are first analysed for missing, erroneous or inconsistent values. Two-hundred-and-sixty-two property wards fall within the urban agglomeration area. Enumerators at the property tax department within the municipal corporation collect this data, so the data for each non-residential building is available. The data is spatially aggregated to the tax ward. In order to capture building-volume data, a Digital Elevation Model (DEM) was prepared using Indian Remote Sensing Satellite CartoSAT – I images with a spatial resolution of 2.56 metres.

After removing outliers and unrealistic values, a standard error of around 3.5 metres was found when DEM values were compared to the actual observed building height values. The number of jobs (data for 2001 and projections for 2011) from the Gujarat Infrastructure Development Board (GIDB (2001) study, which were computed in that study by conducting a sample survey, and later on expanding the sample to the entire Ahmedabad region. The data is a little dated, but it is the only dataset that enumerates jobs at a disaggregated scale. The job projections in the GIDB were found to accurately reflect the growth in the number of jobs in the city. Data from Census offices provides classifications of total jobs in nine categories that include jobs in manufacturing, construction, trade and commerce, transport and communication, and other services. Jobs for each activity in the tax zone were estimated based on the proportion of floor area in that tax zone for that activity with respect to the total floor area in the entire urban agglomeration for that activity for the year 2007. The sum of jobs in all activities in a property tax ward then gives the total number of jobs in the ward.



* $j_{ia} = (f_{ia} / F_i) \times J_a$
Where j = jobs in activity *a* in municipalpal tax zone *i*,
f = floor area under activity a in tax zone i, F = floor area under use in the tax zone i for entire agglomeration area, and
J = total jobs in Ahmedabad employed in activity a

**Eij = AiPiGjf(cij)
Where Eij = Jobs in each grid cell
Ai = Balancing factor for Jobs in Property tax zones
Pi = Total jobs in each property tax zone
Gj = (Total jobs in Ahmedabad/Total built Volume non – residential use in Ahmedabad) x (Total built up non – residential volume in grid cell j)

Figure 3-10: Distribution of Employment (Jobs) Data

Data on building volumes is aggregated for each grid cell and fused with data on land use for that grid cell to arrive at building volume per grid cell under non-residential use. The total number of jobs in each property tax zone is redistributed over all the grid cells in the study area. This is done using a singly constrained gravity function, with non-residential building volumes per grid cell as attractor and using the distance from the centre of the grid to the centroid of the property tax zone. The average value of the distance decay function is set equal to the median value of distance (565 meters) between centroids of neighbouring tax wards. The process ensures a smooth density surface of job distribution and simultaneously a logical distribution of jobs using building heights, land use and distance as weights. This way of creating a density surface of jobs differs from earlier parametric and non-parametric approaches, as building volume data is considered as a weight in addition to distance between the location and property tax zone centroids. This method is considered appropriate, especially in the context of India, as the only available data exists at larger spatial units as compared to the Anglo-American context, and additional data acquisition of building volume data acquired from remote sensing ensures a more appropriate spatial distribution of jobs.

Land use and floor space data

Data on floor area used per use (activity) is required to compute both indexes representing land use diversity. Data on land use is available from the land use map in Figure 3-5. Floor area for each land use is obtained from property tax enumeration data. Floor area per activity is distributed using a singly constraint gravity function as shown in Figure 3-10, but a few additional rules are applied.

These rules are based on observations in the validation sample set shown in Figure 3-12 (on page 55). These rules are:

- Institutional, Industrial and Recreational uses
- Allocated according to the land uses in the Figure 3-5
- Commercial land use
- Will not have residential use; within commercial uses retail will only be located on the ground floor and the first floor of multi-storied buildings; corner buildings are more likely to have commercial land uses as compared to buildings in the middle of the road.
- Residential land use
- Can be mixed; Retail and commercial land use will be located near major roads, with a right of way higher than 12 mts; Retail use will only be located on the ground floor of buildings with multiple stories.

First-floor space of industrial, institutional and recreational land use is distributed to their individual uses. This is followed by distribution of retail floor space, it is found that 22 percentage of retail and 9 percentage of commercial use is mixed with residential use. The level of mixing also differs in the five clusters shown in Figure 3-12. In the core city areas, 65 percentage of retail use is mixed whereas in the outer areas only 7 percentage of retail is mixed with residential use. Twenty-three percentage of commercial use in the core area and 3 percentage in the outer areas are mixed with residential use. For each of these areas these proportions of land use are set aside while the rest is allocated to locations with commercial and retail land use in Figure 3-5. As most retail and commercial land use is mixed with residential use, the remaining allocation of retail and commercial land use is then allocated to the locations marked under residential purpose using the above-mentioned rules.

Individuals below poverty line

The indicators developed in the Swarna Jayanti Shahari Rozgar Yojana (SJSRY) are used to identify those Below Poverty Line (BPL) (those who are priority households), and these indicators are based on certain non-economic parameters. Seven non-economic parameters have been identified for this purpose as mentioned earlier. Each parameter consists of six attributes indicating the condition from 'worst to better'. Accordingly, a 'Weightage Score' has been assigned to each attribute, that is, from 100 (worst condition) to 0 (better condition). In other words, a beneficiary who has been assigned the highest 'weighted score' among the urban poor is given top priority under the program. Table 3-3indicates different categories, from top priority to lowest priority as per 'Weightage Score' to be assigned to a household or future beneficiary.

Table 3-3 Eligibility of a Household for BPL under the SJSRY

Parameter	Weightage Score for Each Attribute					
	100	80	60	40	20	0
	(A)	(B)	(C)	(D)	(E)	(F)
(a) Living Condition						
(i) Roof	Thatch	Tarpaulin	Asbestos	Wooden	Tiles	Cement
(ii) Floor	Earthen	Bajri	Bricks	Cement	Chips	Stone
(iii) Water	No water supply for 500 yards	Community Handpump	Community Tubewell	Private Handpump	Private Tubewell	Private Piped water supply
(iv) Sanitation	Open Defecation	CommunityDry Latrine	Community Pour Flush Latrine	Private Dry Latrine	Private Pour Flush	PrivateFlush Latrine
(b)Educational Level	Illiterate	Primary Pass	Middle Pass	Matric Pass	10+2 Pass	Graduate Pass
(c) Type of Employment	Unskilled Casual Labourer/ Unemployed	Semi-Skilled	Self-Employed . Street/ Push Cart	Own Work Place	Own work Place & Selling Place	Organized Sector with Social Security
(d) Status of Children in the household	Working children & not attending school(WCNS) / NFE/ Literacy classes	Working children but attending school(WCS)/ NFE/ Literacy classes sometimes	WCS/ NFE/ attending Literacy classes regularly	Children Not working as well as not attending any classes	Children not working and attending school/ NFE/ Literacy Classes sometimes	Children not working and attending school/ NFE/ Literacy Classes regularly

NOTE : This list of elegibility parameters is suggestive.The town cell, in consultation with community- based organizations concerned, can develop another set of parameters based on local conditions/factors to identify who is the poorest of the poor in the town.

Weightage score (type of priority) 1. 80 - 100 I Priority (Highest Priority);. 60 - 80 (II Priority); 40 - 60 (III Priority) 20 - 40 (IV Priority), 0 - 20 Priority (Lowest Priority)

*This is in addition to the norms based on income parameters, which envisage top priority to the household which is below poverty line.

Census data at the enumeration block level is used to quantify the number of households in the priority categories 1 and 2 (after up scaling the computed score for living condition by 4). The households were converted into population using a mean household size of 5.4 (Bhatt, 2003) to find the below poverty line population in 2001. These population values were then projected for 2007, using population growth rate in the city, the BPL population in 2007 has been computed as 1.7 million persons. To distribute the population, slum pockets were identified using the Cartosat–1 image and were digitized. In addition to this, data from the Municipal Corporation of Ahmedabad was used to identify slums and chawls in the city with help from Anada publication and Setu publication maps. *Chawls* are small one to two room houses that were constructed to house factory workers. As a rough estimate it was assumed that 85 per cent of the total BPL population would live in slums, and the rest in other areas. Allocation of BPL population from the Census Enumeration Block data to slum pockets was done using spatial overlay methods, and the rest was distributed evenly across the city.

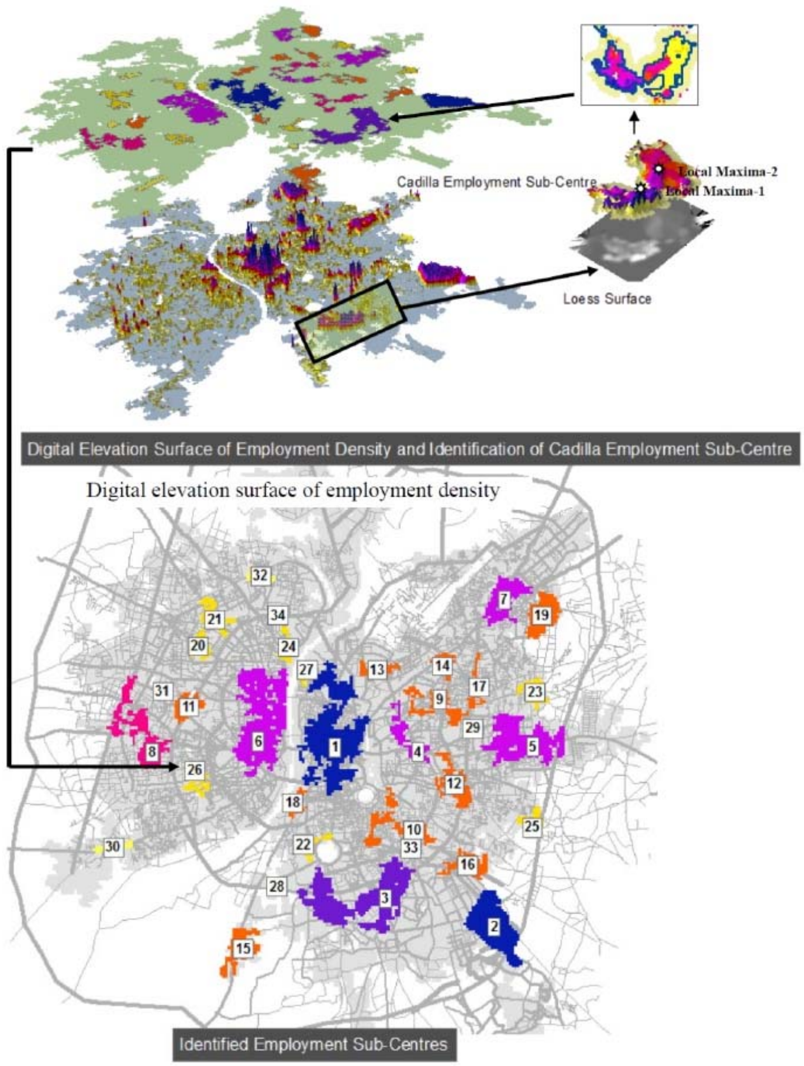


Figure 3-11: Identification of Employment Sub-Centres

Identification of employment sub-centres

From the quantified jobs as shown in Figure 3-11, one can see the computed employment density surface. The prominence of the region east to river Sabarmati (the so-called walled city area) is evident; this can be considered as the Central Business District of the city. Another notable feature is the sprawl of jobs along radials and connecting radials and prominence of jobs along the eastern periphery of the city where the industrial clusters are located.

As an example of the identification of sub-centres from job (employment) data, in Figure 3-11, a representation of the methods used to identify the 'Vatva Gam (Cadilla)' employment sub-centre is shown. The location has several small peaks along the main road, which connects to the central areas of the city. Two distinct areas within the cluster can already be identified by their local maxima, i.e., the high-density area in the west of the city and a lower density area in the east. This is a case where industries, trade and commerce have developed alongside each other. Identification of the sub-centres is done in two steps as described earlier, to end up with two Loess surfaces. For the first surface, a non-parametric density value of 236 (mean (94) + ½ (standard deviation (284)) is used as the cut off value. Locations with values higher than this are identified as the employment sub-centre in step 1. The location identified in step 1 is then deducted from the reconstructed Loess surface. In this remaining surface the non-parametric density values of 93 (mean (39) + ½ (standard deviation (108)) is used as the cut-off value to identify location of the sub-centre. Combined areas of step 1 and step 2 are finally identified as the Cadilla sub-centre. This procedure is repeated to identify 32 employment sub-centres next to the existing CBD city centre. Twenty-two of these are east of the river Sabarmati and eleven are to its west.

Data validation

Data on building footprints are used to validate the distribution of jobs. The dataset contains land use and building height information for 12,652 buildings across 67 neighbourhoods in the city. The basic input data to this study includes the land use and height information of buildings in Ahmedabad, which required an extensive field survey. The classification of buildings is done in six land-use categories and further sub-divided into building types, as depicted in Table 3-4.

The data on building heights and land use are aggregated at grid cell level. This is done by intersecting both layers in a GIS overlay operation, and then summarizing both sets of data per grid cell. The computed building volumes are multiplied by the known average employment per land use to compute total employment per grid cell used for validation purpose per validation grid cell. These employment values are used for validation of the estimated employment values per grid cell described in the previous section. The sum of least squares (R2) value is computed over 70 validation grid cells to estimate the accuracy of employment distribution.

The accuracy of prediction is 95 per cent with a standard error estimate of 13.6 jobs per grid cell, and 97.5 per cent for population data with a standard error estimate of 3.5 persons per grid cell. Allocation of mixed land-use area was found to have 84 per cent accuracy. Given that most of the validation grid cells have high job densities, the distribution of jobs can be considered as an accurate estimation.

Table 3-4: Land-use classification and building categories validation dataset

	Residential	Commercial	Industrial	Institutional	Infrastructure	Mixed
1	Slum	Big markets	Factory	Hospital	Railway station	Residential +Commercial
2	Apartment	Retail mall	Small manufacturing. units	Educational	Bus station	Residential + Institutional
3	Bungalow	Office building		Government offices	Airport	Commercial + Institutional
4	Tenement	Hotels		Religious building		Residential+Commercial +Institution
5		Shop building		Bank		
6		Shop + Office		Others		

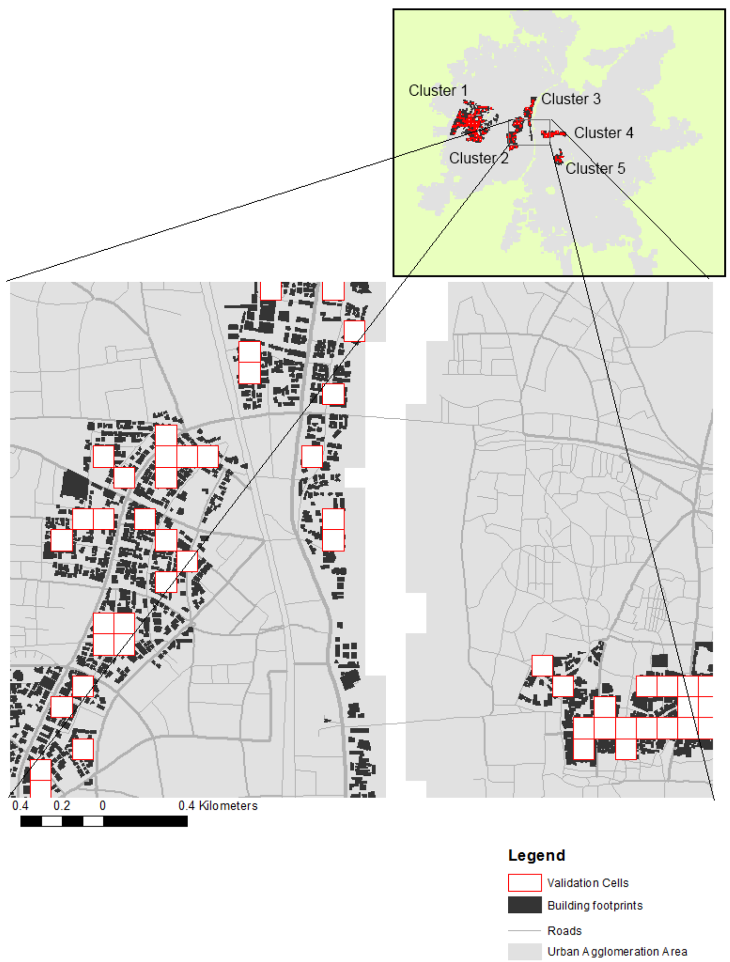


Figure 3-12: Data Validation

3.3 Pattern of built form

To describe the pattern of built form, the statistical distribution properties of the built-form measures are studied. These include spatial distribution and statistical distribution. First, the statistical distribution properties using central tendencies is studied, the observed properties of the built form measures are compared with values observed in Anglo-American context to note down the contextual differences. Voronoi maps are constructed from a series of polygons around the location of a sample point (ESRI, 2008). These maps provide a number of options to study the spatial distribution properties of sample points or observations. In this case Voronoi maps are used to study the distribution properties of built-form measures. The cluster tool of Voronoi, which is mainly used to identify local outliers, is used in the study. The cluster tool places all the observed values into five class intervals. These classes are computed using the interquartile range of the frequency distribution. If the class interval of a cell is different from each of its neighbours, it is considered as an outlier and is displayed in a different colour (grey). This method of looking at spatial distribution properties of data gives a good image of the spatial distribution of a value across the landscape and is therefore used to study the spatial distribution properties of all the measures.

3.3.1 Density (intensity of use)

Table 3-5 shows the descriptive statistics of all the quantified built-form measures. Among the intensity of use parameters, including the disparity measure, the skewness of frequency distribution increases from population density to job density to BPL population. This indicates an increase in the concentration of larger quantities of these activities at fewer locations. But the frequency values also indicate sprawl, especially of jobs. The mean net residential density value is 19710/sq. kilometre and net job density is 4825 persons/sq. kilometre. According to Wilbur Smith Associates (2008) report, the gross density of Ahmedabad in 2001 was 4462 persons/sq. kilometre. Compared to Ahmedabad, Pune had a residential density of 6000 persons/sq. kilometre, Surat had 4544 persons/sq. kilometre and Hyderabad 7092 persons/sq. kilometre. From gross density values, it appears that Ahmedabad has a lower population density compared to other metropolitan cities in India (net residential densities are not available for other cities). But in western context, the Transit Oriented Development Guidelines published by the Center for Urban Transportation Research (CUTR) at the University of South Florida, recommend population density of higher than 85 person/acre (2890 persons/ sq. kilometre) and 500 jobs/acre (17000 jobs/sq. kilometre) in core urban areas to promote transit use. The net residential density (population per unit of developed land) recommended in Cervero and Kockelman (1997) was 619 persons/sq. kilometre and mean employment was 202 persons/sq. kilometre. The mean residential density in Ahmedabad is higher than what is suggested by CUTR (CUTR, No Date), and likewise true for most metropolitan cities in India.

Table 3-5: Descriptive statistics of built-form variables

Independent Variable	Mean	Std Deviation
Net Residential Density(100 persons/Hectare*)	1.97	2.68
Net Job Density(100 jobs/Hectare)	0.46	1.45
BPL Population (100 Persons/Hectare)	0.46	2.65
Floor Space Dissimilarity	0.29	0.33
Floor Space Entropy	0.38	0.21
Job-Housing Ratio (Jobs/Household per Hectare)	1.16	4.64
Kernel Density Roads	9.63	4.44
Kernel Density Road Junctions	70.05	57.37
Kernel Density Public Transit Stops	60.30	75.93
Kernel Density Accidents	0.06	0.12
Space Syntax Global Integration	0.35	0.05
Space Syntax Local Integration	1.62	0.87
Distance to Transit Stops (Kilometres)	0.26	0.21
Access to job by public transit(10000 jobs)	11.32	14.70
Access to job by SOMV (10000 jobs)	31.48	25.51

* The unit Hectare is used here to represent the equivalent area of a grid cell

Therefore, most locations in the city will have a higher residential density than what is recommended for the urban core for transit-oriented land use in Florida. Mean job density in Ahmedabad is equal to the job density recommended for local bus hubs, but again substantially higher than densities suggested in Cervero and Kockelman (1997). Thus even though the urban development policies promote sprawl and restrict development of floor space, the per capita use of floor space for residence and employment in Ahmedabad, and also in other cities in India, is low and therefore cities in India are naturally compact.

Spatially, the distribution of population density is bi-polar and the effect of the river on these values is apparent. To the right of the river (east Ahmedabad) we find more densely populated areas in comparison to the western part of the city which has lower and more dispersed residential density values. The visual correlation between major roads and job density is apparent from the location of grid cell with high density values. Cluster 1 and 2 (interquartile ranges with lowest density values) are widely spread and fill up the space in between the major roads in the central parts of the city. Based on Figure 3-13 and Figure 3-14, one can expect that in the eastern parts of the city, choice of walking and transit mode will naturally be high and vehicle miles travelled by individuals is likely to be low.

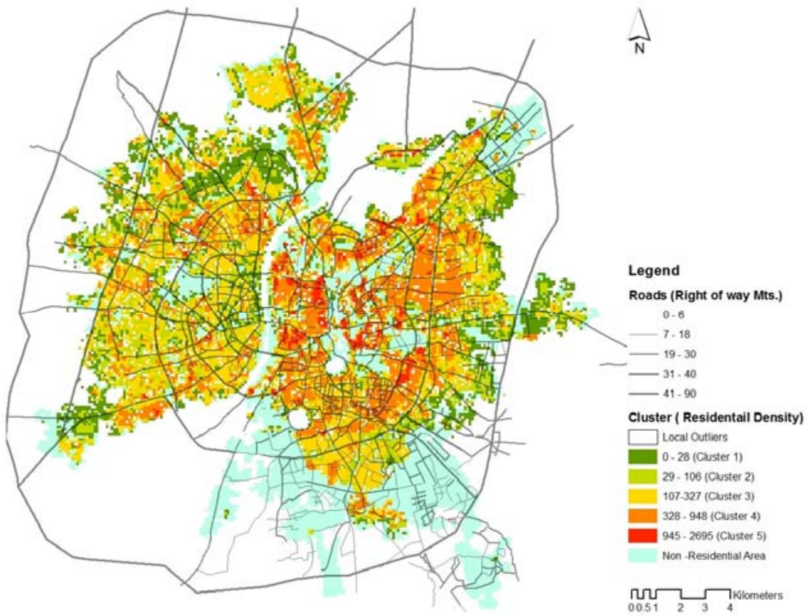


Figure 3-13: Net Residential Density

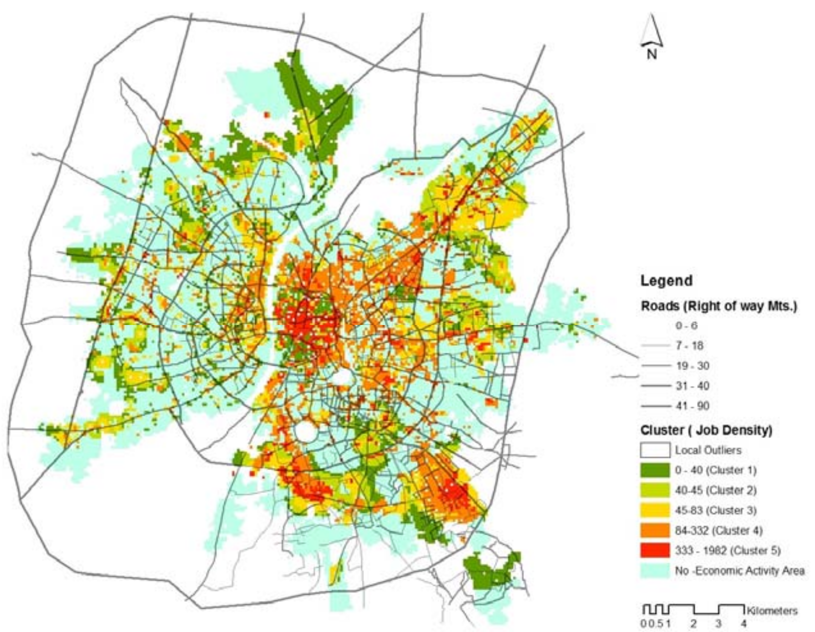


Figure 3-14: Net Job Density

3.3.2 Land-use mix

Five land uses are considered while computing the Entropy Index. As observed from Table 3-5 for Ahmedabad, the mean Entropy Index value is 0.3802, which is a little higher than the Entropy Index values of 0.325 observed by Kockelman (1997), and lower than the mixed use entropy value of 0.471 observed in (Frank and Pivo, 1994). The values observed for mixing of land uses is close to the values observed in other studies in the United States of America. The land use is a heterogeneous mix in many parts of Ahmedabad, resulting in dissimilarity index value close to 1, in those areas. The mean dissimilarity index value observed for Ahmedabad in this study is 0.29, which is substantially higher than the mean dissimilarity index value of 0.13 observed by Cervero and Kockelman (1997).

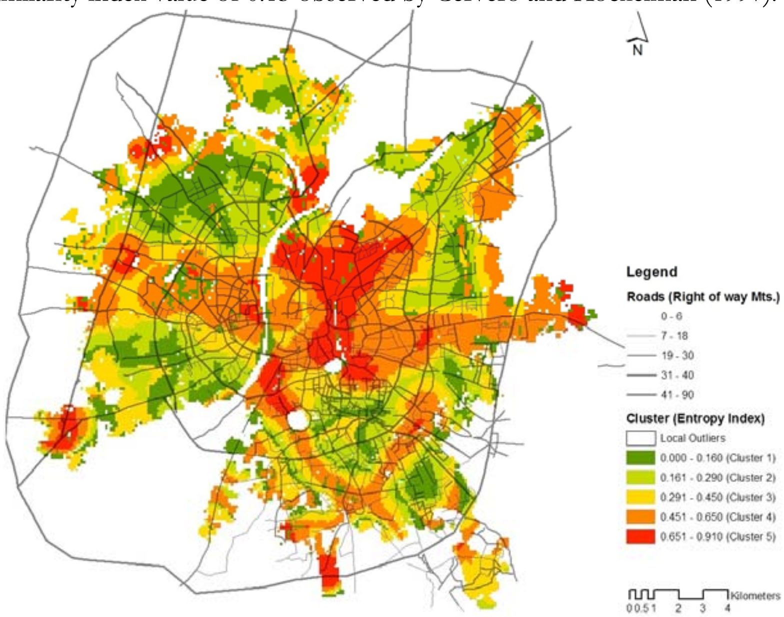


Figure 3-15 : Entropy Index

Figure 3-15 and Figure 3-16 show the spatial distribution of land-use mix (dissimilarity index) and balance (entropy index) values. It can be observed that proximity to major roads seems to have a visual correlation with land-use mix values, areas closer to major roads have higher land-use mix compared to interior portions. However, as the inner area accessibility by road decreases, one observes less mixing of land use. Therefore, mixing at the neighbourhood level is less discrete and more evenly distributed. Central locations in the city have higher dissimilarity and entropy index values compared to the peripheral locations. Therefore, it can be said that locations abutting, on both sides, the wall encircling the walled city have land uses, which favour lower travel distance, and greater transit use and walking.

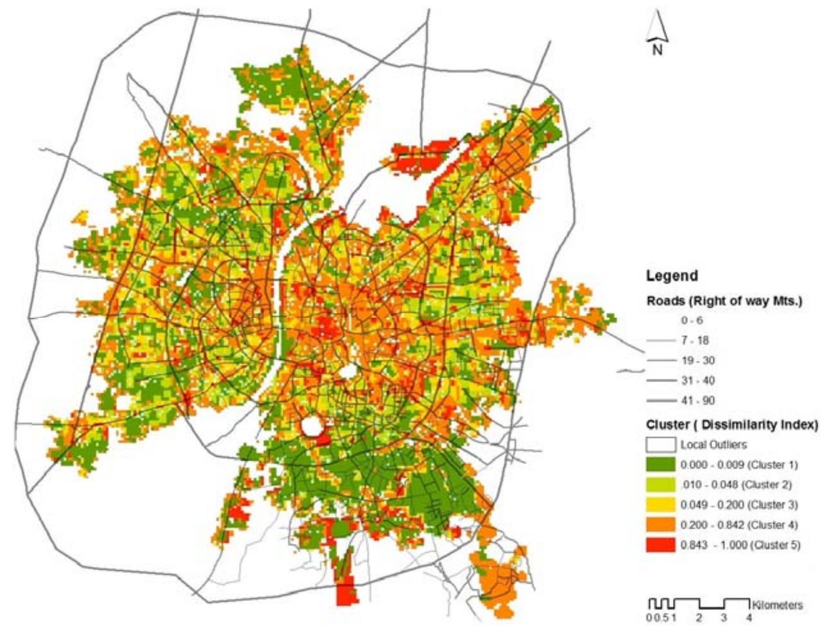


Figure 3-16: Dissimilarity Index

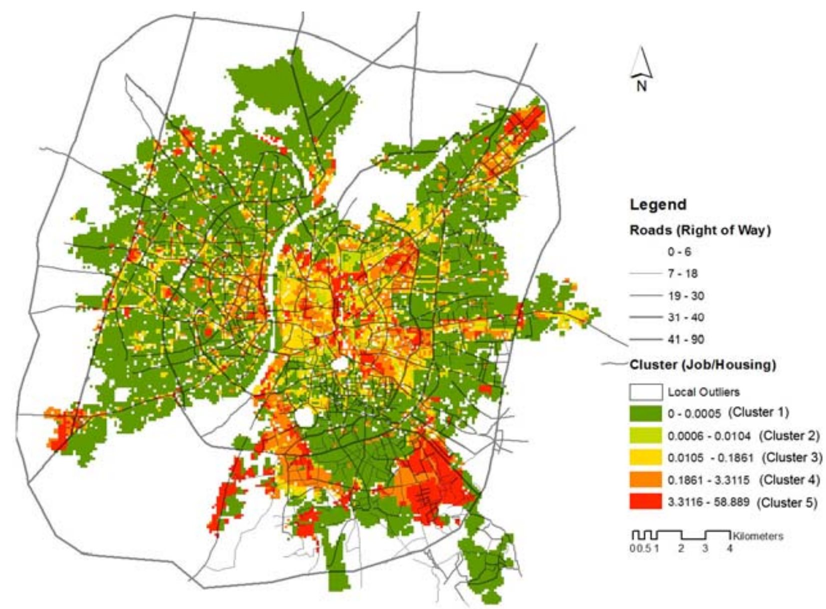


Figure 3-17: Job - Housing Balance

Figure 3-17 shows the job-housing balance. As is apparent, the walled city has high job and housing densities, therefore the ratio is moderate. The locations in green are predominantly residential, and the cluster 5 locations are non-residential. One can expect that individuals residing in clusters 4 and 5 (that is, at locations which are pre-dominantly non-residential) will have lower travel distances, and their probability of choosing non-motorized modes will be higher.

3.3.3 Density of transit stops and distance to transit stops

The distribution of kernel density values for transit stops has high skewness, indicating concentration of values only at certain locations. In contrast to kernel density of transit stops (Figure 3-18), it is observed that distance to transit stops (Figure 3-19) has a mean distance value of 261 m. This indicates shorter travel distances to the bus (transit) stops and equitable distribution of stops, the mean travel distance to transit stops being within the recommended distance to transit stop of 500 m. Therefore, it can be said that the population field (number of routes) in kernel density of stops distorts higher density values towards higher side only at a few locations, located in the central parts of the city. Therefore, although bus stops are more evenly spread, bus routes are concentrated only at a few locations, which affects the accessibility that individuals have to transit facilities in the city.

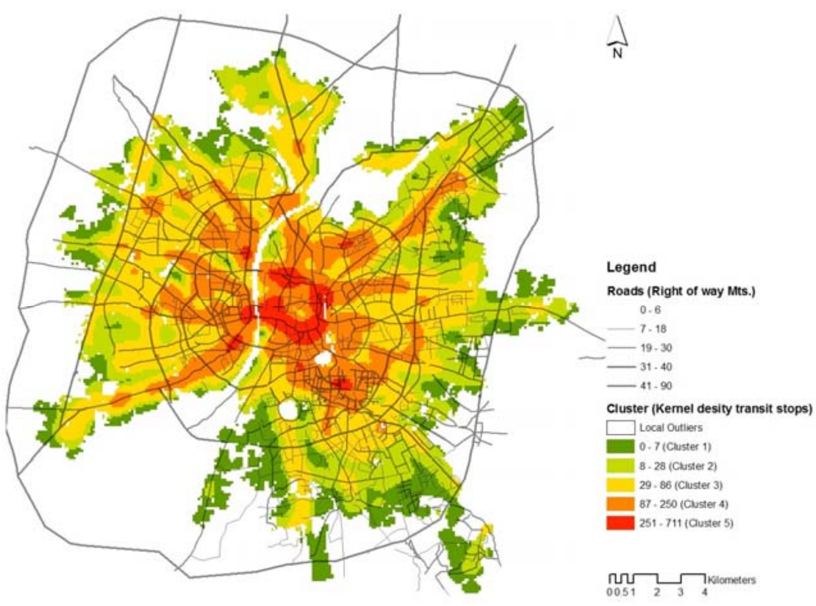


Figure 3-18: Kernel Density Transit Stops

* 750 Mts Radius and number of routes at the each stop is used as the population field

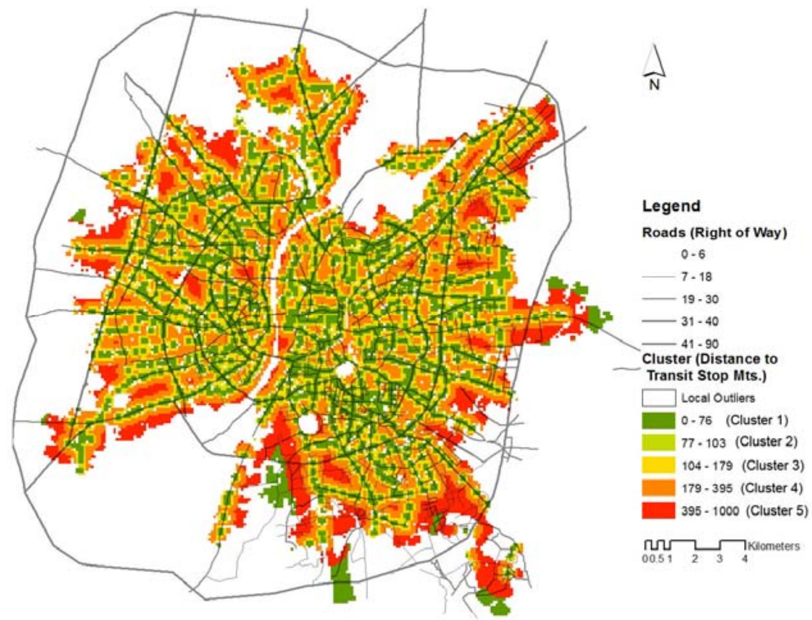


Figure 3-19 : Distance from Transit Stop

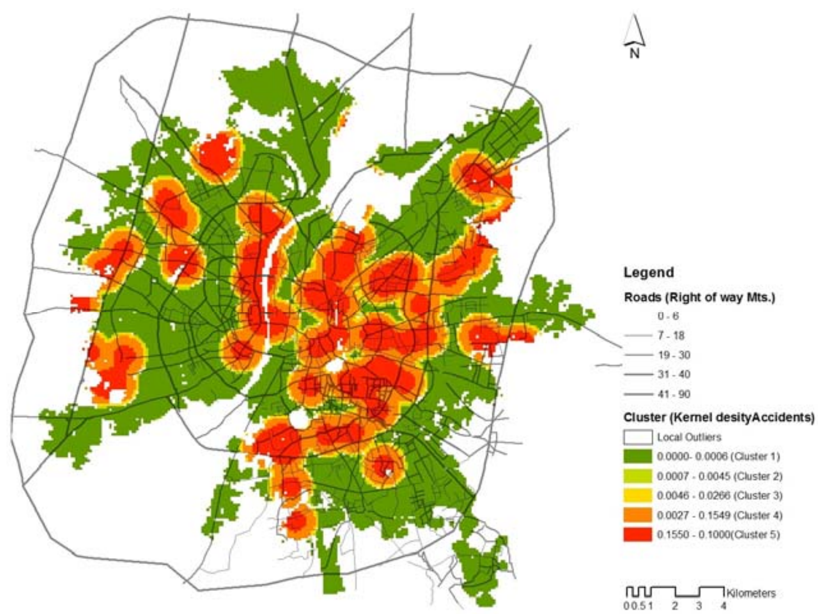


Figure 3-20: Kernel Density of Accidents

*Kernel density computed using 750 Mts radius

3.3.4 Road network properties

Kernel densities of roads in Ahmedabad, have more statistically distributed values. In an ideal situation where proper road hierarchies are followed, this would indicate an even distribution of road space and junctions.

Space Syntax local integration values in Ahmedabad range from 0.21 to 6.76, and for global integration the values range from 0.18 to 0.46. Rodríguez et al. (2008) had observed the range to be between 0.53 and 1.39 (global integration values) and between 0.21 and 3.84 (local integration values); for more modern cities with grid layouts and high road densities the range was 0.22 -1.30 (global integration) and 0.13-5.22 (local integration). Thus, in comparison the local integration values computed are a little higher and the global integration values for Ahmedabad are, in comparison, very much lower, which indicates that the local access provided by streets in Ahmedabad is relatively good, but global access is poor. It can be inferred that there are certain locations in the city with dense network configuration and high Space Syntax local integration parameter values, but the overall integration of the network remains poor.

