Quantification of Urban Form Indicators

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Quantification of Urban Form Indicators

by

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Abstract

Sustainable urban development and sustainable transport are key concerns of policy makers. Many sustainability studies have been conducted by national governments and international organization like OECD, the EU, and the UN giving rise to sets of indicators to assess related economic, social and environmental issues. Many indicators proposed are described only at conceptual level without providing an associated specific quantifiable measure. These concepts need to be translated into a mathematical framework from which numerical estimates can be drawn.

General objective of the research was to quantify urban form based compactness indicator. Limitations of the previous methods of quantifications were identified and considering the modern urban spaces, effects of poly-centrism on compactness were studied. In recent years city planners, developers and policymakers have turned focus on designing a more compact city in order to achieve a more sustainable urban form. Major concern among researchers is to quantify urban sprawl and compactness.

In this study, a mathematical framework has been developed to quantify compactness. Modified ‘m-Compactness’ measure proposed in this study, based on Zhang and Guindon (2006), incorporates poly-centric urban form of modern cities. Subcenters within Ahmedabad city were successfully identified adopting the criterion used by Giuliano and Small (1991). Huff probabilistic gravity model was utilized to estimate trip attraction potentials of sub-centers. Dispersion and compactness indices based on weighted travel distance and population were computed and compared for Ahmedabad city considering mono-centric and poly-centric urban forms. The causality between travel behaviour and compactness was examined using Statistical analysis.

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1. Introduction

1.1. Backgrou nd

Transport accounts for a large portion of energy consumption and greenhouse gas emissions. It is also responsible for urban air pollution and noise nuisance. At the same time, transport is an essential element of our modern society. It ensures access to education, goods and services, jobs and leisure activities. Transport is considered fundamental to the manner in which urban development takes place.

Rising economies like India have been undergoing tremendous urban growth. There is an increasing trend of expansion of urban sprawl and auto-mobilization with rapid growing economies and population. This has direct impact on travel pattern and transport demand creating many environmental, economical and social problems (Bajracharya, 2008). These changes put an enormous pressure on sustainable development.

Sustainable transport is a key to sustainable development not only because it is an essential element to development in general but also because it contributes significantly to a broad range of environmental problems (Benfield and Replogle, 2002). According to EU sustainable development strategy, the overall objective of sustainable transport is to ensure that transport systems meet society's social, economic, and environmental needs whereas minimising their adverse impacts on the economy, society and the environment (EU SDS, 2006).

In order to achieve sustainable transport it is necessary to understand what is to be achieved and there should be some means to determine if achievement has occurred. Thus indicators, numerical information defining to which extent transport performance is improving, are needed (CST, 2002a). Gudmundsson (2003) defines indicators as 'variables constructed and selected to say something important about a particular social concern in a significant way'. CST's working definition of indicators, which is similar to Gudmundsson's definition, is that they are 'selected, targeted, and compressed variables that reflect public concerns and are of use to decision-makers' (CST, 2002a).

Wong (2006) describes four step methodology of Indicator development as follows –
(Adopted from Wong 2006, pp.105-118).

1) Conceptual Consolidation – First step in indicators development is to clearly understand the concept behind and the purpose of indicators development. The indicators should clearly identify the policy driven criteria against which they will be used. Basic questions that need to be addressed are 'What policy instruments will be used?' 'And what is the appropriate spatial unit of analyses?'

2) Analytical structuring- The second step is to develop analytical framework which can be seen as the operational plan that provides a platform and requirements upon which key elements of the indicators will be developed and assessed. There are two broad approaches to develop a framework of analysis. The Bottom-up approach mainly involves the listing of key issues or factors that are considered important. In Top-down approach, a prior analysis of the concept concerned is carried out. The causal relationship between different factors then can be derived to provide a study framework (Coombes and Wong, 1994 in Wong 2006, pp. 109).

3) Identification of indicators- After conceptual consolidation and analytical structuring, the next step involves a laborious search for a wide range of possible indicators to measure the issues identified in the analytical framework. Formulation of a 'wish list' of indicators is usually based on an extensive review of related policy practice and academic literature.

4) Synthesis of Indicator values- One common practice is to develop a composite index by synthesizing the proposed indicators, according to their relative importance, into a single measure that will be used for policy targeting. If a single most representative indicator can be identified for each key factor in the analytical framework developed, the issue of weighting can simply concentrate on the relative importance of each factor without the need to consider individual indicators. However, practical problems such as data availability usually impose constraints on the selection of indicators and their quality. Because of this limitation, it is important to examine the properties and the reliability of individual indicators in the process of creating a combined index.

In summary, Sustainable transport is a key to sustainable development. Selection and formulation of proper indicators is crucial in sustainability studies. It is widely acknowledged that urban form characteristics have potential impact on urban transport and hence sustainability. In this study an attempt has been made to select and quantify urban form indicators having impact on land use efficiency and transportation.

1.2. Justification

Travel patterns are results of individual's choice of activity, choice of destination, choice of mode, choice of route and time (Munshi, 2003). Peoples desire to engage in activities gives rise to travel as activity locations are spatially distributed (Dalumpines, 2008). Thus urban form characteristics have potential impact on urban transport. A review by Stead and Marshall (2001) highlights numerous studies explaining the relationship between urban forms and travel characteristics. It is widely acknowledged that urban form characteristics such as population density, employment distribution, land-use density, land-use diversity and compactness have potential impact on urban transport and hence sustainability.

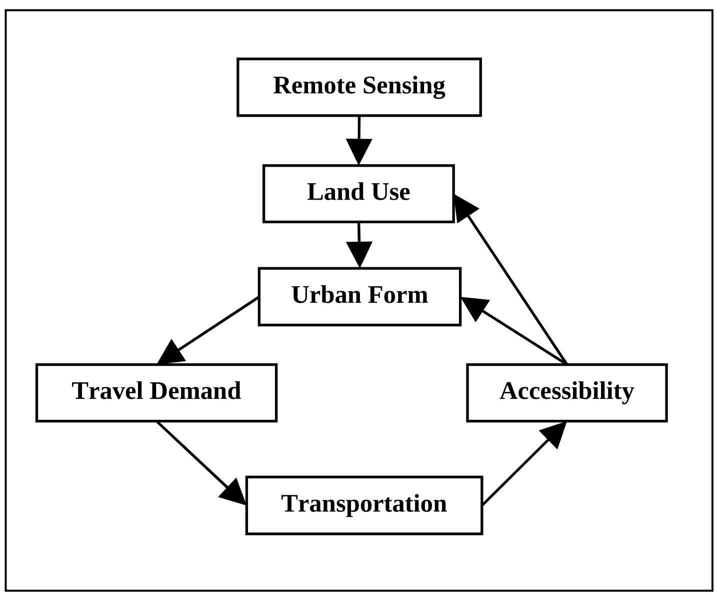


Figure 1.1 Land-use, Urban Form and Transportation
Adopted from Zhang and Guindon (2006)

Many sustainability studies have been conducted giving rise to sets of indicators. Many indicators proposed are described only at conceptual level. These concepts need to be translated into a mathematical framework from which numerical estimates can be drawn. Formal methods for indicator quantification are needed if indicators are to be used to assess spatial-temporal trends in sustainability (Zhang and Guindon, 2006). A number of indicators proposed encapsulate aspects of land cover, land use and urban form. Such geospatial information can be resourcefully extracted and analysed in GIS. Considering all these aspects there is a need to develop formal methods for indicator quantification based on geospatial data using GIS techniques.

1.3. Research Problem

Many sustainability indicators proposed by non technical policy makers are described only at conceptual level without providing an associated specific quantifiable measure. These concepts need to be translated into a mathematical framework from which numerical estimates can be drawn. Hence, there is a need to develop formal methods for indicator quantification if they are to be used to assess spatial-temporal trends in sustainability and to compare relative sustainability aspects (Zhang and Guindon, 2006).

Sustainable urban development and sustainable transport are key concerns of policy makers. Many sustainability studies have been conducted by national governments and international organization like OECD, the EU, and the UN giving rise to sets of indicators to assess related economic, social and environmental issues. Many indicators proposed are described only at conceptual level. A number of indicators proposed encapsulate aspects of land cover, land use and urban form. Many geospatial information extraction techniques exist but not considerable work has been done on indicator quantification and hence there is a need to develop formal methods for indicator quantification.

Urban travel pattern is known to depend on urban form with respect to its landuse. However, the causality is still debated among scientists, engineers, planners (Sriram, 2008). In recent years city planners, developers and policymakers have turned focus on designing a more compact city in order to achieve a more sustainable urban form. Major concern among researchers is to quantify urban sprawl and compactness.

1.4. Research Objective

Referring to the research problem, the following section highlights the general and the sub objectives of this thesis.

1.4.1. General Objective

The general objective of the research is to quantify spatial indicators based on compact urban form that in turn is assumed to act as surrogates of sustainability.

1.4.2. Sub Objectives

- Select relevant urban form indicators and describe relations with land-use, transport and environment.

- Indicator formulation and quantification

  Define methodology: Spatial analysis and statistics

- Implementation and assessment

  Derived indicators will be implemented taking Ahmadabad as a case study. Assessment will be done using ancillary data.

1.5. Research Questions

For each of the sub-objective, several research questions have been formulated.

Sub-objective 1: Select relevant urban form indicators and describe relations with land-use, transport and environment.

- Does the indicator encapsulate aspects of land cover, land use and compact urban form?
- What is the relation between urban form indicator and sustainable transport?

Sub-objective 2: Indicator formulation and quantification

- What is the key information needed for quantification?
- What is the quantifiable measure of selected indicator?

- What should be the unit of analysis and the grid size?
- What is the level of complexity of the indicator and accordingly which methodology should be used in formulation?

Sub-objective 3: Implementation and assessment

- Do the trends in sustainability or the relative sustainability aspects derived from indicator implementation are comparable with relevant studies?
- How ancillary data and previous studies could be used in assessment?
- What is the relation between compact urban form and sustainable transport?

1.6. Research Design

The research methodology for this study is derived by considering the methodology used for the indicator quantification by Zhang and Guindon (2006) and the indicator development process of Wong (2006). An overview of research methodology is presented in Figure 1.2 and the following paragraph explains the steps involved.

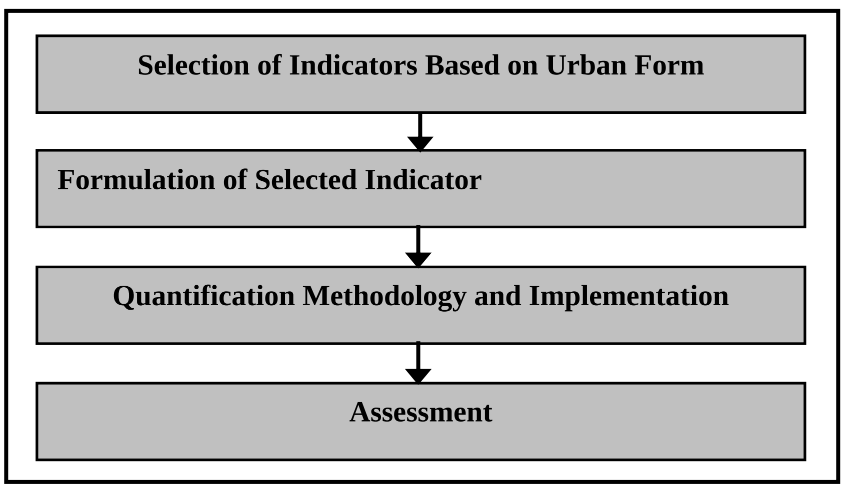


Figure 1.2: Research Design

A number of indicators proposed encapsulate aspects of land cover, land use and urban form. Indicators that are based on compact urban form will be considered in quantification for sustainable transport.

Criteria used in indicator selection are adopted from Zhang and Guindon (2006) which is:

Indicators –

a. meet the needs of targeted users, i.e. the need to support makers of urban sustainability strategies and policies;
b. are easily understood;
c. are efficient and, ideally, unambiguous measures of the targeted issue;
d. are feasible for operational use—feasibility is based on the availability of relevant datasets required to quantify them. ”

The methodology used for quantification will be based on spatial analysis and statistics depending on the complexity level of indicator. The main focus of the study will be on formulation and quantification of urban form indicator. Selected indicator will be implemented taking Ahmedabad as a case study. Ancillary data, household survey data made available primarily from the PhD work of Munshi (2007) and information from relevant studies will be used in the assessment.

2. Study Area

This chapter contains a brief overview of Ahmadabad city and its urban form and transport system.

2.1. Introduction

Ahmadabad is the biggest city in Gujarat, a state in the western part of India. It is the Seventh largest city of the country with a population of 3.520 Million according to 2001 census and an area of 190.84 square Km (AMC, 2008). Being a leading industrial and commercial city of Gujarat and one of the important centres of trade and commerce the city is growing very fast with rapid urbanization.

Ahmadabad, being a good example of highly urbanizing cities in developing countries like India faced with tremendous pressure on its transport system, was selected as a case study. Also, this research is part of several ongoing research initiatives concerning transport sustainability of the city and thus provides a useful background in assessing the outcomes. Many cities in developing countries exhibit similar concerns as Ahmadabad and the results from this research might be useful in carrying out similar studies and assess city's transport system and overall development.

Figure 2.1: Ahmedabad City, India

2.2. Urban Area and Population

The area within the AMC limits consists of the traditional city centre within the fort walls, old city, with relatively high-density development with all major commercial and business activities. The western sector, well planned with wide roads, mainly contains major institutions and high income residential with newly developed commercial areas (Bajracharya, 2008). These newly developing commercial and business nodes indicate that the city is transforming to a polycentric city from a mono-centric city affecting travel patterns of the individuals (Munshi, 2003). The eastern part mainly contains large and small industries with low income residential settlements predominantly labour class.

Table 2.1: Ahmadabad city Population

Year	Population (Millions)	% Growth
1981	2.059	29.91%
1991	2.876	20.79%
2001	3.520	22.36%

Source: AMC, Ahmedabad

2.3. Urban Form

Land use distribution shows almost 46 percent of total area is under residential use. Approximately 16 percent of total area is under commercial and industrial use. Almost 15 percent of total area is under roads and 15 percent parks.

Table 2.2: Land-use distribution in Ahmadabad

Land use Type	Total Area Sq. Km	% Area
Residential	68.7	36%
Commercial	3.8	2%
Industrial	28.6	15%
Open land	45.8	24%
Village settlement	9.5	5%
Water body	7.6	4%
Road	13.4	7%
Rail	3.8	2%
Other	9.5	5%
Total	190.8	100

Source: AMC, Ahmedabad

The city has grown concentrically around its original old development referred to as 'old city' or the 'walled city'. The city is divided into two halves, eastern and western region, by river Sabarmati. The eastern sector accommodates low income residential areas with large and small industries and narrow roads. The western sector accommodates high income residential areas with major institutions and wide roads.

The population with in the AMC limits has increased to 3.520 million in 2001 from 2.876 million in 1991. The growth is not uniform and shows large variation in densities across the city. The population densities in eastern areas range from 2126 to 92882 per square Km and densities in western region range from 9174 to 28453 per square Km (AMC, 2008).

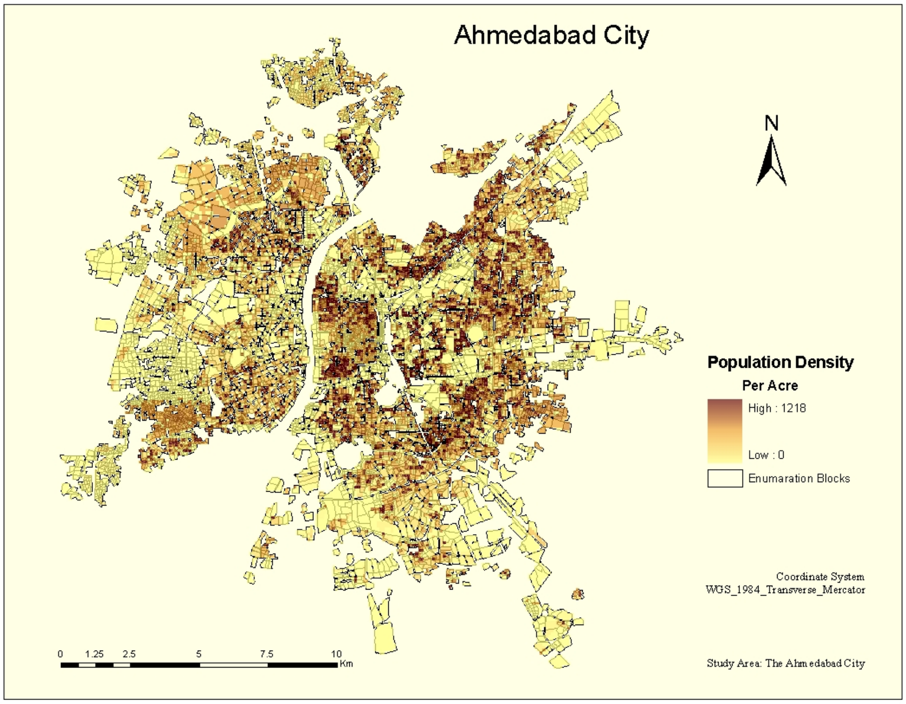


Figure 2.2: Ahmedabad City Population Density

2.4. Transport Modes and Travel Characteristics

A total number of 1.49 million vehicles are registered in the year 2004 of which 73% were two wheelers. The growth rate of privately owned vehicles especially two wheelers is very high. Rapid growth and high densities of vehicles have significantly worsened the transport situation. AMTS, a municipal body, provides public transport facilities in the city and operates 550 buses serving 250,000 passengers a day (Bajracharya, 2008).

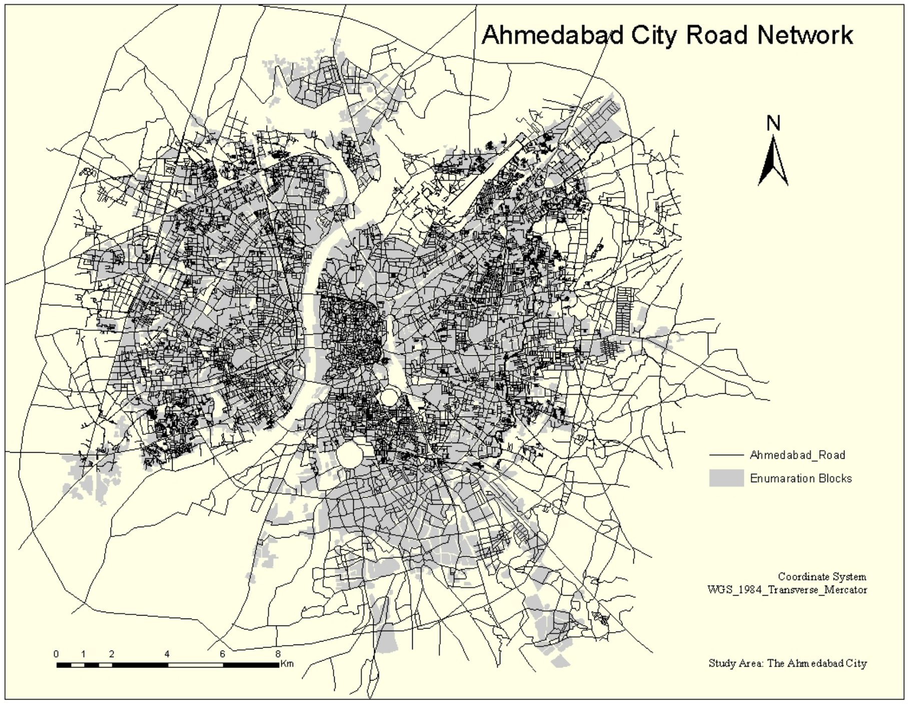


Figure 2.3: Ahmedabad City Road Network

Frequent traffic jams during morning and evening peak period are observed. Heavy Traffic flow from west to east in the morning and vice versa in the evening is observed as eastern part has industrial estates and western part has evolved mainly as residential area (Bajracharya, 2008).