Kernel density of accidents (Figure 3-20) also has positive skewness values, indicating that most areas in the city have lower fatal accidents. All accidents have not been considered here, as most of non-fatal accidents are not reported to the police. So one can expect small pockets where fatal accidents are concentrated along the routes where movements of large-size vehicles (buses or trucks) is high.

Figure 3-21 and 3-22 show the spatial distribution of kernel road density and kernel road junction density values. Both these values more or less visually correspond to each other. Areas north and east of the walled city area have lower densities of roads and junctions; similarly, locations in the southern periphery have low road densities, locations along the inner ring road in the western city have low road and junction densities, and other locations have a more equitable distribution of roads and junctions. The dichotomy of this infrastructure provision is that an increased number of junctions usually favour the use of non-motorized vehicles, but access to major roads also increases the probability of using self-owned motorized vehicles. Therefore, polarity in the road infrastructure provision could affect all types of mode choices. In ideal a circumstance, that is when roads have provision of good pedestrian and bicycle infrastructure, one could expect that when road and junction densities are similar to those in the walled city area, the networks design will favour NMT use.

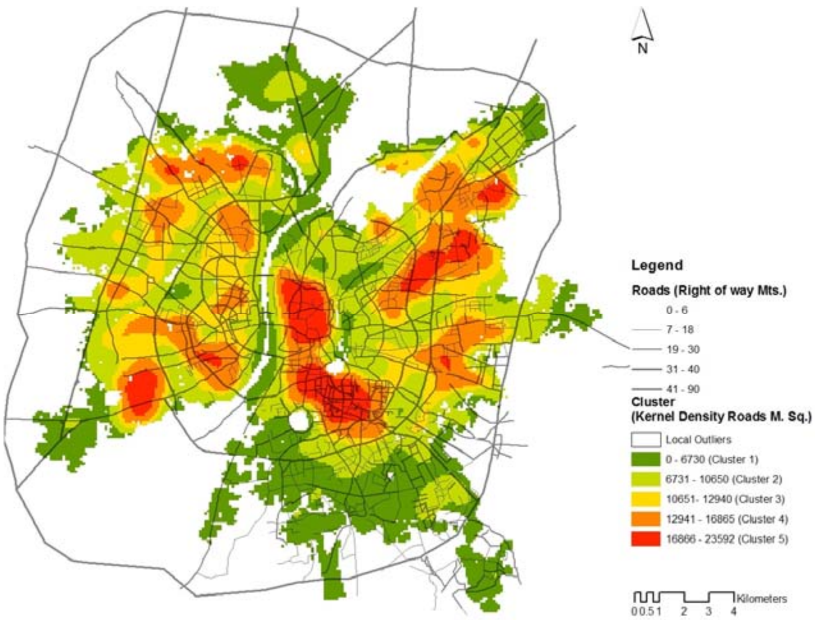


Figure 3-21: Kernel Density of Roads
*Kernel density computed using radius of 750m, road as population field

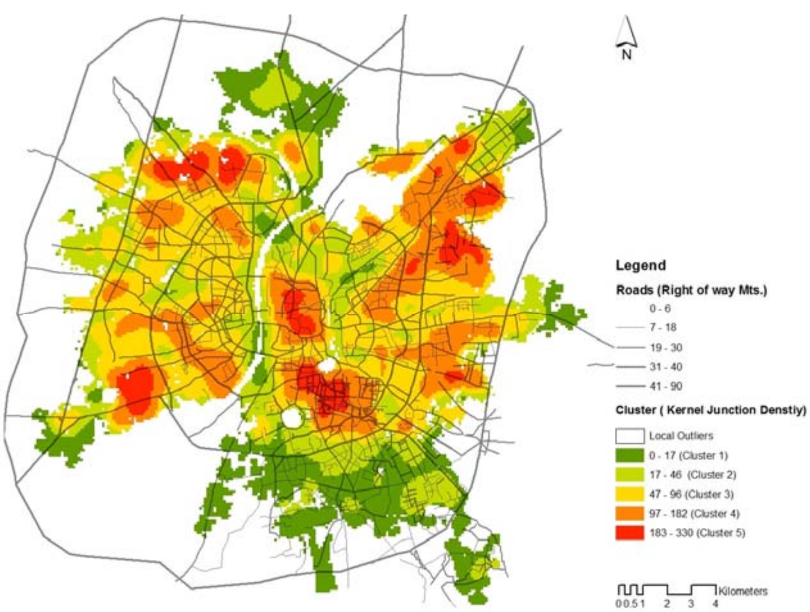


Figure 3-22: Kernel Density of Road Junctions
*Kernel density computed using 750 Mts radius

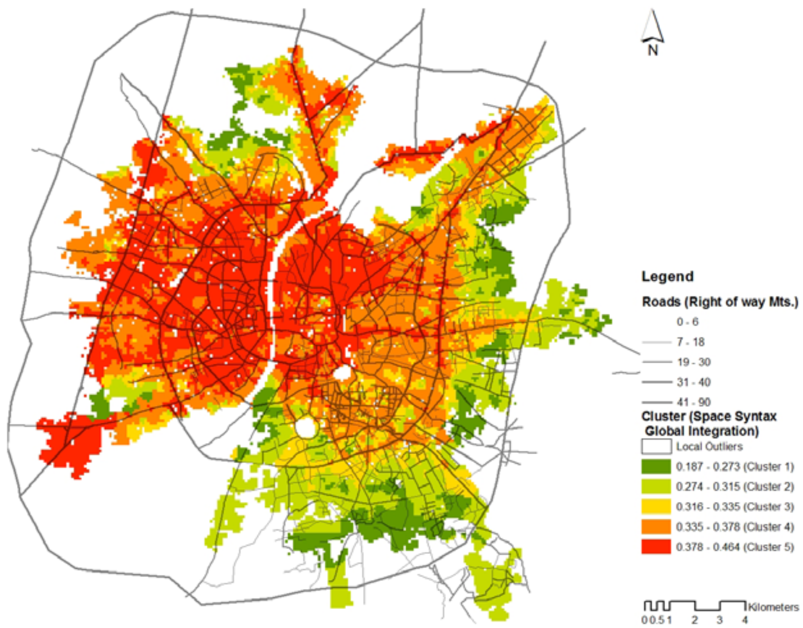


Figure 3-23: Space Syntax Global Integration Voronoi Clusters

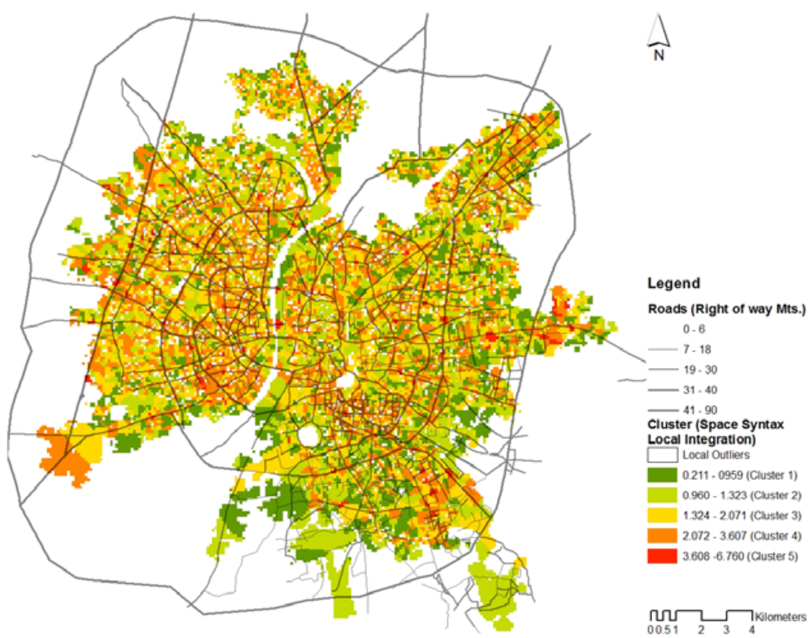


Figure 3-24: Space Syntax Local Integration Voronoi Clusters

In a properly networked road layout, it is expected that a location, which has a higher road density value, should also have a higher Space Syntax Global Integration. Moreover, as we move towards central locations, the Space Syntax Global Integration should increase. Figure 3-23 shows that, overall, most areas in the western part of Ahmedabad have higher Space Syntax Global Integration values and, the global integration is high along radial and connecting radials on both sides of the river, especially along the ring abutting the walled city area. It can be inferred that the road network in western Ahmedabad has better topological connectivity in comparison to the network in the eastern part of Ahmedabad, where despite road densities being high, the roads are not properly interconnected. As Space Syntax Local Integration values (Figure 3-24) look at connectivity in a smaller space, these values and network density values have a better visual correlation. Space Syntax Global Integration values are higher on streets near the CG Road-Ashram Road area, and around the connecting radial in the eastern part of Ahmadabad.

Space Syntax Local Integration values are high in locations where densities and diversity values favour NMT and transit use. Better local integration should encourage short-distance pedestrian and non-motorized modes of travel. Moreover, given these conditions Space Syntax Local Integration and Global Integration should encourage public transit use if these values correspond to transit stop locations and transit terminal locations respectively (Jayasinghe and Munshi, 2011).

3.3.5 Access to destination

Accessibility to jobs by car and transit modes is presented in Figure 3-25 and Figure 3-16. Central locations have high network density and better public transit coverage and thus, higher number of jobs. Outer peripheral locations have less coverage area. Therefore, the influence of proximity to the walled city and accessibility of locations in central parts of the city is high. Secondly, the influence of major roads on accessibility by car (or SOMV) is obvious. East Ahmedabad has better accessibility to jobs because of the presence of the walled city and industrial areas in close proximity to each other. Access to jobs by transit is influenced by locations of stops and density of routes on these stops. Therefore, access to jobs on routes along the radial is high and diminishes as we move towards the outer locations in the city. From the meta-study done by Ewing and Cervero (2010), it is known that access to destination has the maximum influence on distance travelled by individuals, those living in locations with better access to destination travel less in comparison to those living in locations with poor accessibility to destination. This is true for both transit and non-transit modes. Therefore, one can expect individuals living in the western part of Ahmedabad and in the peripheral areas of the city to travel longer distances compared to those living in the central parts.

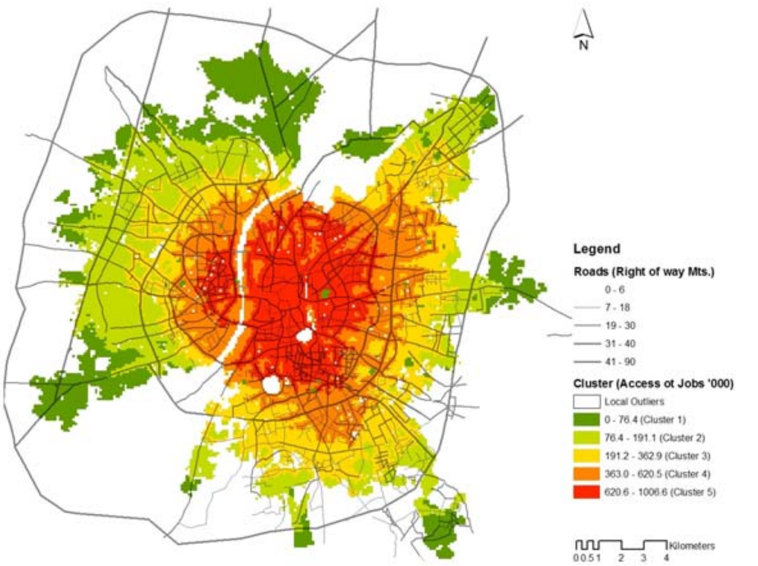


Figure 3-25 Access to Job by Car –Voronoi Clusters

* SOMV = Self Owned Motorized Vehicles, *Cumulative jobs accessible within 5.4 kms. distance (mean trip length of all modes)

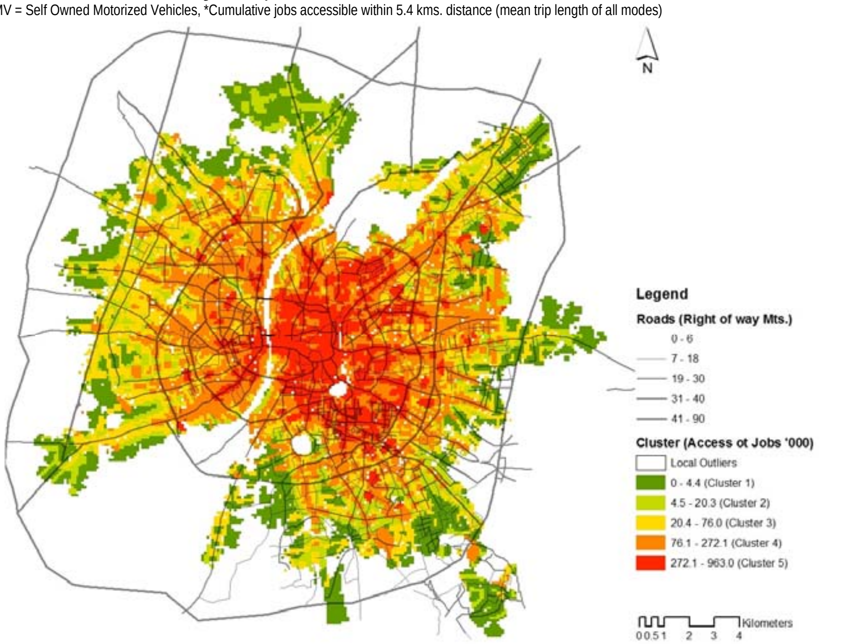


Figure 3-26: Access to Job by Public Transit

* AMTS is considered as public transit mode, * Cumulative jobs accessible within distance of 6.8 km.- Cumulative jobs accessible within distance of 1.2 kms.

3.3.6 Disparity

The Voronoi clusters map in Figure 3-27 reveals that a majority of the poverty pockets are located along the river in the east, and a few along the western part of the river. Location in east Ahmedabad where accessibility to jobs is high also have higher density of BPL population, an indication that most poor people in the city reside close their work destinations. In the context of Indian cities including Ahmedabad one can expect, based on work of Tiwari (2001), Pucher et al. (2005), Munshi et al. (2004) and Dimitriou (2006a), that currently poverty could be one of the major drivers for choosing non-motorized and public transit modes.

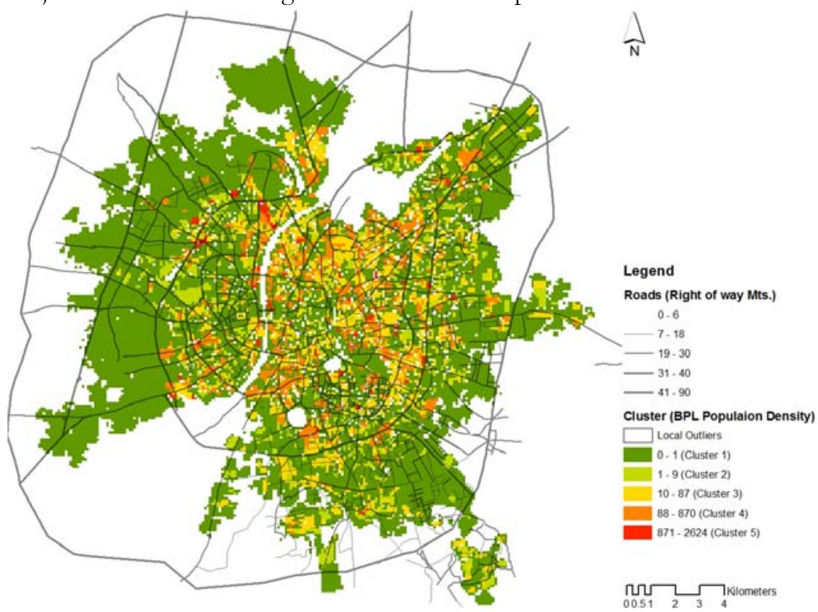


Figure 3-27: BPL Population – Voronoi Clusters

3.3.7 Employment sub-centres in Ahmedabad

As observed earlier, sub-cantering of employment locations and configuration of these sub-centres can influence choice of modes and distances individuals travel. Location of employment sub-centres are shown in Figure 3-11. Growth of these centres is presented in Table 3-6. It is observed that the number of sub-centres with employment of more than 10000 increased from 9 in 1980 to 21 in 2010, and more employment sub-centres that have employment in the range of 3000 to 10000 have developed. The percentage of total employment in the walled city area has come down from 22 per cent in 1980 to 12 per cent in 2010. The total employment in all identified employment sub-centres (Figure 3-11) has reduced to 69 per cent in 2010 from 83 in 1980. These developments indicate the phenomenon of polarisation reversal (Richardson, 1980), increased sprawl type of development, and poly-nuclear development in the city. How these developments will influence travel will also depend on how it has influenced the overall activity pattern in the city and access to job by transit and by self-owned motorized vehicles. Formation of centres in the western part of the city and topology of employment (Figure 3-28) have come up along major transport corridors at a distance of around 6 to 7 kilometres from the centre of the walled city (identified as 1 in Figure 3-11) and Ashram Road – C.G Road area (identified as 6 in Figure 3-11). This distance happens to be almost equal to the average trip length by motorized modes in the city (GIDB and CEPT, 2006). Third-order centres can be seen in the topology map as small peaks in-between these larger centres. It can be assumed that these smaller centres mainly have lower-order retail shops. The pattern of employment in the eastern part is not so clear. The second-order centres have come up at a much closer distance of around 3-4 kilometres from the core of the central area. Considering that the core itself is around 2 kilometres wide, these areas are located very close to the central core. The other four larger centres, which are known industrial districts, are around 8-9 kilometres from the central core area. Employment across all sub-centres is also not uniform; employment sub-centres located centrally like the Ashram Road - C.G. Road area have observed moderate growth in the past two decades.

Table 3-6: Sub-centres: Growth of employment activities.

Sr.no	Emp. Centre Name	Employment (1000 persons)							
		1980	% Emp	1990	% Emp	2000	% Emp	2010	% Emp
1	Walled City	125	21.3	143	17.2	166	14.9	184	11.8
2	Vatva	21	3.6	44	5.3	78	7.0	156	10.0
3	Cadila	75	12.8	85	10.2	112	10.1	105	6.7
4	Memco	56	9.6	78	9.4	99	8.9	95	6.1
5	Odhav	25	4.3	40	4.8	50	4.5	83	5.3
6	Ashram Road	53	9.1	65	7.8	74	6.7	82	5.2
7	Naroda	33	5.6	48	5.7	56	5.0	77	4.9
8	Judges Bungalow	2	0.4	8	1.0	33	3.0	39	2.5
9	Aahuja Park	9	1.5	18	2.2	26	2.3	37	2.3
10	Khokra Gam	18	3.1	23	2.7	22	2.0	29	1.8
11	Gurukul Road	4	0.7	9	1.0	17	1.5	18	1.2
12	Amraiwadi	6	1.0	10	1.2	15	1.3	17	1.1
13	Girdhar Nagar	15	2.5	9	1.1	11	1.0	15	1.0
14	U.G. Vasahat	9	1.6	15	1.8	10	0.9	15	1.0
15	Saijpur	2	0.4	14	1.7	10	0.9	15	1.0
16	C.T.M	6	0.9	13	1.6	15	1.4	13	0.8
17	Balkrishna Nagar	1	0.2	3	0.4	5	0.5	10	0.7
18	Calico Mill	9	1.6	11	1.4	7	0.6	10	0.7
19	Nava Nikol	0	0.0	1	0.1	5	0.4	10	0.7
20	Sola Gam	1	0.2	2	0.2	4	0.4	10	0.6
21	Chandlodiya	1	0.2	3	0.4	5	0.5	10	0.6
Total (All 32 Employment Centres)		587	83	831	80	1112	78	1561	70

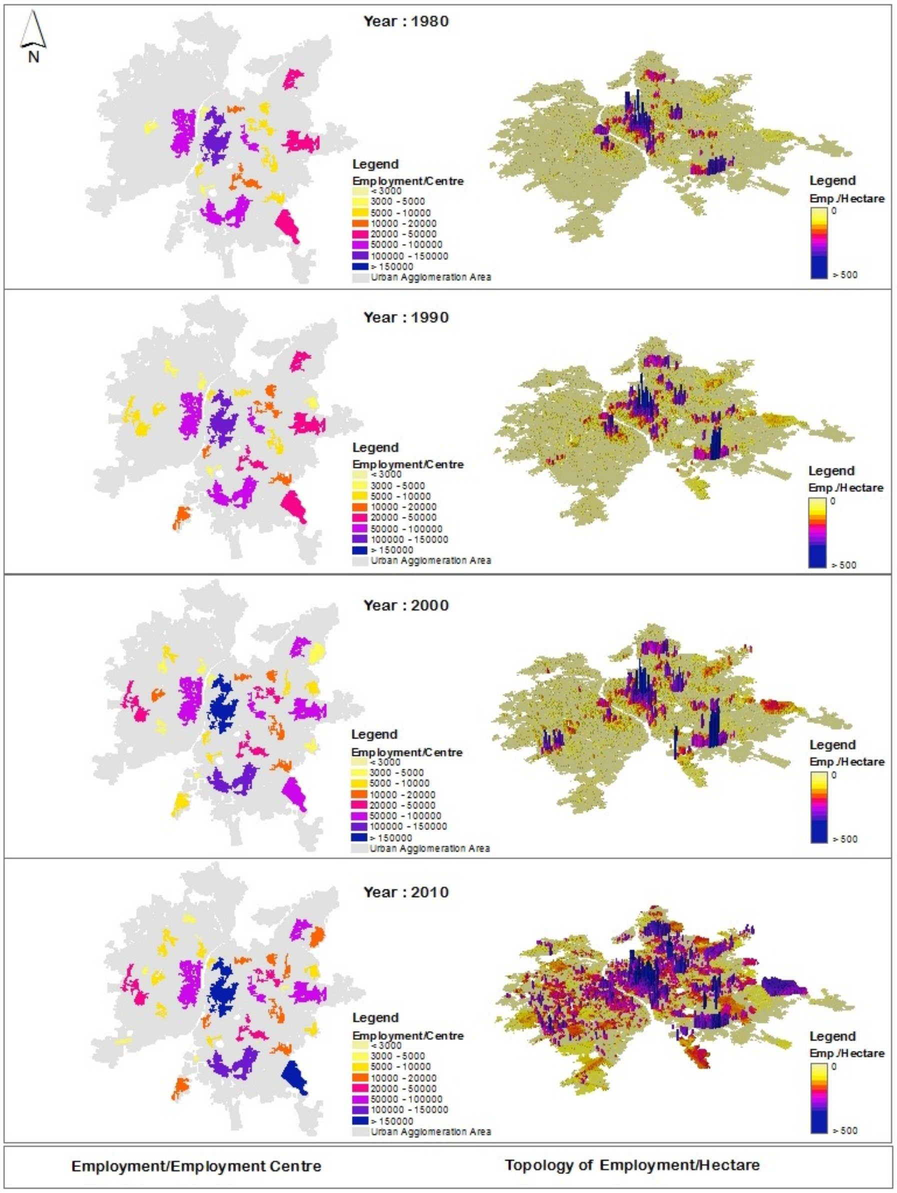


Figure 3-28: Topology of Employment

From Figure 3-28 it can be observed that development till 2000 was clustered at a few locations, while in 2010 sprawl can be observed, which is apparent from uncontrolled growth of employment areas and the emergence of small employment sub-centres. Further investigation reveals that in 2001 Development Control Regulation (DCR) in the city was amended and commercial development was allowed on any road with a width of more than 12 metres. These DCRs along with other development constraints can be the reason for this sprawl.

Table 3-7: Employment sector primacy and growth of economic activities

EC#	Employment Sector											
	Commerce				Retail				Industries			
	Floor Area	CGAR			Floor Area	CGAR			Floor Area	CGAR		
	1980	1980-90	1990-00	2000-10	1980	1980-90	1990-00	2000-10	1980	1980-90	1990-00	2000-10
1	455.10	1.21	1.1	0.64	145.50	6.68	4.80	8.19	481.80	0.51	0.20	0.64
2	2.20	7.62	5.84	8.06	2.00	10.47	17.77	7.55	13.40	6.12	2.05	2.84
3	6.60	14.14	2.69	3.51	84.70	5.83	3.78	-0.51	243.30	-0.63	1.96	3.18
4	12.20	4.46	1.24	0.88	31.20	6.12	5.88	0.93	92.40	3.17	1.36	1.56
5	3.60	7.92	5.18	4.07	16.70	10.81	7.03	8.07	122.30	3.38	-1.39	4.41
6	280.70	2.39	1.02	3.47	82.30	7.95	6.05	3.96	17.50	1.85	3.71	1.19
7	16.90	3.27	2.03	4.61	14.00	9.46	4.75	8.19	48.20	5.80	2.62	3.27
8	5.60	9.31	4.99	3.47	40.20	4.71	5.06	9.41	117.80	6.38	3.19	1.62
9	1.00	33.66	8.56	14.92	19.30	14.35	15.66	-0.97	0.50	10.32	19.29	0.73
10+33	38.8	2.20	2.06	5.35	25.40	9.44	9.74	3.97	259.00	0.40	0.32	0.96
11	4.10	3.56	4.89	1.49	15.80	6.25	5.99	9.16	77.70	4.19	3.49	2.31
12	50.20	1.06	0.53	3.27	11.70	10.85	6.21	9.75	10.60	3.36	1.15	1.05
13	10.30	1.63	0.37	3.09	17.30	2.41	3.45	9.82	83.40	5.58	0.67	0.26
14			10.83	25.56	12.50	6.49	3.08	7.87	4.50	4.27	-0.21	8.61
15	0.20	33.94	6.48	5.91	17.10	5.88	4.57	7.58	49.60	3.08	3.92	0.15
16	1.60	8.29	1.02	4.07	11.50	4.87	4.16	9.11	17.50	5.66	2.97	1.74
17	5.60	1.02	0.72	0.23	7.30	1.48	7.94	9.39	83.60	4.02	0.35	0.66
18		0.20	53.23	16.86	0.46	38.13	13.73	7.27	0.20	13.76	5.31	1.48
19	19.90	0.12	0.92	12.23	5.69	5.24	17.54	9.41				2.85
20	0.50	23.30	13.31	6.52	23.54	6.30	4.91				0.25	
21	3.30	17.75	2.48	3.84	22.06	10.07	5.41	7.72	3.90	5.39	4.06	4.41
22	3.20	3.44	2.44	6.81	12.03	5.93	9.50	-21.89	35.30	4.79	1.13	4.42
23	0.50	2.04	4.94	28.78	4.11	12.89	8.01	8.51	14.70	6.51	9.98	2.85
24	6.70	0.70	4.29	8.05	4.60	9.79	5.14	10.13	3.40	3.32	3.19	1.31
25			11.30	17.10	13.36	8.98	7.85	7.29	0.50	31.04	13.44	2.85
26	1.00	9.80	14.03	4.70	5.90	17.58	4.62	7.35		40.57	12.72	11.46
27	7.60	10.87	0.04	0.37	2.33	3.66	4.33	23.82	221.10	1.11	-4.41	0.81
28		54.31	2.44	1.58	0.19	40.32	19.24	7.29			67.10	-0.73
29	0.50	2.80	2.29	6.23	4.73	5.86	4.97	10.76	1.80	3.38	9.66	4.97
30	0.30	24.20	4.01	18.79	8.82	8.22	10.18	-43.68	4.60	5.46	7.23	8.27
31	3.00	8.82	7.71	11.46			7.34	7.45				0.35
32	0.70	0.13	10.42	4.78	10.87	3.90	0.98	18.19	2.10	7.86	0.02	
34	0.10	38.78	0.33	6.35	6.43	5.65	6.53	8.00	0.10	15.99	2.09	0.48

Note: EC = Employment Centres

Table 3-7 helps one to understand how activities have developed in the past 30 years within these centres with 1980 as the base year. It is observed that in 1980 the commercial sector establishments were centrally located. Even though most retail is still located in the walled city, the growth of this sector is high in the peripheral locations, mainly west of the Sabarmati. Overall, industrial growth has been slow, retail and commercial centres have grown very fast, locations in the periphery have grown faster compared to those in the central parts. Commercial offices and educational institutions have favoured locating in or near smaller clusters. Locations in the western part of the city are more balanced in terms of location of activities.

A distinct pattern of employment sub-centre formation can be observed. It appears to be closely linked as stated earlier with mean trip length by motorized modes to these locations. From analysis of topology of employment and how employment sectors have grown, two types of agglomerations are apparent: one related to trade and commerce and the other to industry. Incidentally, in the case of Ahmedabad, these are separated by the river that divides the city in two parts. Industry is located in the eastern part, whereas trade, commerce and the banking sector are mostly located in the west. Trade and commerce in the form of commercial offices and retail trade have grown fast in the city and more at a location near the peripheral areas.

From the discussion above it can be said that DCRs and zoning regulation have/ allowed activities to sprawl. Ideally planners should have intervened and allowed commercial development at certain nodes so as to avoid externalities caused by such development elaborated in Brotchie et al. (1996). Externalities from low-carbon transport point of view can be both negative or positive. The negative externality could be lower use of public transit and higher use of SOMV as public transport provision is non-concurrent with development of sub-centres, and as a higher number of sub-centres will also lead to lower job density in each employment sub-centre node. The positive externality could be lowering of trips lengths as jobs also sprawl with development, as observed by Adhvaryu (2009).

3.4 Discussion

The aim of this chapter was to answer two research questions: first, what data and methods can be used to quantify built form in a typical metropolitan cities in India like Ahmedabad, and second, about the pattern of built form in Ahmedabad.

The data required to quantify built-form measures is available from various sources, and different datasets have diverse spatial aggregation scales, attributes and years of production. To suitably represent and compute data on built-from measures, a uniform grid of 100 m. x 100 m. size has been used. Data(including remote sensing data)is used as input for spatial overlay methods in GIS to compute built-form measures. To identify employment sub-centres (identified as locations that have substantially higher employment as compared to their neighbouring areas) a combination of cluster-based employment cut-off measure and non-parametric approach has been used.

The datasets discussed in the chapter for the case city of Ahmedabad can be considered atypical for any metropolitan city in India, except the Enumeration Block data, which is available with the Census departments and can be accessed with appropriate permissions. Most cities have property tax enumeration records, data from comprehensive mobility plans or from other transport studies. In recent times, many cities also have good GIS land-use data as part of the National Urban Information Scheme of the Government of India. In case GIS data on land use is not available, other sources like Anada Prakashan maps can be used to generate reasonably accurate land-use datasets. Despite availability of the mentioned datasets, issues related to multiplicity of scale and timeframes have to be addressed, which consumes a lot of time, effort, and energy. The present study, however, demonstrates that it is possible to quantify built-form indicators even at a disaggregated scale of 100 m, x 100 m, in metropolitan cities in India.

In the statistical and spatial distribution of built-form measures in Ahmedabad, the east–west divide induced by the river is apparent. The western part of the city (west of the Sabarmati) has comparatively lower densities, better and safer roads, less mixing and heterogeneity of land use, and lower densities of BPL population. The density values of population and jobs in the eastern part of Ahmedabad, as expected in these conditions, are exceedingly high, land use is heterogeneous at many locations mainly near the major roads, but the overall balance is good. Provision of road network is patchy, high in certain locations and very poor at a few other locations. Moreover, many locations in the eastern part of the city are not safe to travel. Ahmedabad has expanded and has transformed from a mono-centric to a polycentric city with as many as 34 employment sub-centres, 12 of which have substantially high employment. However, the provision of public transit is concentrated towards the central core and does not visually correlate well with sub-centre formation. It is therefore clear that public transit has had no role in the development of the sub-centres. Conversely, the development of employment sub-centres has also not led to rationalizing of public transit routes.

To develop an understanding of how these values of built form impact travel behaviour, the next chapter looks at the built form and travel behaviour relationship. Elasticity values for the case city of Ahmedabad are computed and compared with what has been empirically found in the Western countries.

4 Establishing the built form – travel relation for Ahmedabad

4.1 Introduction

In this chapter, the relation between built-form measures quantified in Chapter 3 and travel behaviour of individuals quantified from the household survey has been analysed and studied. The chapter answers questions related to the methods used to study built form - travel relation and the observed relation between built form and travel for the case city Ahmedabad.

The chapter begins with an explanation of the relation between built form and travel behaviour found in Western countries. This is followed by a discussion on methods that have been used to study the relation between built form and travel behaviour elsewhere and in this study. Next, the relation between built form and travel behaviour is presented, and the chapter ends with a discussion on the findings.

4.2 Relating built form and transport

The interest shown by the state and local governments in the concepts of new urbanism and smart growth has encouraged policy debate leading to a number of studies that have examined this relation. From studies in the Western countries (in Ewing and Cervero (2010), the weighted elasticity values representing built form and travel behaviour are presented in Figure 4-1. In the relation between built-form measures and VKT (vehicle kilometres travelled) negative elasticity values are desired because, as stated earlier, the overall aim of these studies is to reduce the total distance travelled in a city. It is observed from the work of (Ewing and Cervero, 2010) that access to destination measured as distance to the city centre (measured as network distance or proximity) and job accessibility by auto, considerably reduces the vehicle kilometres travelled (VKT). Higher intersection and street density and higher percentage of intersections also reduce distances travelled by individuals. Other variables that have comparatively marginal influence on travel distance are land-use mixing, household/population density, job accessibility by transit and distance to transit stops. Therefore, locations that are close to jobs or the traditional central business district with high street density and good land-use mix with high population density reduce travel distances.

Positive elasticity values are desired for non-motorized and public transport mode choices. It is observed that the walking and transit mode choice are influenced positively most by design indicators measured as intersection or street density, then by land-use mix, and marginally by density variables.

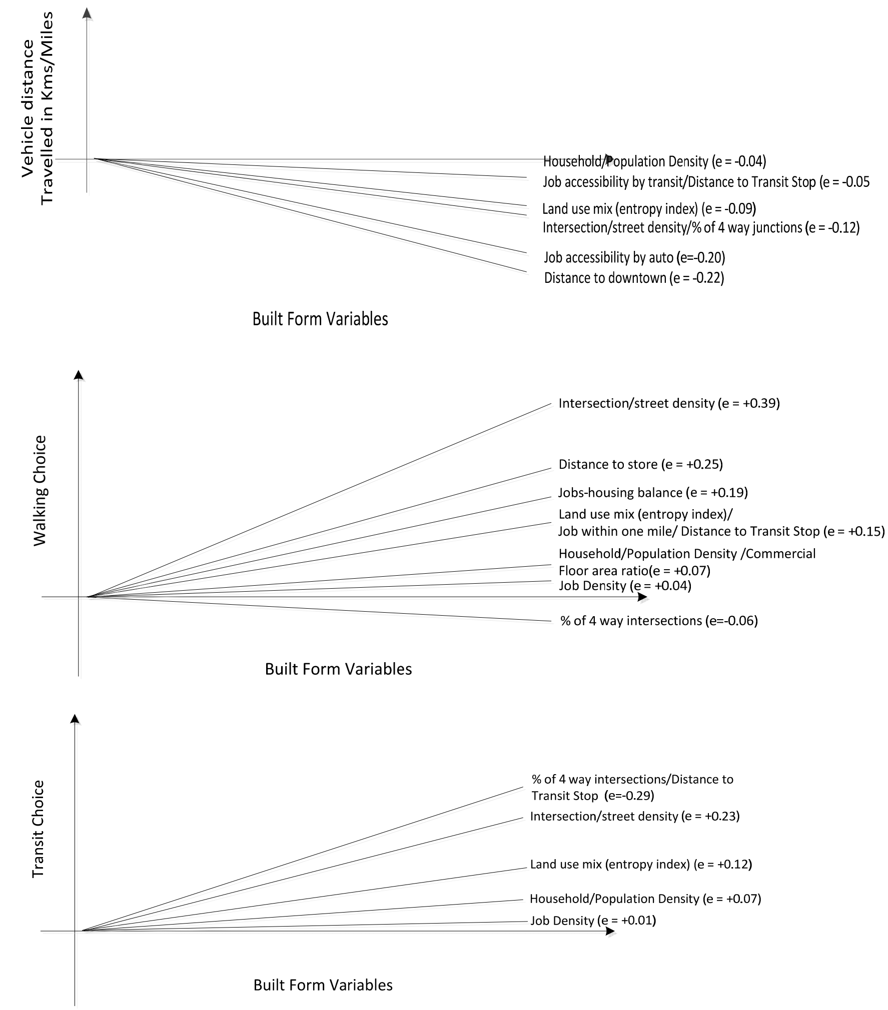


Figure 4-1: Weighted Average Elasticity of vehicle distance travelled, walking and transit mode choice with respect to built-form variables (as observed in Ewing and Cervero (2010))

Mixed findings have been reported in individual studies on impact of built form on travel behaviour. The observed impacts vary from weak to strong; moreover, measures found significant in some studies are found insignificant in other studies. To cite an example, the relation between population/household/job with vehicle distance travelled in general is unidirectional, but variation in the elasticity values can be observed in the range from -0.34 (Bhatia, 2004) to -0.04 (Kuzmyak, 2009), and from -1.05 (Chatman, 2008) to -0.04 (Boarnet et al., 2004) for non-work trips. The relation with job density is inconsistent, very low but positive elasticity values are observed in studies done by Zhou and Kockelman (2008), Greenwald (2009) and Boarnet et al. (2004), whereas Chatman (2008), and Ewing et al. (2009) have found negative elasticity for the relation. The elasticity values for VMT and land-use mix (diversity) relation in individual studies range from +0.03 (non-retail housing balance VMT per household relation in Greenwald (2009)) to -0.27 (Entropy Index – VMT per household in Kuzmyak (2009), but is most commonly observed to be around -0.10 (Kuzmyak et al., 2006, Kockelman, 1997, Pushkar et al., 2000, Sun et al., 1998, Ewing et al., 1996). Similar differences can also be observed in range and direction of relation in elasticity values of design measures. More consistent results have been observed in relation access to the destination variable have with VMT, these values range mostly around -0.20 (Zegras, 2007, Pushkar et al., 2000, Boarnet et al., 2004).

The statistical and practical significance of these relations reiterate the importance of their urban planning application. The average weighted elasticity values observed in Ewing and Cervero (2010) have broader application in evaluating land-use plans and policies according to their impact on vehicle distance travelled and transit and walk choice. Consequently, they also impact energy conservation, and pollution and greenhouse gas emission reduction. The average weighted elasticity can be used as quick inputs in studies to prepare land use or land development plans, which promote non-motorized and public transit modes of travel. However, the variation observed in individual studies makes it necessary to study the relation in the given context, especially in the developing country context

4.3 Modelling travel behaviour and built form relation

In Table 4-1 methods that have been used in empirical studies concerning land use/built form and travel behaviour are presented. Multi-variable linear regression (MLR) and logistic regression (LR) models are most commonly used to study the relation between built form and travel behaviour, where travel behaviour is the dependent variable and built form is the independent variable. MLR is mostly for VKT - built form relation and LR for mode choice relation.

Travel behaviour in this research is represented by the distance individuals travel to accomplish work and non-work activities and the modes they choose for travel. In this sense, the behaviour represents decisions of consumers when they are confronted with alternatives. These alternatives are the distances they intend to travel and the choice of mode to accomplish the travel. This behaviour is best studied by considering the behaviour of individuals. Thus, the developed model is based on real decisions an individual makes in his or her travel behaviour and the factors, which influence these decisions. In the context of this study, the influencing factors will be the built-form variables.

Table 4-1: Common methods used to study built form - travel behaviour relation

Data	Method of Analysis*#	#
Aggregate	Linear regression	5
	Nonlinear regression	1
	Simultaneous linear equation	1
Disaggregate	Linear regression	28
	Logistic regression	16
	Negative binominal regression	6
	Probit regression	3
	Tobit regression	3
	Propensity score matching	2

* Attitudinal, crime, level of service, socio-economic variables, station, weather and work place variables are used as controls,* Socio-economic variables are the most common controls used, , # = No of times method of regresson analysis has been used in built form travel behaviour analysis as reported in (Ewing and Cervero, 2010)

As presented in Table 4-1, linear regression models are usually used to model the relation between travel distance and built-form measures. The category of models that attempts to model probability of making the transport mode choice is called 'probabilistic models'. These models measure the value of built-form measures as input or a tool to analyse the individual's choice of travel behaviour, for example mode choice. For analysing mode choice, binary (0,1) data inputs are used and analyse the probabilistic discriminant model of choice behaviour. The logit model estimates express the log of the odds of choosing a particular mode over other modes as a function of log of built-form measures that are found to significantly explain choice of the mode under consideration. The framework of logit model in a stochastic mode choice framework is based on the work done by McFadden (1974), Luce and Suppes (1965) and others. For every individual i with n alternative mode choice options, it is assumed that the individual i associates to each alternative j a systematic utility, which is a function of the observed attributes of alternative j and of the observed characteristics of the individual i. Furthermore, it is assumed that the individual chooses a transportation mode for which the associated utility is the highest. The utility of U_{ij} of mode j to an individual i is expressed as a linear combination of variables expressed as:

$$V_{ij} = \alpha + bX_{ij} + cZ_{ij} \text{……………………………………………Equation 4-1}$$
$$U_{ij} = V_{ij} + \epsilon_{ij} \text{……………………………………………………Equation 4-2}$$

Where X_{ij} and Z_{ij} are vectors that determine the choice of the particular mode. These could be socio-demographic characteristics of the individual, characteristics of the mode or in the case of the study, α is the alternative specific constant and is normally interpreted as representing the net influence of all unobserved characteristics of the individual in the utility function (de Dios Ortúzar and Willumsen, 2001). The discrete choice model adds a random part ϵ_{ij} to the utility V_{ij} to constitute the random utility model as expressed in Equation 4-2. ϵ_{ij} reflects the unconventional behaviour and tastes of the individual along with measurement or other errors in the model. The outputs of such a model give the relation between choice of transport mode and the built-form measures, the strength of association between the two, the proportion of choice or uncertainty explained by the hypothesized relation and confidence in prediction of future predictions.

The probability that a person will choose a particular transport mode j is expressed as the following equation, which is also called the standard multinomial logit model where k refers to a set of alternative mode choices.

$$P_j = \frac{\exp(U_{ij})}{\sum \exp(U_{ik})} \qquad \text{Equation 4-3}$$

As described by de Dios Ortúzar and Willumsen (2001), the sum of people using a certain transport mode will be equal to the sum of each individual's probability of choosing that particular mode.

The odds ratio shows the strength of association between a predictor (in this case the built-form variable and the response set (mode choice in this case). The odds ratio is expressed as in Equation 4-4. If the odds ratio is one, there is no association; if the ratio is higher than one that means the association is positive; if the ratio is less than one, the association is negative. Thus, the original coefficient 'β' represents the 'additive effect' of a unit change in the built-form measure under consideration, while the odds ratio represents 'multiplicative effect' of a unit change in built-form measure on the odds of choice of a particular transport mode.

$$\text{Odds} = \frac{\text{Prob(mode choice)}}{\text{Prob(no mode choice)}} \qquad \text{Equation4-4}$$

When modelling the relation between built form and travel behaviour, an important consideration is the issue of spatial self-selection (Kitamura et al., 1997, Krizek, 2003, Schawanen and Mokhtarian, 2005, Handy et al., 2005, Mokhtarian and Cao, 2008). Spatial self-selection indicates the tendency of individuals to locate in areas that meet their travel preferences. For example, an individual who travels a lot on transit likes to locate near transit stops. With self-selection of location, it is difficult to establish a relation between built form and travel behaviour. The residential self-selection is a phenomenon where residents choose to live at a place that matches their desired travel pattern, instead of adopting their travel pattern to built-form characteristics (Tracy et al., 2011). The problem of self-selection varies from region to region and it can be difficult to distinguish the effect of built form because of the self-selection problem (Mokhtarian and Cao, 2008). However, (Naess, 2009) studied the problem and suggested that even after accounting for self-selection, the influence of built form on travel behaviour is significant. Many recent studies address this self-selection by using carefully selected socio-economic and demographic variables as control variables. Naess (2009) observes that these control variables can reduce the influence of the built-form variables; for example, individual income can affect the influence of density. Therefore, it is important to select only a small number of control variables (Tracy et al., 2011).

4.4 Methodology

Travel behaviour data

As data on modes used for travel and travel distance for work and non-work purposes is not available from any of the previous transport studies conducted for the city of Ahmedabad, it was decided to conduct a household survey. Travel behaviour is quantified as vehicle kilometres travelled (VKT) by each individual per day for work and non-work purposes. Thus, the following variables are used to quantify different aspects of travel behaviour.

i. Home-based daily VKT per person for work;
ii. Home-based daily VKT per person for non-work purpose;
iii. Public transport used for work-purpose travel (trips made by public transit, Intermittent Public Transport (IPT) and shared IPT modes);
iv. Public transport use for non-work-purpose travel;
v. Non-motorized use for work-purpose travel (Walking and Bicycle);
vi. Non-motorized use for non-work-purpose travel;
vii. Self-Owned Motorized Vehicles (SOMV) (Cars and Two-Wheel Motorcycles) for work-purpose travel; and
viii. SOMV use for non-work-purpose travel.

The total distance travelled includes return trips. If multiple modes like walking and public transit are used for a single purpose, both modes are considered as modes used for the purpose and are accounted for separately. As stated earlier, this data is spatially represented using points that are geo-referenced to the residential location of the surveyed household. After cleaning the dataset, 4950 valid household samples are available that has travel behaviour information of 16124 individuals (only individuals older than 16 years were considered for analysis) and 29880 trips. Presented in Table 4-2 is the purpose-wise distribution of trips and the Mean Trip Length (MTL) for each of these purposes. Work-purpose trips account for around 30 per cent of total trips, and MTL for work-purpose trips is 5.50 km. Trips for all other purposes are of shorter distance except trips for social purposes.

Table 4-2: Trip purpose and mean trip length

Trip Purpose	Frequency	Percentage	Mean Trip Length (Km.)
Return Home	14973	49.9	3.59
Work	8855	29.5	5.50
School/Education	2046	6.8	3.59
Shopping	2309	7.7	2.12
Recreation	533	1.8	3.26
Social	951	3.2	5.02
Health	313	1.0	3.50
Total	29980	100.0	4.08

In Ahmedabad, six modes of travel are common. These are walking, bicycle, public transit (PT), auto-rickshaw (Intermittent Public Transport or IPT), shared auto-rickshaw (SIPT), and two-wheel motorcycle (TWM). Table 4-3 clearly shows that walking and two-wheel motorcycle are the most common modes of travel in Ahmedabad. Walking, bicycle and public transit account for 50 per cent of total trips made in Ahmedabad, whereas there is very little use of car, IPT and SIPT modes. The mean trip length is high for public transit and cars as compared to other modes and, on an average, individuals walk a little over 1.34 kilometres.

Table 4-3 : Modes used and mean trip length.

Trip Purpose	Frequency	Percentage	Mean Trip Length (Km.)
AMTS (Public Transit)	3691	12.3	7.08
Auto-rickshaw	1249	4.2	4.53
Bicycle	3845	12.8	4.01
Car	618	2.1	6.41
Shared auto-rickshaw	1078	3.6	4.15
Two-wheel motorcycles	9298	31.0	5.42
Walk	9350	31.2	1.34
Other modes	851	2.8	4.38
Total	29980	100.0	4.08

In the following section, the method used to relate travel distance and mode choice for work and non-work purpose travel with built form is described.

Data processing

An earlier discussion clarifies that built-form measures are quantified and represented using a 100 m. x 100 m. uniform grid, and travel behaviour variables collected from the household survey are represented as points. Overlay function (Figure 4-2) is used to combine built form and travel behaviour datasets to create a new data table that has information of both travel behaviour and built-form measures.

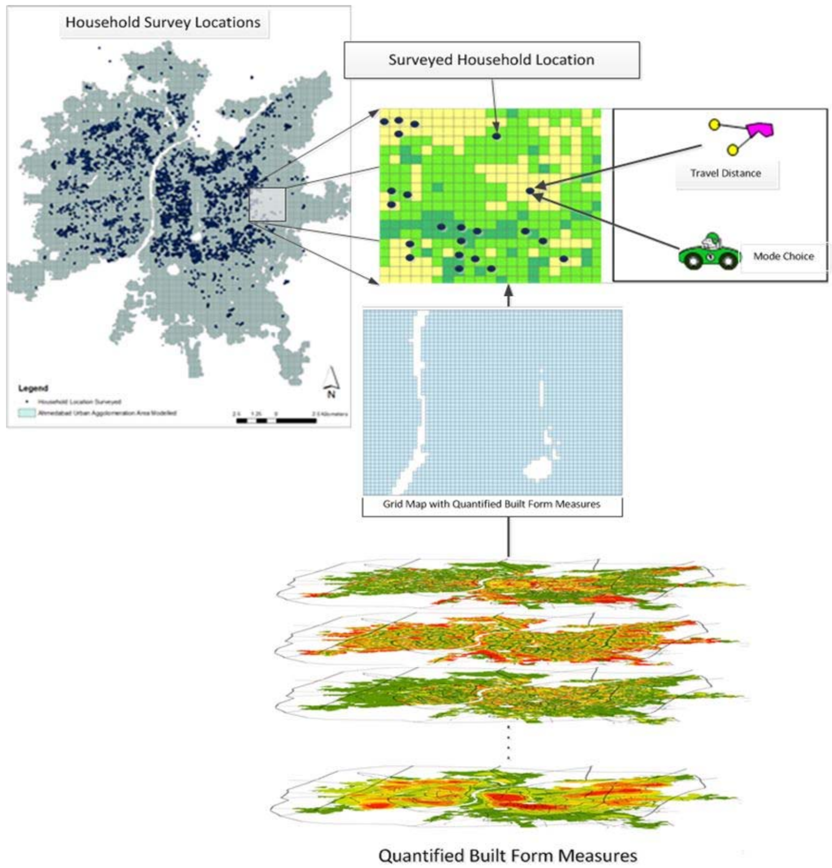


Figure 4-2: Operationalizing Built Form - Travel Relation

4.5 Preliminary analysis

From the data source, over 25 socio-demographic and built-form variables were generated, and analysed for relationship with dependent variables (travel behaviour variables). Explanatory variables that were found to have little correlation with travel behaviour were discarded. Explanatory variables with multi-co-linearity were also removed. For some variables like between job - housing ratio, entropy index, and kernel junction density - kernel road density, multi-co-linearity was found to be high for the respective correlations. However, their correlation with travel behaviour varied. For example, job - housing ratio has a better correlation with the use of two-wheel motorcycle for work-purpose trips as compared to entropy index, whereas entropy index has better correlation values with the use of public transit for work-purpose trips. In this situation, from the two variables the variable that has higher correlation with the dependent variable analysed is used; so, for the cited example, entropy index is used to study the choice of the public transport ode whereas job - housing ratio is ignored in the analysis. Of the many explanatory variables created and tested, only 18 were eventually selected for inclusion in the model.

Household demographics

The following four non-built-form variables were taken from the travel survey, and are included as control variables: respondent's age, sex, personal income, and number of motorized vehicles owned by the respondent. Including these variables helps to address the previously mentioned problem of residential self-selection to a certain extent.

Multiple regression is used to predict total kilometres travelled by each individual per day, and the binomial logit model is used to compute the mode choice probabilities for work and non-work purpose trips. Trips made for shopping, recreational and social purposes are considered as non-work purpose trips. To compute the regression model, step-wise linear/logistic regression methods are used, and the analysis is conducted in three blocks. The control variables are introduced as the first block in the regression model in forward step. The variable that has the best correlation is introduced first, then the second best, and so on. The first block is considered as the control model. In the second block, statistically significant built-form measures are added to the control model to produce the model termed as 'the built-form model' in this study. In the third step, employment sub-centres' influence on travel distance and mode choice is studied (if work and non-work destinations are any of the employment centres). The stepping-level criteria (probability of F at the entry level of 0.5 and for exit 0.10) are used to introduce variables into the equation.

4.6 Results

4.6.1 Vehicle kilometres travelled

The results of the analysis for travel distance model are presented in Tables 4-4 and 4-5. The F-statistics of all individual variables and models suggest that they significantly explain variations in the dependent variable. The strength of the equations is very moderate and explains little over 23 per cent variation in vehicle kilometres travelled (VKT). The R2 values in the model derived are in similar ranges as observed in Ewing and Cervero (2002) and Tracy et al. (2011).

The total VKT for work purpose (including return home trips) (Table 4-4) and the control variables, namely, number of motorized vehicles owned by the individual and individual income are significantly associated. These results look logical as vehicle ownership increases a person's capacity to travel, whereas individual income is a motivator for the individual to travel more (Dijst and Vidakovic, 2000).

Table 4-4: Travel distance model for home-based work travel

	Control Model		Built Form Model		Employment Centre Model	
	Coefficient	Standard. Coefficient	Coefficient.	Standard Coefficient	Coefficient	Standard Coefficient
(Constant)	4.465		9.931		13.499	
Personal Income****	0.788	0.148	0.561	0.105	0.570	0.107
No of MVs Owned#	0.385	0.067	0.098	0.017	0.046	0.008
Job Access. (SOMV)*			-0.075	-0.282	-0.072	-0.271
Kernel Density Transit Stops**			-0.003	-0.070	-0.002	-0.050
Kernel Density Accidents**			2.702	0.042	2.595	0.041
Job - Housing Ratio***			*-0.048*	-0.036	-0.042	-0.030
Cadila					*-0.264*	-0.008
Walled City					*-4.026*	-0.270
Aahuja Park					-4.869	-0.240
Ashram Road					-3.714	-0.181
Gurukul Road					-3.301	-0.082
Judges Bungalow					-2.691	-0.060
Other job locations					1.565	0.153
Adjusted R2	0.151		0.234		0.025	
Std Err of Est.	5.85		5.65		5.43	
F Statistics	174.92		Change = 102.613		Change = 122.872	

Variables in italics have statistical significance > 95%, variables in italics and underline have statistical significance > 90% , all other variables have statistical significance > 99%, # No of cars and motorized two-wheelers owned, * Cumulative accessibility to 10000 jobs , ** Measured for 750 m radius ,
*** Household is a family with an independent kitchen , **** Personal income = (Income in Rs) /2500

Table 4-5: Travel distance model for home-based non-work travel

	Control Model		Built Form Model		Employment Centre Model	
	Coefficient	Standard Coefficient	Coefficient.	Standard Coefficient	Coefficient	Standard Coefficient
(Constant)	*-4.163*	-	*-1.159*	-	*0.828*	
No. of MV. Owned	1.766	0.105	1.379	0.082	1.017	0.060
Age	0.260	0.084	0.215	0.069	*0.164*	0.053
Job Access (SOMV)			-0.010	-0.060	-0.022	-0.129
Kernel Density Accidents			-2.485	-0.063	-2.274	-0.058
Kernel Density Road Junctions			*-0.004*	-0.047	-0.006	-0.068
Job-Housing Ratio			*-0.056*	-0.042	-0.074	-0.056
Walled City					1.774	0.157
Khokra Gam					2.171	0.139
Girdhar Nagar					4.392	0.112
Ashram Road					2.131	0.106
Aahuja Park					*-0.806*	-0.041
Adjusted R2		0.150		0.190		0.450
Standard Error of Estimate		4.500		4.460		4.340
F Statistics		67.22423		Change = 40.96		Change = 145.63

Variables in italics and underline have statistical significance > 90%,, variable in italics have statistical significance > 95%,, all other variables have statistical significance > 99%

In the built-form model, the signs of variables are consistent with expectations, which are based on (Ewing and Cervero, 2010). It is found that accessibility to jobs using self-owned motorized vehicle, proximity to transit stops, job - housing ratio and Space Syntax Global Integration (SSGI) have negative relation with VKT for work. Similarly, kernel density of accidents has positive relation with VKT by individuals for work-purpose trips.

For work purpose travel, when the destination (employment centre) choice is included in the equation, there is a marginal improvement in the R Square value, and the equation is able to explain 25.4 per cent variation in VKT. It is found that if the Walled City, Ashram Road (locations with highest commercial and retail employment), Gurukul Road or Aahuja Park (fast-developing retail and commercial destinations) are the work destinations, then the individual travels less. Consequently, it can be concluded that individuals like to live close to their work destinations, moreover, it can be said that by developing nodes that have high concentration of retail and commercial jobs would, on an average, reduce the distance individuals travel to work.

For non-work purpose trips, VKT increases with an increase in age and ownership of motorized vehicles. So older people travel longer distance for shopping and other non-work purposes. The built form model explains 19 per cent variation in VKT for non-work trips. The density of accidents has a negative relation with VKT for non-work purpose travel unlike VKT for work-purpose travel. For mandatory trips like work trips, individuals travel despite safety issues, but for non-mandatory trips they are a little cautious and travel less. Moreover, as expected, density of junctions and job - housing ratio have a negative relation with VKT for non-work travel. Specialized shopping and better health and recreational facilities are present in the Walled City and Ashram Road employment centres, so individuals travel longer distance to these locations for non-work purpose trips. This is also an indication that these facilities are not equitably distributed, as also found by (Ilhamdaniah et al., 2005).

4.6.2 Non-motorized mode choice

Presented in Tables 4-6 and 4-7 are non-motorized mode choice equations for work and non-work trips respectively. For work-purpose trips, as expected, motorized vehicle ownership and personal income have a negative relation with bicycle choice and walking choice. Motorized vehicle ownership is also a proxy for higher income. Therefore, bicycle choice is limited to a section of population that is poor but can still afford to hire or purchase a bicycle.

The built form-model is able to predict around 29 per cent of variation in bicycle choice. Accessibility to jobs by SOMV, dissimilarity index and kernel density of accidents have a positive relation with bicycle mode choice, indicating higher vulnerability of these captive users. Increase in road density has a negative relation with bicycle choice, an indication of poor bicycle road infrastructure. The mode choice for walking explains around 19 per cent of variation in choice. The variable, access to job by public transit, proximity to transit stops and population density have a positive relation with walking choice. This highlights the connection between choice of public transit and walking for work-purpose travel. Few people travel to the walled city area using bicycles. whereas for destination areas like Aahuja Park, where many poor people live in the neighbouring areas of the employment sub-centre, the probability of using bicycles increases. An interesting observation is that if we only consider built form, then the walled city should have a high probability of individuals wanting to ride bicycle for work-purpose trips. However, because of the congested street network and poor street infrastructure for bicycles, that is not so. This is also an indication that if bicycle lanes are provided in the walled city, the probability of individuals wanting to use bicycles for trips to work will increase significantly.

Table 4-6: Non-motorized mode choice work travel

	Control Model		BuiltForm Model		Employment Centre Model	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Bicycle Mode Choice						
Constant	-0.521	0.594	-0.33	0.719	-0.354	0.702
Sex (Male)	*0.817*	2.264	0.803	2.232	*0.695*	2.004
Sex (Female)	0.762	2.144	0.782	2.186	0.786	2.194
Personal Income	-0.325	0.723	-0.316	0.729	-0.317	0.728
No. of MVs Owned	-0.75	0.473	-0.716	0.489	-0.708	0.493
Job Accidents (Car)			0.005	1.005	0.005	1.005
Kernel Density Roads			-0.039	0.961	-0.036	0.964
Kernel Density Accidents			*0.619*	1.857	*0.418*	1.518
Kernel Density Transit Stops			-0.002	0.998	*-0.001*	0.999
Dissimilarity Index			0.316	1.372	0.314	1.369
Walled City					-0.46	0.631
Aahuja Park					0.599	1.82
Chi-Square		783.159		change = 77.266		change = 83.801
-2 Log Likelihood		6327.006		6242.673		6158.449
Nagelkerke R Sq.		0.264		0.288		0.304
Walking Mode Choice						
Constant	-0.893	0.409	-1.347	0.26	-1.26	0.284
Personal Income	-0.227	0.797	-0.217	0.805	-0.215	0.806
No. of MVs owned	-0.369	0.691	-0.345	0.708	-0.323	0.724
Job Access (Public Transit)			0.011	1.011	0.011	1.011
Distance to PT stop			*1.092*	2.98	*1.121*	3.067
Net Population Density			0.026	1.026	0.023	1.024
Kernel Density Accidents			-1.141	0.32	-1.178	0.308
Cadila					-0.816	0.442
Ashram Road					*-1.255*	0.285
Khokra Gam					-0.519	0.595
Chi-Square		226.855		change = 46.277		change = 66.244
Nagelkerke R Sq.		0.157		0.187		0.231

Variables in italics and underline have statistical significance > 90%,, variable in italics have statistical significance > 95%, all other values have statistical significance > 99%, Exp (B) = Odds

For work trips on foot, it is mainly the poor who walk, and it is observed that individuals prefer to live very close to their work destination (indicated by accessibility to jobs). However, for travel to destinations like Ashram Road or Khokra Gam employment sub-centres, which are less accessible to poor people, or have more jobs for individuals in the higher income category, individuals prefer other modes for travel.

Table 4-7: Non-motorized mode choice for non-work travel

	Control Model		Built-form Model		Emp. Sub-Centre Model	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Bicycle Mode Choice						
Constant	-3.472	0.031	-3.153	0.043		
Personal Income	0.247	1.281	0.235	1.265		
No. of MVs Owned	-0.563	0.570	-0.591	0.554		
Net Population Density			-0.070	0.933		
Chi-Square		35.336	change =5.302 (0.021)			
Nagelkerke R Sq.		0.111		0.121		
Walking Mode Choice						
Constant	0.943	2.567	0.545	12.746	0.019	7.532
Sex (Male)	-1.874	0.154	-1.606	0.201	-1.303	0.272
Sex (Female)	-0.713	0.490	-0.681	0.506	-0.664	0.515
Personal Income	-0.139	0.870	-0.121	0.886	-0.116	0.891
No of MVs Owned	-0.282	0.754	-0.240	0.787	-0.220	0.803
Job Access (Car)			0.006	1.006	0.008	1.008
Job Access Public Transit			0.010	1.010	0.010	1.010
Ker. Density Accidents			0.832	2.297	0.766	2.152
Kernel Density Transit Stops			-0.002	0.998	-0.002	0.998
Kernel Density Road Junctions			0.002	1.002	0.003	1.003
Walled City					-0.737	0.478
Ashram Road					-1.332	0.264
Aahuja Park					0.379	1.461
Khokra Gam					-0.618	0.539
Girdharnagar					-2.353	0.095
Chi-Square		278.007	change = 94.617 (0.000)		change = 150.855 (0.000)	
Nagelkerke R Sq.		0.206		0.274		0.449

Exp (B) = Odds

Concerning non-work trips (Table 4-7) personal income has a positive relation with bicycle use, but SOMV has a negative relation. Therefore, an individual who is rich enough to own a bicycle but not rich enough to purchase a motor vehicle uses a bicycle for shopping. Bicycle use for non-work trips also increases with an increase in population density. Given the spatial pattern of population density in Ahmedabad, this indicates greater use of bicycle in the eastern parts of the city as compared to the west. Walking mode choice model for non-work trips explains 27 per cent of variation. Compared to males, more females prefer walking for non-work trips. The preference increases with better access to jobs by SOMV and public transit, and surprisingly, also at locations where accident density is high. Therefore, these individuals are captives of the walking mode as they cannot afford other modes of travel. Walking relates negatively to SSGI, which means that better global integration of the network does not encourage an individual to walk. When the destination for non-work trips is any of the sub-centres except Aahuja Park, the preference for walking reduces, which, as in the case of the bicycle mode, is an indication of poor availability of walking infrastructure in these areas. Most such locations, therefore, have built-form variables that favour walking as the preferred mode but very poor NMT infrastructure.

4.6.3 Public transport mode choice

Three public transport modes are commonly used in Ahmedabad, namely, public transit, auto-rickshaws and shared auto-rickshaws. For the public transit (AMTS bus service) mode choice, the signs of control variables are on the expected lines, that is, the poor who do not have access to SOMV would use ATMS buses. A negative relation with age is, however, unexpected, as the old are expected to use public transit service. However, the direction of the observed relation in the study reflects poor quality of service of public transit provided by AMTS buses. This does not relate with capacity restraints faced by the disadvantaged sections of the population like the aged. Proximity to transit stop, kernel density of transit stops, population density and density of BPL population increases the use of AMTS bus service. Interestingly, however, accessibility to job and entropy index reduces public transit use. Furthermore, kernel density of accidents reduces public transport use. Transit use increases if the destination is the walled city or Ashram Road employment centre, which can be explained by the higher density of PT routes leading to these locations. It can be inferred that AMTS provides travel to work opportunity for individuals living in areas with lower job densities but with high population density especially of the BPL category. The travel destinations of these trips are locations with high job densities like the Walled City and Ashram Road employment sub-centres. However, AMTS provides less opportunity for individuals living in the central parts of the city to travel to work using AMTS buses.

Results from this study reveal that the choice of intermittent public transport service (auto-rickshaws) for work-purpose trips has a negative relation with income, accessibility to jobs and dissimilarity index. Choice of auto-rickshaw as a travel mode, however, has a positive relation with the entropy index. Therefore, locations where the balance of land use is good, preference for auto-rickshaw is comparatively higher. This preference also increases if the destination is either the Walled City or Khokra Gam employment sub-centres. It can therefore be inferred that individuals who are not rich and live in areas that have poor accessibility to jobs, use auto-rickshaws for work-purpose trips. Congested locations like the walled city also attract more work trips by auto-rickshaw, which mostly substitutes for personalized modes of transport for individuals who prefer not to use AMTS because of its poor service quality.

Table 4-8: Public transport choice for work travel

	Control Model		Built Form Model		Employment Centre Model	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Public Transit Mode Choice						
Constant	-1.078	0.340	-0.931	0.394	-0.828	0.437
Age	-0.009	0.991	-0.009	0.991	-0.008	0.992
Personal Income	-0.160	0.852	-0.161	0.851	-0.174	0.840
No. of MVs Owned	-0.189	0.828	-0.185	0.831	-0.211	0.810
Job Access (Public Transit)			-0.005	0.995	-0.009	0.991
Distance to Transit Stop			-0.715	0.489	-1.344	0.261
Net Population Density			0.016	1.016	0.005	1.005
BPL Density			0.016	1.016	0.011	1.011
Kernel Density Accidents			-0.386	0.680	0.147	1.158
Kernel Density PT Stops			0.001	1.001	0.000	1.000
Kernel Junction Density			-0.001	0.999	-0.002	0.998
Entropy Index			-0.177	0.838	-0.252	0.777
Walled City					1.024	2.783
Cadila					-0.407	0.666
Ashram Road					0.664	1.942
Aahuja Park					-0.468	0.626
Gurukul Road					0.367	1.443
Chi-Square		99.88(0.000)		Change = 23.59(0.000)		Change = 73.24(0.000)
Nagelkerke R Sq.		0.132		0.161		0.256
Auto-Rickshaw Mode Choice						
Constant	-2.985	0.051	-2.600	0.074	-2.675	0.069
Personal Income	-0.264	0.768	-0.269	0.764	-0.270	0.764
No. of MVs Owned	*-0.176*	0.839	*-0.224*	0.799	*-0.232*	0.793
Job Access (Car)			-0.013	0.987	-0.016	0.985
Dissimilarity Index			*-0.597*	0.550	*-0.619*	0.538
Entropy Index			*1.149*	3.154	*1.165*	3.207
Walled City					*0.512*	1.669
Khokra Gam					*0.821*	2.272
Chi-Square		78.326		Change=64.460(0.000)		Change=34.650(0.000)
Nagelkerke R Sq.		0.120		0.216		0.258
Shared Auto Mode Choice						
Constant	-3.061	0.047	-3.424	0.033	-3.384	0.034
No. of MVs Owned	-0.574	0.563	-0.531	0.588	-0.514	0.598
Net. Population Density			0.052	1.053	0.051	1.052
Net Job Density			0.080	1.083	0.079	1.082
Ashram Road					*-0.903*	0.405
Chi-Square		55.311		Change = 15.33(0.000)		Change =6.173(0.000)
Nagelkerke R Sq.		0.134		0.173		0.189

Variables in italics and underline have statistical significance > 90%,, variable in italics have statistical significance > 95%,, all other values have statistical significance > 99%, Exp (B) = Odds

Shared auto-rickshaws compete with AMTS and operate on routes where AMTS provision is deficient (Munshi, 2003). Preference of this mode for work-purpose trips increases with increase in job density and population density and decreases if the work destination is Ashram Road. Therefore, those who use this mode are individuals who do not have a self-owned motorized vehicle and travel to destinations that are not centrally located like the Ashram Road employment sub-centre. Demand for shared auto-rickshaw is a proxy for demand for AMTS bus service. AMTS needs to augment its supply of buses on routes where shared auto-rickshaws operate. The locations that have high population and job densities (like the Walled City) need to be connected well with other parts of the proper public transit service.

Table 4-9: Public transport choice for non-work travel

	Control Model		Built-form Model		Emp. Centre Model	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Public Transport (AMTS) Mode Choice						
Constant	-2.723	0.066	-2.695	0.068	-2.790	0.061
Age	0.015	1.016	0.015	1.015	0.015	1.015
No. of MVs Owned	-0.167	0.847	-0.177	0.838	-0.188	0.828
Job Access Public Transit			-0.018	0.982	-0.018	0.983
Kernel Density Transit Stops			0.003	1.003	0.002	1.002
Walled City					0.808	2.244
Ashram Road					0.601	1.823
Aahuja Park					-1.592	0.203
Girdharnagar					1.030	2.802
Chi-Square		20.048		change = 15.19 (0.001)		change =70.98 (0.000)
Nagelkerke R Sq.		0.113		0.199923077		0.591076923
Auto Rickshaw (Intermittent Public Transport) Mode Choice						
Constant	-2.804	0.061	-3.499	0.030	-3.788	0.023
Age	0.014	1.014	0.016	1.016	0.017	1.017
Net Population Density			0.061	1.063	0.062	1.064
Kernel Density Transit Stops			0.001	1.001	0.001	1.001
Dissimilarity Index			0.423	1.526	0.396	1.486
Walled City					0.694	2.002
Ashram Road					0.614	1.847
Khokra Gam					0.606	1.833
Girdharnagar					2.554	12.855
Chi-Square		10.69		change = 40.73 (0.000)		change =24.422 (0.000)
-2 Log Likelihood		2081.660		2040.924		1967.3
Nagelkerke R Sq.	0.017			0.080142857		0.191857143
Shared Auto (Shared Intermittent Public Transport) Mode Choice						
Constant	-2.37	0.093	0.875	2.400	0.435	1.544
No. of MVs Owned	-0.601	0.548	-0.482	0.617	-0.497	0.608
Job Access. (Car)			0.010	1.010	0.009	1.010
Kernel Density Roads			-0.074	0.929	-0.069	0.933
Job - Housing Ratio			0.039	1.040	0.039	1.039
Cadila					1.159	3.188
Chi-Square		49.555		change = 32.26 (0.000)		change =9.188 (0.000)
Nagelkerke R Sq.		0.14		0.24		2.62

Exp (B) = Odds

Public transit choice for non-work travel (Table 4-9) relates positively with age and kernel density of transit stops. However, it has a negative relation with access to jobs. Use of public transit for non-work trips, as for work-purpose trips, increases when the destination is the Walled City or Ashram Road. Therefore, choice of public transit, as stated earlier, is related to quite an extent to the provision of the system. Choice of auto-rickshaw for non-work trips also increases with age, population density and dissimilarity index. Use of auto-rickshaw for non-work trips is also higher if the trip destination is either the Walled City, Ashram Road, Khokra Gam or Girdharnagar employment sub-centre. Shared auto-rickshaw use increases with increase in access to job by SOMV (computed as accessibility by car) and job - housing ratio. Therefore, in locations that are close to commercial /retail/industrial locations, the use of shared auto-rickshaw is high. Moreover, the preference for shared auto-rickshaw increases if the destination is the Cadilla employment sub-centre.

4.6.4 Self-owned motorized vehicle mode choice

The preference for two-wheel motorcycles, which as can be seen from Table 4-3, are the most common mode used in the city of Ahmedabad, increases with an increase in income and motor-vehicle ownership. Among the built-form variables, preference for two-wheel motorcycles increases with increase in job density and kernel density of junctions. Net population density, job - housing ratio, Space Syntax global integration and dissimilarity index have a negative relation with preference for two wheel motorcycles for work-purpose trips. Therefore, at locations that have congested road network with high job densities but a poor mix of land use and regional integration of road network, the choice of two-wheel motorized vehicles for work-purpose trips is higher. Figure 4-1 shows that most of these built-form variables encourage the use of non-motorized modes and public transport modes. The analogy is very clear--increasing densities and land use mixing can only result in higher pedestrian, bicycle and public transport use if these modes and infrastructure supporting these modes are sufficiently provided. If not, these built-form variables will only result in more trips, leading to higher traffic flows to these locations, which would make these streets less safe for bicycles and pedestrian movement, thus encouraging higher use of two-wheel motorcycles. In locations where non-motorized transport loses out because of poor infrastructure facilities, two-wheel motorcycle gains because of its ease of use on congested and poorly designed streets.

Like two-wheel motorcycles, the choice of cars also has a positive relation with income and SOMV and the beta (B) values are also, as expected, significantly higher. Preference for car for work-related trips also increases with an increase in kernel density of accidents, increase in access to jobs by public transit, distance to public transit stop and net population density. The relation that choice of car has with density of accidents and residential density is logical. This can be inferred as higher use of cars because it is safer to travel by car in accident-prone locations compared to other modes. Moreover, lower residential density means higher per-capita use of residential space, which is usually associated with rich people and with more space for roads, which are logical factors that encourage car use. However, its relation with access to job by public transit and distance to transit mode is unexpected. The probable explanation is that most transit stops are located on major streets that have good local access and high property value. Thus, individuals living close to these stops are likely to be rich people who would use cars to travel to work and not public transport modes. Therefore, access to public transport stops is also a proxy indicator for access to major streets, which might influence car use positively.