Table 2.3: Modal Split for all trips

Mode	Modal Split (%)
Motorscooter	32%
Auto Rickshaw	1.9%
Bicycle	26.4%
Walk	4%
Bus	24%
Car	2.3%
Other	9.6%
Total	100%

Table 2.4: Trip purpose

Trip Purpose	%
Work	51.6%
Education	34.0%
Other	14.4%
Total	100%

Source: House Hold Survey Report, 2001

Work and study purpose trips account for 55% of daily trips made. More than 33 % of trips are made on foot, more than 30% by public transport and around 15% by individual vehicles.

2.5. Conclusio n:

With rapidly growing population, number of vehicles is also increasing. Modal split reveals the highest share of two wheelers. Public transport comparatively has small share in the total trips. Rapid growth and high densities of vehicles have significantly worsened the transport situation. These problems of transport system are leading it to inefficient mobility and insufficient accessibility.

3. Identification and Selection of a Urban Form Indicator

3.1. Transport Trends and Sustainability

Continuing growth in travel has led concerns about the environment and sustainability. Though transport is an essential element to development it causes negative impacts of various kinds including use of resources (land and fossil fuel), traffic congestion, accidents and fatalities, noise and air pollution and so on. The demand for transport is increasing especially in most polluting sectors, viz. road and air (Geenhuizen and Thissen, 2002). Increasing transport demand is posing increasing stress on the environment and quality of life.

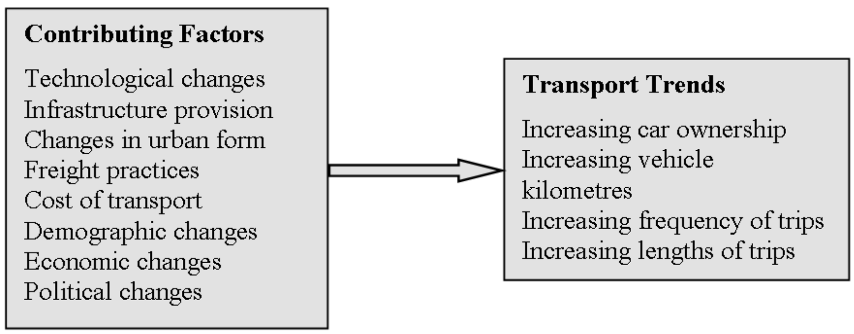


Figure 3.1: Transport Trends; Adopted from Marshall and Banister (2000)

It is necessary for transport policies to address reduction of these adverse environmental impacts. A fundamental means, transport policies should have to reduce adverse effects, is to attempt to reduce the amount of travel itself. For travel reduction Marshall and Banister (2000) mention that the trip lengths should be reduced and travel by public transport and green modes of transport that is cycling and walking should be promoted. For policy makers to tackle adverse impacts it is necessary to understand transport system and symptoms of unsustainable transport system.

3.2. Transport System and Urban Form

Urban transport system, defined by land use and transport policies is a complex structure. With urban sprawl and change in land use, travel patterns change in terms of choice of modes and trip lengths. All movements and their impact through the system must be considered as change or improvement in one element has direct or indirect impact on other. For complete understanding, all elements of transport system must be considered such as means of transport, the network facilities including transfer points and terminal and so on.

A Casual Loop Diagram (CLD) is used to represent the System with its important components and their interactions in a simplified way as shown in figure 3.2. Any urban transport system and relationship among its components is complex. System depicted in Figure 3.2 is not a complete representation and only a single adverse effect on environment that is pollution is considered.

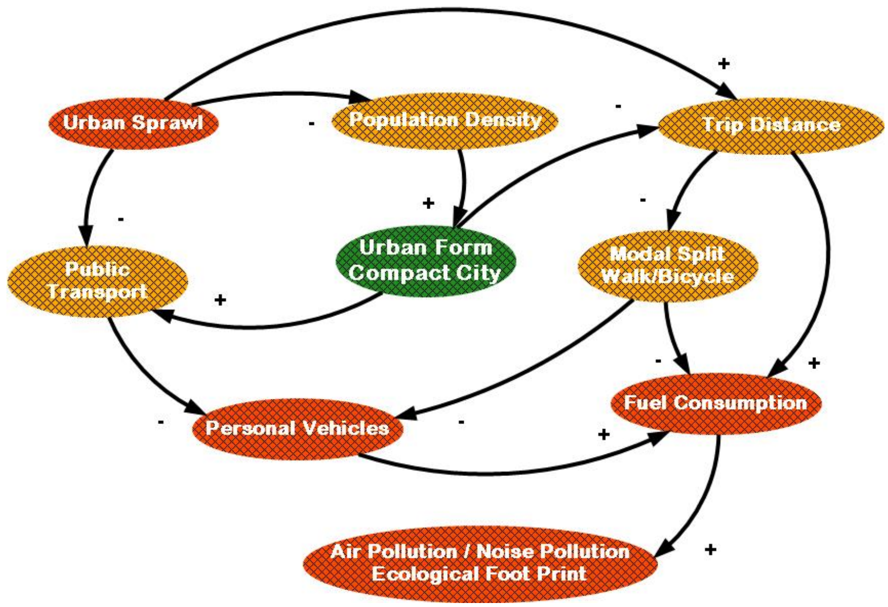


Figure 3.2: Urban Transport System

More urban sprawl will lead to less compact cities, more trip distances, and more fuel consumption leading to more pollution. More mixed land use will lead to shorter trip distances. People would prefer to use bicycle or walk leading to less fuel consumption and less pollution. Higher proximity of residential units to public transport will promote more use of public transport which will reduce use of personal motorized vehicles leading to less fuel consumption and pollution.

As discussed in previous section sustainable transport development should promote less use of personal motorized vehicles and alternative transportation modes such as walking, bicycling and public transport. As can be seen proximity to public transport, land use mix, compactness and so on that is urban form has direct impact on travel characteristics such as trip distance, modal split, use of personal motorized vehicles and so on and in turn on transport sustainability. The symptoms of unsustainable transport system are in urban form. For sustainable transport development it is necessary to understand the relation between urban form and Travel Patterns.

3.3. Relation between Urban Form and Travel Pattern

Concerns about the sustainability of current land use and transportation practices are increasingly issues of policy concern in most countries of the world. The close relationship between urban land use and transport is common knowledge among spatial and transport planners (Meurs, 2003). Cera (2005) in her paper highlights several researches showing the relationship between land use and travel patterns. The author shows consensus on the fact that the policies for sustainable transportation have to focus on the distribution of activities in the urban spaces that is land use and urban form.

The relation between urban form and travel is complex. Growing number of studies are concerned with the relationship between urban form and travel pattern. In this section the urban form variables used and results of studies concerning urban form and travel patterns are discussed. From the review of past studies the important urban form aspects considered are distance to city centre, density of development, mixing of land uses, neighbourhood type, provision of local facilities and proximity to public transport. Different studies have examined impact of above urban form variables on travel patterns such as trip length, modal split, and transport energy consumption and so on.

3.3.1. Distance to City Center

Two major concerns of urban form are urban sprawl and compactness. In general with urban sprawl distances of residence and activities increase from the central business district (CBD) resulting in increased travel distances for both work and non work journeys. Naes *et al*. (1995) found that the travel distance per person in Oslo increases with increase in distance between home and the urban centre. Naess and Sandberg (1995) studied effect of geographical location of workplace and the energy use for journeys to work. In general authors found that commuting distance increases with increasing distance of work place from city centre. Milakis *et al.* (2008) studied the relationship between urban form and travel in Athens, Greece and found that the distance from the centre constitutes a crucial parameter influencing trip length by car. According to authors' findings, an increased distance from city centre by 1,000 meters is capable of increasing a trip's length by 210 meters. Many authors have further studied effect of distance to city centre on transport energy consumption and ecological foot print of transport.

Studies show that among influencing factors, car ownership followed by distance to city centre has the greatest influence on transport energy consumption (Stead and Marshall, 2001). Naess *et al.* investigated the distance of home from urban centre on transport energy consumption and found that energy consumption increases with increase in distance of home from urban centre. Newman and Kenworthy (1988) in their study reported that residents living at 15 Km from the CBD in Perth consume about 20 % more transport energy than the residents living in 5 Km from CBD (Newman and Kenworthy, 1988 in Stead and Marshall, 2001). Naess and Sandberg (1995) used modal split and trip distance as the main factors in computing energy use. Energy use increases with increasing distance between the workplace and downtown Oslo. Authors conclude that the employees of workplaces in peripheral, low-density parts of the urban area with less public transport accessibility are far more frequent car drivers and use considerably more energy for journeys to work than employees of workplaces located in central, high-density areas with high public transport accessibility. Milakis *et al.* (2008) also investigated influence urban form and travel and in tern on energy consumption in Athens, Greece. Distance from city centre and the extent of road network mainly influence trip length and energy consumption by car. Similarly, Muniz and Galindo (2005) examined the effects of urban form and socio-economic variables on ecological foot print of transport left by commuters in municipalities of the Barcelona Metropolitan region (BMR). Authors found that distance to the centre of municipalities has higher impact on trip lengths. Authors conclude that Municipalities located in the outer periphery with low-density levels have a higher per capita ecological footprint of commuting than central areas with high-densities.

Thus studies demonstrate increasing distance of home or an activity from city centre are associated with increase in trip lengths, proportion of travel by car and increase in transport energy consumption.

3.3.2. Density of Development

The terms commonly used to measure density of development are population density and to a smaller extent employment density. Four reasons for linking population density to travel pattern put forward by ECOTEC (1993) are as follows – Higher population densities increase opportunities for the development of local activities and personal contacts without extensive use of motorized travel. Secondly, longer travel needs are reduced as higher population densities extend the range of services that can be supported in the local area. Thirdly, travel distance is reduced as higher densities tend to reduce average distances between homes, services, employment and other opportunities. Fourthly, high densities might be more favourable to public transport operation and use and less favourable to cars ownership and use (ECOTEC 1993 in David Banister; Unsustainable Transport). Theses findings and implications are examined in many studies as discussed in this section.

Cervero (1996) identified two features of the built environment, densities and levels of land-use mixture, to be exerting a significant influence on travel behaviour. Author found that neighbourhood density and mixed land-uses reduce vehicle ownership and are associated with shorter commutes. Neighbourhood densities have a stronger influence on automobile and mass transit commuting mode choices. The probability of non-auto commuting increases considerably as neighbourhood densities raise. Naess and Sandberg (1995) found that high building densities near work places have negative correlation with proportion travelled by car. Authors conclude that the employees of workplaces in peripheral, low-density parts of the urban area with less public transport accessibility are far more frequent car drivers and use considerably more energy for journeys to work than employees of workplaces located in central, high-density areas with high public transport accessibility. Cervero and Kockelman (1997) investigated how the 3Ds that is density, diversity and design affect trip rates and mode choice of residents in the San Francisco Bay Area. They verified effect of built environment on variation in the vehicle miles travelled per household and mode choice, mainly from non work trips. Compact development was found to have a strong association with mode choice for non-work trips, as urban density increases, car use diminishes and use of public transport and walking increases. Muniz and Galindo (2005) also found that proportion of trips made by car is affected by density. Authors, in their study of effect of urban form and socio-economic variables on ecological foot print of transport, found that Municipalities located in the outer periphery with low-density levels have a higher per capita ecological footprint of commuting than central areas with high-density. Lee and Moudon (2006) examined a large number of environmental variables and isolated strongly associated variables with walking. Measured land-use and urban form correlates were grouped as destinations, distance, density, and route: the 3Ds + R. Net residential densities were significantly associated with walking. Higher net residential density of the respondent' home parcel was strongly associated with increased walking. Milakis *et al.* (2008) found that residential density is a key factor influencing mainly modal split. Residential densities are positively correlated with the use of public transportation and walking while negatively correlated with car trips, mean trip lengths, and energy consumption by car.

In summary there is a substantial amount of research that suggests a link between density of development and different aspects of travel pattern especially mode choice, trip distance and energy consumption.

3.3.3. Landuse Mix

Spatial distributions of various urban land uses reflect where people reside, work and shop. Land use mix is considered the degree to which urban land use components are spatially interspersed within an area (Zhang and Guindon, 2005). Land use mix is generally measured using job ratio or non-residential activities in the vicinity. Land use mix affects the physical separation of activities and determines travel demand (Stead and Marshall, 2001). STPI report summarizes link between land use mix and transportation as – "The geographic scale at which mixed use is appropriately measured depends on the mode of transportation. For example, to support a high degree of walking and cycling, residential and employment uses must be mixed on a very small scale. To support transit, jobs and residential uses can be mixed on a larger scale, defined by a reasonable transit trip time, e.g., an area defined by a 20-minute transit trip" (CST, 2002a).

Giuliano and Small (1993) examined the commuting pattern for the Los Angeles considering spatial distributions of job and housing locations. Authors found that a large fraction of commuting can not be explained by the geographical imbalances in current locations of housing and jobs and that job ratio has a statistically significant but relatively small influence on commuting time. They conclude that changes in metropolitan structure of land use are likely to have small impacts on commuting patterns. Cervero (1996) found that having grocery stores and other consumer services within 300 feet of one's residence encourages walking, bicycling and commuting by mass transit. In addition, neighbourhood density and mixed land-uses were found to reduce vehicle ownership and were associated with shorter commutes. Lee and Moudon (2006) examined large number of environmental variables and secluded strongly associated variable with walking. Measured land-use and urban form correlates were grouped as destinations, distance, density, and route: the 3Ds + R. 'Destinations' represented the availability and proximity of certain land use from home locations. Grocery-stores, individually and clustered with restaurants and retail stores, were found positively associated, while office and educational uses were negatively associated with walking. 'Distance' measures used to quantify the built environment represented both land use and urban form aspects. Grocery stores/markets and eating/drinking places located near homes were found positively associated with walking. Network distance to the closest bank was also associated with the increased walking.

In summary, there are relatively few studies concerning the effect of land use mix on travel patterns. Different studies have used different measures of travel patterns in their analysis. Quantifying land use mix aspect of urban form is not straight forward and its implication is mode dependent.

3.3.4. Provision of Local Facilities

Provision of local facilities and services might reduce travel distances and increase proportion of short journeys potentially travelled by non-motorised modes. From neighbour case studies, ECOTEC (1993) reports that there is a clear relationship between the distance of a local centre, frequency of its use and average journey distance (Stead and Marshall, 2001). However there are relatively few studies concerning the effect of provision of local facilities and travel patterns.

Winter and Farthing (1997) found that the provision of local facilities in new residential developments does not considerably affect the proportion of journeys by foot but reduces average trip distances. Similar finds are reported by Stead (1999) that the propinquity of local facilities is positively related with average trip distances. Distance measures used by Lee and Moudon (2006) to quantify the built environment represented both land use and urban form aspects. The authors found that grocery stores/markets and eating/drinking places located near homes were found positively associated with walking also network distance to the closest bank was also associated with the increased walking. Route directness to the closest school and grocery store were also found significant variables. Handy *et al.* (2005) studied effect of change in built environment on travel behaviour. Both cross-sectional and quasi-longitudinal analyses were incorporated to examine the causal relationship between the built environment and travel behaviour while taking into account the role of attitudes. Authors conducted factor analysis as many parameters of built environment measured were highly correlated. One of the six factors for neighbourhood characteristics is accessibility which explains easy access to a regional shopping mall, easy access to downtown, availability of nearby amenities such as a community centre, shopping areas within walking distance, Good public transit service (bus or rail). The results of this study showed that an increase in accessibility leads to a decrease in driving and vehicle miles driven (VMD).

Thus there is a broad consensus about the effects of provision of local facilities and services on travel patterns. In most of the studies the effect on mode of choice that is non-motorized – walking/cycling is considered. Provision of local facilities and services might reduce travel distances and increase proportion of short journeys

3.3.5. Neighbourhood Type

Neighbourhood type is a composite variable used to characterize relatively homogeneous areas of cities based on a range of attributes. The attributes typically include the age of development, traditional or conventional style of development and type of street network such as grid or loop (Stead and Marshall, 2001).

Cervero and Kockelman (1997) found that neighbourhood design, measured by a large number of variables such as attractiveness for transit passengers and pedestrians, reduces commuting distances, trip rates and car ownership levels. They found that neighbourhoods with a high amount of four-way intersections and restricted on-street parking adjacent to commercial establishments have a tendency to reduce drive-alone travel for non-work purposes. McNally and Kulkarni (1997) found that the overall trip rates are 30 % higher in planned unit development (PUD) characterised by circuitous transportation networks, limited access points in the neighbourhood and low residential densities compared to traditional neighbourhood design (TND) characterised by grid like transportation network, many access points into the neighbourhood and high population densities. As mentioned earlier, Handy *et al.* (2005) conducted factor analysis as many parameters of built environment measured to study effect of change in built environment on travel behaviour were highly correlated. Six factors for neighbourhood characteristics analysed are accessibility, physical activity options, safety, socializing, outdoor spaciousness, and attractiveness. Different factors explain different characteristics such as sidewalks throughout the neighbourhood, parks and open spaces nearby, good public transit service, bike routes beyond the neighbourhood, lots of off-street parking and big street tress and so on. The authors found that the vehicle miles driven per week by residents of suburban neighbourhoods is 18% higher than for residents of traditional neighbourhoods. They found that the highest level of driving for traditional neighbourhoods (161 miles per week) is still lower than the lowest level of driving for suburban neighbourhoods (166 miles). Lee and Moudon (2006) found that smaller block sizes and longer sidewalks along major streets were among significant route variables and are associated with increased walking. Route directness to the closest school and grocery store were also found significant variables associated with increased walking. Estupiñán and Rodrı´guez (2007) examined the relation between built environment at the stop level and bus transit use by employing neighbourhood environmental and socio-demographic information for Bogota's Bus Rapid transit (BRT). Authors highlight the importance of built environment to support transit use. Environmental supports for walking and barriers to car use were found to be related to higher BRT boarding. Also, safety and security were found to be associated with transit use.