Table 4-10: SOMV choice for work-purpose travel

	Control Model		Built Form Model		Employment Centre Model	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Two-Wheel Motorcycle Mode Choice						
Constant	-1.641	0.194	-0.885	0.413	-1.080	0.340
Sex(Male)	*1.045*	2.843	*0.977*	2.657	*1.035*	2.814
Sex(Female)	*0.133*	1.143	*0.115*	1.122	*0.133*	1.142
Personal Income	0.213	1.237	0.204	1.226	0.200	1.222
No. of MVs. Owned	0.688	1.989	0.677	1.967	0.667	1.947
Net. Population Density			-0.024	0.976	*-0.022*	0.979
Net Job Density			0.032	1.033	*0.029*	1.030
Job-Housing Ratio			-0.041	0.960	-0.038	0.962
Kernel Junction Density			0.003	1.003	0.003	1.003
SSGI			-2.232	0.107	*-1.931*	0.145
Dissimilarity Index			-0.237	0.789	-0.225	0.798
Cadila					0.786	2.195
Ashram Road					0.405	1.500
Khokra Gam					0.420	1.522
Gurukul road					*0.476*	1.610
Chi-Square		1271.308 (0.000)		Change = 91.01(0.000)		Change = 58.776
Nagelkerke R Sq.		0.306		0.327		0.340
Car Mode Choice						
Constant	-5.308	0.005	-4.063	0.017	-4.069	0.017
Personal Income	0.351	1.420	0.304	1.356	0.291	1.338
No. of MVs. Owned	0.409	1.505	0.356	1.428	0.335	1.399
Job Access (Public Transit)			-0.035	0.966	-0.034	0.967
Distance to PT stop			*-1.780*	0.169	*-1.758*	0.172
Net. Population Density			-0.104	0.901	-0.097	0.907
Kernel.Density Accidents			1.893	6.641	1.959	7.093
Ashram Road					0.582	1.789
AahujaPark					*-1.050*	0.350
Chi-Square		119.290		Change = 72.38(0.000)		Change = 16.34(0.000)
Nagelkerke R Sq.		0.213		0.288		0.302

Variables in italics and underline have statistical significance > 90%,, variable in italics have statistical significance > 95%,, all other values have statistical significance > 99%, Exp (B) = Odds

Three socio-demographic variables considered in the control model, namely, sex of user, personal income and ownership of motorized vehicle, influence the choice of two-wheel motorcycle for non-work purpose trips positively. The relation with sex indicates that individuals from both sexes prefer to use two-wheel motorcycle for non-work trips, but the proportion of male users is significantly larger. Personal income and the ownership of motorized vehicle also have a positive relation to this mode, so higher the income higher is the use of two–wheel motorcycles for non-work trips. Built-form variables, access to jobs and entropy index have a negative relation with preference for two-wheel motorcycles for non-work purpose trips, but the preference increases if the destination is either the Walled City, Ashram Road, Judges Bungalows, Khokra Gam or Gurukul Road employment sub-centre.

Therefore, individuals who live in the central parts of the city, such as Ashram Road and the Walled City, prefer not to use two-wheeler motorcycles for non-work purpose travel. It is rather, individuals, who visit these areas that show greater preference for using the two-wheel motorcycle. The relation that the choice of car has with the control variables, the built-form variables and the employment-centre variables are similar to the choice of this mode for work-purpose trips. So the car for shopping purpose trips is used more from locations that have poor accessibility to jobs and higher incidents of accidents, and by people who are rich and have high motor-vehicle ownership. Non-work purpose car trips are mostly made to employment sub-centres that are outside the Walled City and have better road infrastructure like Ashram Road, Gurukul Road and Khokra Gam.

Table 4-11: SOMV choice for non-work purpose travel

	Control Model		Built Form Model		Employment Sub-Centre Model	
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Two wheel motorcycle Mode Choice						
Constant	-2.520	0.080	-1.530	0.220	-1.680	0.190
Sex (Male)	2.670	14.430	2.110	8.250	2.000	7.400
Sex (Female)	0.890	2.430	0.880	2.410	0.860	2.370
Age	-0.020	0.980	-0.020	0.980	-0.020	0.980
Personal Income	0.200	1.220	0.170	1.180	0.160	1.180
No. of MVs Owned	0.580	1.780	0.510	1.660	0.480	1.610
Job Access (Car)			-0.010	0.990	-0.010	0.990
Entropy Index			-0.740	0.480	-0.670	0.510
Walled City					0.590	1.800
Ashram Road					1.180	3.260
Judges Bungalows					0.960	2.600
Khokra Gam					0.620	1.860
Gurukul road					0.600	1.820
Chi-Square		448.770	change = 79.311 (0.000)		change = 51.87 (0.000)	
Nagelkerke R Sq.		0.310		0.360		0.390
Car Mode Choice						
Constant	-5.360	0.000	-4.060	0.020	-4.230	0.010
Personal Income	0.230	1.250	0.180	1.200	0.180	1.190
No. of MVs Owned	0.670	1.950	0.570	1.770	0.550	1.730
Job Access (Car)			-0.030	0.970	-0.040	0.960
Kernel Density Accidents			2.970	19.480	2.670	14.480
Ashram Road					1.230	3.410
Khokra Gam					1.410	4.080
Gurukul Road					1.350	3.840
Chi-Square		103.830	change = 37.06 (0.000)		change =24.422 (0.000)	
Nagelkerke R Sq.		0.250		0.340		0.400

Exp (B) = Odds

4.7 Urban policy implications

Urban planning is intervention in the public domain and is traditionally based on a comprehensive analysis of the existing situation. The analysis of the present situation is input into policy formulation, which results in a plan, which is the desired future of urban development and growth of the city. The public policy mechanisms that government authorities use to intervene in the process of urban development in India can be identified as four major interventions. These are: 1) the processes of Development Planning/Master Planning, which is a statutory plan mandated in the State of Gujarat by law under the Gujarat Town Planning and Urban Development Act (1976); 2) the City Development Plans; 3) the process of preparing Town Planning Schemes, and 4) the process of regulating land using General Development Control Rules. Policies are formulated in the Development Plan; strategies to achieve these are formulated in the City Development Plan and/or in the City Mobility Plans; these strategies are translated into action planning using Town Planning Schemes; and the urban built form is monitored, controlled and maintained using the General Development Control Rules (GDCRs). A critique of this process is presented in Chapter 2, which points out that the major drawbacks have been in deriving information from ground realities and translating these into policies. Policies and strategic programs are often independent exercises. The objective of this research in not to alter the urban planning practice in India, but to demonstrate how information from empirical work on ground realties can provide inputs to policy formulation.

Figure 4-3: The Municipal Urban Planning and Management Pyramid (adopted from (Huxhold, 1991)

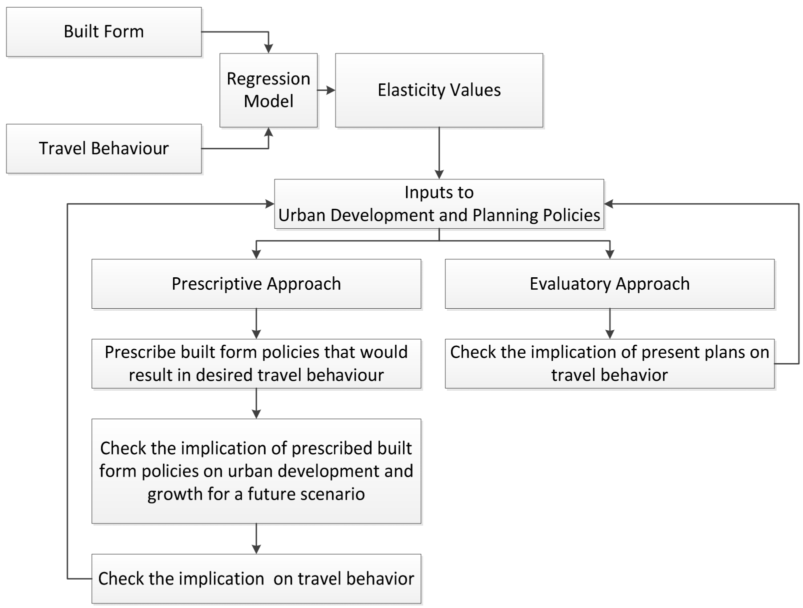


Figure 4-4: Approaches to using built form - travel behaviour relation in urban planning policy formulation

The developed built form and travel behaviour regression models described earlier in this chapter provide essential elasticity values that define how built form influences travel behaviour. These results bridge the essential knowledge gap in the Indian context that will allow the decision-makers to evaluate built-form policies according to their impact on vehicle kilometres travelled by individuals and their modal choices. As shown in Figure 4-4, two approaches can be adopted depending upon the status of town planning policy in the concerned urban area. The first approach can be the evaluatory approach, where the elasticity values can be used to evaluate the implication of the proposed plans (for example, the Development Plan) on travel behaviour. This could either be used as an input into the transport modelling process leading to transport infrastructure provision or as a feedback to the urban development and policy itself. The second approach is to take a prescriptive approach. In this approach, the elasticity values between the built form and travel behaviour relation lead to the formulation of built-form policies. These policies can be used in an urban development and growth simulation model, in a sort of 'what if' analysis, to derive future urban development and growth and these are then checked for travel behaviour implications, which can be used as feedback into future policy formulation. The subsequent step can be an evaluation approach to arrive at an urban development policy with known built form, which is acceptable to the policy-makers.

4.7.1 Information

The built-form measures that are found to significantly influence travel behaviour need to be looked at from two points of view: first, in terms of their elasticity value which determines their impact on travel behaviour, and second, the number of desired travel behaviour variables that the built-from measure has a desired influence on. In Figure 4-5 the elasticity values of the built form variables that were found to significantly influence travel behaviour are presented. From the low-carbon transport development perspective, the desired influences of built form are as follows.

- Reduce the vehicular distances travelled
- Increase walking as the mode choice
- Increase the bicycle mode choice
- Increase public transit mode choice
- Reduce the use of two-wheel motorcycles
- Reduce the use of cars.

The green dots in the figure indicate the influence that built form has on travel behaviour in these desired directions--the darker the colour of the green dots, the higher is the elasticity value. The dotted green lines connect all the desired travel behaviour influences of each built-form measure. Thus, the measures that have dark green dots and many connected dots should be high on the priority list of urban planning policy. The red dots and red lines indicate the built-form measures that negatively influence the above-mentioned travel behaviour outcomes, and should thus be avoided.

The information that can be derived from Figure 4-5 is that there are several built-form measure that garner the desired travel behaviour, and there are quite a few built-form measures that encourage more than one desired travel-behaviour outcomes. The built-form measure 'Job accessibility by car' influences five of the six preferred outcomes listed above with very high elasticity values. Therefore, by increasing accessibility to jobs results in lower travel distance, higher walking and bicycle-mode choices and lower two-wheel motorcycle and car mode choices. The 'Population density' measure has a high negative influence on the use of cars and two-wheel motorcycles, and has considerable influence on walking as the mode of choice and a marginal influence on the public transit mode choice. Therefore, after accessibility by car, increasing population density is the second built-form measure that should be high on the planning policy agenda. The third built-form measure that is found significant with all positive/desired elasticity direction is land-use mix and design indicator.

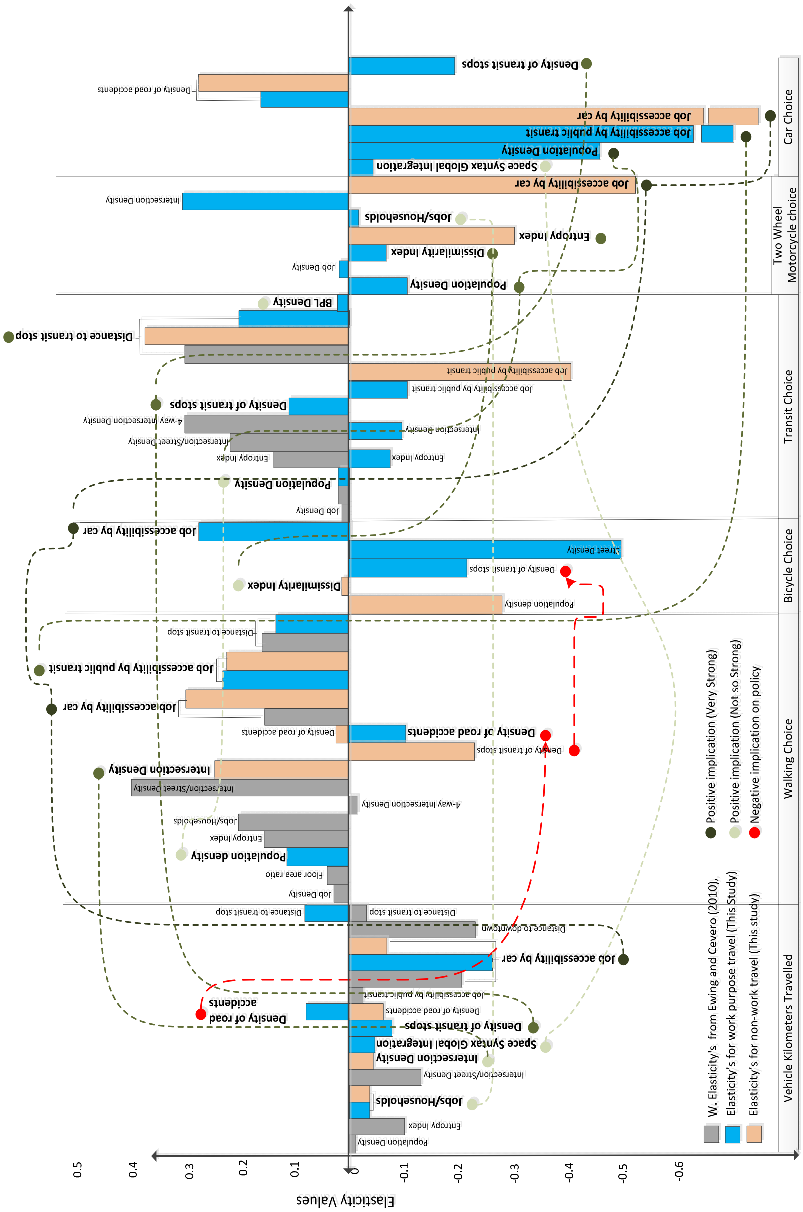


Figure 4-5: VKT, Mode-Choice Elasticity Values

The indicators, job-household ratio, entropy index and dissimilarity index have the desired influence on vehicle kilometres travelled, bicycle choice, two-wheel motorcycle mode choice and choice of car. It can therefore be said that access to destination, density and diversity indicators have substantial influence on travel behaviour and are desired planning policy initiatives in a metropolitan city like Ahmedabad.

The built-form design measures have either a mixed relation with travel behaviour or their elasticity values are low. Densities of intersections and streets have the desired influence on vehicle kilometres travelled (negative influence), walking choice (positive influence) but simultaneously also a strong negative relation with choice of bicycles and a very strong positive relation with choice of two-wheel motorcycles. Similarly, increase in density of transit stops (also representing density of the public transit routes), has a desired influence on vehicle kilometres travelled, choice of public transit and choice of car, but simultaneously has a negative influence on walking and bicycles as modes of choice. The space syntax global integration index also marginally lowers the use of cars and also leads to lower travel distances. These attitudes need a pragmatic consideration; in normal circumstances, where the road is laid out with proper bicycle lanes, one can expect higher use of bicycles with an increase in supply of road infrastructure. However, when this is not done, a network of junctions and streets, which facilitates the use of the motorized modes, will only make the use of bicycles more difficult because of the conflicts it will create with other modes. Likewise, in consideration of public transport choice, recommendations of transit-oriented design suggest that locations around public transit stops should have good intersection density, a good mix of land use, and a system that provides good accessibility to jobs (Bertolini et al., 2009, Carlton, 2009). Consequently, it can be said that demand for public transit as the preferred choice at this moment is defined by proximity to bus stations, level of transit service and density of poor people. However, use of transit (as also indicated by the density of stops indicator) is so much dependent on the supply of the transit system, and on good access and egress infrastructure. From Figure 3-18 it is obvious that transit supply is concentrated towards the Walled City and Ashram Road area (Figure 3-11), where also most jobs are located, so people like to travel to this area, not from these locations. Therefore, in a good urban planning policy we would want to promote higher network density (streets and junctions) that has a good infrastructure for pedestrians and bicycle movement, and to simultaneously support the transit system by providing more routes and stops (density of transit stops).

In addition to the influence of built form using the six Ds, this research also studies the influence of polycentric development on vehicle distance travelled and mode choice. The influence of the employment sub-centre as a destination is studied over and above the influence of the six Ds, where built-form measures like accessibility to jobs can represent a significant portion of the correlation that an employment centre as a destination has with travel behaviour. The question being asked here is whether the formation of sub-centres have an influence over and above the six Ds considered in this research.

Table 4-12: Influence of employment centers on travel behaviour

Employment Centre/Sub-Centre	Type		VKT	Bicycle	Walking	AMTS	TWM	Car
Work Trips								
Walled City	City Centre	β	0.187	-0.094		0.212		
		Odds Ratio		0.630		2.780		
Ashram Road	Commercial and Retail	β	-0.003		-0.059	0.039	0.019	0.039
		Odds Ratio			0.285	1.940	1.500	1.795
Gurukul Road		β	-0.001			0.005	0.015	
		Odds Ratio				1.443	1.610	
Judges Bungalow		β	-0.001					
		Odds Ratio						
Khokra Gam	Mainly Industrial	β	-0.017		-0.023		0.019	
		Odds Ratio			0.595		1.522	
Ahuja Park		β	-0.004	0.032		-0.025		-0.063
		Odds Ratio		1.820		0.630		0.350
Cadila		β			-0.016		0.013	
		Odds Ratio			0.442		2.195	
Girdharnagar		β	-0.004					
		Odds Ratio						
Non-work trips								
Walled City	City Centre	β	0.010		-0.119	0.167	0.096	
		Odds Ratio			0.498	2.244	1.800	
Ashram Road	Commercial and Retail	β	0.002		-0.062	0.036	0.055	0.082
		Odds Ratio			0.264	1.823	3.260	3.410
Gurukul Road		β	-0.004				0.025	0.001
		Odds Ratio					1.820	3.840
Judges Bungalow		β	-0.005					
		Odds Ratio						
Khokra Gam	Mainly Industrial	β	0.002		-0.028		0.043	0.090
		Odds Ratio			0.539		1.860	4.080
Ahuja Park		β	-0.001		0.016	-0.086		
		Odds Ratio			1.461	0.203		
Cadila		β	-0.008					
		Odds Ratio						
Girdharnagar		β			-0.106	0.015		
		Odds Ratio			0.095	2.806		

The general inference is that the development of employment sub-centres has lowered distances that individuals travel in the city. In addition, it has also encouraged the use of two-wheel motorcycles, cars and public transit (for employment sub-centres, and the traditional central business district (walled city) located in the central part of the city). The lack of walking and pedestrian infrastructure in locations with high density of jobs can also be considered as a reason why people do not walk to these areas. In fact, locations that attract a large number of trips, if not supported with proper walking, bicycle and transit infrastructure, can be counter-productive for these modes because, as mentioned earlier, higher conflict of walking with motorized vehicles will lead to lower walking-mode choice. These variables have also been introduced into the equation as dummy variables (in binary format 0 =trip not made to the employment centre, and 1 = trip made to the employment centre). Therefore, the Odds Ratios presented in Table 4-12 represent the odds of increasing the chances of using a particular mode if the trip is made to one of the employment centres. The Odds also indicate a strong inclination towards using motorized vehicles when trips are being made to the employment sub-centres. Two inferences encourage the development of employment sub-centres, first the influence of employment sub-centre development on vehicle distances travelled, and second, the positive relation of large employment centres where public transport connectivity is good with the use of public transport. The third major urban policy implication derived from the empirical information emerging from the results of this study is that employment sub-centre formation should be encouraged, and public transport connectivity to these centres should be good, with good access and egress NMT network.

4.7.2 Action

The outputs of this study and its assessment of the urban development scenarios in terms of environmental, societal and economic benefits demonstrate how built form can be used to achieve low-carbon transport development. Presented in Table 4-13 are built form measures used in this study and the current planning mechanisms that are associated with planning and execution of built form elements. As presented in Table 4-13, the Development Plan preparation is the key process that can help to incorporate the interventions suggested in this research. Because it is such an important process, it should be backed up with empirical evidence that has been presented above.

As discussed earlier, polycentric development and accessibility to jobs are synergistic. A suggested strategy drawn from built-form policy emerging from the information derived empirically is that polycentric development can be used as a tool to achieve higher job accessibility levels. As strategized in Figure 4-6 and depicted in Figure 4-7, adapted from Ma and Banister (2007) and (G.A.O, 2009), it is suggested that alongside urban development, poly-centric development should be encouraged as this will ensure that accessibility of jobs is high and also that travel distances are low. These locations also have transit system connectivity. The transit node can be at the core of each of these sub-centres, and a catchment around transit stations can be created where density and mix of land use are designed in such a way that enough opportunities can be accessed from the transit stops and enough individuals have access to the transit station. Thus, the connection between the sub-centres is through transit, and to a sub-centre from other areas is by NMT modes, and there is a provision for people who want to use SOMV to park at transit stations and use the transit system. Besides, development zoning regulations should promote a good network density and safer streets, along with appropriate land-use mix and balance.

Table 4-13: Built-form measures and the current planning mechanisms

Indicator	Variables	Planning Tool	Mechanism
Density	Net population density	Zoning regulation and Floor area ratio	Development Plan and GDCRS
	Net job density		
Diversity	Job - housing balance	Zoning regulation, Local area planning	Development Plan and Town Planning Schemes
	Floor space dissimilarity index (land- use mix)		
	Floor space entropy index (land-use balance)		
Design	Road/Road junction kernel density	Planning of transport network	Development Plan and Town Planning Schemes
	Public transport stops kernel density		
	Space Syntax Parameters		
Destination	Access to jobs by self-owned motorized vehicle	Zoning regulation and planning of transport network	Development Plan and Town Planning Schemes
	Access to job by transit network		
Polycentric Development	Trip destination location		
Distance from Transit Stop	Distance from transit stop	Planning public transit network	Public Transit Authority

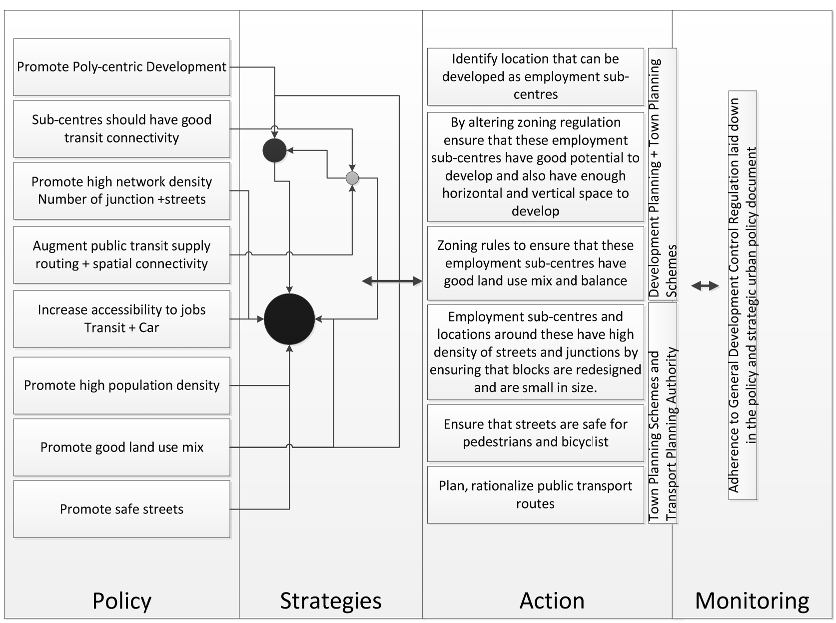


Figure 4-6: Translating Built Form - Travel Behaviour Relation into Urban Policy Actions

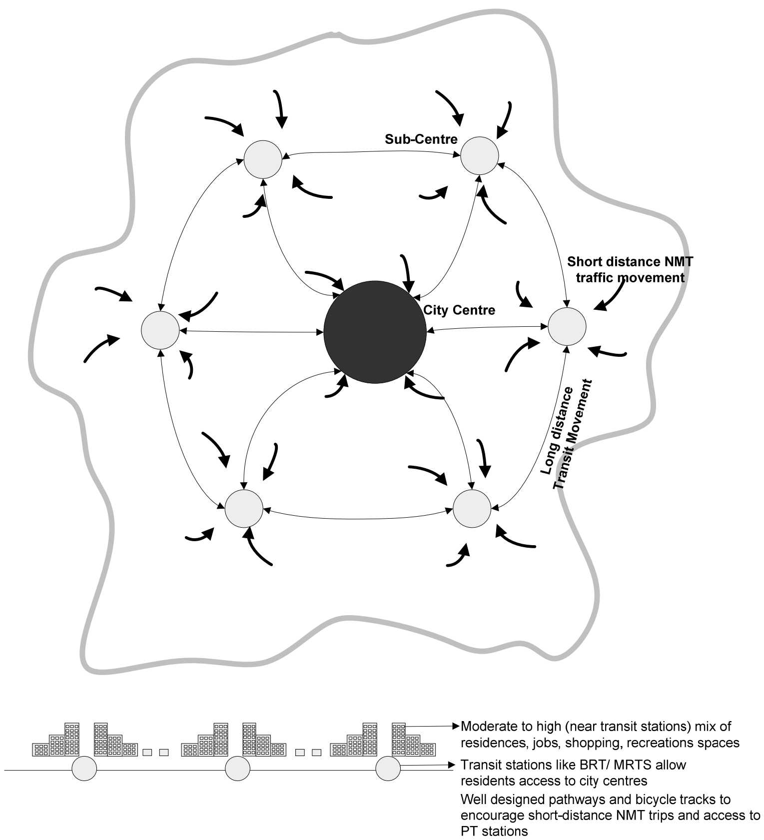


Figure 4-7: Polycentric Model of a City Favouring NMT and PT Use.

As stated earlier, the making of the development plan is the most important process as it can strategize development and its type. However, efficient town planning schemes will directly determine the density, diversity and design of built-form measures, and will also influence the other built-form measures in an indirect manner. The process of preparing the town-planning scheme is therefore an important policy instrument to achieve low-carbon transport development. Two important interventions made in the town planning schemes are very relevant to the discussion of this research: first, determining the road network (in line with arterials and other roads proposed in the development plan), and second, assigning land use for various public amenities such as schools, parks, health facilities, and housing for the economically weaker sections of society. In the present method, reorganizing of the plots determines the block size, and thus the street network, which is influenced by the original plot holdings and their sizes as described by Ballaney and Patel (2008). This laissez-faire type of intervention will not always result in the desired built form. A more pro-active approach is required, which encourages more compact (in terms of building density), mixed use and smaller city blocks (for higher intersection density). As suggested by the Working Group on Transport for the 12th Five Year Plan (Government of India, (2012), streets need to be assigned functions, and accordingly hierarchy. The town planning schemes should include street design so that these are pedestrian and bicycle friendly, and oriented in such a manner that it is easy to access and egress from public transport modes. Town planning scheme are only prepared for unplanned areas and are a one-off affair. However, urban planning is an iterative process, and plans have to be revisited. For locations that are already built up, the old town planning scheme can be revisited by probably preparing plans at an higher aggregation scale like ward plans(Ilhamdaniah et al., 2005) which, especially address locations of land space, design of streets and the possibility of infill development.

As stated in Chapter 2, at present transport in India is the responsibility of no organization, nor do any of the planning organizations employ qualified transport planners or engineers. Therefore, the process of transport planning an important intervention is practically absent. Whatever transport management is done is distributed over several agencies; for example, different agencies are responsible for junction design, traffic signals and road signs, public transport route rationalization and stop identification. Transport planning is important and needs to be given adequate importance alongside urban planning and, as also suggested by Agarwal and Chauhan (2011), a Unified Transport Planning and Management Agency should be created at the city level that would manage the transport policy level issues at the urban level in a comprehensive manner.

4.8 Discussion

The chapter develops multiple regression models to analyse the impacts of built form on travel behaviour (travel distances and mode choice). Spatial overlay methods in GIS were used to arrive at the final dataset that is used to compute the regression models. The built form - travel distance relation is analysed using the multivariate linear regression model, whereas the built form - mode choice relation is analysed using binary logit models. In both regression models, the independent variables are introduced into the equation in a manner that the problem of residential self-selection is addressed and the influence of employment sub-centres on travel behaviour is also separately analysed (after controlling for socio-demographic and other built-form variables). Thus, the developed models allow the analysts and the decision-makers to estimate the influence of effects of various changes in built-form measures (like higher residential/employment density, mixed land-use development, etc.) on reduction in travel distances and choice of non-motorized and public transport modes. The developed regression models also help the decision-makers in deciding the macro-structure of the urban area, for example, should they encourage development of employment sub-centres or not. Thus, this study contributes first, by demonstrating that in India, built form - travel behaviour relation can be developed, which can be used to influence the micro-level built-form indicators like land-use diversity (land use mixing) measured at a scale of grid cell, and macro-level built-form indicators like employment sub-centre formation measured at the urban area level on travel behaviour.

Findings from the present research show that built form has a definite influence on travel behaviour in metropolitan cities like Ahmedabad, and in Figure 4-3 a comparison of elasticity values for work-related trips with Weighted Elasticity Values (WEV) as observed in Ewing and Cervero (2010) is presented. Conventionally, (Figure 4-1) one can expect that by increasing Density, Diversity, access to Destination, and certain Design elements, individuals residing in Ahmedabad will travel less and will lower the use of self-owned motorized vehicles. In the study, the observed relation of VKT with built form and travel behaviour relation is along the expected lines. However, built-form measures, density of intersections and streets that are found to significantly influence VKT in Western countries are not found to meaningfully influence VKT in Ahmedabad. Land-use mix (job - housing ratio) has a lower influence on VKT as compared to WEV observed in Ewing and Cervero (2010). As regards the relation of NMT mode choice with built form, this study shows that the influence of density, diversity, access to destination and distance to transit is along the expected lines. However, the measures representing design indicators were found to have an indifferent relation, which could possibly be because of poor supply of NMT infrastructure--the city lacks bicycle tracks, and the quality and design of pathways do not encourage individuals to walk. The public transit choice in relation with built form indicates that the supply of public transit in the city is deficient. The disutility of travel probably overrides the utility of built form around transit nodes. Therefore, it is not surprising that the observed relation between built form and transit choice has elasticity values that are the opposite of WEV elasticity values observed by Ewing and Cervero (2010) for land-use mix and access to destination measure.

The empirically-derived built form and travel behaviour relation is able to bridge the information gap on how these influence travel behaviour in India. The key information can be used to formulate policies that are targeted to lower or contain the carbon emissions in the city. The three main planning-policy suggestions that emerge from analysing the elasticity of the relation between built form and travel behaviour are: 1) improve accessibility to jobs, 2) promote land-use diversity and population density, encourage higher order public transport infrastructure and better supply and design of streets, and 3) encourage polycentric development in the city. These policy guidelines can be inputs to urban planning processes to enable the formulation of urban strategies and policy that lead to low-carbon transport development as shown in Figures 4-6 and 4-7.

Although Ahmedabad, in many ways, is a typical metropolitan city of India, from this case study it is difficult to generalize the different impacts of built environment variables on travel behaviour for all metropolitan cities in India. This study, however, shows the possibility and feasibility of conducting similar case studies in other similar-sized Indian cities for a meta-analysis that can potentially lead to important policy debate and reflection on the existing urban and transport policies in the country.

In the next chapter, methods that can be used to develop models that are able to analyse the impact that using built form - travel behaviour relation can have on the environment and on benefits to society for a future development scenario are discussed.

5 Built Form driven Low-Carbon Transport Development: Methods

5.1 Introduction

The purpose of this chapter is to develop methods that help to demonstrate how built form - travel behaviour relation can be used to achieve developments that are low-carbon transport development. This chapter seeks to answer two main research questions: What is low-carbon development and how is it measured? How can built form and transport relation help in achieving future scenarios that are low-carbon transport developments?

This chapter is further organized into three sections. The first section discusses the concept of low-carbon development and how it can be measured. This is followed by a discussion on how built form - travel behaviour can be used for low-carbon transport development, wherein methods used to build future development scenarios, work out the environmental impact resulting from travel behaviour induced by these developments, and compute economic and societal benefits are discussed. The last section reflects on the methods described in this chapter.

5.2 Low-carbon transport development

As mentioned in chapter 1, the 'Bali Action Plan' was agreed to at the United Nations Climate Change Conference in Bali in December 2007. The Plan stressed the need to move towards comprehensive Low-Carbon Development Strategies (LCDS). For India, according to Höhne et al. (2008), transport is one of the three key sectors where the potential of Nationally Appropriate Mitigations Actions (NAMAs) could be realized. There is no commonly agreed definition of Low-Carbon Development (LCD), but the view of using 'less carbon for growth' is considered as the common denominator (Mulugetta and Urban, 2010). Thus, the idea is to effectively reduce CO2 emissions without compromising economic growth and the well-being of the population.

As transport is one of the largest consumers of fossil fuels, the concept of low-carbon transport is integral to the agenda of achieving LCD. It is also one of the main focus areas of the World Bank (Ebinger, 2009). The first phase of LCD, from the perspective of the land use and transport relation, will be to ensure low carbon emission from total transport movements in the city without compromising its economic development. In terms of land use, this would mean accommodating growth in activities and population that would occur with development of the economy in such a manner that the consequent CO2 emissions resulting from the related transport activities are minimized. This can be achieved by first minimizing the total distance travelled by individuals using Self-Owned Motorized Vehicles (SOMVs); retaining current non-motorized vehicle and public transit users; encouraging SOMV users to shift to walking, cycling and public transit modes; and improving the SOMV technology so that the carbon footprint of SOMV users is minimal. From an individual point of view, this needs to be achieved with minimal or no reduction in accessibility to opportunities. As stated in the earlier section, accessibility to jobs (access to destination), intensity of use of land (population and job densities), diversity in land use, and proper design of network and land use elements can help in achieving the objectives of the first phase of LCD. The second phase is where the government would intervene to change travel behaviour of individuals, like influencing a change in mode choice from motorized vehicles to non-motorized or transit modes.

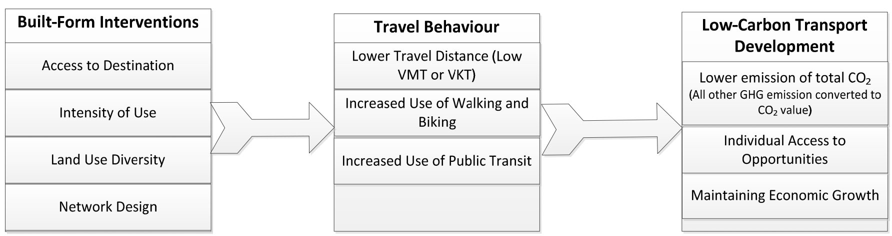


Figure 5-1: Built Form, Travel Behaviour and LCD

Given this background, it is observed that most studies on built form and travel behaviour research have concentrated on identifying the influence of built form on travel behaviour. Ewing and Cervero (2010) state the possibility of using the built form and travel relation and elasticity values of the relation as the guiding principles in planning urban area. The guiding principles in Transit-Oriented Design, Smart Urban Growth and other similar concepts are also drawn from the stated relation. However, the impacts of using built form and travel behaviour on a city's travel behaviour, and there by the impact of travel behaviour on the environmental, needs to be visually represented otherwise it will be difficult for the decision-makers to comprehend the impact and value of using the built form and travel behaviour relation for urban planning decisions. Secondly, as urban development plans are prepared for a twenty-year period, the decision-makers would also like to visualize urban growth for a future year (20-years hence) scenarios and its impact on travel behaviour for these scenarios.

As low-carbon development aims at either maintaining the CO2 emissions at the present level or at a lower level, and at ensuring societal benefits and economic well-being, the next section looks at the methods that can be used to quantify and represent CO2 emissions and societal and economic benefits.

5.3 Future low-carbon transport development scenarios

The relations between built form and travel behaviour were developed and discussed in Chapter 4. The developed regression models apply to the situation in the base year (2007). Thus, the built form properties of each grid cell in the base year can be used to predict the impact of built form on travel behaviour (in terms of mode choice and travel distance) for all locations in the city, and likewise, the impact of transport on the environment in the base year. As indicated by (Ewing and Cervero, 2010), such elasticity values -- of the relation between built form, travel and environment – when developed in a given context, can be used to guide the development of urban areas, for example, aiming at reducing the total vehicle kilometres travelled and increasing the use of non-motorized and public transit modes. In the scenario where distance to destination is a major driver in reducing distances that individual residents travel in the urban area, it is easy to decide to restrict urban growth. However, from the point of view of the well-being of individuals residing in the city, it is required that the stated development should not compromise the economic development of the urban area. In an ideal scenario, concurrent travel behaviour measures aimed at reducing total carbon emissions while ensuring urban development and economic growth need to be sustained. Environmental impact and societal benefits can both be measured using methods described in the preceding section.

To further the above-stated argument, this chapter aims to demonstrate how built form and travel behaviour relations can guide urban development and minimize environmental impacts of travel. For this purpose, it is important to develop two urban development scenarios. In the first scenario which is called the 'Business As Usual' (BAU) scenario, past growth trends and the existing development control norms are used to project the future urban development. The second scenario is called the 'Low-Carbon Development' (LCD) scenario. In the LCD scenario, while demand for urban development is the same as is computed for the BAU scenario, the development control regulations are modified to suit LCD development as suggested in Figures 4-6 and 4-7. Thus, these modifications are guided by elasticity values between built form and travel behaviour, while the simulated future urban development scenario is based on the modified General Development Control Regulation (GDCR). A twenty-year horizon is considered and both scenarios are developed for the year 2030 and are later tested for their transport-related environmental impact. The compromise in developing these scenarios is that it was not possible to test how preferences of individuals will change in scenarios where better infrastructure for non-motorized modes and public transport modes is provided or even for changes in the technology of transport.

The next section provides a literature review of methods used to develop or model the future urban development scenarios. The methods used to simulate the future urban growth of Ahmedabad are discussed. In the fourth section, both scenarios are simulated and urban growth simulation results are discussed. Therefore, the objectives of this chapter are to: A) develop an operational model for urban land-use change, and B) simulate the future urban growth of Ahmedabad based on the two scenarios (BAU and LCD), and predict the spatial extent of land-use change through to the year 2030.

5.3.1 Simulation of urban development and growth

Urban growth models have proven to be significant for describing and estimating land-use changes, and consequently have proved to be valuable for informed urban planning decisions (Vaz et al., 2012, Clarke and Gaydos, 1998, Herold et al., 2003). Previous studies (e.g.,Jokar Arsanjani et al. (In Press), Clarke et al. (1997), Lo and Yang (2002), Dubovyk et al. (2011), Thapa and Murayama (2012)) also emphasized the need and importance of a spatio-temporal analysis of urban growth, in particular in assessing the impacts of future (land-use) scenarios in terms of locations, characteristics and consequences.

The key drivers in urban dynamics are availability of space for urban growth and the ageing process of developments associated with growth (Batty et al., 1999a). Nivola (1999) states that growth can be in four directions: 'in, up, down and out'. Therefore, the objective of successful implementation of land-use development and growth models is to identify what land use will develop and where. Moreover, the 'what if' question needs to be addressed: what repercussions a particular land-use development will have on other developments. If land use is believed to be a Self-Organizing System (Cheng, 2003), then interaction between land uses is the source of higher-level organization of the system. The changes to be considered when modelling urban development are changes from vacant to built-up land and the reverse, and changes in the land use itself, for example, from residential to commercial. The study of these relations necessitates the use of statistical methods such as logistic regression, which helps to define the transition probabilities of land uses(Cheng, 2003).

The empirical evidence on urban growth modelling and prediction dates back to the 1950s. As stated in Torrens (2006), early urban growth models were developed, for example, by Chapin et al. (1962), Tobler (1970)and Nakajima (1977). However, the interest in urban growth modelling faded away in the following years and it only gained momentum in the 1990s (Cheng, 2003) as a result of the improvements in spatial data availability and computing ability (Wegener, 1994). Allen and Lu (2003) observed that in empirical studies on urban growth modelling, urban systems have been viewed in several contrasting ways, which has led to several subsequent theories and models (Wegener, 1994, Southworth, 1995, Thapa and Murayama, 2012). Several land use change and urban growth models have been developed to model these dynamic processes. These include rule-based models such as Cellular Automata (CA) models (Clarke et al., 1996). As observed by Zhao (2011), the work of (Tobler, 1979) has initiated several modifications to the then existing CA models to make them suitable for simulating and predicting urban growth (Batty et al., 1999b, Clarke and Gaydos, 1998, O'Sullivan, 2001, White and Engelen, 2000, Wu, 2002, Yeh and Li, 2002, Yen and Li, 2001). These include the coupling of cellular automata with fuzzy logic (Liu, 2012), Markov chain algorithms (Cheng and Cao, 2011), relative probability and/or regression models (Pinjanowski et al., 1997, Hu and Lo, 2007), statistical models (Landis, 2001) and artificial neural network models (Almeida et al., 2008, Li and Yeh, 2002).

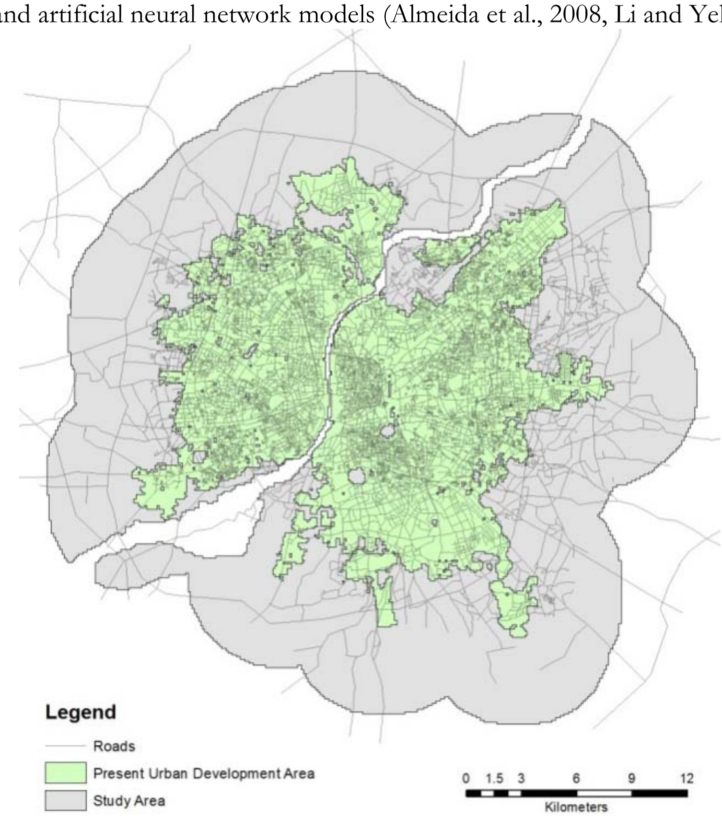


Figure 5-2: The Study Area

The logistic regression based cellular automata model was first proposed by Wu (2002). This hybrid approach, also proposed by Paulmans and Van Rompaey (2009), helps to overcome the individual limitations of logistic regression, which has the inability to quantify the spatial and temporal change (Jokar Arsanjani et al., In Press) and of the CA approach that oversimplifies urban reality and does not provide enough evidence for informed urban planning and decision making (Sui, 1998, Allen and Lu, 2003).

The objective is to develop and implement a logistic regression and cellular automata based model to predict retail, commercial and residential land use in the city of Ahmedabad. Following Wu (2002) and Jokar Arsanjani et al. (In Press), the approach used in this research integrates principles of CA modelling and logistic regression in the development of an urban growth simulation tool. The approach provides space for incorporating certain ground realities of activity location regulation and development control. The method used for urban growth simulation is innovative and different from earlier simulation methods on three counts. First, it simulates the growth of floor space; second, it uses principles of gravity modelling for location-allocation analysis to distribute activities over space; and third, it provides opportunities to incorporate certain ground realities about activity location.

The study area

The study area for this research is the city of Ahmedabad in Gujarat, India. The estimated population living in the city in 2011 was around 6.5 million. In this study, we use the present built-up agglomeration area of around 210 square kilometres as the base-year area, while for the future year a simulation area of around 650 square kilometres (using a buffer of three kilometres on the development area) is considered consisting of the existing built-up area and its surroundings (Figure 5-2).

Modelling approach

This section discusses the methods used in this study for modelling. An overview of the modelling approach is given in Figure 5-3. The approach consists of five major steps. The first step provides a projection for the activity and population growth in Ahmedabad city for the year 2030. The second and third steps develop the logistic regression model that determines the probability of a particular activity to develop at a particular location. As input to this model, accessibility and property value models are estimated. In step 4 the transition probability matrix is calculated which defines the probabilities with which the state of each cell is likely to change to another state. These calculations incorporate the probability of activity location of each cell, the quantity and age of development of activities, and other rules that define how activities locate. The output of this step is used in a CA framework in step 5 to distribute the input activity and population growth from each property tax enumeration zone to each grid cell. This is done for a two-year period; the resulting urban development and growth values are fed again into the accessibility and property tax models in step 2, and all the independent variables are recomputed, to be able to redistribute population for the next two years. This process is applied recursively another nine times to reach the activity allocation for the year 2030.

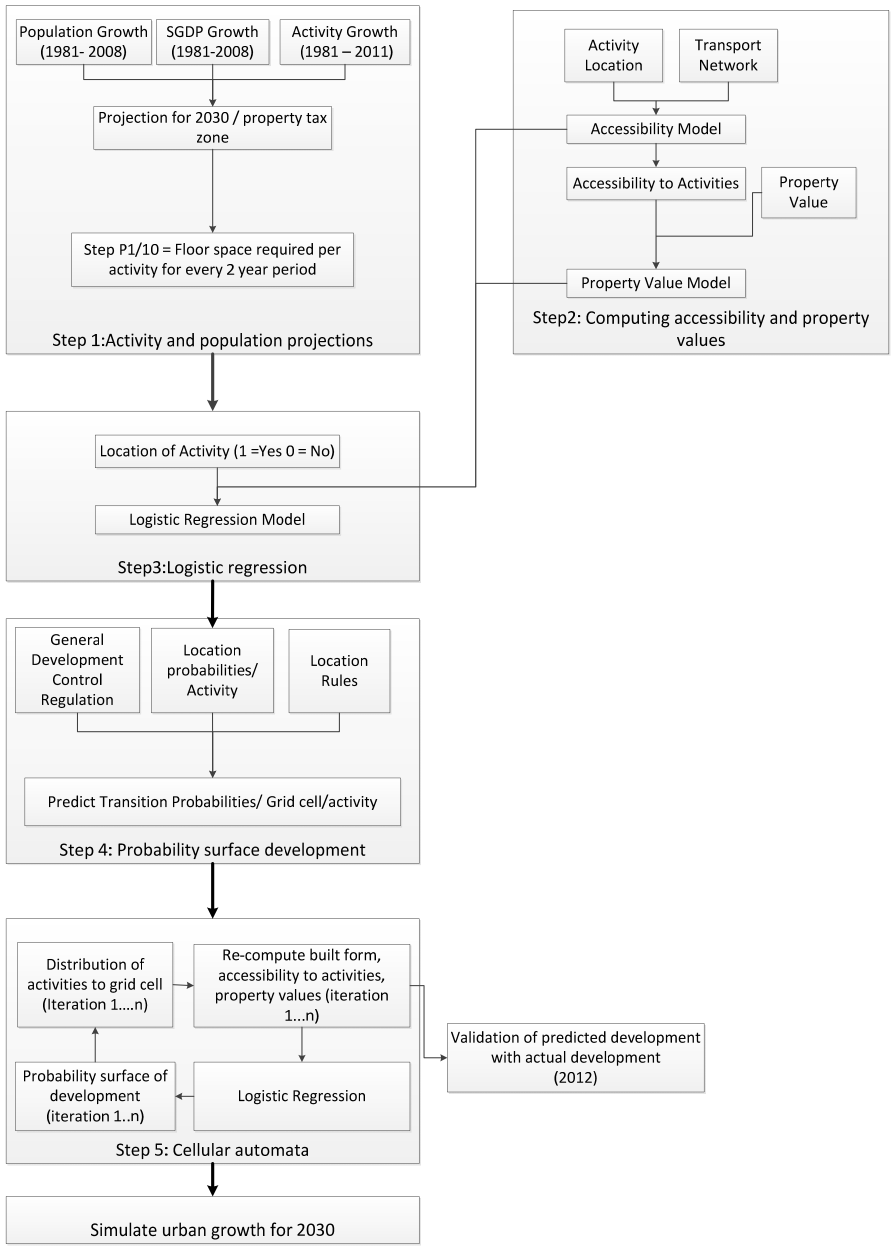


Figure 5-3: Simulating Urban Growth of Ahmedabad: Model Overview

*SGDP= States gross domestic produce

Step 1: Population and Activity Growth Estimation

The growth in total population and the number of activities in the city until the year 2030 is derived by first estimating the ratio of activity and population growth to growth in State Gross Domestic Product (SGDP) between the time periods 1980-1990 and 1990-2000. After this, the mean value of this ratio between activity and population growth and SGDP is computed, and future estimates of SGDP and the ratio of SGDP to each activity are used to forecast the activity space requirements in the designated years (i.e. 2010, 2020 and 2030) as well as the population for the years 2020 and 2030. The activity and population projections are done for each property tax zone. The model is accordingly validated using activity data for the year 2010 for each property tax zone. Subsequently, linear interpolation is used to get a figure for incremental development every two years as in Ahmedabad construction of a building, on an average, takes about two years (Shah, 2012). Therefore, the simulation cycle for locating activities is done in a 2-year cycle. Consequently, all activities and residences that would develop in the next two years are allocated to spatial locations in each iteration.

Step 2 and Step 3: Logistic Regression

Following the work of Wu (2002),Hu and Lo (2007) and Arsanjani, et al. (In Press) logistic regression models are developed to derive a land-use change probability surface. The dependent variable in this model is a binary value representing the location of a land-use (0 if the land-use is not present at the location, and 1 if the particular land-use is present at the location).

In line with the work done by Cheng (2003), Allen and Lu (2003)and Vaz and Nijkamp (2009) in this study non-linear interactions between land-use location choices and a number of structural and functional spatial indicators are adopted to accurately interpret urban growth transitions. Adolphe (2001) defines four urban structural variables: built form, land-use intensity, land-use heterogeneity and connectivity. In addition to these variables, we allow that activities at one location are affected by or affect the location of other activities (Adolphe, 2001; Landis & Zhang, 2000). Accessibility to similar and other activities is also used as a structural parameter that might influence the location of activities and thereby urban growth. In addition to these, the property value, which also represents other parameters that are not captured by the built form measure, such as locational characteristics, age of the development, quality of construction etc., have been included in this research. These three independent sets of variables and their indicators are listed in Table 5-1. All these variables are dynamic and change with each temporal iteration described later on. The default selection criteria in the statistical software package PASW Statistics (a probability at entry level of F=0.5 and for exit F=0.10) are used to introduce variables into the equation. In the second step, statistically significant built-form measures were added to the base model, again using the procedure of forward selection, with the above-mentioned F statistic determining the selection criteria. The variables that were used as independent variables are listed in Table 5-1.

Table 5-1: Independent variables for activity location model

Accessibility to Activities	
Residential	
Retail	
Commercial Offices	
Government Offices	
Entertainment	
Education	
Religious	
Industrial	
Property Value	
Residential	
Office	
Retail	
Built-Form Measures	
Density	Net population density
	Net job density
Diversity	Job-housing balance
	Floor space dissimilarity index (land-use mix)
	Floor space entropy index (land use balance)
Design	Road/Road junction kernel density
	Public transport stops kernel density
	Space syntax parameters
	Adjacent to 18m plus, 12 – 18 m., 6-12 m. roads
Destination	Distance from the railway station
	Distance from the airport
Distance from transit stop	Distance from transit stop
Disparity	Below poverty line population

Step 4: Urban Growth and Development Transitions

The results from the logistic regression calculations in step 3 give the probability of an activity to locate at a particular location. However, even if the probability of an activity to locate at a particular location is high, it is possible that it may not establish itself there because of space constraints, due to zoning regulations or suitability of the location. Activities require a minimum operational space; for example, a restaurant will not operate from a location, which has very little floor space available. The same location, however, might be suitable for the establishment of a retail or commercial office. To operationalize this constraint, minimum floor space is used (i.e., the mean plus two standard deviations to avoid outliers) to check if there is enough space to accommodate a particular activity. Secondly, certain locations are not suitable for certain activities, e.g. a retail activity will not locate on the tenth floor of a building. Such activities will locate on the ground floor only, or at the most on the first floor of the building. Therefore, retail activities are not located at locations where no floor space is available on the ground floor and first floors of the buildings. Lastly, zoning regulations are also applied; development of a location for commercial and economic purpose activities is restricted by a norm that uses width of the adjoining road. Commercial purpose development is allowed only on the ground floor on all streets having widths (right of way) of 9 meters and above, on the ground floor and first floor on streets with widths greater than 12 meters, and on all floors along streets with widths of more than 18 meters. These restrictions on floor level development are implemented by restricting the proportion of a particular land use development from the total floor space that can develop on the whole plot area. This is computed by deducting the area under roads and green space from the area of the grid cell for those abutting roads with width higher than 9 metres. For example, for retail and commercial development on a grid cell abutting a roads having width higher than 9 meters but less than 12 meters, the maximum permissible retail or commercial development is restricted to 10% of the total plot area in the grid cell.

Step 5: Location-Allocation of Activities

In the fifth phase of the model, the location-allocation of activities to the different cells is done. The actual allocation is performed using a gravity function formulated as shown in Equation 5-1. Thus, activities search for a more central location for development around the functional centroid of the property tax zone. However, the development is influenced and proportioned based on the probable floor space that is likely to develop under the particular activity.

$$A_{\mathrm{ig}} = \mathrm{F_{zi}} \mathrm{T_{gi}} \mathrm{D_{gz}^{-2}} \quad \text{..................Equation 5-1}$$

where, A_{ig} is the development of activity *i* in grid cell *g*, F_{zi} is total floor space under activity *i* that will develop in the tax zone *z* ;T_{gi} is total probable floor space that will develop under activity *i* in grid cell *g* and D_{gz} is the distance between grid cell *g* and property tax zone *z*.

In the location-allocation operation, first, the floor space per activity and population is projected for each property tax zone for the year 2030 (see Figure 5-4). In the next step, the total probable floor space that will develop per activity in each grid cell is computed by multiplying the total space available for development with the transitional probability (calculated on a scale of 0 to 1, which will be 0 if zoning rules or location suitability does not favour activity location). The available space for development is computed using Floor Space Index (F.S.I) norms in the General Development Control Regulation (GDCR). The F.S.I indicates the ratio between the built-up area allowed and the plot area available and is one of the components of GDCR that quantifies the development. The Ahmedabad Urban Development Authority (AUDA) area is displayed in Figure 5-4and shows the proposed development plan for the urban development authority jurisdiction of the city. In the zoning regulation, three development zones are marked, Residential 1(R1), Residential 2(R2) and Residential 3(R3). For locations that are not identified as R1, R2 and R3 zones, the R3 zoning rules apply. Different intensities of development are allowed within these development zones. In zone R1 a maximum F.S.I of 1.8 is allowed, in zone R2 a maximum F.S.I of 1.2 is allowed, while in zone R3 a maximum F.S.I of 0.3 is allowed, based on standards set by Ahmedabad Municipal Corporation (AMC, no date). If the F.S.I in a an area is 1, then on a 1000 square metre plot an equal area of built-up space, can be constructed on it. In zone R1, already an additional 25% of F.S.I is allowed where the permissible height cannot be achieved after consumption of F.S.I. To compute the total allowable built-up space in each grid cell, the area that is already developed as a road or a garden plus the existing built up area is deducted from the probable floor space that can develop in each grid cell on all plot areas in the grid cell. Already developed floor area for a building that is less than 50 years old is deducted from the total floor space that can be potentially developed in the grid cell to get the space that is presently available for development in each grid cell.

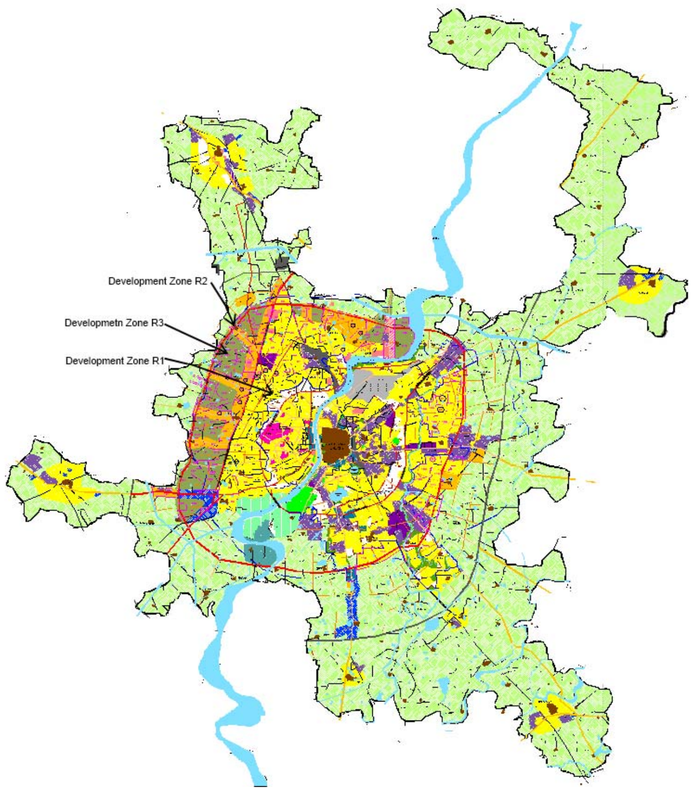


Figure 5-4: Ahmedabad Urban Development Authority (AUDA) Development Plan Proposal for 2011

Source: Revised Draft Development Plan of AUDA – 2011AD Part I ,Vol . 2

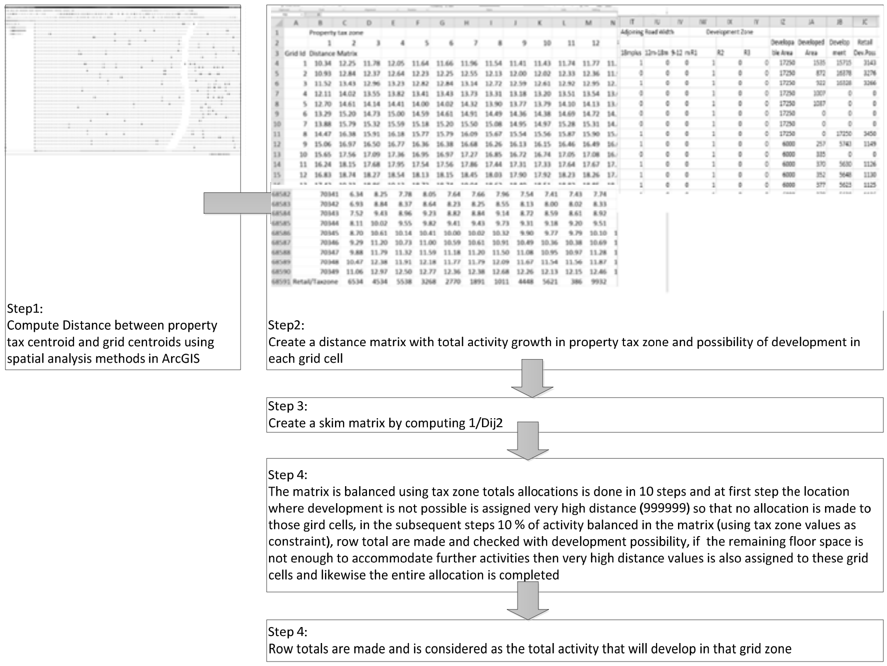


Figure 5-5: Operationalizing Urban Growth Model in Microsoft Excel Software

Figure 5-5 presents how the allocation model in Equation 1 is operationalized to allocate activities to different locations in the widely available spread sheet Microsoft-Excel. First, a large distribution matrix (266 x 68,587 cells) is created. Second, the distance between the functional centroid of the property-tax zone and the grid cells is computed using ArcGIS software, which is then used to create a skim matrix with travel impedances. The matrix is accordingly balanced using activity floor space from the property-tax zone as a mass on the one hand and the probability of each the activity to develop in the grid cell as a mass on the other hand. As retail properties in Ahmedabad have higher property value, at particular locations where transition probability is high for retail and other land-uses, it is assumed that first retail activities will develop followed by other land-uses like commercial activities. Thus, for each iteration a first allocation of all retail activities is done, followed by commercial and residential respectively.

Once the allocation of activities is done, the transitional probabilities are re-calculated as discussed in step 4 and re-assigned, following which allocation of activities is done for the next two years. To do this, allocated activities (for every two-year time period) are fed as an input to the accessibility and property value model. This is used to re-compute the transition probability for each activity using the developed logistic regression model. This step is then followed by the distribution and location-allocation steps to allocate activities for the subsequent two years. These allocated activities are again fed as an input to the accessibility and property tax model, which is then, again, used to allocate activities for the next two years. This procedure is recursively applied for 11 iterations to allocate all activities that will develop until the year 2030, where the first iteration is to simulate growth for the year 2010 as the land-use and transport data is only available for the year 2008.

As stated earlier, two urban growth scenarios, namely, the BAU scenario and the LCD scenario, are developed. In the BAU scenario, the space available for development is computed based on the General Development Control Regulations (GDCRs) in the city and the existing development. In the LCD scenario, the inputs from built form and travel behaviour relations developed in Chapter 3 are used to alter GDCR, while the allocation of land uses is based on these altered GDCRs and existing developments. Thus, whereas the probable area that will develop per grid cell under a particular activity is altered in the LCD scenario; the other modelling sequence remains the same for both the scenarios.

To estimate the accuracy with which the developed urban growth and simulation model is able to predict growth for activities, a validation exercise for the 2012 prediction values was conducted. For this validation exercise building footprint data for the locations marked in blue in Figure 5-6 were digitized from Google earth data by CEPT University students (CEPT, 2012). Land-use and height information for each building were collected by means of a field survey. This validation data set consists of data on 13,396 buildings located in six different clusters across the city, which constitutes about 19% of the urban area. The results of land-use prediction after the second iteration are compared with the locations in these six clusters. The first step is to identify the locations from the validation data that were built in the period between 2008 and 2012. The second step is to separate the development predicted between 2008 and 2012 from the urban growth and development simulation outputs, while the third step is to compare the two maps and find the disagreements between the two maps. Following the Worchester, MA, USA example in Pontius et al. (2008), correct predictions for all the three simulated land-uses and three types of prediction errors are identified. Correctly predicted grid cells are cells where built up is predicted as built up (a) Incorrectly predicted cells are identified as locations that were non-built up but were predicted as built up by the model (b), locations that were built up but were predicted as non-built up (c), and locations that have more than ±10% error in predicting the floor space development (d). Based on Pontius et al. (2008) four indexes are identified from these measurements. The 'figure of merit' is computed as the ratio of observed change to correctly predicted change (figure of merit = a/(a+b+c+d)). If the predicted ratio is 0% than the accuracy of prediction is also zero, where 100% ratio represents a perfectly accurate prediction. Two other conditional accuracies are computed; the producer's accuracy, which indicates the proportion of area that the model predicts accurately in reference to the observed changes (producers accuracy = a/(a+c+d)) and user accuracy which is measured as the proportion of area that the model predicted accurately to the sum of correctly predicted land use and other wrongly predicted land use (user accuracy = a/(a+b+d)).

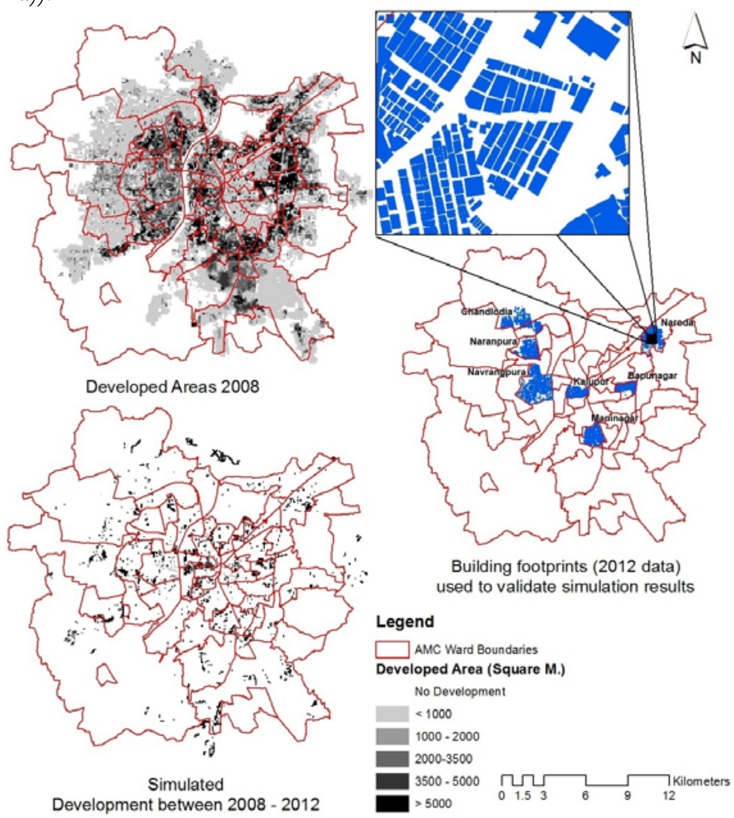


Figure 5-6: Validation data

5.3.2 Environmental impact

To predict future mode choice and distance individuals travel in the base scenario can be done by synthesizing the mode choice and travel distance models to all areas in the city. The three-stage regression equations necessitate three datasets, first on socio-demographics (number of males, number of females, average age, average income and average vehicle ownership), the second dataset on the built-form measures, and the third on employment centres. The data on built form and employment centres is available for the base year, but data on socio-demographic characteristics is not available for the base year for all the grid cells. Kriging function in ArcGIS is used to interpolate socio-demographic data for all grid cells.

For future development scenarios, land use and population are computed using the methods mentioned above for all grids cells in the study area. Land use also helps in computing the number of jobs in a grid cell by converting floor area per land use into number of jobs. Jobs/floor area for each land use is used for this computation. Jobs are used to compute the new employment centres that will develop. The simulated population, jobs, land use and the proposed transport network (in AUDA-proposed development plan for the year 2030) are used to compute built-form variables for both BAU and LCD scenarios. Per capita income in India (and likewise in Ahmedabad) is estimated to rise by more than two-and-a-half times by the year 2030 (John, 2006), which is used to predict the socio-demographic variables for the future projection years. When predicting mode choice, estimates of the number of individuals were also made who will be added to the various categories of motorized mode ownership, namely, one vehicle owned, two vehicles owned, three vehicles owned and more than three vehicles owned per household. Increase in per-capita income was projected by using the growth factor of change for all population. The projected built-form and socio-demographic variables are used to predict travel behaviour for both future scenarios. Subsequently, the environmental impact of the resultant travel behaviour is worked out, as described in the following section.

Environmental impact of transport

Carbon dioxide (CO_2) is by far the most prominent greenhouse gas released by human activities, accounting for about 85 per cent of total emissions weighted by the global warming potential. Although uncertainty exists as to the likely climatic changes that the greenhouse effect may bring about, the role of the transportation sector in the production of greenhouse gases is clear. CO_2 is a by-product of any engine that burns carbon-based fossil fuels. The amount of CO_2 released per unit of transportation service (i.e., per tonne-kilometre) is directly related to the energy consumption of the mode providing that service. One litre of petrol fuel releases 2.28 kilograms of CO_2, while one litre of diesel releases 2.58 kilograms of $C0_2$ (SRU, German Advisory Council on Environment, 2005).

For accounting purposes, the environmental cost of air pollution is often converted into monetary terms to indicate the cost of pollution. The National Research Council of the United States of America (NRC, 1991) suggests that such cost is in the range of $10 to $20 per ton of CO_2 emitted. Estimation of this cost is based on externalities of CO_2 on human health and on the environment in general. Apart from representing air pollution in terms of environmental costs, several indices measure sustainability of the urban environment. Bohringer and Jochem(2007) surveyed major sustainability indices, including the Living Planet Index (LPI) developed by the World Wildlife Foundation, the Ecological Footprint (EF),the City Development Index(CDI) suggested by the United Nations Centre for Human Settlements (HABITAT), and the Human Development Index (HDI) proposed by the United Nations Development Program (UNDP). The Ecological Footprint, being a spatial representation, appears to be an efficient accounting tool to visually communicate human impacts on the environment.

The Ecological Footprint (Wackernagel and Rees, 1996) is based on the quantitative land and water area requirements to sustain a (national) living standard into infinity thereby assuming certain efficiency improvements. Although the EF method of accounting sustainability has mainly been done for nations, there are already several examples where the ecological footprint has been used as an indicator of sustainable transport (Guangqing and Brian, 2005, Muniz and Galindo, 2005, Barrett and Scot, 2003). The EF accounting has the potential to be used for accounting the impact of travel on sustainability of an urban area but the method has a few drawbacks as in the manner in which global and local hectares of land required for carbon sequestration are calculated. The land used for transport infrastructure can have a very different account in tropical countries; in some countries the infrastructure could occupy arid non-productive land, and hence should have no consequence on associated bio-capacity (Kitzes et al., 2009). Moreover the equivalent land calculated only includes emissions of carbon dioxide using the carbon sequestration method; the emission of other greenhouse gases like NOx and SOx are not computed beyond energy required from their creation (Kitzes et al., 2009).

Therefore, to measure the environmental impact as stated in this section, two measures are used. In the first measure, air pollution occurring from urban travel is converted into a total carbon dioxide (CO_2) equivalent, in order to understand human exposure to these pollutants. In the second measure, CO_2 emissions and land used for transport infrastructure is used to compute the ecological footprint of transport, a representation of environmental resources consumed by transport.

Bose et al. (2001) compiled fuel economy and GHG factors. These factors are presented in (Bajracharya et al., 2008) and in Table 5-3 The average occupancy of each of these modes has been worked out from a household travel survey conducted in 2008 and from other transport studies on Ahmedabad. The occupancy of the mentioned modes is presented in Table 5-3.

Table 5-2: Vehicle type and CO_2 equivalent GHG emissions

Vehicle Type	GHG (CO_2 equivalent grams/VKT)
Gasoline Motor Scooter	52
Gasoline Mini Car	119
Gasoline Car	265
CNG Car	198
Diesel Bus	975
CNG Bus	1050
Auto-rickshaw/Shared Auto-rickshaw	110

Source:(Bose et al., 2001)

Table 5-3: Ahmedabad: vehicle occupancy

Vehicle Type	Average Occupancy	Source
Motor Cycle	1.02	Primary Survey
Car	1.08	
Auto-rickshaw	1.02	
Bus	28.4	From (GIDB, 2001)
Shared Auto-rickshaw	6	

The total CO_2 equivalent emissions for trips made are computed as follows:

$$C_i = \sum_j \left(\frac{P_i \times T_i \times M_j}{O_j}\right) \times G_j \text{ ....Equation 5-2}$$

WhereCi = Total CO_2 emitted by vehicle "j" from grid cell "i", P_i = Total persons residing in grid cell "i", Ti = Average vehicle kilometres travelled by persons residing in the gird cell, Mj = Trip length adjustment factor for mode "j", Oj = occupancy rate for mode "j", and Gj = CO2 emission gram/kilometre by mode

The trip length adjustment factor is used to adjust for variation in mean trip length for different modes, for example, walking and public transport. For mode 'j' this is computed by normalizing the mean trip length in the city by mode 'j' with mean trip length by all the modes in the city.

For evaluating scenarios in this study, the ecological footprint has been used as one of the main measures as it accounts for both CO_2 emissions from vehicle fuel consumption and occupied land area for the road infrastructure in a single measure. The biological land required for sequestering the CO_2 emitted from vehicular emissions is expressed as hectares of forest land required. Following (Muniz and Galindo, 2005) the transport ecological footprint is derived by combining the physical footprint and the energy footprint. The physical footprint is the surface area used as right of way for roads. For the energy footprint derivations, since local conversion factors for Ahmedabad are not available, a global average is used, which states that one hectare of forest can annually absorb 1.8 tonnes of Carbon, thus 6.6 equivalent tonnes of CO_2 (considering atomic mass of both gases). To compute the annual ecological footprint, daily trips are converted into annual trips by multiplying a daily trip by 254 (annual working days in India) for working trips, and by 107 (considering 2.1 shopping purpose trips/week observed from the primary survey). The methods used in this study do not account for emissions resulting from road construction and maintenance, which is compensated by considering it as 45 per cent of the total emissions from the vehicles as suggested by (Wackernagel and Rees, 1996). Therefore the annual CO_2 (computed by multiplying the product of Equation 5-2 by 254) is multiplied by 1.45 to derive the total adjusted annual CO_2 emission, which is used to compute carbon sequestration. The adjusted annual CO_2 emission in tonnes is normalized by 6.6 to get the energy footprint in hectares. Finally, the physical footprint and energy footprint are summed up to get the total ecological footprint for each grid cell.