3.3.6. Proximity to Transport Networks

Proximity to transport networks influences travel patter and intern transport energy consumption. Proximity and better access to major to major transport networks, particularly road and rail networks may lead to travel patterns characterised by long travel distances and high transport energy consumption. Whereas higher proximity of residential units to public transport will promote more use of public transport which will reduce use of personal motorized vehicles leading to less fuel consumption and pollution. Major transport networks can also influence dispersal of development (Stead and Marshall, 2001).

Kitamura *et al*. (1997) found that the choice of mode is affected by the distance of the nearest bus stop and railway station from home. With increasing distance to the nearest railway station the proportion of rail journeys increase. The proportion of car journeys increases with increasing distance from the nearest bust stop while proportion of non-motorized journeys increases with decreasing distance from the nearest bus stop. Naess and Sandberg (1995) in their study of effect of geographical location of workplace and the energy use for journeys to work found that the accessibility to the workplaces by public transport directly influences proportion travelled by car. Authors conclude that the employees of workplaces in peripheral, having less public transport accessibility are far more frequent car drivers and use considerably more energy for journeys to work than employees of workplaces located in central areas with high public transport accessibility. Muniz and Galindo (2005) considered population density, distance to city centre, and distance to nearest transport axis urban form variable in their study on the effects of urban form and socio-economic variables on ecological foot print of transport. Authors found that the distance to the transport axis (DA) have higher impact on trip distance. Shorter the distance to the transport axis greater is the accessibility. Authors found that the two accessibility indicators, distance to the centre and distance to the nearest transport axis, are correlated as average distance to the axis increases with distance to city centre. Municipalities located in the outer periphery with low accessibility levels have a higher per capita ecological footprint of commuting than central areas.

Thus studies show the effect of the proximity to transport networks on travel patterns especially trip length and mode choice. Proximity to major to major transport networks lead to travel patterns characterised by long travel distances and high transport energy consumption whereas proximity to public transport might increase proportion of non-motorized journeys. As proximity to transport network affects trip lengths and mode of choice it in tern determines the transport energy consumption and ecological foot print of transport.

In summary there is a substantial amount of research that suggests a link between land use and travel patterns and its effect on sustainability. In recent years city planners, developers and policymakers have turned focus on designing a more compact city in order to achieve a more sustainable urban form. Cera (2005) discussed urban transportation and sustainable urban form with particular regard to the concept of ‘compact city’. Urban sprawls are not considered sustainable and high density mega cities have their pros and cons. Urban sprawls, ultra high densities and compactness of urban spaces are discussed in the following sections.

3.4. Unsustainable Urban Forms - Sprawls and Ultra High Densities

Urban sprawls with low population densities imply long distances and make necessary the use of personal automobiles. Salingaros (2006) calls Sprawl as a remorseless phenomenon and regards sprawl as auto dependent landscape. Studies demonstrate, increasing distances of home or an activity from city centre are associated with increase in trip lengths, proportion of travel by car and increase in transport energy consumption putting an enormous pressure on sustainable development A compact, high density, mixed use city is considered as an energy efficient form of urban development that reduces travel distances, car dependencies and maximizes prospects for public transport provision. But there are also considerations that it may result in overcrowding, traffic congestion and high air pollution concentrated in urban spaces affecting the quality of life. Thus, among researchers concept of high density compact city has its pros and cons. According to Salingaros (2006), high-rise apartment and office towers are equally unsustainable as urban sprawls and mentions that ultra-high-density urbanism creates more problems than it solves.

The correct solution is intermediate density compact city. The compact city is sustainable where as both sprawl and ultra-high-density megacities are not. The author mentions that we should produce viable settlements at optimal densities for the human scale through thoughtful planning. There is nothing wrong with either high or low densities as such, as long as different urban land use densities are well integrated with each other and are in the right place.

3.5. Compact City

Urban Sprawl, Sub-urban areas, subcenters these terms have one common aspect of moving farther from the city center and could be used ambiguously. The sub-center term refers to ‘employment subcenter’, the spaces outside of central spaces with large employment that rival the city center as places of work (McMillen, 2Q/2001). A clear distinction between a metropolitan area with polycentric urban structure and one with much more dispersed suburban employment has important policy implications (McMillen, 2Q/2001).

Transport and environmental sustainability in urban spaces is strictly linked to land use and urban form. Cera (2005) highlighted several researches pointing out the fact that travel patterns and therefore fuel consumption and pollution are strongly related to land use and the degree of “compactness” of towns. The author discusses urban transportation and sustainable urban form with particular regard to the concept of ‘compact city’.

As discussed earlier, the compact city is sustainable where as both sprawl and ultra-high-density megacities are not. A mono-centric city has its employment clustered in the centre with much lower employment densities serving the residential suburbs in the outer areas. Another pattern could be a polycentric city with its employment dispersed into discrete subcenters. Sprawl likely could be less problematic in an urban area whose suburban jobs are concentrated in subcenters. Trip lengths will reduce if population density pockets have sufficient jobs confined to a nearby subcenter. Public transportation could be designed to cater subcenters which can alleviate problems such as traffic congestion.

Thus in transport theory the concept of compactness is more complex than simple measurements such as population density and distance to city centre.

Formulation and quantification of compactness of a city is one of the prime concerns of planners and policymakers.

3.6. Compactn ess Index

In recent years city planners, developers and policymakers have turned focus on designing a more compact city in order to achieve a more sustainable urban form. Major concern among researchers is to quantify urban sprawl and compactness.

There is a substantial amount of research on measuring sprawl and compactness of urban spaces and its effect on travel patterns. Obvious measurements of compactness are population density, employment density or density of development (Naess and Sandberg, 1995; Cervero, 1996; Cervero and Kockelman, 1997; Banister, 2005; Muniz and Galindo, 2005; Lee and Moudon, 2006; Milakis *et al*., 2008) and distance to city centre (Newman and Kenworthy, 1988; Naes *et al*., 1995; Naess and Sandberg, 1995; Muniz and Galindo, 2005; Milakis *et al.,* 2008). But as discussed above, compact city form is not confined just to distances, shapes or densities. Land use mix, Provision of facilities and proximity to activity centers also comprise aspects of compactness, as will be discussed in following sections.

3.6.1. Compactness Index proposed by Zhang and Guindon (2006)

A basic feature of urban sprawl is inefficient land use reflecting high urban land use per capita. Urban population density σ_U, is simply expressed as:

$$\sigma_U = \frac{P_U}{L_U}$$

…………………..Equation 3.1

Where,
P_U - is the population living in the urban area and
L_U - is the total land used for urban activities.

Authors consider urban land use per capita to be a rudimentary indicator. It is based on a simple premise that a spread out city will (i) increase trip distances and (ii) public transport will be less feasible, thereby encouraging greater private vehicle use. Chief drawbacks of the indicator are (i) difficulty in inferring its explicit impact and (ii) potential ambiguity in indicator values. Authors illustrate the later point by considering the case shown in figure 3.3 (a and b) of two cities with identical population and also total land used for urban activities. Both cities would have identical measures of urban land use per capita. In a scenario of commuting to the city centre, the urban form shown in figure 3.3 (a) is most efficient since it is optimally concentrated near the centre. On the other hand, the city shown in figure 3.3 (b), i.e. a central core surrounded by isolated satellite communities, naturally would involve in greater weighted travel distances.

High Compactness Mono-centric City	Low Compactness Mono-centric City

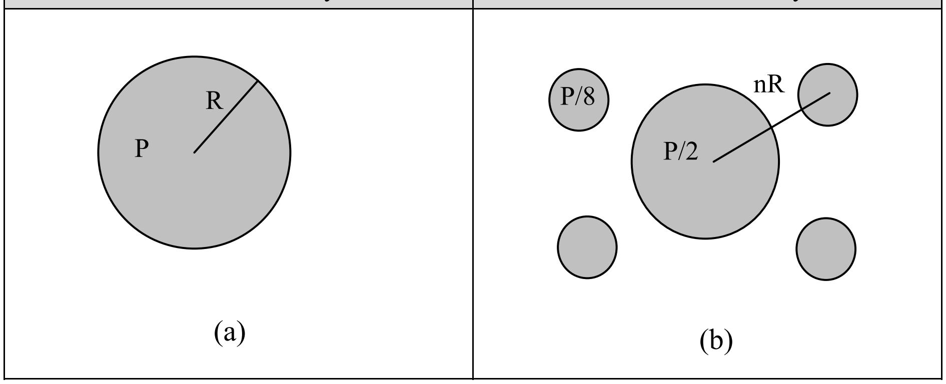


Figure 3.3: Compactness – Mono-centric City

Authors propose a measure of urban compactness which incorporates urban form and captures the concept of accumulated travel distance. From an analytic formulation point of view authors proposed concept of dispersion, D, the inverse of compactness, C –

$$C = \frac{1}{D}$$ …………………..Equation 3.2

Dispersion for accumulated travel distance is -

$$D = \sum P_i \times R_i$$ …………………..Equation 3.3

Where, the summation is over all residential units. P_i is the unit's population and R_i is the distance of the unit from a reference point. The authors have considered reference point to be the city centre and thus dispersion measures are for a mono-centric city where all employment and shopping related activities are conducted in a highly concentrated CBD.

For the purpose of inter-city comparisons authors have used benchmark urban form for normalization. A suitable benchmark form proposed is a circular city of constant density, σ_B. The radios, R_B of a city with overall population P would be then

$$R_B = \sqrt{\frac{P}{\pi \sigma_B}}$$ …………………..Equation 3.4

And its dispersion would be –

$$D_B = \int_0^{R_B} (2\pi r \sigma_B) r dr = \frac{2P^{1.5}}{3\sqrt{\pi \sigma_B}}$$ …………………..Equation 3.5

Where,

P is the total population of the city and

σ_B is constant population density,

Benchmark population density σ_B, considered in this study is a value within the range of population densities observed for major Canadian cities.

Normalized Dispersion (*ND*)–

$$ND = \frac{D}{D_B}$$ …………………..Equation 3.6

Compactness Index (*C*)–

$$C = \frac{1}{ND}$$ …………………..Equation 3.7

Thus compactness for any city is calculated by computing dispersion using equation 3.3. Ratio of observed dispersion to benchmark dispersion, computed using equation 3.5, gives normalized dispersion. Inverse of the normalized dispersion gives compactness index.

3.7. Limitations of the Compactness Index and Proposed m-Compactness Index

The compactness index proposed by Zhang and Guindon (2006) is certainly an improvement over rudimentary urban form indices such as population density or distance to city centre but assumes cities to be mono-centric.

However the metropolitan areas are increasingly becoming decentralized and traditional CBDs account for a smaller proportion of jobs than in the past. Effect of polycentrism and a modified compactness index proposed in this study are discussed in this section.

3.7.1. Effect of Polycentrism on Compactness

Almost all large metropolises sooner or later experience spatial reorganization from a predominant mono-centric employment structure to a poly-centric employment structure as central land prices and internal transport costs rise (Balck, 2003).

The compactness index proposed by Zhang and Guindon (2006) assumes cities to be mono-centric. Authors illustrate concept of dispersion by considering the case shown in figure 3.3 (a and b) of two cities with identical population and also total land used for urban activities. In a scenario of commuting to the city centre, the urban form shown in figure 3.3 (a) is most efficient. On the other hand, the city shown in figure 3.3 (b), i.e. a central core surrounded by isolated satellite communities, naturally would involve greater weighted travel distances. This assumption is very true in case of mono-centric city but as discussed in previous sections, metropolitan areas are increasingly becoming decentralized and traditional CBDs account for a smaller proportion of jobs than in the past.

A polycentric city with its employment concentrated in sub-centres will reduce trip lengths. Thus the effect of polycentrism would be reduced weighted travel distances there by reducing dispersion as illustrated in figure 3.4 (II).

Low Compactness Mono-centric City	High Compactness Poly-centric City

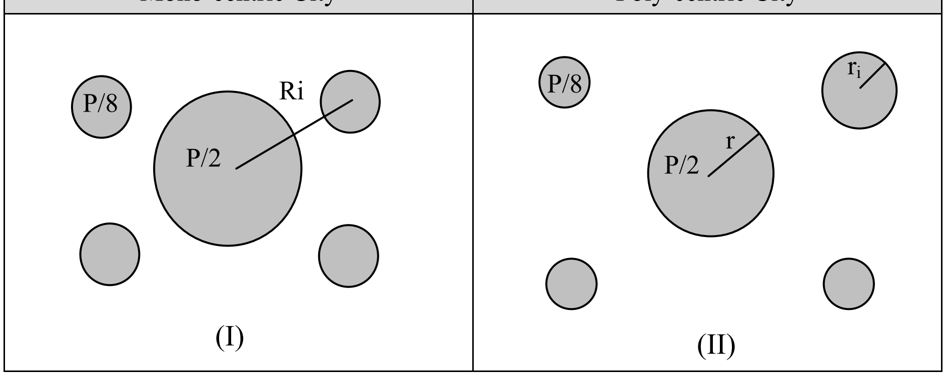


Figure 3.4: Polycentrism and Compactness

Dispersion for case (I)

$$D = \sum P_i \times R_i$$ ……………………..Equation 3.8

Dispersion for case (II)

$$D = \sum P_i \times r_i$$ ……………………..Equation 3.9

Where,

P*i* – is Units population

R_i – is distance to city centre.

r_i - Distance to subcenters

Dispersion for case I (mono-centric city) would be naturally higher compared to case II (poly-centric city) as R_i, distance to city centre would be higher than the distance to subcenters r_i.

An urban form presumed to have low compactness could in fact have a high compactness considering compact city with many employment sub-centres that rival the city centre as places of work as shown is figure 3.4 (II). Hence a modified compactness index has been proposed that incorporates concept of polycentrism and accumulated travel distance estimation. Next chapter explains conception and formulation of proposed modified compactness index – m-Compactness.

4. m-Compactness Index Conception and Formulation

In previous chapter the effect of polycentrism on compactness has been discussed. This chapter explains notion of m-Compactness and its formulation.

4.1. m-Compactness Index Conception

Proposed modified compactness index incorporates concept of poly-centrism and weighted travel distance estimation. The subcenters within a city are identified on the basis of employment. Total employment of a sub-center and its distance from each unit are used to estimate trip attraction potential using Huff probabilistic gravity model. Trip attraction potentials of subcenters are used in estimating weighted distance for each unit. Dispersion and in turn m-Compactness are then computed based on unit's population and its weighted distance.

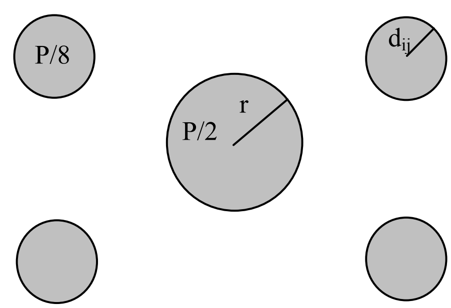


Figure 4.1: Polycentric City with High Compactness

An urban form shown in figure 4.1 would exhibit high compactness if employment of density pockets is concentrated at their respective centers that are city subcenters. Dispersion for such a city would be naturally less as distance to subcenters or weighted distance is considered rather than distance to city centre.

4.2. m-Compactness Index Formulation

Thus for the example city shown in figure 4.1, Dispersion would be -

Dispersion

$$D = \sum P_i \times Dw \qquad \text{……………………..Equation 4.1}$$

Where,
D_W - is the Weighted distance

Normalized Dispersion

Normalized dispersion is computed by comparing observed dispersion with bench mark dispersion as explained in section 3.6.1. Bench mark dispersion based on the formula explained in section 3.6.1 would be -

$$D_B = \frac{2P^{1.5}}{3\sqrt{\pi\sigma_B}} \qquad \text{………………..Equation 4.2}$$

Where,
P is the total population of the city and
σ_B is constant population density,

Benchmark population density σ_B, considered in this study is 16000 persons / Km_2.

Normalized Dispersion would be -

$$ND = \frac{D}{D_B} \qquad \text{……………………..Equation 4.3}$$

m-Compactness then would be –

$$mC = 1/ND \qquad \text{……………………..Equation 4.4}$$

In above formulae, population is an observed or measured phenomenon. The effect of polycentrism would be on weighted distance D_w. The weighted distance of any unit is estimated on the basis of its distance from sub-centers and the trip attraction potential of each sub-center.

Identification of sub-centers using Giuliano and Small (1991) method is explained in the next chapter. The following sections explain use of Huff probabilistic gravity model in estimating trip attraction potential of sub-centers and computing weighted distance.

4.2.1. Trip Attraction Potential of Sub-centers: Huff Probabilistic Gravity Model

The gravity model is the most common formulation of the spatial interaction method. It governs its name from Newton's formulation of gravity. Accordingly, the attraction between two objects is proportional to the product of the two masses and inversely proportional to the square of the distance between them. Thus, the general formulation of spatial interactions to reflect this basic assumption in transport theory would be:

$$T_{ij} = \frac{P_i P_j}{d_{ij}^{\beta}} \qquad \text{……………………..Equation 4.6}$$

Where

T_{ij} - Magnitude of the gravitational force or interaction between unit *i* and *j*

P_i - Trip production potential of unit *i*

P_j - Trip attraction potential of unit *i*

d_{ij} - Distance between two locations

β - Transport friction parameter related to the efficiency of transport system

In transport engineering, the amount of travel between two areas is considered to be proportional to their population, numbers of jobs, factories, offices, schools and so on but inversely proportional to the square of the distance or some measure of the separation or deterrence between them. The gravity model takes the trips produced at origin and distributes them to destinations. A destination with a higher attraction potential will receive a greater number of distributed trips (Beimborn and Kennedy, 1996). The number of trips to a destination decreases with increase in the distance.

In this study Huff Probabilistic model is used to estimate trip attraction potential of sub-centers. The Huff model was introduced by David Huff in 1963. It is conceptually appealing, relatively easy to use and applicable to a wide range of problems. "The model is based on the premise that when a person is confronted with a set of alternatives, the probability that a particular item will be selected is directly proportional to the perceived utility of that alternative" (Huff and McCallum, 2008).

$$P_{ij} = \frac{U_{ij}}{\sum_k U_{ik}}$$ …………………..Equation 4.7

"Where P_{ij} is the probability that an individual i will select alternative j given the utility of j relative to the sum of the utilities of all choices n that are considered by individual I" (Huff and McCallum, 2008).