5.3.3 Quantifying societal benefits

Accessibility measures are measures used to determine if residents in the city have access to their daily needs(Curtis and Scheurer, 2010) and activities associated with their economic well-being. In a way, accessibility measures also represent societal benefits (Salomon and Mokhtarian, 1998). In this study, based on work done by Geurs and van Wee (2006), activity-based accessibility is the accessibility measure considered to represent the social benefits that individuals can derive from a particular location. Using the measure, accessibility to jobs, entertainment facilities, schools, and population is computed.

To compute accessibility to the above stated activities, which represent accessibility of social and economic opportunities, several types of location-based accessibility measures can be used. These include distance and contour, and potential measures and balancing factors of spatial interaction models (Guers and Eck, 2001). Proximity to social and economic activities computed and the mean trip length (6.2 km.) derived from the primary survey done in 2008 has been used as a contour to compute cumulative accessibility to the stated activities. As stated in (Geurs and Eck, 2001), the contour accessibility measure, also called the 'cumulative opportunities measure', indicates the number of opportunities reachable within a given travel time or distance.

5.4 Discussion

The purpose of this chapter was to demonstrate how the built from and travel behaviour relation can be used to achieve future development scenarios that reflect low-carbon transport development. Low-carbon transport development essentially refers to development that does not increase carbon emissions from transport, and also does not compromise the economic and societal goals of the city. To ascertain whether the future urban development scenario includes low-carbon transport development or not, both these indicators would have to be quantified and checked. The environmental impact of transport is computed from mode choice probabilities and distance that individuals are willing to travel, which can be computed for all scenarios from the results presented in Chapter 4. Two measures have been used to visualize the environmental impact resulting from passenger transport movements: first, all air pollution is converted to total carbon dioxide equivalent. The second measure used is the ecological footprint of transport, which represents environmental resources consumed by transport. The societal benefits are estimated by computing accessibility to activities that give economic and societal benefits to individuals.

To be able to visualize impacts of future scenarios, it is important to develop an urban growth model that is able to simulate land-use development and urban growth for the city of Ahmedabad. It should be a model that is easily replicable in other similar contexts. The urban growth and development simulation model developed for this study uses a hybrid approach--a combination of a logistic regression and a Cellular Automata based model to simulate future urban development and growth of the city. The development projections are calculated and validated for each property tax zone and these estimates are used as inputs into the urban growth simulation model. Existing zoning and development control regulations, outputs of the logistic equation as well as other activity location rules have been used to calculate transitional probabilities for activities in each grid cell. These probabilities are an input to the location-allocation model to simulate urban growth. The model allows the possibility of designing alternate scenarios with different zoning and development control regulations. The projections made at a disaggregated scale are distributed to the grid cells depending upon their propensity to develop or redevelop, and attractiveness of the location for the activity to develop.

In the next chapter the methods discussed in this chapter are operationalized and the possibility of developing low-carbon transport development using built form and travel behaviour relation are discussed.

6 Built Form driven Low-Carbon Development: Results

6.1 Introduction

The purpose of this chapter is to present the results of our analysis to show how built form-travel behaviour relation can be used to achieve low-carbon transport development. The chapter has five sections. The first section analyses the simulation of trend line projections of urban growth and development, their influence on travel behaviour and consequently on the environment as well as on societal benefits (computed as accessibility to locations). The second section looks at the above analysis from a policy perspective as a support to strategic urban planning and policymaking. In doing so, this chapter answers questions related to how built form can be used to develop future development scenarios from the policy perspective that lead to low-carbon transport development.

The next section discusses the results of simulation of urban and development growth scenarios. This is followed by the results of environmental impacts of these scenarios, and by the quantification of accessibility to activities as a measure of societal and economic benefits. The fifth section presents a discussion of the policy implications of the results, which is followed by a discussion of the results.

6.2 Urban development and growth scenarios

The methods that are used to develop urban growth scenarios have been discussed in Chapter 5. Two development scenarios are modelled, the first scenario predicts the growth and development of the city in business-as-usual (BAU) conditions. That is, development projections are made assuming the past trends of development will continue without any planning intervention. The second scenario is Low-Carbon Transport Development scenario (the LCD scenario). In this scenario, the aim is to contain or reduce the total kilometres travelled by individuals residing in the city, and encourage higher use of non-motorized and public transit modes of travel. The elasticity values between built-form variables and travel behaviour have been presented in Chapter 4. In the LCD scenario these elasticity values are used to drive policies which support reduction in total distances travelled by residents and promote the use of non-motorized and public transit modes. From results presented in Chapter 4 it is observed that travel distances reduce when the travel destination is an employment centre with more than ten thousand jobs, as identified in Chapter 3. If the work-purpose destination is a location outside any of these identified employment centres, the observed travel distances are longer. Moreover, accessibility to jobs, distance to transit stops and density of transit stops have a negative relation with travel distance. Likewise, higher population density, dissimilarity index values, entropy index values, a higher number of intersections and increased street density are positivity related with non-motorized and public transit mode choices for work and non-work travel.

It is, therefore, clear that in the LCD scenario urban development will have to be contained within certain nodes, thereby also ensuring an increase in the accessibility to jobs through both the transport network (represented as job accessibility by SOMV) and public transport network. The nodes must have more than ten thousand jobs and be equitably distributed to ensure proper access to jobs from all areas. These employment nodes and surrounding areas will have a coarse network of roads and road junctions, and good public transport connectivity to ensure good job accessibility by public transit and to public transit networks.

In the following section, urban growth projections are presented which are input into the cellular-automata-based model, which is used to predict spatial growth and development of the city for both scenarios mentioned above. In the case of the LCD scenario, the GDCRs are altered to allow higher density of development at nodes presented in Figure 4-7, and to simultaneously facilitate development of built form at these locations that induce the desired travel behaviour for low-carbon transport development.

6.2.1 Urban growth projections

In Table 6-1 the results of the activity growth projections are presented, which are input into the urban development and growth simulation model. From the projections it is apparent that the city of Ahmedabad will have a population of more than 9 million by the year 2030, which is almost one-and-a-half times its current population. If no urban planning interventions are made, it is obvious that this demand could lead to a large urban sprawl as observed in other cities with a similar population, like Bengaluru and Bangkok.

The projections presented in Table 6-1 indicate that industrial growth will slow down considerably in the city. The small-scale industries represented as parts of factories are likely to have moderate to high growth, but large-scale ones like textile and chemical industries might grow only at very marginal rates. Trade and commerce sectors like retail, commercial offices, hotels, banks etc., are likely to grow much faster in comparison to the industrial sector, especially large-scale industry. These urban growth projections are input in the cellular-automata-based model that is used to simulate urban growth and development. The transition rules for each grid cell in the study are defined, as stated in Chapter 5, by the probability of activity development and second by GDCRs. In the next section we present the results of the logistic regression mode which is used as one input in deriving the transition rules for the grid cells.

Table 6-1: Projected growth of activities in Ahmedabad

		Area from property tax data				**Projected area**			**% Deviation (b from a)**
		Year							
		1980	1990	2000	2010(a)	2010(b)	2020	2030	
Gujarat State GDP Growth (USD Billion)		15.69	24.17	51.27	90.65		108.44	133.64	
Population(Million Inhabitants)		2.05	3.26	4.43	6.53	6.73	8.45	9.99	3.09%
Industries	Factories (F)	5048	8163	11278	13018	16137.51	16190.49	17577.22	23.96%
	Chemical(CI)	143	297	452	504	753.79	694.32	906.48	49.56%
	Textile(T)	436	593	627	640	746.50	708.99	814.23	16.64%
	Metal (M)	40	118	195	414	477.19	752.84	892.86	15.26%
	Print (P)	251	612	973	1477	1934.98	2302.91	2865.77	31.01%
	Food and Bev.(FB)	143	176	208	262	257.37	297.17	333.47	1.77%
	Other Industries(OI)	19	41	62	95	114.26	140.29	171.30	20.27%
Retail	Retail(Re)	3489	4930	6372	8578	8779.61	10411	12160.07	2.35%
	Food and Bev. Ret (FBR)	60	90	119	218	188.94	290.47	329.11	13.33%
	Storage(RS)	1115	1983	2851	4138	4616.35	5587.17	6759.15	11.56%
Commerce	Commerce Offices(CO)	583	963	1691	2517	2780.37	3434.09	4189.94	10.46%
	Hotel(H)	550	648	746	1146	968.06	1338.94	1453.44	15.53%
	Entertainment(E)	162	195	228	339	295.81	396.03	434.58	12.74%
	Bank(B)	157	230	303	490	454.03	628.14	721.72	7.34%
Govt. Office (GO)		145	177	210	472	328.23	622.29	664.48	30.46%
Education(EDU)		1964	2323	2681	3839	3393.50	4416.03	4827.84	11.60%
Bank(B)		157	230	303	490	454.03	628.14	721.72	7.34%
Religious (RI)		153	222	292	568	467.41	760.98	853.42	17.71%
Medical(Md)		400	526	651	1016	905.14	1240.32	1392.92	10.91%

* Floor space in 1000 m2

* Activity growth from year 1980 – 2000 was used to project activity growth and year 2010 data was used to validate the activity growth model, where (a)represents floor space values for year 2010 and (b) is projected floor space for the same year.

* Source for SGDP is http://financedepartment.gujarat.gov.in (accessed on 1/12/2011)

6.2.2 Logistic regression

The results of the logistic regression modelling are presented in two parts. The prediction accuracy of the models are shown in Table 6-2 and are in the range of 44% to 82%, which are considered acceptable. In comparison, the goodness of fit (Nagelkerke R^2) values observed in Allen and Lu (2003) are in range of 36% to 69%. In general, the modest R^2 values are understandable as there can be other parameters that can influence location decision of these activities. For example, location of entertainment activities can be influenced by zoning regulations.

The odds ratios in Table 6-2 indicate the odds of an increase in the probability that an activity can develop in the grid cell with one unit change in the value of the variable. An odds ratio value of one indicates neutral or no influence; values higher than one indicate a positive influence, while an odds ratio lower than one indicates a negative influence. The results show that there is a tendency to develop towards the centre of the town. As distance to the railway station (located in the central part of the town) increases, the probability of the activities to locate, especially retail and residential activities, decreases. This is in line Von Thünen's (1826) Concentric zone theory. Accessibility to other activities has a mostly positive influence on the location of activities, which shows that activities have a tendency to cluster, and locate in close proximity to each other. This tendency of activity location is also reflected in the strong influence that the 'dissimilarity index' has on location of activities, i.e. a location with a high dissimilarity index (represented as land-use heterogeneity) attracts all activities considered in this study except residential activities. Land-use mix at the neighbourhood level (represented as the Entropy Index) has a mixed influence on the activity location; it has a negative relation with the location of banks, entertainment, activities and hotels. Therefore, certain activities like retail, hotels etc. prefer to locate at locations where heterogeneity is high. Activities like commercial offices locate where both heterogeneities of land-use and balance of land-use are high. Residential activities have a strong negative relation with the Entropy Index measure, indicating that most locations where residential activities are located have poor land-use mix. Likewise, commercial offices and retail activities like to develop adjacent to major roads. This could be because of the GDCRs and other market area related concerns. This is also reflected in their relation with property values, since activities as retail and commercial offices are also willing to locate where property values are high. Therefore, activities like retail and commercial offices that have the potential to generate more profit, locate at locations where property values are high, and at locations where they have better access to their markets (i.e. the potential clients). Activities like education and government offices that require more land area and floor space to function, locate in areas where land prices are lower and further away from the main streets.

One input into the logistic regression are property values. The property value of a location can change as accessibility to activities from that location would change after new development. In the allocation model used in this study, activities are allocated for every two-year iteration. Presented in the next section is the 'change in property value model' that calculates changes in property value after each iteration of distribution of activities to grid cells as shown in Figure 5-3.

Table 6-2: Logistic regression for activity location

	Commercial activities								Retail		Residential	
	Bank		Entertainment		Hotels		Commercial offices					
	B	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*	*B*	*Exp(B)*
Constant	-3.00	0.05	-3.52	0.03	-2.49	0.08	-6.70	0.00	0.06	1.06	1.81	6.12
Distance from												
Railway Station	-0.11	0.90	-0.14	0.87	-0.11	0.90			-0.19	0.85	-0.27	0.76
Airport									0.04	1.04	0.14	1.15
Accessibility to												
Residential					0.01	1.01	0.03	1.03	0.07	1.07		
Retail	-0.01	0.99	0.01	1.01	-0.01	0.99			0.02	1.02		
Hotel							0.02	1.02	0.02	1.02	-0.01	0.99
Govt. Offices							0.03	1.03	-0.02	0.98		
Entertainment	0.02	1.02	0.07	1.07	0.01	1.01	-0.04	0.96	0.02	1.03	-0.01	0.99
Education	0.02	1.02			0.02	1.02	0.01	1.01			0.01	1.01
Religious			-0.04	0.96					0.01	1.01	0.02	1.02
Property Value												
Retail Prop.	0.01	1.01	0.01	1.01			0.01	1.01	0.07	1.07	-0.01	0.99
Resi. Prop.					0.03	1.03	0.05	1.05	-0.09	0.91	-0.01	0.99
Office Value									0.03	1.03		
On 18m+Road	-0.37	0.69	-0.36	0.70	-0.44	0.65	-0.64	0.53	0.22	1.24	0.11	1.11
On 12- 18 m. Road	-0.51	0.60	-0.33	0.72	-0.44	0.64	-0.92	0.40	0.49	1.63	0.27	1.31
On 6-12 m. road												
Structural Variables												
SSLI	0.12	1.13	0.24	1.28					-0.13	0.87		
Dissimilarity Index	3.18	24.13	2.88	17.90	4.24	69.13	2.73	15.40	2.99	19.81		
Entropy Index	-5.56	0.00	-3.77	0.02	-2.89	0.06	3.86	47.65			-7.63	0.00
Ker. Density Junctions	0.04	1.04	0.01	1.01			0.06	1.06	0.00	1.00		
Chi-Square		8713.76		6937.97		11538.49		4705.69		23288.73		6785.69
-2 Log Likelihood		14252.67		12800.27		14668.14		5925.53		8656.14		23603.45
Nagelkerke R Sq.		0.48		0.44		0.56		0.49		0.82		0.34

p(B) =Odds

6.2.3 Change in property value model

Table 6-3 presents the model that can be used to compute the change in property value. The adjusted R^2 values are in the modest range of 0.27 to 0.43. The large constant value indicates that there are more factors than those captured in the modelled equation that explain the variation in the property values.

Overall proximity to the railway station has a positive influence on property values. Property values have a negative relation with proximity to religious places, the airport and government offices. The observed signs with individual variables are in conjunction with values observed in the results of the logistic regression modelling are presented in two parts. The prediction accuracy of the models are shown in Table 6-2 and are in the range of 44% to 82%, which are considered acceptable. In comparison, the goodness of fit (Nagelkerke R2) values observed in Allen and Lu (2003) are in range of 36% to 69%. In general, the modest R2 values are understandable as there can be other parameters that can influence location decision of these activities. For example, location of entertainment activities can be influenced by zoning regulations.

The odds ratios in Table 6 2 indicate the odds of an increase in the probability that an activity can develop in the grid cell with one unit change in the value of the variable. An odds ratio value of one indicates neutral or no influence; values higher than one indicate a positive influence, while an odds ratio lower than one indicates a negative influence. The results show that there is a tendency to develop towards the centre of the town. As distance to the railway station (located in the central part of the town) increases, the probability of the activities to locate, especially retail and residential activities, decreases. This is in line Von Thünen's (1826) Concentric zone theory. Accessibility to other activities has a mostly positive influence on the location of activities, which shows that activities have a tendency to cluster, and locate in close proximity to each other. This tendency of activity location is also reflected in the strong influence that the 'dissimilarity index' has on location of activities, i.e. a location with a high dissimilarity index (represented as land-use heterogeneity) attracts all activities considered in this study except residential activities. Land-use mix at the neighbourhood level (represented as the Entropy Index) has a mixed influence on the activity location; it has a negative relation with the location of banks, entertainment, activities and hotels. Therefore, certain activities like retail, hotels etc. prefer to locate at locations where heterogeneity is high. Activities like commercial offices locate where both heterogeneities of land-use and balance of land-use are high. Residential activities have a strong negative relation with the Entropy Index measure, indicating that most locations where residential activities are located have poor land-use mix. Likewise, commercial offices and retail activities like to develop adjacent to major roads. This could be because of the GDCRs and other market area related concerns. This is also reflected in their relation with property values, since activities as retail and commercial offices are also willing to locate where property values are high. Therefore, activities like retail and commercial offices that have the potential to generate more profit, locate at locations where property values are high, and at locations where they have better access to their markets (i.e. the potential clients). Activities like education and government offices that require more land area and floor space to function, locate in areas where land prices are lower and further away from the main streets.

One input into the logistic regression are property values. The property value of a location can change as accessibility to activities from that location would change after new development. In the allocation model used in this study, activities are allocated for every two-year iteration. Presented in the next section is the 'change in property value model' that calculates changes in property value after each iteration of distribution of activities to grid cells as shown in Figure 5 3. The results of the logistic regression modelling are presented in two parts. The prediction accuracy of the models are shown in Table 6-2 and are in the range of 44% to 82%, which are considered acceptable. In comparison, the goodness of fit (Nagelkerke R2) values observed in Allen and Lu (2003) are in range of 36% to 69%. In general, the modest R2 values are understandable as there can be other parameters that can influence location decision of these activities. For example, location of entertainment activities can be influenced by zoning regulations.

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Table 6-2, thus indicating that for locations where retail and commercial properties develop, property values increase. Secondly, the attraction of such locations for other retail and commercial establishments to locate also increases. In the next section we present the result from the urban growth and development simulation exercise.

Table 6-3: Regression equation: Change in property value

	Office Property		Retail Property		Residential Property	
	Unstandard Coefficient	Standard Coefficient	Unstandard Coefficient	Standard Coefficient	Unstandard Coefficient	Standard Coefficient
(Constant)	11.010		32.530		6.364	
Distance from						
Railway Station	-0.270	-0.263	-0.945	-0.250	-0.075	-0.127
Airport	0.192	0.051	0.517	0.037	0.091	0.042
Accessibility to						
Residential					-0.046	-0.356
Commercial Offices	0.353	0.497				
Retail	-0.027	-0.142	0.245	0.395	-0.058	-0.524
Educational Institutions	0.127	0.768	0.370	0.608	0.096	1.007
Entertainment			0.138	0.100	-0.017	-0.078
Government Offices	-0.061	-0.254	-0.315	-0.356	-0.013	-0.096
Religious Places			-0.169	-0.204	-0.024	-0.182
Hotels			0.078	0.123	0.016	0.156
R^2		0.337		0.271		0.428

6.2.4 Urban development and growth

Validation

To estimate the accuracy with which the developed urban growth and simulation model is able to predict growth for activities, a validation exercise for the 2012 prediction values was conducted. For this validation exercise building footprint data for the locations marked in blue in Figure 7 were digitized from Google earth data by CEPT University students (CEPT, 2012). Land-use and height information for each building were collected through a field survey. This validation data set consists of data on 13,396 buildings located in six different clusters across the city, which constitutes about 19% of the urban area. The results of land-use prediction after the second iteration are compared with the locations in these six clusters. The first step is to identify the locations from the validation data that were built in the period between 2008 and 2012. The second step is to separate the development predicted between 2008 and 2012 from the urban growth and development simulation outputs, while the third step is to compare the two maps and find the disagreements between the two maps. Furthermore, based on Pontius, et al. (2008) four indexes are identified (as described in chapter 5) from these measurements. The 'figure of merit' is computed as the ratio of observed change to correctly predicted change (figure of merit = a/(a+b+c+d)). If the predicted ratio is 0% than the accuracy of prediction is also zero, where 100% ratio represents a perfectly accurate prediction. Two other conditional accuracies are computed; the producer's accuracy, which indicates the proportion of area that the model predicts accurately in reference to the observed changes (producers accuracy = a/(a+c+d)) and user accuracy which is measured as the proportion of area that the model predicted accurately to the sum of correctly predicted land use and other wrongly predicted land use (user accuracy = a/(a+b+d)).

Thus, a validation exercise is carried out by comparing the land-use of about 20% (23.08 square km. of area from 241.03 square kilometre of total developed area in 2012) of the urban area, which constitutes a significant portion of the built up area. Moreover, care has been taken to select representative areas from inner areas (Kalupur and Navrangpura), the mid region area (Maninagar, Bapunagar and Naranpura), from the peripheral area (Chandlodia and Naroda) and from both sides of the river Sabarmati (east and west), so that the sample taken for validation is representative.

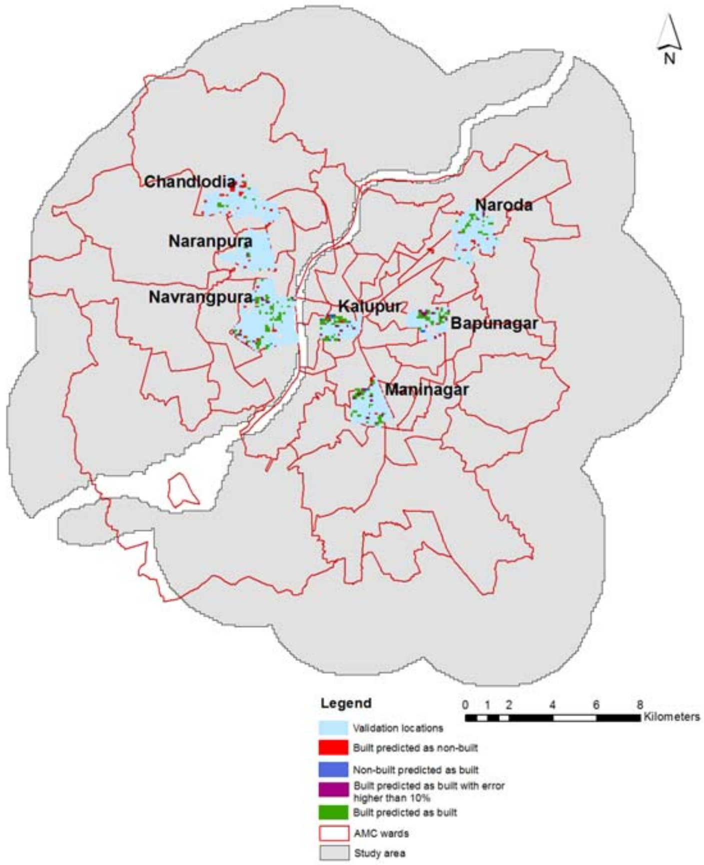

Figure 6-1: Validation locations and outcome of validation exercise

The validation exercise, which was conducted after the second iterations, intends to check the accuracy of the model. The results of the validation are presented in Figures 6-1 and 6-2. It was found that the methods used to simulate urban growth and development in this study were able to predict more than 75% of the floor space under retail, commercial and residential development accurately. Even though the accuracy in predicting retail floor space in Table 6-4 is slightly lower, the model is able to predict the spatial growth of retail activity with a high level of accuracy, especially in the central parts of the city. The locations marked green in Figure 6-1 are predicted with more than 90% accuracy for all three land-uses (a), the gain of built (non-built predicted as built, b) is shown in blue, the loss of built (built not predicted, c) is marked in red colour and locations with more than 10% error in land use prediction are marked in the purple colour.

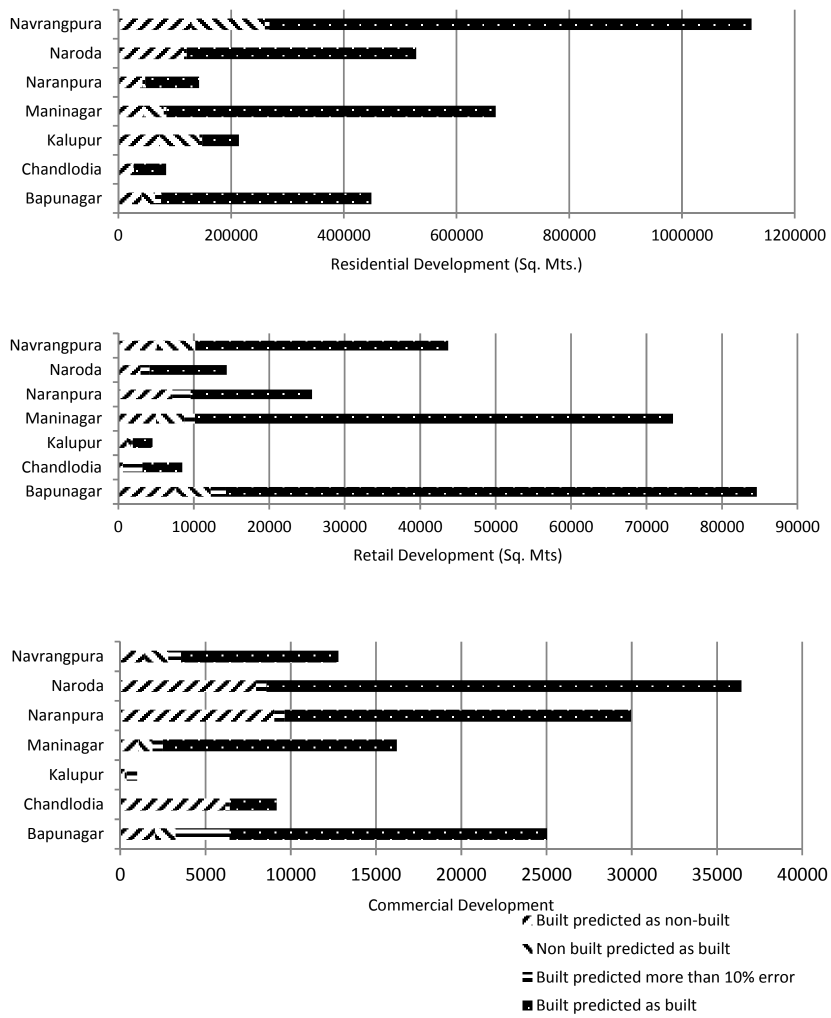

Figure 6-2: Validation of activity floor space, accurate predictions and predictions with error

In Figure 6-2, each of these errors are presented as proportions of the total development in each validation ward. It is observed that the proportion of built up predicted as built up is significantly high in all areas except for areas under commercial development in Kalupur and Chandlodia. Within the errors, the proportion of loss of built up is generally higher than the proportion of gain in built up. The proportion of wrongly predicted built up areas should be equal to the proportion not predicted floor space areas, so that the total predictions in the ward is equal to the total built. However, as can be seen from Figure 6-2, wrongly predicted floor space is not equal to the proportion of not predicted floor space. This difference in prediction can be caused by the inaccuracy in the projection of floor space for these activities as presented earlier in Table 6-1. It also indicates that the overall estimates of activities are on the lower side for the locations that have been considered for validation in this study. Table 6-4 presents the indexes of prediction accuracy, the 'figure of merit' representing overall accuracy is higher than 70 % for all three land uses, and the index of users accuracy and index of predictors accuracy are also on the higher side, with respective overall average accuracy more than 72% and 83 % for all activities . Relative lower accuracy of prediction were observed for the Kalupur ward (Centrally located) and in Chandlodia ward (periphery ward), which are also the location where predicted and built volume are low. On the other hand, the location where the built up volumes are high the prediction accuracy was accurate to very large extent.

Table 6-4: Index of prediction accuracy

City Wards	Residential			Retail Development			Commercial Development		
	Figure of Merit	User Accuracy	Predictors Accuracy	Figure of Merit	User Accuracy	Predictors Accuracy	Figure of Merit	User Accuracy	Predictors Accuracy
Bapunagar	83.22	87.99	91.49	83.16	87.93	91.43	74.43	78.23	80.99
Chandlodia	67.21	67.21	98.09	62.37	62.37	67.11	30.05	30.05	91.16
Kalupur	30.60	45.48	46.69	57.93	66.14	76.56	0.00	0.00	0.00
Maninagar	87.31	92.03	93.72	86.24	90.85	92.49	84.61	89.04	90.63
Naranpura	66.93	66.93	95.27	62.71	62.71	86.94	67.82	67.82	97.08
Naroda	77.08	77.08	98.85	71.23	71.23	89.44	76.47	76.47	97.85
Navrangpura	76.13	86.09	86.09	76.70	86.81	86.81	72.23	81.14	81.14
Overall	75.93	82.58	89.13	79.07	83.66	89.42	71.06	72.98	90.21

Urban Growth Trends

The trends of urban development shown in Table 6-1 essentially imply that the demand for location of small firms will be high. From the established transition rules, certain transitions can be expected. For green-field locations, where new developments are computed, it is expected that initially property values will be low and accessibility to activities will also be low. Therefore these locations are likely to first develop as residential areas. Development of a residential area has a positive relation with the development of retail activities, which are likely to develop near the road junctions. Similarly, educational and religious activities also develop, but these tend to locate away from the major roads. In the course of time, the diversity of activities in these newly-developed locations increases as other activities like commercial offices and hotels would also start locating here.

The second possible transition that will happen is because of the tendency of all activities to locate towards central locations in the city. Therefore properties that are located along roads that are wider than 18 meters are likely to convert to trade and commerce uses, mainly to retail and commercial offices, as these activities would be willing to pay more rent/property value for centrally-located areas or locations that are along major roads. The third process will be migration of residents from locations that have converted in use from residential to commercial or retail, to the outer parts of the city, thereby further increasing urban sprawl. While simulating urban growth it is assumed that industrial activities will follow zoning regulations and only grow in designated industrial locations.

The Business-as-Usual Scenario

The results of urban growth and development projections for the year 2030 in business-as-usual scenario are presented in Figures 6-3, 6-4 and 6-5. The FSI regulation in the R1, R2 and R3 zones and zoning regulations are applied here. The allowed FSI and the margin rules, which only allow development in separate units, ensure that the development is less compact. The results are in line with the expectation that most locations along a major road in the interior part of the city are projected to develop commercial and retail uses. However, the space available at these locations is not able to meet the total demand for these activities, so the activities sprawl to an extent of around 3.5 kilometres outside the present agglomeration area. Therefore, a sprawling of retail and commercial activities along the major road junctions outside present agglomerations can be observed.

Demand for residences will arise as a result of natural population growth and from intra-urban migration and in-migration from rural areas and small towns. In the business-as-usual scenario, some of these developments will be accommodated by increased intensity of development (to the maximum allowed) at locations interior to major roads, which will not be enough to satisfy the demand for development. In the outer areas these are likely to develop as sparsely spread-out individual units in the periphery of the city because of R3 zone regulations. One adverse outcome of this exercise, which has not been modelled in this study, is that of the housing scenario. In the BAU scenario the housing market presents only two options to its clients, either buy a property at a location where pressure on land development is very high, thus property values are high, or buy a property on the periphery, where land consumed by development is high, so the property values too are high.

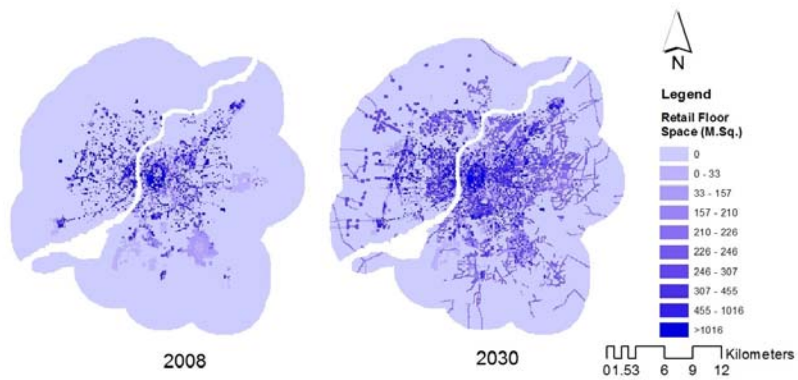

Figure 6-3 Retail Development, BAU Scenario

Figure 6-4: Commercial Development, BAU Scenario

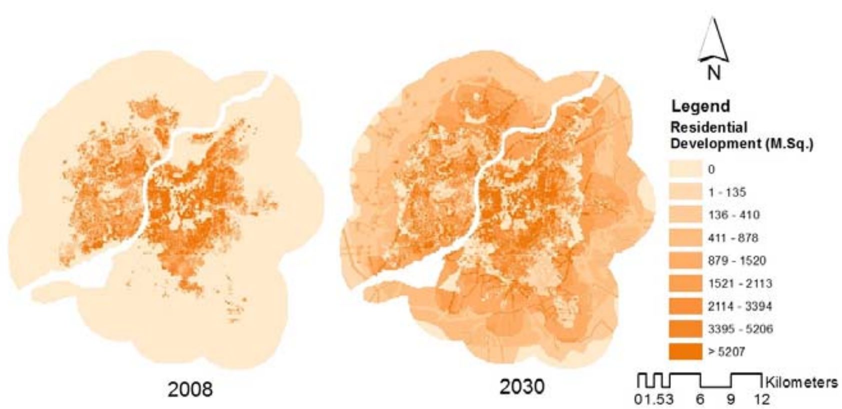

Figure 6-5: Residential Development, BAU Scenario

Figure 6-6 is a schematic representation of the distribution of activities in the BAU scenario, from which it is evident that activities will sprawl along major roads. Table 4-4 (in Chapter 4), shows that employment centres that provide more than ten-thousand jobs and offer a good mix of activities, help in reducing travel distances for work purpose trips. On the other hand, small employment sub-centres with less than 3000 jobs, and jobs at locations which are not part of sub-centres, have an opposite effect and induce longer travel distances. Moreover, in conjunction with these observations, it is observed that accessibility to jobs also reduces travel distance. Therefore, as a *primafacie* observation it can be said that in peripheral locations, travel distance will be longer unless the supply of public transit routes and stops in the region is high. In the inner area, the stated pattern of development will result in high dissimilarity index values around major roads, which gets lower as we move away from the inner areas. Thus, non-motorized trips are encouraged, especially from areas near major roads. However, in the BAU scenario, very few residences are likely to be in areas near major roads, and the lower income categories of population, the ones who mostly walk, are more likely to live away from locations that have higher property values. Therefore, how these values translate and eventually influence travel behaviour remains to be seen. To support this type of sprawl, public transport supply will need to be high, which is not a feasible option as the observed pattern of development is more likely to promote the use of self-owned motorized vehicles, especially two-wheel motorcycles. Thus given this situation it is more prudent to look at options to alter the GDCRs so that these are able to contain sprawl and encourage development that will result in lower travel distance and higher non-motorized mode and public transit choices.

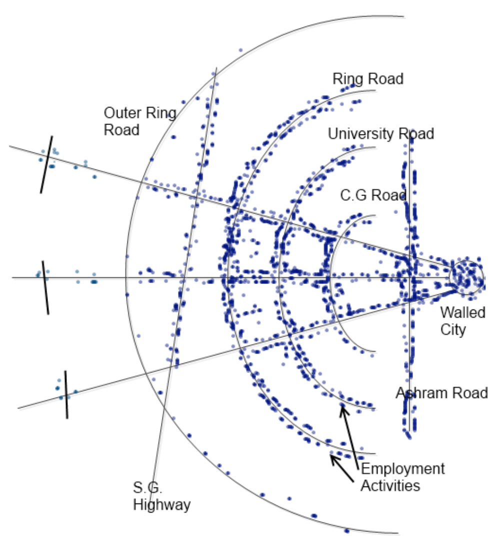

Figure 6-6: Schematic representation of distribution of employment activities in business-as-usual scenario growth projection for the year 2030

Low-Carbon Transport Development Scenario

As stated in chapters 1 and 5, there is no agreed definition of Low-Carbon Development (LCD), but the common denominator is using less carbon for economic growth (Mulugetta and Urban, 2010). In the case of the LCD scenario for Ahmedabad, two aspects of low-carbon development are addressed by meaningful interventions in GDCRs. The first aim is to reduce the total carbon resulting from travel in the city. The second aim is to maintain economic growth, wherein it is assumed that the total activities that are likely to develop in the city are kept constant. Moreover, accessibility between activities that like to cluster, and accessibility that individuals have to these activities are not compromised. The spatial configuration of the urban area thus achieved will be supportive of economic development, given that other economic drivers are in place.

From the discussion above and in the schematic representation in Figure 6-6, it is clear that in the LCD scenario urban development will have to be contained within certain nodes, thereby also ensuring an increase in the accessibility to jobs through both the transport network (represented as job accessibility by SOMV) and public transport network. The nodes must have more than ten-thousand jobs and be equitably distributed to ensure proper access to jobs from all areas. These employment nodes and surrounding areas will have a coarse network of roads and road junctions, and good public transport connectivity to ensure good job accessibility by public transit and to public transit networks. In addition, all these nodes and the connecting networks will have urban design elements which will ensure the safety especially of pedestrians and bicyclists on these roads.

The results of the LCD scenarios are presented in Figure 6-7, 6-8 and 6-9 for retail, commercial and residential activities respectively. The first purpose here was to restrict the sprawl, which when we compare both scenarios, is apparently achieved. The second objective was to attract more development towards the existing employment sub-centres. In the business-as-usual scenario, even though these locations are more attractive for firms to locate, the existing GDCR's FSI norms restrict the amount of area that can develop at this location. Therefore, in the LCD scenario, it is proposed to have a FSI of five in the identified employment sub-centres and in an area one kilometre around it. From a low-carbon transport perspective, it is important that these locations have a higher land-use diversity and entropy index. Some of this development occurs naturally, because of self-organization of the land uses, as retail development is only confined up to the first floor, so development of the higher floors is controlled in such a manner as to get a more balanced and mixed development of four land uses: retail, commercial, institutional and residential.

Figure 6-7: Retail Development, LCD Scenario

Figure 6-8: Commercial Development, LCD Scenario

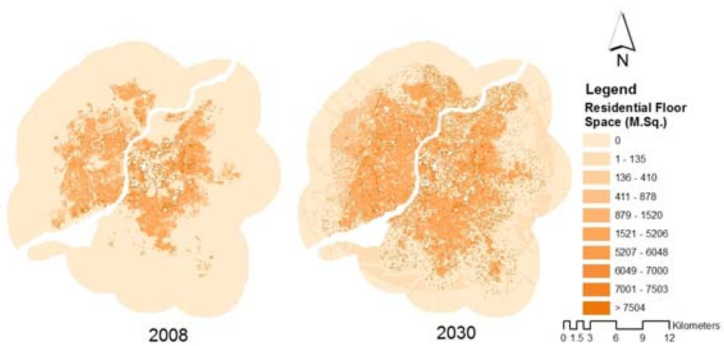

Figure 6-9: Residential Development, LCD Scenario

6.3 Environmental impact

6.3.1 Travel behaviour projections

As stated earlier, by 2030 the per capita annual disposable income of Indians living in urban areas is likely to grow from around Rs. 65000 at present to Rs. 239000 (Sankhe et al., 2010). At the same time motorized vehicles are also likely to grow three-folds. From the elasticity values presented in Chapter 4, it is known that VKT and income have a positive correlation. Moreover, the existing development control and zoning regulations place strong restrictions on the density of development, forcing decentralization of activities in parts of the city and inducing sprawl-type development. All of these have an influence on the projected trip lengths in the business-as-usual scenario, as can be seen in Figure 6-10. The inner parts of the city have an average trip distance travelled in the lower ranges of around 1 to3 kilometres. Individuals living in the outer parts of the city, in the case of the BAU scenario, might have to travel, on average, more than 12 kilometres one way for work purpose trips.

This also corresponds with the percentage of population within different trip length ranges as presented in Table 6-5. The number of jobs increase as we move from the periphery to the central core of the city, following the conventional relation that improved access to destinations reduces vehicle kilometres travelled. As presented in Table 4-4, the VKT by residents decreases as we move towards the central core areas. Because of the sprawl-type development in the BAU scenario for the year 2030, a large section of the population will reside in peripheral locations, therefore more than 60 per cent of the population will reside in grid cells where mean trips length for work-purpose travel could be more than 10 kilometres. Because of this sprawl, the average trip length in the city is likely to increase from 6.2 km. in the present scenario to 9.80 km. in the BAU scenario.

In the LCD scenario, where built form is used to influence reduction in travel distance, two things have been achieved. First, the development is confined mostly to the presently developed area, so the distance from the core of the city to its periphery is considerably lower as compared to that in the BAU scenario. Second, in the LCD scenario, because the density of jobs and population is substantially increased at the nodes that are identified as employment sub-centres, the mean trip length of population residing at these locations and locations surrounding it is considerably lower when compared with the BAU scenario. The mean trip length in the LCD scenario is likely to be 5.14 km., which is even lower than the present mean trip length. As a result, considerable savings in CO_2 emissions are expected. The mean trip length for non-work purpose travel (shopping, recreation and social purpose trips) is 1.6 km., which is lower than the projection in BAU scenario of 1.9 km. and also the present mean trip length of 2.1 km. In the LCD scenario, because of good mixing of land uses and higher density of population, the majority of non-work purpose trips will be in the range lower than 1 kilometre. These values also comply with observed walking distance ranges, and are therefore more favourable for walking if other supporting conditions like safety and proper walking infrastructure on streets are satisfied.

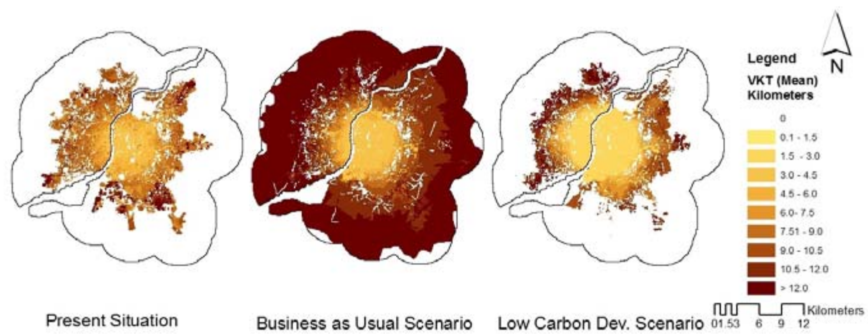

Figure 6-10: Mean Trip Length

Table 6-5: Percentage of population in different Mean Trip Length ranges

Mean Trip Length	Urban Development Scenario		
	LCD	BAU	Present
	% of Population in the range		
Non-Work Purpose Travel			
1-2 Km	87	64	44
2-3 Km	12	36	50
3-4 Km	1	1	6
4-5 Km			1
Work Purpose Travel			
1-2 Km		0	0
2-3 Km	34	0	8
3-4 Km	14	14	15
4-5 Km	10	4	18
5-6 Km	11	3	14
6-7 Km	7	3	14
7-8 Km	7	4	18
8-9 Km	4	4	10
9-10 Km	4	6	2
10-12 Km	6	26	1
> 12 Km	3	36	1

In Ahmedabad, the choice of motorized vehicles increases with the rise in vehicle ownership levels and with an increase in per capita income. Both these values have been projected based on past trends, and get reflected in mode choice probability. Mode choice in both the BAU and LCD scenarios favours higher use of two-wheel motorcycles over other modes in all parts of the city. These results are a reflection of the attitude of the current residents. From Figure 6-11, where work-purpose mode choice probabilities are presented, it can be seen that in BAU scenario more than 80 per cent of the population will reside at locations where the probability of choosing a two-wheel motorcycle as a mode for work purpose travel is more than 80 per cent. In the LCD scenario the proportion of individuals residing at locations that have high two-wheel motorcycle choice probabilities decreases, but the proportion of residents is still higher when compared to the present scenario in the more than 80 per cent choice probability category. However, the proportion of population living in grid cells is substantially lower in the subsequent two categories, that is, categories representing 50-80 per cent mode choice probabilities. Therefore, the weighted mode choice of two-wheel motorcycles is lower in the LCD scenario as compared to the present scenario. This means that there are sufficient locations where positive mode choice change can be achieved (from motorized to non-motorized modes). However, to retain residents in their current mode choices (that are non-motorized and public transit modes) in many parts of the city, in addition to built-form interventions, other measures will be needed to change individual travel behaviour attitudes in favour or non-motorized modes and public transit modes of travel.

It is observed that in the present situation, individuals residing in the Walled City and its surrounding locations to the east show a higher probability of choosing walking as their preferred mode. In the BAU scenario, because of an increase in per capita income and motorized vehicle ownership, there is an overall reduction in locations that have a high probability of residents choosing walking as a mode. Even in the Walled City and other locations in the eastern part of the city, the probability of walking to work goes down. In the LCD scenario, because of favourable built form, walking as the mode of choice for work-purpose trips is confined not only to the eastern parts of the city, other locations too have a considerably large portion of grid cells where residents have a high probability of choosing to walk for work- purpose travel. This positive shift towards walking mode choice in densely populated areas also results in a higher proportion of individuals residing at locations that have comparatively higher choice probabilities for walk as the mode for work purpose trips. However, in the LCD scenario more than 90 per cent of the population will reside in areas where the walk choice probability for work-purpose trips is lower than 20 per cent. Based on Boer et al. (2007), Cervero et al. (2009), and Oakes et al. (2007), one can imagine that higher walking mode choice probabilities can be achieved with better walking infrastructure.

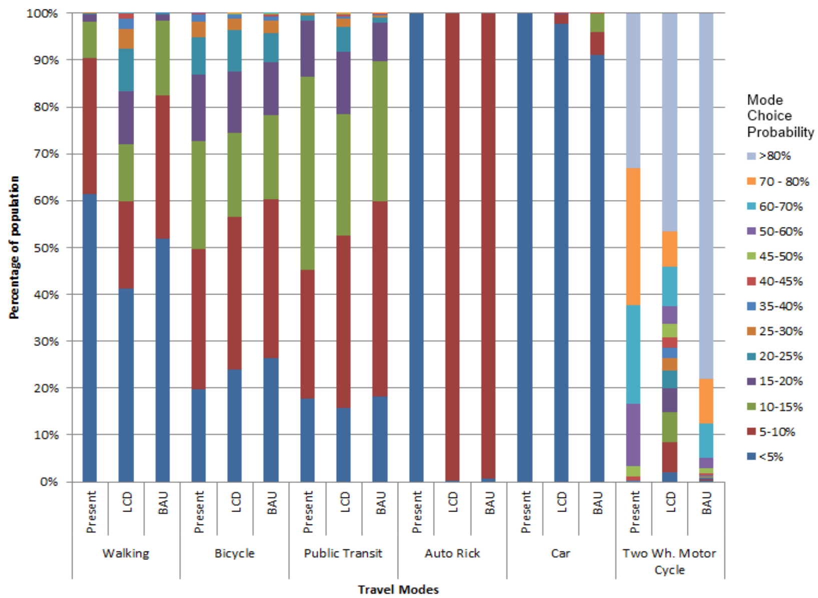

Figure 6-11: Work-purpose Mode Choice Probabilities and Population Covered

In addition to walking as a mode of choice and reduction in VKT in the LCD scenario, other desired shifts are also anticipated such as increased probabilities for choosing bicycle and public transit modes. As can be seen from the results, the proportion of population that prefers to use public transport or bicycles in the BAU scenario increases only marginally. This is an obvious influence of individual preference towards two-wheel motorcycle use for work-purpose travel. The proportion of individuals using public transit in the LCD scenario only increases marginally, but the choice of the bicycle mode decreases. Therefore, it can be said that the built-form measures used in this research have marginal influence on choice of bicycle and public transit modes. Like for walking choice, these interventions will have to be supported by other measures in order to influence a change in attitudes of residents towards these modes. An individual's income has a distinctive influence on mode choice, so some of the interventions could be aimed at influencing the higher -income individuals to use bicycles and public transport modes, probably by providing better and higher-end transport service and infrastructure that suits the travel needs of these income categories. However, whether this happens or not is a matter of further research and cannot be answered from the revealed choices analysed in this study.

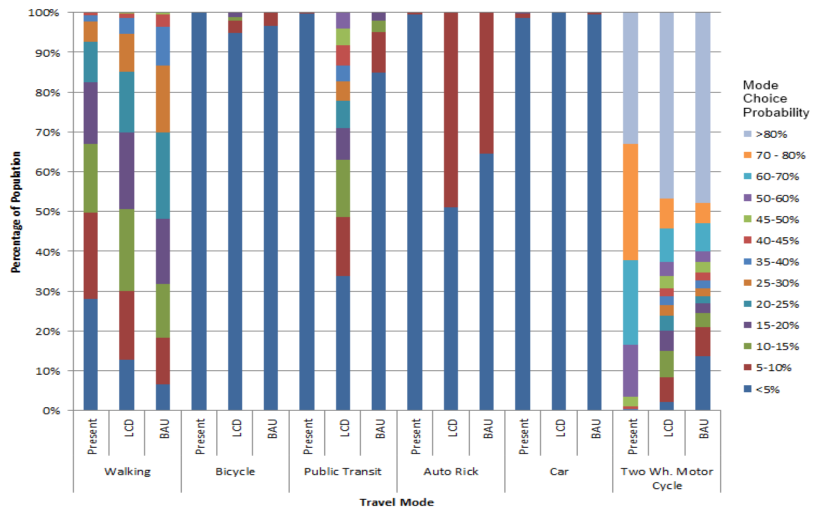

Figure 6-12: Non-Work Purpose Mode Choice Probabilities and Population Covered

For non-work purpose travel, it is estimated that the population choosing to walk will increase in both BAU and LCD scenarios. The possible reason for this is a strong relation that the built-form measure Diversity Index has with both location of most land uses, and the choice of walking for non-work purpose travel. Similarly, positive shifts are also achieved towards bicycle and public transit modes in the LCD scenario. So, when we couple the results of mode choice probabilities with savings in vehicle kilometres, less polluting vehicles, lower air pollution can be expected in the LCD scenario. Considering that these obligatory trips constitute about 17 per cent of the total trips in the city, these can be considered significant in the overall context of the city.

6.4 Environmental implications

In Table 6-6 the combined footprint (work purpose trips +non-work purpose trips) of all the three scenarios is presented. The total ecological footprint of transport is also visualized in Figure 6-13 and 6-14.

It can be observed that in the BAU scenario the ecological footprint of transport will increase from the present footprint of about three times the developed area to about four times the urban development area in the BAU scenario, and to twelve times the present urban development area of the city. In the LCD scenario, this footprint is reduced to two-and-a-half times the BAU urban development area and seven times the present development area. Muniz and Galindo (2005) computed the ecological footprint of transport for Barcelona, Spain, as 157657 ha. Barcelona has one-third the population of Ahmedabad, therefore in comparative terms

Ahmedabad is better off than Barcelona. However, the Ahmedabad district has a forest cover of 177 sq. km. (17700 sq. ha.) and the Gujarat state has a forest cover of 15,152 sq. km (1,515,200 sq. ha.). It is evident that even in the present circumstances, emissions generated from the transport sector alone in Ahmedabad overshoot the capacity of the area to absorb it. In the future the transport emissions from the city alone will require more than 17 per cent of Gujarat state's total forests to sequester all its transport emissions. The ecological footprint from transport improves when built-form measures are used to influence travel behaviour. It is clear that these measures are not enough, and that in future the total carbon emissions in the city will have to be addressed by other mechanisms as well, which will include the use of more efficient and environment-friendly fuel and vehicle technologies. There is a marginal increase in per capita ecological footprint of transport from the present footprint of 0.009 hectares/person to 0.015 hectares/person in the LCD scenario. In the BAU scenario this per capita footprint is 0.029 hectares/person, which is considerably higher than the present footprint values.

Table 6-6: Ecological footprint of transport in Ahmedabad city

Scenario	Urban Population	Urban Dev. Area (Hectares)	Travel Purpose	EF of Transport (Hectares)
Present	6.2 Million	21653	Work Purpose	54865
			Non-Work Purpose	6677
			Total	61542
BAU Scenario	9.18 Million	68587	Work Purpose	242183
			Non-Work Purpose	28660
			Total	266505
LCD Scenario	9.18 Million	23425	Work Purpose	125439
			Non-Work Purpose	22263
			Total	143364

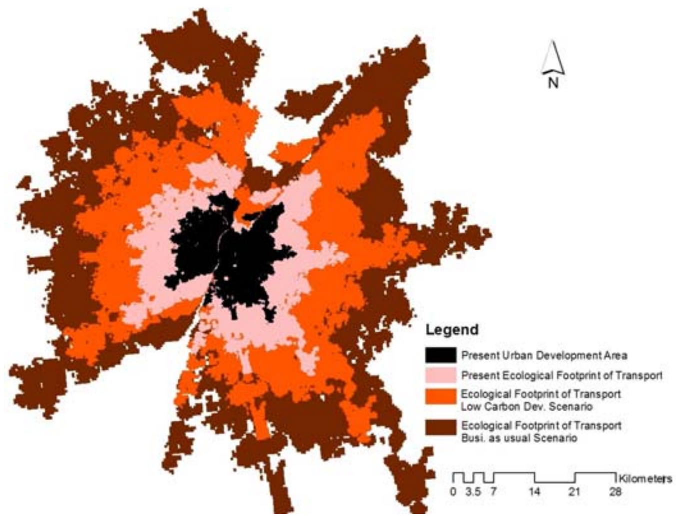

Figure 6-13: Ecological Footprint of Transport in Ahmedabad City

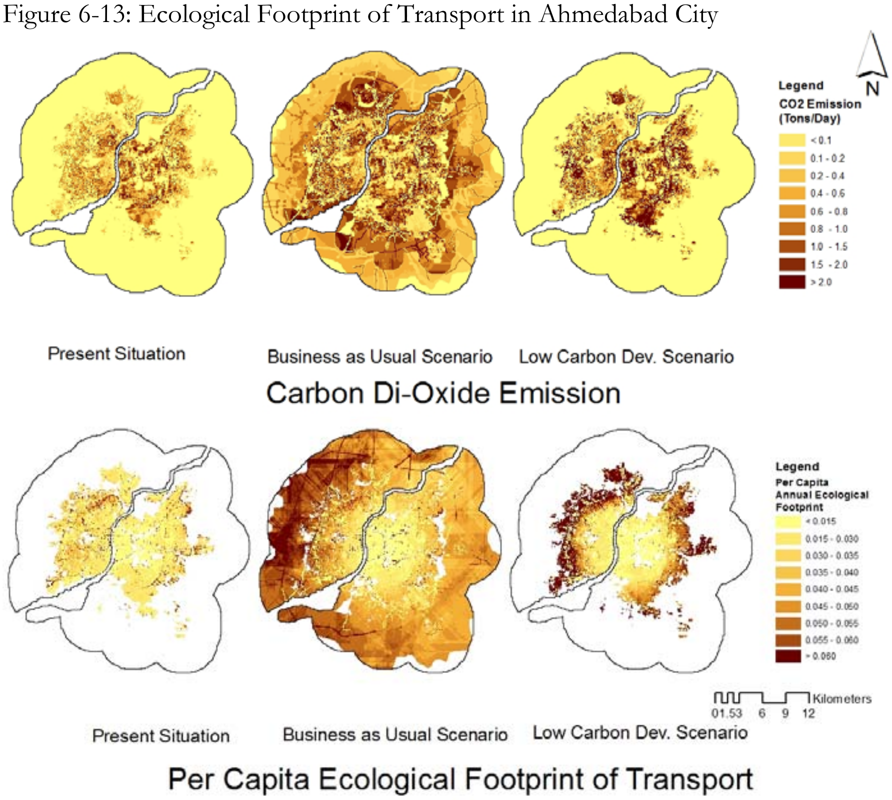

Figure 6-14: Work-purpose Travel: CO_2 Emissions and Per Capita Ecological Footprint of Transport

In Figure 6-14, the results of per day CO_2 emission, and per capita annual ecological footprint resulting from transport emissions are presented for work-purpose travel. In the first set of maps representing daily CO_2 emissions, it can be observed that the CO_2 emissions, and therefore the ecological footprint of transport in the BAU scenario, are considerably large in peripheral locations, more specifically in the R3 zone of development (see map in Figure 5-4).

In the LCD scenario the total CO_2 emissions and the ecological footprint of transport are more concentrated and therefore higher in the developed area. However, the per capita footprint in the LCD scenario is considerably lower than in the BAU and present scenarios, especially in the inner core areas where the density of development is increased by changing the FSI norms. Similar patterns are also observed for non-work purpose trips.

The paradox of compact development (as proposed in this research) is that more individuals could also be exposed to emissions as both emissions and residents are concentrated in the same spatial locations. As can be seen from Figure 6-15, locations that are exposed to more than 15 tonnes of CO_2 per hectare of development in a day are more in the LCD scenario and less in the sprawl type circumstances represented by the BAU scenario. Moreover, this research proposes an increase in the FSI, which could lead to a further increase in congestion levels and thus decrease in speeds. As we know, the relation of speed with emissions is a U-shaped curve, and the added congestion is only likely to increase air pollution. This further stresses the need for promoting the use of NMT and public transit modes at these locations as well as from other locations that connect with these.

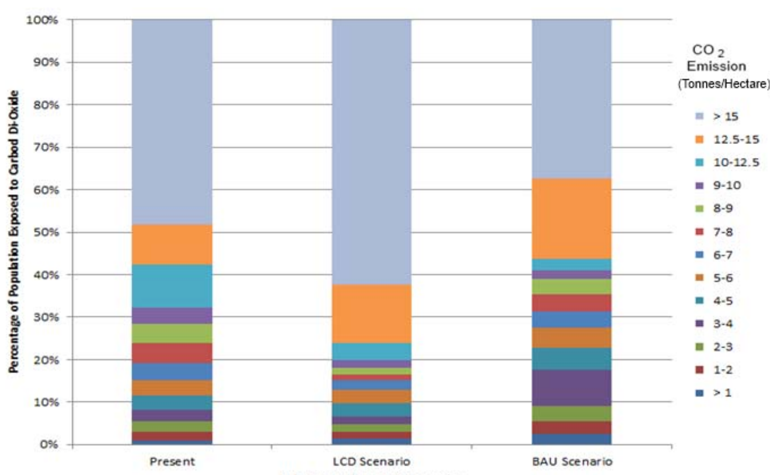

Figure 6-15: CO_2 Emission and Percentage of Population Exposed

The impact of congestion along with the influence of technology and better transport infrastructure quality and supply on travel behaviour has not been studied in this research for several reasons. Nor are congestion and its relation with modal choices incorporated in this study for lack of reliable data. Technology, both fuel and vehicle, is likely to generate less per-kilometre pollution and more efficient vehicles and fuels. However, even the technology direction and its impact on the situation of cities in India is not defined clearly (information is not available on post-Bharat IV emission standards and norms), and therefore is difficult to assume. The stated behaviour for infrastructure provision and improved transport supply, for example, better and walkable footpaths and increased supply of public transit services, are not part of the computations. Distance to transit stops and access to jobs by public transit covers the transit supply aspect, but the supply is far below the demand. Therefore how the relation will change when a better and more efficient transit system that caters to the transit demand, for example, a Metro Rail, is put in place is not known and thus is not part of the present analysis. Nevertheless, one can assume that when these alternatives are introduced, their influence on travel behaviour can be studied through a pilot in the locations where these interventions are introduced and can be incorporated in the framework and in the urban planning decisions.

6.5 Societal and economic benefits

The proximity/accessibility measure that computes the number of social and economic activities that can be accessed within a distance of 6.2 km. from a given location is considered to represent the benefits that society can derive from the use of the transport system. Accessibility to residential areas, educational institutions and entertainment locations represents societal benefits whereas access to retail and commercial locations represents economic benefits.

Accessibility to all these facilities in both the future scenarios is presented in Figure 6-16. Because of a sprawl-type development in the BAU scenario, the accessibility values are more spread out, and on the lower side. Contrary to this, in the LCD scenario accessibility values are more concentrated and higher in the central portion of the city. Presented in Table 6-7 is the change in accessibility to activities, which is computed by subtracting accessibility to the stated activities in the BAU scenario from accessibility values to these activities in the LCD scenario. In the latter scenario, because population and jobs are concentrated at a few nodes, a sizeable section of population--about 35 per cent--will have lower accessibility to residences than in the BAU scenario (which could be an important consideration for social trips); for the rest of the population, accessibility to residences increases.

Table 6-7: Change in accessibility and percentage of population covered

Activity	Change in Accessibility (1000 M. Sq.)	% Population Covered in LCD Scenario
Residences	< -25	25.0
	-25 - 0	9.7
	0 - 25	6.9
	25 - 50	15.6
	> 50	43.0
Educational Institutions	< -5	17.2
	- 5.0 -0.0	19.3
	0.0 – 5.0	54.9
	> 5.0	8.6
Entertainment Locations	< 0	7.7
	0 - 1	59.1
	1 - 2	33.2
Retail	< -2.5	23.4
	-2.5 - 0.0	15.0
	0.0 - 2.5	8.6
	2.5 - 5.0	6.2
	5.0 - 10.0	15.9
	> 10.0	30.9
Commercial Offices	< 0	37.0
	0.0 - 2.5	18.6
	2.5 - 5.0	4.5
	5.0 - 10.0	4.5
	> 10.0	35.3

It can be observed from Table 6-7 that accessibility to residential locations, which are usually accessed for social purpose travel, increases in the LCD scenario for more than 75 per cent of the population. The locations where access to residential locations decreases are peripheral locations and locations that are not part of the node where built-form interventions are proposed. For a large section of the population, accessibility to education and leisure activities (entertainment locations) also improves in the LCD scenario. Thus in the LCD scenario the accessibility of activities from which individuals derive societal benefits is much higher as compared to the BAU scenario. There is an overall increase in accessibility to commercial offices for all individuals in the LCD scenario as compared to the BAU scenario. Accessibility to retail activities also increases for a majority of the population.

Therefore, alongside environmental benefits, the societal and economic benefits improve in the LCD scenario. Hence it can be inferred/concluded that the use of built-form intervention can help in achieving low-carbon transport development.

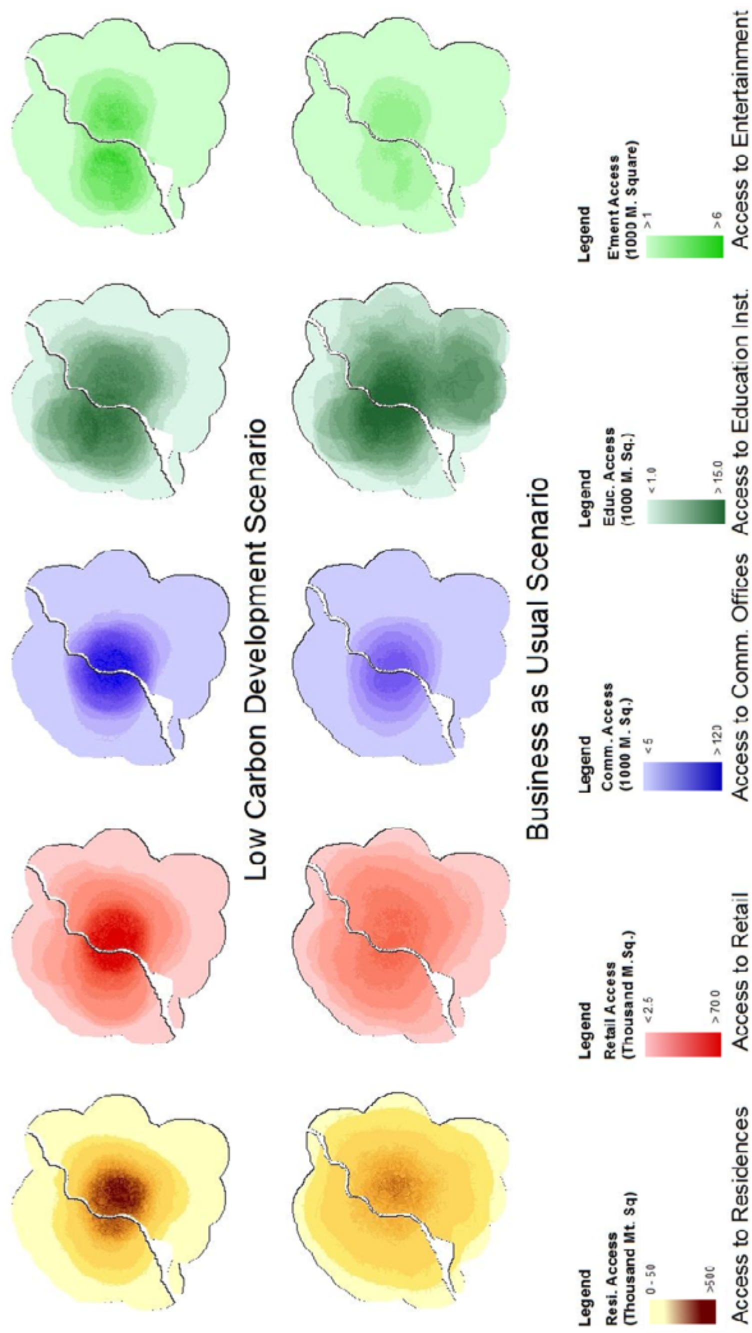

Figure 6-16: Accessibility to Activities

6.6 Policy making

From the analysis and discussion in the above section it is clear that built-form interventions can influence travel behaviour which can lead to low-carbon transport development. This also proves that the hypothesis of this thesis is valid and the null hypothesis can be rejected.

From the policy perspective this would require mechanisms that will enable development where the future built form is developed in such a manner that it favours use of non-motorized and collective modes of transport. The government authorities in India use four major public policy mechanisms to intervene in the process of urban development. These are the processes of Development Planning/Master Planning, which is a statutory plan mandated in the State of Gujarat by law under the Gujarat Town Planning and Urban Development Act (1976); the City Development Plans; the process of preparing Town Planning Schemes; and the process of regulating land use with the General Development Control Rules. The critique of these processes is discussed in Chapter 2; here we reflect on how these can be used to support the methods suggested in this research.

The above-stated exercise would have been futile if individuals attached to urban governance of the city could not relate with its usefulness. Therefore a presentation of the methods used in the research, the results and conclusions was made to the urban planning professionals working for the Ahmedabad Municipal Corporation, Ahmedabad Urban Development Authority and Rajkot Municipal Corporation. A similar presentation was made to the academics who have worked on the development of the city in close coordination with the government agencies. Those who attended these discussion are as follows.

1. Prof. Robert Cervero[1] (Professor, University of Berkeley, California)
2. Prof Utpal Sharma (Dean, Faculty of Planning and Public Policy (FoPPP), Ahmedabad)
3. CEPT faculty: Prof. Dinesh Mehta (Ex-Dean FoPPP and head UNDP (South-east Asia)), Prof. Meera Mehta (Ex-Dean FoPPP and worked for the World Bank), Prof. Anjana Vyas (Professor, FoPPP and Dean, Faculty of Geomantics), Dr. Bhargav Adhvaryu (HOD, Masters in Infrastructure Engineering and Management), Dr. Mona Vyas (Associate Professor, FoPPP), Dr. Deepak Baindur (Assistant Professor, Infrastructure Planning), Dr. Minal Pathak (Assistant Professor, Faculty of Climate Change)
4. Rajkot Municipal Corporation: Mr. Vijay Anatkar (City Engineer)
5. Ahmedabad Urban Development Authority (AUDA): Ms. Neela Munshi (Senior Town Planner), Mr. R.B. Joshi (Assistant Town Planner), Mr. H.N.

[1] The work was presented to Prof. Cevero individually when he visited Ahmedabad

Thakker (Deputy Town Planner), Arindam Majumdar (GIS – AUDA), Arvind Chauhan (GIS –AUDA)

6. Ahmedabad Municipal Corporation (AMC): Ms. Deepa Maniar, Mr. Mayank Rawal, Mr. Prasad Tilan (AMC).

The overall comments received in all the above meetings were that the work done is extensive and very comprehensive; and that this should be followed up with a set of guidelines, which would help urban development process. The main comments are presented below; responses to the comments, wherever required, are presented in italics.

- Prof Cervero observed that the work was extensive and exhaustive. He also observed that the work and empirical findings from this research should substantially help urban planning and policymaking.
- Neela Munshi and other AMC and AUDA professionals working on the Development Plan for the city of Ahmedabad said that the study is very useful for them, and that the findings from this research should be translated into a set of guidelines from them. To prepare the guidelines they suggested a follow-up exercise where three newly-planned town planning schemes could be taken up to work on how the results of this research can be translated into micro-level plans.
    - *Yes, as of now this thesis only demonstrates macro-level interventions but as a follow-up exercise it should be possible to plan a model town planning scheme or a combination of town planning schemes to demonstrate how these built-form measures can be incorporated in micro-level plans.*
- Neela Munshi also observed that this study is based only on household surveys. If a similar survey had been conducted in the market area, it could have given very different results.
    - *The choice of destination is part of the relation models so, in a way, it captures the influence of trip destination on travel behaviour. But yes, this study only looks at the home-based trips, and therefore only considers the influence of built form on the trip generation end.*
- Mr. Thakkar talked about the saturation point of development (carrying capacity). He also suggested that the study should in the end come up with an overall set of urban development guidelines for the Ahmedabad Urban Development Authority.
    - *Carrying capacity of a location is a function of available GDCRs and physical and social infrastructure provision, which to a large extent can be controlled. However, as of now the Floor Space Index (FSI) in Ahmedabad is very low so there is certainly scope for increasing it. However, how much the FSI can be*

increased would depend, as stated, on the availability of physical and social infrastructure.

- Mr. Thakkar also observed that this type of analysis will help them to better plan urban areas. For example, they are not required to provide transit-oriented development along the BRT corridor. Had this been known, they could have planned the BRT at locations where conducive built form is present.
    - *Yes, locations where built form is conducive for Bus Rapid Transit System can be identified using the data and elasticity of built form with transit choice. But for future growth and management, this study also demonstrates how to identify nodes that can form employment sub-centres, and this can form the basis of future mass transit plans.*
- Mr. Joshi and Mr. Thakker observed that the grid cell size is too small, and that about 500 m. would have been a more apt size for Ahmedabad. They suggested that a follow-up exercise to this work could be a gravity model or a land use transport model to make the analysis more interactive.
    - *Yes, the travel behaviour outcomes of this study can be used as inputs into a conventional four-step model or any other transport planning model.*
- Prof. Utpal Sharma said that the methods adopted and the simulation look logical, and give a good picture of urban development at the macro scale. But as in the LCD scenario interventions are sought at locations which have already developed, it might involve a lot of redevelopment. Secondly, the transport network and other infrastructure facilities will have to be checked to see whether they can support an FSI of 5. He suggested that the follow-up work to this exercise could look at how suggested measures could be operationalized at the town planning scheme level.
    - *Yes, an approach similar to town planning mechanism can be used to plan redevelopment at locations that are already developed.*
- Prof. Dinesh Mehta questioned the annotation of built form used in this study. He said that for him built form of an urban area would be linear, circular, radial, compact etc. He also questioned its quantification on 100 m. x 100 m. grid, and said that larger grid cell size would have been better. He and Dr. Bhargav Adhvaryu also commented on the usefulness of identifying the employment sub-centres in this research, but later on agreed on the importance of looking at the significance of poly-centricity on travel behaviour.
- Mona Iyer said that she expected a blow-up footprint map as the present method of visualization is not good. Dr Pathak and Prof Dinesh Mehta said

that there is no need to quantify ecological footprint, carbon footprint is good enough.

  - *Yes, there is a redundancy, but ecological footprint maps are used to visually communicate the impact of travel choice on the environment.*

- Vijay Anatkar said that to influence decision-makers the cost/benefit of the proposal could have been worked out. He observed that most urban decisions are influence by financial considerations of implementation. He also felt that how to govern and how to implement and control this development would also be important concerns.
- Vijay Anatkar said that such visualizations can help urban planners in making decisions. He said that planners mostly face difficulty in explaining the consequences of their decisions as they visually conceive repercussions (positive and negative) of their decision. The kind of analysis presented in this research will help them justify their decisions, like the implementation of the BRT to a standing committee (political government).
- He also felt that the sewerage network etc. should have the capacity to permit more development because the existing systems are always designed taking into account factors of safety, so the design should be sufficient for future expansion. He said that FSI is related with road-width, so the carrying capacity of roads should be checked before proposing an increase in FSI.

6.7 Discussion

In this chapter, built form and travel behaviour relation is used to demonstrate how low-carbon transport development can be achieved. To ascertain low-carbon transport development, environmental and societal benefits have also been quantified and checked.

Two scenarios for the year 2030 are considered, the first representing the base situation, which is the Business-as-Usual scenario. For the second, built-form interventions are incorporated to develop a so-called Low-Carbon Development scenario. It is called LCD as this scenario is aimed at lowering the carbon emissions without compromising with development (both human and economic) and societal benefits.

Results of the analysis first demonstrate the obvious, that mode shares and shifts that are desired to lower carbon emissions from transport in the city increase in the Low-Carbon Development scenario as compared to the Business-as-Usual scenario. A major advantage of now allowing the development to sprawl is that distances travelled by individuals are contained; in fact, because of a more compact and mixed development, the mean trip length in the LCD scenario could actually be lower than the present situation for both work and non-work purpose travel. In the present LCD scenario, the activity location requirements are satisfied when FSI at existing employment sub-centres is increased in areas that are located more towards the central parts of the city. Similarly, the distance travelled by individuals in the peripheral locations is still high. To counter this, urban planning could take a more futuristic look at sub-centres that could develop in the next fifty years and already earmark and plan for these locations based on the existing pattern of sub-centre formation.

Despite the projected four-fold increase in per capita income in the LCD scenario, the projected share of walking, public transit and bicycle for work and non-work increases. Given the present mode choice attitudes of the residents, the total share of these modes in the business-as-usual scenario would reduce drastically, and two-wheel motorcycles would be the dominant mode with much higher mode choice probabilities than in the present situation.

The shift in travel distance and mode choice in the desired direction result in lowering the CO_2 emissions, but these are still higher than in the present situation. To further contain the CO_2 emissions and the consequent ecological footprint, change in vehicle and fuel technology and individual attitudes will be required.

The most widely used land-use policy tool for achieving the desired built form is zoning regulation which in India is implemented by preparing the Development Plan. The Plan is implemented at the micro-level using the mechanism of Town Planning Schemes. As the development plan is the city-level land-use strategy document at the macro level, macro-level land-use policies such as formation of employment sub-centre nodes, mass transit provision and major road network can be planned and proposed in the Development Plan. Other built-form policies can be introduced using the town planning scheme and development control regulations. However, as demonstrated in this study, these plans should be scenarios which need to be tested for environmental impact and the societal and economic benefits they provide to the residents. To be able to research the environmental impact of transport it is imperative that a Unified Transport Planning and Management agency is set up where all transport-related decisions are taken in conjunction with urban planning decisions.