The Huff probabilistic gravity model has been used in modelling preference of a sub-center on the basis of its attraction power determined by its relative employment and distance form a unit under consideration.

$$W_{ij} = \frac{A_j \, d_{ij}^{-\beta}}{\sum_k A_k \, d_{ik}^{-\beta}}$$ …………………..Equation 4.8

Where,

W_{ij} - is the visit probability or the trip attraction potential of sub-center

A_j - is the attractiveness of sub-center (relative employment)

d_{ij} - is the distance of sub-center from i, the unit under consideration

Procedure for estimating trip attraction potential of each sub-center for every unit using Huff probabilistic gravity model is illustrated by considering a unit i as shown in figure 4.2 with two sub-centers located at different distances from the unit i, having different employments.

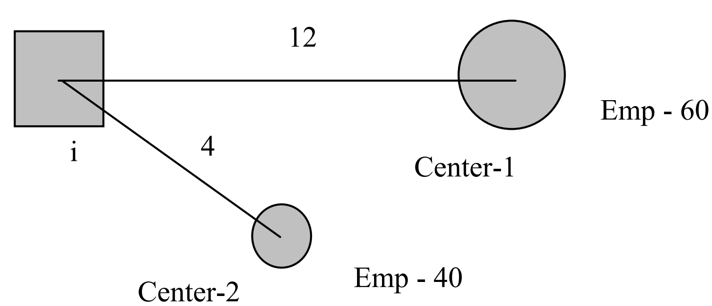


Figure 4.2: Huff Probabilistic Gravity Model Illustration

Based on Huff model, trip attraction potential of Center-1 that is the probability that a person from unit i would travel to Center-1 would be –

$$W_{i1} = \frac{60 \times 12^{-2}}{(60 \times 12^{-2}) + (40 \times 4^{-2})} \quad = \quad 0.14$$

And trip attraction potential of Center-2 would be –

$$W_{i2} = \frac{40 \times 4^{-2}}{(60 \times 12^{-2}) + (40 \times 4^{-2})} \quad = \quad 0.86$$

Having estimated trip attraction potentials of each subcenter for all units (grid cells), procedure for estimating weighted travel distance for each unit is explained in subsequent sections.

4.2.2. Weighted Travel Distance

Dispersion of a unit is the product of its population P_i and its distance from a reference point. As discussed earlier, in case of a mono-centric city the distance of a unit to the city center is considered while in case of a poly-centric city weighted distance is considered.

People will travel to a sub-center that is comparatively more attractive and relatively near. The trip attraction potential of each sub-center, computed using Huff gravity model, and distance of the unit from sub-centers are used in estimating weighted travel distance for each unit.

The weighted travel distance for each unit is calculated as follows –

$$D_w = \sum d_{ij} \times W_{ij} \qquad \text{......................Equation 4.9}$$

Where,

D_W – *Weighted travel distance*

d_{ij} – Distance of unit i to sub-center j

W_{ij} – Weight or Force of attraction of Sub-center I

Consider the example of two centers, 1 and 2, and a unit i explained above –

Table 4.1: Trip Attraction Potential

Center	Distance (d_{ij})	Trip Attraction Potential (W_{ij})
1	12	0.14
2	4	0.86
Total	-	1.00

Weighted travel istance (D_w) for unit i according to Equation 4.9 would be –

$$D_w = 12 * 0.14 + 4 * 0.86$$
$$= 5.12$$

In case of mono-centric city with CBD as reference or in the above illustration center-1, the distance of the unit from the reference point would be 12. As discussed, the effect of poly-centrism would be reduced distance to the reference point. If we consider center-2 the weighted distance computed is 5.12. If there are more important sub-centers near the unit under consideration, the weighted distance will be still less.

4.3. Summar y

Estimation of m-Compactness based on normalized dispersion enables inter-city as well as intra-city comparison of compactness. Thus in summary, following steps are involved in computing m-Compactness for any city –

- Identification of Sub-Center
- Estimation of Weighted Distance
- Estimation of Dispersion
- Estimation of Benchmark Dispersion
- Estimation of Normalized Dispersion
- Estimation of m-Compactness

Following Chapter explains methodology in detail and the implementation of m-Compactness for case study Ahmedabad city.

5. Quantification Methodology and Implementation

5.1 Methodology

This chapter explains methodology followed for computing compactness indices using both Zhang and Guindon (2006) methodology and the proposed methodology for the modified compactness index; m-Compactness. Both procedures are discussed in the previous chapters 3 and 4. Flowchart shown in figure 5.1 depicts step by step procedure for computing compactness indices. Subsequent chapters explain each step in detail

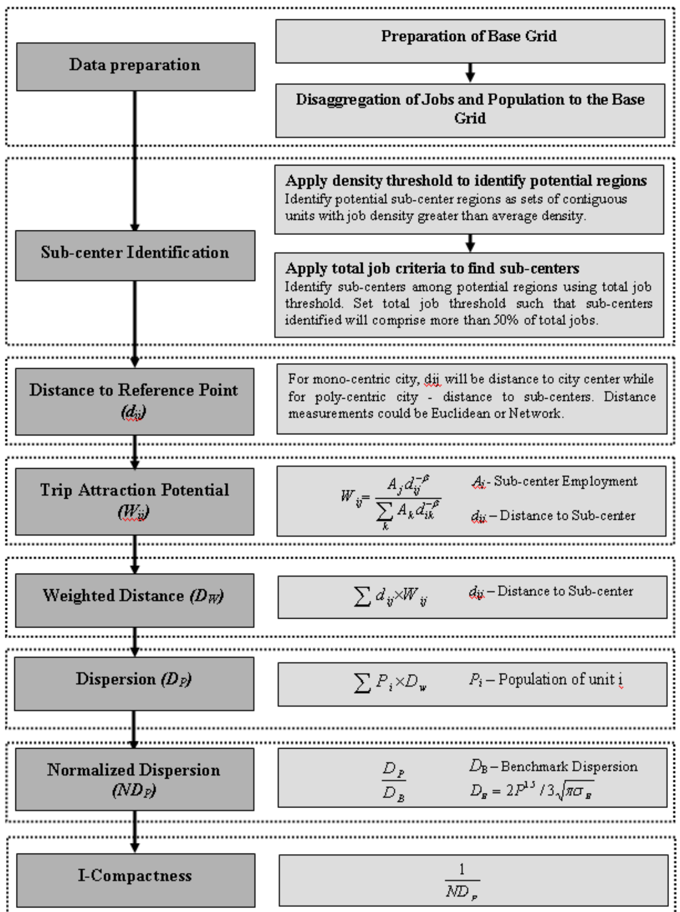


Figure 5.1: Methodology for computing compactness

5.2 Data Preparation

The data made available primarily from the PhD work of Munshi (2007), is summarized in the Table 5.1

Table 5.1: GIS data used in Analysis

Sr. No	File Name	File Details	Metadata
1.	ebblockedi.shp	Polygon shapefile delineating the enumerations blocks within the study area	PCS: WGS 1984 Transverse Mercator GCS: GCS WGS 1984 Bounding coordinates (DD) West: 72.459562 East: 72.735901 North: 23.190684 South: 22.907653
2.	roads.shp	Polyline shapefile delineating the roads in Ahmedabad Urban agglomeration area	PCS: WGS 1984 Transverse Mercator GCS: GCS WGS 1984 Bounding coordinates (DD) West: 72.459562 East: 72.735901 North: 23.190684 South: 22.907653

The data preparation process mainly includes 2 steps, a) preparation of base grid and b) disaggregation of jobs to the base grid, which is explained in the following sections.

5.2.1 Preparation of Base Grid

The square gird defines the extent of the analysis unit and has size 251 by 250 cells. The urban form is categorized by typology of land use and socio-demographic parameters. Thus the size of the grid cell should be such that observed variations in urban form characteristics are not lost. “The smallest traffic analysis zone in the densely populated wall city area is 0.013 sq kms, and in the municipal corporation area is 0.28 sq kms” (Munshi, 2007). Hence

100 meter resolution grid covering entire study area, prepared by Munshi (2007), has been used in analysis. Analysis unit (grid cells) used is smaller than the census zone and larger than a household unit therefore issues related to aggregation and disaggregation need to be addressed.

5.2.2 Disaggregation of Jobs to the Base Grid

The Population, employment and other parameters of each Enumeration Block (EB) can be disaggregated to the grids, based on the area of EB that is distributed in each grid cell.

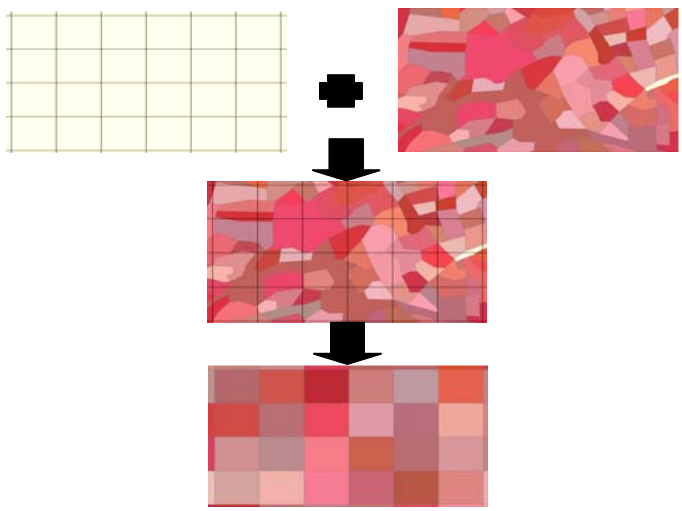


Figure 5.2: Disaggregation of Jobs to the Base Grid

5.3 City Sub-centre Identification

The methodology for identifying sub-centers is adopted from Giuliano and Small (1991). The authors have used descriptive statistics to identify the sub-centers in an urban area with a case study of Los Angeles. In this study the sub-center term refers to 'employment sub-center', the spaces outside of central spaces with large employment that rival the city center as places of work (Daniel, 2001).