The results were also presented to the city's Urban Development agencies and to academics in the city and elsewhere. According to the feedback of these professionals, the results of this study look realistic and the importance of using the methods presented in this research in urban and transport planning were universally accepted. The planner from AUDA, the city's urban development authority, also suggested that this study should be followed up by preparing a set of guidelines that will help the Authority in implementing the suggested built-form policy measures.

7 Synthesis

7.1 Introduction

This thesis centres on the understanding that built form plays an important role in defining the manner in which individuals travel in an urban area, and that understanding can be used in urban policymaking to help plan future spatial development that is oriented towards low-carbon transport development. Appropriate urban planning policies that aim at reducing air pollution from transport are particularly important for cities in India, as most cities are distinguished by rapid urbanization, growth in motorized vehicles, and poor urban policy and management response. The objective of this thesis is not policymaking, but to look at methods that can provide key information on how built form influences travel behaviour, which can help in policy formulation. The research provides an insight into how built form can be used to derive future spatial development scenarios that are low-carbon transport developments. Ahmedabad, a rapidly growing metropolitan city in India is used as a case study for this research.

Based on the findings of the previous chapters, an open general question is addressed in this chapter, which is: What are the contributions of the new findings of this research to the process of planning and to the relevant scientific field? With this question in mind, this chapter is organized into five sections. The next section (Section 2) is a reflection on the methods used to derive the built form and travel behaviour models and on the outcomes of these models. Section 3 discusses the planning implications of these results, and Section 4 reflects on the methods and outcomes of the spatial-temporal model used to model future growth and development of Ahmedabad. The last section, Section 5, discusses the results in the context of urban policy in India and defines the future scope of work.

7.2 Built form and travel behaviour relation

The meaning of built form is given in Chapter 1. As a general concept, built form is the representation of urban morphology, that is, the spatial patterns and arrangement of individual urban elements. In studies concerning the relation of built form with travel behaviour, built elements that influence travel behaviour are considered and are represented as a reflection of how intensely a particular area is developed, what range of land-use opportunities the developed area presents to the residents, how good is the supply of transport infrastructure, etc. These indicators essentially measure the transport-demand-generating and transport-supply urban elements, which are then checked for their influence on travel behaviour. A list of indicators that have been used in empirical research to study these relations have been listed in Tables 1-1 and 1-3. Section 1.2.2 also defines these indicators and also the measures that have been used to operationalize these indicators.

The urban development reality of cities in India has been discussed in Chapter 2. The general observations are that cities in India have grown very fast mainly led by rapid urbanization resulting from rural – urban migration, mainly to escape poverty. The planning and management of urban areas in India has been criticized for its arbitrary decision-making, poor integration of policies and sub-optimal provision of land use, housing stock and infrastructure, including transport infrastructure. Consequently, land is intensely used (a result of poor housing supply), land use is heterogeneous (because of planning regulation and control) and the supply of transport infrastructure is poor. Given this reality, the built-form indicators used in this study are identified in Chapter 2 and defined in Chapter 3. Two additional indicators are considered, first, to understand the influence of concentration of poor people on mode choice, and second, to understand the effect of polycentric development on travel behaviour.

The methods and data used to quantify built form in the case city of Ahmedabad are described and discussed in sections 3.2.2 and 3.2.3. The application of GIS in analysing the built form and travel behaviour relation serves two objectives, first, to help quantify built-from measures using the multiple data sources available, and second, to help create a comprehensive database containing built from and travel behaviour data to facilitate analysis.

The built-form measures in this research are quantified to a uniform raster grid of 100 m. x 100 m. The use of uniform grid facilitated aggregation or disaggregation of data from multiple sources with different spatial resolutions, using spatial overlay functions in GIS. It also facilitated the use of spatial statistical functions required to quantify built-form measures like land-use diversity and mix. Spatial overlay functions were also used to assign the quantified built-form measures in each gird to the transport survey data conducted for households residing in the grid cell, to facilitate analysis. The use of GIS also allowed the possibility of conducting the analysis at a disaggregate scale of the above-mentioned raster grid cells. This was considered essential in the present research as using a higher unit of analysis would not have been accurate enough to represent appropriately the diverse and heterogeneous built form found in Indian cities, or to capture the influence of built form on short distance trips, such as walking trips.

The pattern of built form is described in section 3.3, which makes obvious the observations made in relation to urban development problems in India cities. The provision of transport infrastructure provision is good only in some patches and very bad in some; the intensity of development is high, and the land-use mix and balance are good. The analysis done to identify employment sub-centres described in sections 3.2 and 3.3.7 proves that Ahmedabad has changed from a monocentric city to a polycentric city.

Multiple regression models were used to analyse the impact of built form on travel behaviour (viz., travel distances and mode choice). The built form - travel distance relation is analysed using a multivariate linear regression model, where as the built form - mode choice relation is analysed using binary logit models. The developed models allow the analysts and the decision-makers to estimate the influence and effects of various changes in built-form measures (like higher residential/employment density, mixed land-use development, etc.) on the reduction in travel distances and choice of non-motorized and public transit modes. The three-stage approach used to model the built form - travel behaviour relation helps the decision-makers to decide the macro urban built-form structure and policies. It provides them with insights on whether they should encourage development of employment sub-centres or not, and how they should intervene on the micro-level built form, such as through policies that address mixing of land use. This study therefore contributes first, by demonstrating how built form-travel behaviour relation can be developed in India, and secondly, by developing a comprehensive model that analyses the influence of both micro-level and macro-level urban built-form indicators on changes in travel behaviour.

The objective of modelling the relation between built form and travel behaviour is to derive built-form policies and land-use planning proposals, and to be able to evaluate their influence on travel behaviour. The particular interest was to study the influence on vehicle distance travelled and choice of non-motorized and public transit modes. The results of the models have been presented in Chapter 4. The research demonstrates that in Ahmedabad accessibility to jobs has a strong influence on vehicle distances travelled by individuals and their travel mode choices. It was found that individuals like to live close to their work destination, and at locations where accessibility to jobs is high they prefer to use non-motorized modes. The research also demonstrates that if the trip destination is one of the employment sub-centres, then the vehicle travel distance is less. Encouraging polycentric development as a planning strategy ensures that as the city grows outwards, accessibility to jobs for individuals residing in the peripheral areas is good; the strategy should therefore be supported. In addition, a compact urban fabric, particularly with a good job and residential balance and high population provides conditions for reduced vehicle travel distance. Similarly, locations with high probability of walking and cycling as modes of choice can also be identified as locations with high population density, accessibility to jobs and intersection density, and for cycle choice at locations, which in addition to good job accessibility also have a high mixing of land use. The choice of public transit usage is high in locations that are near public transit stops and have a high density of public transit routes, high population density, high density of poor residents, and where trip destinations are either in the Walled City or on Ashram Road. However, locations with good accessibility to jobs, a good land-use balance, and higher density of intersections discourage the use of the public transit mode. The research results provide definite direction, which indicates that the travel behaviour changes desired to achieve low-carbon development can be achieved by encouraging polycentric, more compact, mixed-use development with high density of streets and a good supply of non-motorized and public transport infrastructure.

7.2.1 Urban planning policy implications

The urban planning implications of the built form and travel behaviour relations developed in this research are discussed in section 4.7. Urban planning and management of cities require urban planners to make decisions that can be implemented at different scales and for different time horizons. As stated in section 4.5, for urban development and management organizations to undertake informed decisions, the basic information needed will have to flow from observed or empirical evidence. The empirical evidence provided in this research bridges the knowledge gap and provides key direction that would enable decision-makers to evaluate existing built form policies/plans or to formulate new policies/plans that would lead to a desired impact on vehicle distance travelled and modal choices. As shown in Figure 7-1 and discussed in section 4.7, to formulate policies, in the case of this research, the basic information needed is on the interaction between built form and travel behaviour.

Figure 7-1: Built Form -Travel Behaviour Relation and Municipal Urban Planning and Management Pyramid(adopted from (Huxhold, 1991)

As shown by the actions arrow in Figure 7-1, the information on which built-form indicators influence travel behaviour is converted into specific policy statements, which essentially underline what kind of built form should be promoted to achieve low-carbon transport development. The information is then converted into an overall urban development strategy, which in this case is to promote polycentric development, concentrate all other built-form variables around it, and target achieving the built-form measure with the highest priority, which in this case is access to destination. These are then assigned action by associating the existing planning tools and mechanisms that can be used to achieve these strategies. In the end, these indicators also need to be monitored and regulated.

The policy implications at the city level have been discussed in Chapter 4, and presented in Figure 4-5. In Ahmedabad, the Development Plan is used to formulate zoning and land-use policies, and is therefore the city-level land-use strategy document. Based on the information derived from built form - travel behaviour relation, all the macro-level built-form policies and other strategic policies can be decided at this level, such as promoting sub-centre formation, mixed land use, infill development, transport infrastructure and network that supports the use of the desired modes. These policies have to be converted into strategic programs which would include different time horizons and implementation strategies. The city development plan and city mobility plans are the planning tools that can be used for the purpose. The land-use interventions are implemented as actions in Ahmedabad by using the mechanism of town planning schemes. As stated in Chapter 6, to translate transport-related built-form measures into actions, a Unified Transport Planning and Management Agency needs to be instituted where all transport-related decisions are taken in conjunction with urban planning decisions.

7.3 Built form - travel relation and low-carbon transport development

Given the policy implications, Figure 4-4 presents a general approach to how built form and travel behaviour relation can be used as a tool to support or formulate urban planning decisions. Both evaluatory and prescriptive approaches have been applied in this research in a 'what-if' scenario to test the patterns of future urban development and growth. One scenario projects future urban development to evaluate the present urban planning policies and the second approach prescribes urban planning policies based on empirically derived information on built form and travel behaviour relation to demonstrate the benefits of implementing these policies.

The method that is used to translate urban planning policies into future development scenarios, and to test if these are actually low-carbon transport development, is presented in Chapter 5. An urban growth and development model that is able to simulate land-use development and urban growth for the city of Ahmedabad is developed as described in Chapter 5. The model uses a hybrid approach; a combination of a logistic regression and a cellular-automata-based model to simulate future urban development and growth trends of the city. The model is able to predict the future urban development scenarios in a self-organizing land-use development environment for two future urban development scenarios for the year 2030, the first representing the base situation, which is the 'do nothing' scenario. The second scenario is where built-form interventions are incorporated into the development. Thus the methods used present two scenarios to the decision-makers; the first scenario is if development is allowed without making any changes to the present land-use and built-form policies. In this case, the resultant development will be a sprawl, with very low residential and job densities on the periphery of the city. However, if the built from were implemented to suit a desired travel behaviour of achieving lower vehicle travel distance, and higher choice of non-motorized and public transport modes, then sprawl can be contained, and most of the non-residential activities can be clustered as activity nodes. Consequently, the presented results demonstrate that the built form can play an important role in formulating urban development policies that are oriented towards reducing carbon emitted because of individual travel behaviour.

The environmental, societal and economic implications of both scenarios are tested in Chapter 6. Two methods are used to visualize the environmental impact, first, by quantifying and visualizing total carbon emissions, and second, by converting the total carbon emissions to the ecological footprint of transport. The results demonstrate that for the year 2030, the per capita total carbon emissions will be lower than the existing levels, and consequently, the per capita ecological footprint too will be lower. The results demonstrate the implication of not using built form - travel behaviour relation in deriving urban polices in urban planning. The results are presented in Figures 6-13 and 6-14. The visualization of the results in this manner should make it easy for the decision-makers to identify the impacts of built-form policies on travel behaviour and subsequently on total carbon emissions. The results of societal benefits that can be derived from both policy scenarios are presented in Figure 6-16. It is obvious that the urban development policy that is driven by the policy initiative to promote polycentric development and increase accessibility to jobs, also improves access to economic opportunities. By ensuring that the land use is mixed and balanced, the accessibility to activities that provide societal good/benefits also improves for a large majority of the population. Thus both objectives of low-carbon development, to promote development while ensuring lower carbon emissions, are achieved in the scenario where built form - travel behaviour relation is used to drive urban planning policy.

7.4 A reflection on the main themes of this research

The objectives of this research were twofold—first, to quantify the relation between built form and travel behaviour in a metropolitan city in India, and second, to use the information derived from the relation to derive urban policy recommendations from a future spatial development perspective that is low-carbon transport development.

Both the core themes of this research have strong relevance for planning of cities in India. By answering the first component of the objective of this research, key information on how built form influences travel behaviour in the context of Ahmedabad is derived, which also has an implication for urban planning in other cities. Ahmedabad is considered as a typical metropolitan city in India; therefore, the core finding that accessibility to jobs is the key built-form measure that influences vehicle distances travelled and the desirable mode choices to lower carbon emissions in the city, and that it can be achieved by polycentric development, will also be true in other metropolitan cities in India. This is because large sections of population in Indian cities have low incomes, and therefore prefer to reside close to their job locations, often in illegal settlements. By promoting polycentric development, the accessibility of jobs can be more uniform across the landscape, especially for individuals living towards the periphery where most land for future development is available. Land-use mix and balance, and design indicators have a mixed influence on mode choice and need to be researched further. The methods presented in this research should make it possible to conduct similar research in other cities in India leading to meta-analysis and a generalized vision of which built-form measures should be promoted as a general policy across metropolitan cities in India. The exercise of studying built form and travel behaviour relation also cannot be a one-off affair as the behaviour of individuals would be different when better pedestrian and bicycle infrastructure is provided. This research is able to provide the starting information on the relation, which will have to be built upon by subsequent research.

The second core theme of this research was to demonstrate how the information derived from the built form and travel relation can be used to derive urban policies that lead to low-carbon transport development. For this purpose, as discussed earlier in this chapter and in Chapter 4, the development planning process is an important process. This thesis demonstrates how information derived from the empirically derived built form -travel behaviour relation can be used to either evaluate the existing policies or prescribe policies and visualize the resulting urban growth and development scenarios for both scenarios. Because this process is such an important process in the planning of cities in India, the urban growth and development simulation exercise, similar to or more complex than the one demonstrated in this research, should be used to visualize the impacts of different alternatives of urban development policies and adopt the polices accordingly. As a result, this research was able to derive and visualize the consequences of using the above policy in terms of reducing air pollution and improving accessibility to economic and social activities.

Thus by successfully deriving the built form - travel relation and demonstrating that future spatial development of built form is crucial from the perspective of low-carbon development, this thesis is able to prove that the null hypothesis of this research is not valid.

7.5 Future research

This research is the first of its kind that presents empirical evidence of the relation between built form and travel behaviour in India, and therefore several problems were encountered in operationalizing this research. Some of these were solved during the course of the research, and some still remain to be tackled by further research. This research also opens up new vistas to be researched further on the topic in the Indian context. As a conclusion, several areas for future research are proposed.

Built form data and potential of using remote sensing sources of data: This research had to depend upon multiple sources of data and the combined intelligence that can be derived from these using several geo-processing and spatial overlay methods in GIS to quantify built-form data. Similar data is available for all cities in India, but the effort required to collect all the datasets used in this research is enormous. In the Indian context, methods that rely less on published sources of data will have to be further developed. Given the advancement in remote sensing data and the ability of computers to process such data, it could possibly be an important future data source. The current evidence of extracting accurate information on built elements from remote sensing data is nascent and needs further development. Given the heterogeneous nature of development in India, the diversity measure could be the most difficult measure to quantify; a possible direction to quantify it would be to use association rules and tools to extract building-level and land-use-related information from remote sensing data sources.

Quantification of built-form measures: This research has relied more on the form that is built-up and permanent, but temporary structures in India are rampant. These informal and temporary structures might also represent a significant portion of work-trip locations of the urban poor, and therefore need consideration in future research. Other elements that might influence walking or bicycling like presence of trees on the street, distance to the nearest grocery shop, informal activities on the street, presence of blockages like utility boxes, parking on pathways, could also be considered in future research on the topic.

Built form and travel behaviour relation: Built form and travel behaviour relation is statistically weak and built form is only able to explain a small portion of variation in the travel behaviour But the relation is significant and important from the land-use policy point of view. Whereas this study provides the first empirical evidence on the topic in the Indian context, future research on the relation can translate into a meta-analysis with more averaged out built form and travel behaviour relation. This study does not prove the impact that the improvements in pedestrian, bicycle and public transit infrastructure or supply will have on future travel behaviour. A stated preference analysis that analyses these relations can help bridge this knowledge gap. The results of this research mostly rely on the influence of built form at the trip generation end, or on the location of the household. It should also be possible to look at built-form configuration at the trip destination end, which in conjunction with the results produced in this research could be inputs into a spatial interaction modelling framework that can help to analyse other consequences, such as impact on congestion.

Policy recommendations: The policy-level recommendations made in this research are based on the underlying assumption that the urban and state governments responsible for urban planning policies will have the capacity to adapt and adopt these recommendations. Further research is required to understand the capacities of these organizations to implement the recommended built-form measures. This research also suggests incorporating the urban policies related to built form using existing policy-planning tools. This also needs a relook and further questioning about whether the existing tools are good enough, can they be altered, or will future research need addition planning policy tools.

Influence of socio-economic characteristics of individual on travel behaviour: In future years, one assumes, built-form measures will be incorporated into planning of urban areas to influence travel behaviour. But if the percapita income increases, the residential self-selection problem could be different from the present behaviour. Thus further research isolating the influence of built form would help urban development policies in India.

Environmental, economic and societal impact: Future research is required on the manner in which the environmental impact is represented, for example, isnthe ecological footprint a better representation of environmental impact or is the carbon footprint good enough, and, how sensitive are policy makers to the different methods of visualizing environmental impact? In this research, environmental impact has been generalized to the mode type, but each mode can have various sub-categories or types of mode. For example, a car can be a SUV (sport utility vehicle) or a compact 800 cc car; these considerations can considerably change the results, and need to be part of future research on the topic. The impact of transport-related emissionson human health and the environment have not been quantified by the present research, and can therefore be another offshoot of this research needing further treatment.

Because this research is the first of its kind in the Indian context, it poses more questions for further research than it answers. However, the results drawn from this research are significant from the policy perspective, and the methods presented in this research should enable similar research on other cities in India leading to a meta-analysis and creation of a broader policy framework on built form in India.

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Summary

In India, the continuing rapid growth and development of metropolitan cities are a matter of concern. From the perspective of low-carbon transport development it is clear that cities in India cannot continue to grow in the manner they have in the past. There is a need to intervene in a manner that the long-term plans facilitate people to travel less and encourage them to use non-motorized and public transport modes for travel while avoiding negative repercussions on societal benefits for the city residents. Consequently, there is a wide recognition at national policy level that pollution resulting from transport needs to be contained. One of the measures considered is to formulate built-form policies that would encourage individuals to travel less and increase the use of non-motorized transport and public transit modes. However, empirical evidence on the relation between built form and travel behaviour in Indian cities is lacking. Thus, there is a need to identify and represent the influence of built form on travel behaviour in the Indian context. From a strategic urban planning perspective and for decision-making that has as its end objective a reduction of carbon emissions from passenger transport in the city, it is important to demonstrate how this relation can be translated into environmental, societal and economic benefits. In this thesis, the main emphasis lies on the exploration of the relations between travel behaviour and the environment. Therefore, the objective of this research is to quantify the relation between built form, transport, and the environmental externalities of transport for a fast-developing metropolitan city in India, and derive urban policy recommendations towards low-carbon development. The initial hypothesis of this research is: *"In rapidly-growing metropolitan cities in India, such as Ahmedabad, future spatial developments in built form are crucial from the perspective of achieving low-carbon transport development."*

This study therefore has two major research outputs: The first is an analysis of relations between built form and travel behaviour in the Indian context. The second uses this relation to develop future urban development scenarios that can be considered low-carbon transport developments. The empirical research is carried out in city of Ahmedabad. Located in the western state of Gujarat in India, Ahmedabad represents a typical metropolitan city in India with the related urban and transport development problems and opportunities.

'Built form', as a broad concept, implies the spatial pattern or arrangement of individual urban elements such as buildings, streets and land use. Built form is conventionally represented by 6 groups of indicators, referred to as 6Ds (Bourne, 1982). These are density, diversity, design, destination accessibility, distance to transit (transit access), and demand management. In India, as no travel demand management policies exist, travel demand related measures are not considered. However, it is believed that locations with a high concentration of poor people could influence mode choice, thus density of poor people is considered as one of the indicators. In addition to these 6Ds, employment sub-centres that define

macro-level built form can also influence travel pattern, and are therefore considered as an additional indicator representing the influence of concentration of activities at the trip destination end. 'Transport' is represented as the travel behaviour of residents and is measured as the distances travelled by individuals in a day and the modes they prefer to use for the travel. Multiple regression models are used to analyse the impact of built form on travel behaviour (travel distance and mode choice). The developed models allow the analysts and decision-makers to estimate the influence of the effects of various changes in built-form measures (like higher residential/employment density, mixed land-use development) on reduction in travel distances and an increase in the choice of non-motorized and public transit modes. From the relations developed in this study, it was found that the built environment significantly affects travel behaviour of individuals. More mixed and balanced land use and higher densities significantly reduce the distance that individuals travel and also increase the probability of their choosing non-motorized travel options. Proximity to public transit stops, higher route density, higher population density and high density of poor residents increase the use of public transit. However, contrary to what is conventionally found, locations with good accessibility to jobs, a good land-use balance, and higher density of intersections discourage the use of the public transit modes, the reasons for which need to be further researched.

Low-Carbon Development (LCD) means growth and development targets that are achieved using a low-carbon trajectory. Even though there is no agreed definition of LCD, the view of using 'less carbon for growth' is considered as the common denominator. A common feature of low-carbon development in different countries is utilizing less carbon to promote economic growth. Two measures are used to visualize the environmental impact resulting from passenger transport movements. First, all air pollution is converted in terms of total carbon-dioxide equivalent; this is done to understand human exposure to these pollutants. The second measure used is the ecological footprint of transport, which represents environmental resources consumed by transport. The societal benefits are estimated by computing accessibility to activities that give economic and societal benefits to individuals. To visualize impacts of future scenarios, an urban growth model that is able to simulate land-use development and urban growth for the city of Ahmedabad, and that is easily replicable in other similar contexts, was developed. This model uses a hybrid approach; a combination of a logistic regression and a cellular-automata-based model to simulate future urban development and growth of the city. The developed model allows the possibility of designing alternate scenarios with different zoning and development control regulations. The model is used to simulate two future urban development scenarios for the year 2030, the first representing the do-nothing situation, which is the Business-as-Usual (BAU) scenario. The second scenario is where built form interventions are incorporated to develop a so-called Low-Carbon Transport Development (LCD) scenario.

The results of the analysis demonstrate that the use of lower emission travel modes increases in the Low-Carbon Development scenario as compared to the Business-as-Usual scenario. A major advantage of not allowing the development to sprawl in the LCD scenario is that distances travelled by individuals are contained. In fact, because of more compact and mixed development the mean trip length in the LCD scenario is actually lower than the current mean trip length for both work and non-work travel. It was found that despite the projected four-fold increase in per capita income, in the LCD scenario the projected share of walking, public transit and bicycle for work and non-work travel increases. As a result, positive shifts are observed in travel distances and mode choice and therefore CO2 emission in the LCD scenario is considerably lower than in the BAU scenario. Moreover, as the resulting development is compact, accessibility to activities that provide economic and societal benefits improves for a large majority of the population. Thus, the null hypothesis of this research can be rejected.

This study is able to prove that built form influences travel behaviour in a metropolitan Indian city. The understanding of this influence allows policy makers to derive future development scenarios that are low-carbon transport oriented. To achieve this, the existing land-use policy can be used. The Development Plan can be used for macro-level land-use policies like formation of employment sub-centre nodes, mass transit provision and development of a major road network. Other built-form policies can be introduced at the local level, using the town planning scheme and the general development control regulations. However, as demonstrated in this study, these plans should be scenario based and need to be tested for environmental impact and the societal and economic benefits they provide to the residents. The results were presented to the city's Urban Development Agency and to academics in the city and elsewhere. The feedback was that the results look realistic, and the importance of using the methods presented in this research in urban and transport planning was universally accepted. The planners in the urban development authority suggested that this study should be followed up by preparing a set of guidelines that will help the authority in implementing the suggested built-form policy measures.

This study demonstrates the methods that can be used to develop built form and travel behaviour relations, and how to use these relations to prepare low-carbon transport development scenarios for future urban development in metropolitan cities. In the future, it should be feasible to conduct similar case studies in other Indian cities for a meta-analysis that can possibly shed light on policy debates that this study has not been able to cover. Such studies could take place in urban areas of various sizes, in different parts of India, and could address in particular the influence of good quality pedestrian and bicycle infrastructure on mode choice and the overall effectiveness of built-form policies in land-use decision-making.

Samenvatting

De snelle groei en ontwikkeling van metropolen in India is zorgwekkend, mede vanuit het perspectief en de wens om toekomstige ontwikkelingen volgens de principes van duurzaam verkeer en vervoer, in het bijzonder lage-CO_2 ontwikkeling, te laten verlopen. Op nationaal niveau is men het er over eens dat verkeer - en vervoeremissies moeten worden beteugeld. Een van de mogelijke beleidsinterventies om dit te bereiken is het via stedelijke planning stimuleren van mensen om minder te reizen en tegelijkertijd het gebruik van langzaam verkeer en openbaar vervoer te bevorderen. Echter, empirisch bewijs van deze relatie tussen de bebouwde omgeving en reisgedrag in de context van Indiase steden bestaat nog nauwelijks en is daarmee onderwerp van dit proefschrift. Het beter begrijpen en kwantificeren van deze relatie stelt planners en beleidsmakers in staat om strategische beslissingen op het gebied van stedelijke planning en verkeer en vervoer te maken die bijvoorbeeld als doel hebben CO_2 emissies door personenvervoer in de stad te reduceren. Derhalve is het belangrijk om aan te kunnen tonen hoe de relatie bebouwde omgeving en verkeer en vervoer vertaald kan worden in milieukundige, sociale en economische effecten. Het doel van het onderzoek in dit proefschrift betreft de milieukundige effecten. Deze worden gekwantificeerd voor een typische snel groeiende metropool in India en gebruikt om vervolgens mogelijk stedelijke beleid ten behoeve van een lage-CO_2 ontwikkeling af te leiden. De initiële hypothese voor dit onderzoek is daarom ook: "In snelgroeiende metropolen in India, bijvoorbeeld in de stad Ahmedabad, zijn toekomstige ruimtelijke ontwikkelingsscenario's, met name voor de bebouwde omgeving, cruciaal vanuit het perspectief van duurzaam verkeer en vervoer, in het bijzonder lage-CO_2 ontwikkeling".

Deze studie presenteert twee belangrijke resultaten. Ten eerste de gemodelleerde relaties tussen de bebouwde omgeving en verplaatsingsgedrag in de context van Indiase steden. Ten tweede het gebruik hiervan in de ontwikkeling van toekomstige duurzame verkeer en vervoersscenario's. Het empirische deel van dit onderzoek is uitgevoerd in Ahmedabad in de westelijke Indiase staat Gujarat, een snel groeiende stad met de typische verkeersproblemen en ontwikkelingsuitdagingen van een hedendaagse Indiase metropool.

De 'bebouwde omgeving' – als een breed concept – omvat de ruimtelijke patronen of arrangementen van stedelijke elementen zoals gebouwen, straten en landgebruik. De 'bebouwde omgeving' wordt normaal gesproken opgedeeld in zes categorieën, ook wel de 6Ds genoemd (Bourne, 1982). De 6Ds staan voor Dichtheid, Diversiteit, *Design* (Ontwerp), *Destination accessibility* (Bereikbaarheid), *Distance to transit* (Afstand tot openbaar vervoer) en *Demand management* (Vervoersvraagmanagement). Aangezien in India vervoersvraagmanagement volledig afwezig is in beleid, wordt deze categorie in dit onderzoek genegeerd, ondanks het belang van vervoersvraagmanagement voor duurzame ontwikkeling. In plaats hiervan voegen wij locaties met concentraties van stedelijke armen toe,

aangezien betaalbaarheid van verplaatsingen voor hen een groot probleem is en de vervoerswijzekeuze sterk bepaald. Dichtheid van de arme stedelijke populatie wordt derhalve als een van de indicatoren opgevoerd. Hiernaast gebruiken we ruimtelijke informatie over concentraties van werkgelegenheid – zogenaamde subcentra – als een indicator welke verplaatsingsgedrag, m.n. bestemmingskeuze, bepaald. Verplaatsingsgedrag zelf wordt vervolgens gerepresenteerd als verplaatsingsafstand en vervoerswijzekeuze van reizigers. Regressietechnieken worden gebruikt om de invloed van de bebouwde omgeving op het verplaatsingsgedrag (afstand en vervoerswijzekeuze) te bepalen. De geschatte modellen stellen analisten en beleidsmakers in staat de invloed van de effecten van veranderingen in de bebouwde omgeving (bv. hogere residentiële dichtheden, landgebruiksmix enz.) op het verminderen van reisafstanden en toename van langzaam verkeer en openbaar vervoer te bepalen. Deze relaties laten bijvoorbeeld zien dat de gebouwde omgeving van significante invloed is op het verplaatsingsgedrag van reizigers. Gebieden met een hogere mate van landgebruiksmix, een meer gebalanceerde mix van landgebruik en hogere dichtheden worden gekenschetst door kleinere verplaatsingsafstanden en een hoger gebruik van langzame modaliteiten zoals lopen en fietsen. Nabijheid van openbaar vervoer haltes, hogere dichtheid van routes, en hogere dichtheid van bevolking, m.n. van de stedelijke armen, verhogen het gebruik van openbaar vervoer. Echter, in tegenstelling tot wat typisch wordt gevonden in vergelijkbaar onderzoek laten locaties met goede bereikbaarheid tot werkgelegenheid, een hoge landgebruik mix en hogere dichtheden van kruisingen een vermindering van openbaar vervoerritten zien. De redenen hiervoor worden verder onderzocht.

Lage-CO_2 ontwikkeling betekent dat groei en ontwikkelingsdoelen gehaald worden bij lage of zelfs neutrale CO_2 ontwikkeling. Er bestaat geen algemeen aanvaarde definitie voor lage-CO_2 ontwikkeling (*Low Carbon Development* – LCD). De notie ‘minder CO_2 voor groei’ wordt echter algemeen geaccepteerd. Twee maatregelen worden typisch gebruikt om de milieukundige impact die resulteert van personenvervoer te kwantificeren en te visualiseren. Ten eerste, alle emissies worden omgerekend naar CO_2 equivalenten, om hiermee begrip te krijgen van de bijdrage aan broeikasgassen.. Ten tweede wordt de ecologische voetafdruk van transport, welke de consumptie van hulpbronnen kwantificeert en visualiseert, berekend. Daarnaast worden de maatschappelijke baten berekend door bereikbaarheid van locaties te kwantificeren als sociaal - en economische ontwikkelingspotentieel. Om toekomstige scenario’s te kunnen visualiseren is een simulatiemodel ontwikkeld dat landgebruiksontwikkeling en stedelijk groei van de stad Ahmedabad – maar ook gemakkelijk toepasbaar is andere steden met een vergelijkbare context – kan simuleren. Het model gebruikt een hybride benadering, d.i. een combinatie van een logistieke regressie en een cellulaire-automaten model om alternatieve groeiscenario’s met verschillende zonerings – en stedelijke ontwikkelingsrichtlijnen en bouwvoorschriften te simuleren. Twee toekomstige scenario’s voor het jaar 2030 zijn gesimuleerd. De eerste is een nulscenario (*business-as-usual*, BAU) en de tweede een LCD scenario gericht op het gebruik van de bebouwde omgeving als instrument om verplaatsingsgedrag te sturen.

De analyse laat zien dat de bebouwde omgeving gebruikt kan worden als een instrument om het gebruik van duurzame vervoersmodaliteiten te stimuleren. Het grote voordeel van een meer compacte groei is dat reisafstanden afnemen. In het LCD scenario zijn deze reisafstanden voor zowel werk als niet-werk-gerelateerde verplaatsingen gemiddeld zelfs lager dan in de huidige situatie. Dit ondanks de verwachte verviervoudiging van per capita inkomens in dit scenario. De percentages wandelen, openbaar vervoer en fietsen voor zowel werk als niet-werk-gerelateerde verplaatsingen nemen toe. Ook zijn er in dit scenario verschuivingen in ritafstanden en vervoerswijzekeuze die leiden tot een relatieve afname van CO_2 emissies. Aangezien het ontwikkelingstraject compact is, zal de bereikbaarheid van sociale en economische activiteiten verbeteren voor een groot deel van de bevolking. Derhalve, kan de nulhypothese van dit onderzoek worden verworpen.

Dit onderzoek laat zien dat ook in een typische metropool als Ahmedabad in India de bebouwde omgeving van invloed is op verplaatsingsgedrag en daarmee ingezet kan worden als een instrument om toekomstige groei – en ontwikkelingsscenario's, waaronder LCD, te bepalen. Het huidige beleid voor de planning van landgebruik, d.i. het strategische ontwikkelingsplan kan gebruikt worden om de vorming van sub-centra voor werkgelegenheid te stimuleren, voor hoogwaardig openbaarvervoer en de ontwikkeling van infrastructuur. Ook het lokale bestemmingsplan en stedelijke ontwikkelingsrichtlijnen kunnen worden ingezet. Echter, deze studie laat zien dat dergelijke scenario's getest moeten worden op hun milieukundige kosten en sociaaleconomische baten alvorens geïmplementeerd te worden. De resultaten zijn gepresenteerd aan de stedelijke autoriteiten in Ahmedabad en een aantal academici. Zij staan achter de resultaten, vinden deze realistisch en bruikbaar voor stedelijke – en verkeer en vervoersplanning. Medewerkers van de gemeente suggereren op basis van deze studie richtlijnen te ontwikkelen die gebruikt kunnen worden bij het verder ontwikkelen van de bebouwde omgeving met het oog op de verkeer en vervoersaspecten.

Deze studie heeft middels een de toepassing van verschillende methoden relaties aangetoond tussen de bebouwde omgeving en verplaatsingsgedrag, leidend tot beleidsaanbevelingen voor CO2 – arme ontwikkeling. In de toekomst zouden de gebruikte methoden toegepast kunnen worden voor gelijksoortig onderzoek in andere steden in India. Dergelijk onderzoek zou plaats kunnen hebben in verschillende steden en zou bijvoorbeeld in kunnen gaan op de invloed van verbetering van infrastructuur voor lopen en fietsen op vervoerswijzekeuze en kunnen leiden tot definitievere inzichten en daarmee beleid over de invloed van de bebouwde omgeving op mobiliteit en milieu.

Curriculum Vitae

Talat Munshi was born in Ahmedabad, India on October 5, 1971. He completed his secondary education from St. Xaviers Loyala Hall in Ahmedabad in 1990. In July, 1995 he graduated in Construction Technology and in February completed his Post Graduation in Environmental Planning from CEPT University Ahmedabad, India. After completing his university studies in India, he worked as a research associate at the School of Planning, CEPT University, where he worked on consultancy and research projects at CEPT university, mainly contributing to the Gujarat Urban Profile project for the National Institute for Urban Affairs, India. In 1997, he joined Surat Municipal Corporation as Assistant Town Planner and worked on several urban development projects. In 1998, he joined School of Planning, CEPT University as a Lecturer and taught transport planning and remote sensing subjects at the institute.

In 2001, he moved to Enschede, the Netherlands to study at the International Institute for Geo-information Science and Earth Observation (ITC). In 2003, he graduated with MSc degree in geo-information for urban infrastructure management; his thesis was entitled " Planning for Public Transport in Ahmedabad, India". From 2003 till 2004, he continued work at School of Planning,.CEPT University. In 2004 he joined the Urban and Regional Planning and Geo-information Management department at ITC, the Netherlands as Lecturer in Transport Planning and worked there till 2006. In 2006 he returned to India, and worked intially with The Energy and Resouces Institute (TERI) as Associate Fellow and Area Convener of the "Centre for Urban Systems and Infrastructure", he also engaged in graduate teaching at the TERI University.

In May 2007, he started the first phase of his PhD research at ITC on a part-time basis and joined the Faculty of Planning (FP) as Associate Professor. His PhD was funding from the Small Project grant from Volvo Research and Education Foundation and by ITC. He worked simultaneously on his PhD, and engaged in teaching, research and consultancy activities at FP. In the past five years he has supervised more that 50 graduate dissertation thesis, taught course on transport planning, land and housing economics and led a couple of notable research and consultancy projects at the university, which include, "Low-carbon comprehensive mobility plan for Rajkot city" for RESOI centre of United Nations Environmental Program (UNEP), "Land, Transport and Environemnt" for the Volvo Research and Education Foundation and "Accessibility to jobs for urban poor" for the World Bank.

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