5.3.1 Urban Employment and Sub-centers

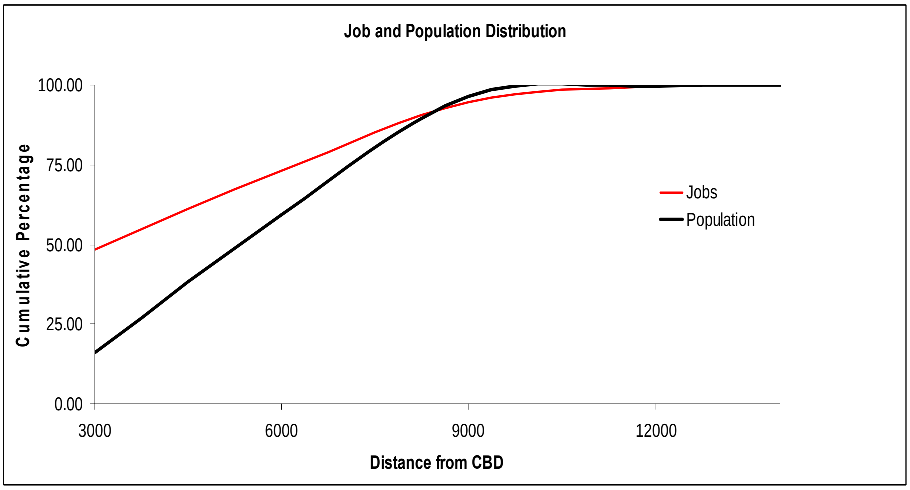


Figure 5.3: Employment and Population Distribution

Figure 5.3 shows cumulative % of employment or job and population plotted against distance from the city center. Population and employment densities are inversely proportional to the distance from the city center. As it can be seen from the graph, only around 20% population is with in 3 Km from the city center whereas employment is 50%. The graph shows that the population is more dispersed throughout the city and hence employment or job density in place of population density has been considered for identifying sub-centers.

5.3.2 Sub-centre Identification Criteria

The criterion for identification of sub-centers as used by Giuliano and Small (1991) is:

- Zones, each above a predefined cutoff employment density (D =10 jobs/acre)
- Set of such zones `contiguous in nature' and together have at least a predefined employment (E= 10,000 jobs).
- Zones, are considered contagious if they share a boundary of 0.4 km

For this study:

Predefined cut-off employment density (D) considered is 45 jobs/acre which is the average employment density for Ahmadabad city. Potential sub-center regions as sets of contiguous units with job density greater than average density were identified. Set of such zones contiguous in nature should have a minimum total employment such that all the zones together should comprise at least 50% of the total employment. Thus to decide total cutoff employment, sub-centers with different cut-off densities were estimated as shown in table 5.2.

Table 5.2: Cutoff employment for Sub-center Identification

Cutoff Employment	Total_Jobs	Number of Sub-centers	Percentage Employment
10,000	301449	2	42.52
5000	314579	5	44.37
4000	342144	10	48.27
3500	356896	14	50.35
3000	369304	18	52.10

Criterion adopted of total cutoff employment of 3500 jobs identifies 14 sub-centers and these sub-centers together comprise slightly more than 50% of overall employment as shown in table 5.2.

Thus, the criterion for identification of sub-centers used for this study was

- Zones, each above a predefined cutoff employment density (D =50 jobs/acre)
- Set of such zones `contiguous in nature' and together have at least a predefined employment (E= 3500 jobs).
- Zones, are considered contagious if they share a boundary of 0.1 km

5.3.3 Sub-centers Identified in Ahmadabad City

With the adopted criteria, 14 subcenters were identified as shown in figure 5.4 and are summarized in table 5.3.

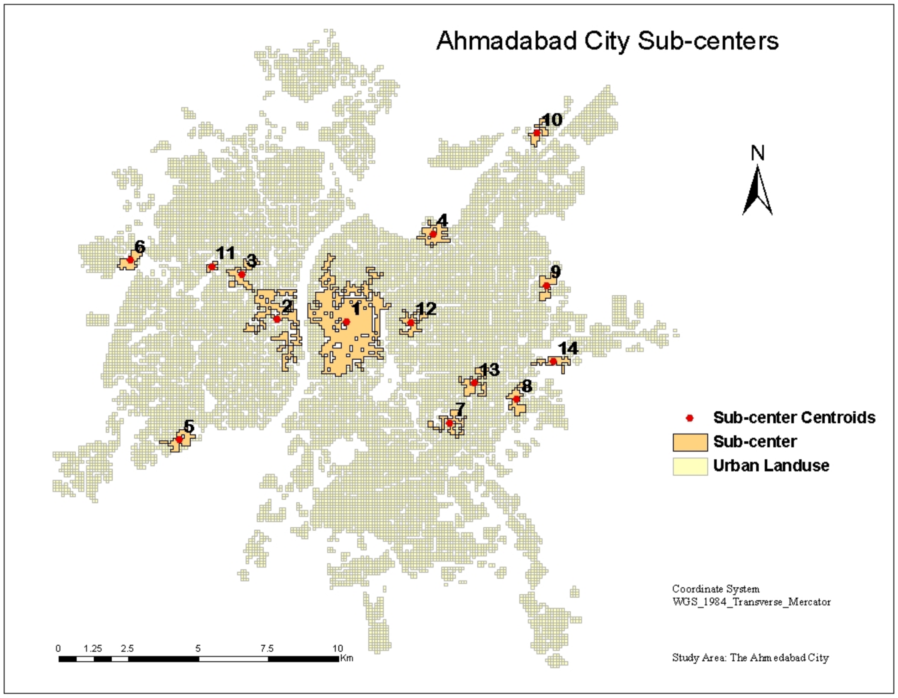


Figure 5.4: Ahmedabad City Sub-centers

Table 5.3: Sub-centers Identified in Ahmedabad City

Sr. No	Maximum Employment Density	Total Employment
1	7844	278877.00
2	528	22572.00
3	512	6688.00
4	422	6442.00
5	451	5331.00
6	387	4624.00
7	303	4604.00
8	366	4428.00
9	487	4367.00
10	413	4211.00
11	831	3888.00
12	188	3712.00
13	158	3626.00
14	266	3526.00

5.4 Trip Attraction Potential of Sub-centers and Weighted Distance

As explained in 4.2.1, Huff probabilistic gravity model has been used in modeling preference of a sub-center on the basis of its attraction power determined by its relative employment and distance form a unit under consideration.

$$W_{ij} = \frac{A_j d_{ij}^{-\beta}}{\sum_k A_k d_{ik}^{-\beta}} \quad \text{……………………..Equation 5.1}$$

Where,

Wij - is the visit probability or the trip attraction potential of sub-center

Aj - is the attractiveness of sub-center (employment)

dij - is the distance of sub-center from i, the unit under consideration

5.4.1 Network Distance Estimation

Network distances of each residential unit to different sub-centers were considered since network distance is a more realistic determining variable than Euclidean straight-line distance. To create a Network Dataset, geo-database was created having road feature class using road shapefile. Topology rules described in table 5.4 were applied to road feature class to get a consistent and clean topological fabric.

Table 5.4: Topology Rules

Topology Rule	Rule Description
Must Not Overlap	Requires that lines not overlap with lines in the same feature class. This rule is used where line segments should not be duplicated
Must Not Intersect	Requires that line features from the same feature class not cross or overlap each other. Lines can share endpoints.
Must Not Have Dangles	Requires that a line feature must touch lines from the same feature class at both endpoints. An endpoint that is not connected to another line is called a dangle.
Must Not Have Pseudonodes	Requires that a line connect to at least two other lines at each endpoint. Lines that connect to one other line (or to themselves) are said to have pseudonodes.

Must Not Intersect Or Touch Interior	Requires that a line in one feature class must only touch other lines of the same feature class at endpoints. Any line segment in which features overlap or any intersection not at an endpoint is an error.
Must Not Self Overlap	Requires that line features not overlap themselves. They can cross or touch, but must not have coincident segments.
Must Not Self Intersect	Requires that line features not cross or overlap themselves. This rule is useful for lines, such as contour lines, that cannot cross themselves.
Must Be Single Part	Requires that lines have only one part. This rule is useful where line features, such as highways, may not have multiple parts.

Process of computing network distances for each residential unit to every subcenter using Network Analyst extension of ArcGIS 9.3 is briefly explained below.

- Network Dataset was create based on geo-database
- Network Analyst was used to generate origin–destination (OD) cost matrix.
  - Origins – Residential units (grid cells with population)
  - Destination – Sub-centers
  - Cost – Distance
  - Output generated was straight lines connecting origins and destinations but the attribute table stores the network impedance.
- 'Feature Vertices to Points' tool was used to generate points at the starting node of out-put lines of OD cost matrix.
  - The point data has total_length attribute along with other attributes of the line features
- Spatial Analyst extension was used to Convert point features to Raster

Based on network distances and total employment of each subcenter, trip attraction potentials were estimated for all residential land units using equation 5.1 which employs Huff probabilistic gravity model.

5.4.2 Weighted Travel Distance

People will travel to a sub-center that is comparatively more attractive and relatively near. The trip attraction potential of each sub-center, computed using Huff gravity model, and network distance of each unit from sub-centers were used in computing weighted travel distance for each unit. The weighted travel distance for each unit is calculated using formula explained in section 4.2.2 which is -

$$D_w = \sum d_{ij} \times W_{ij} \qquad \text{.......................Equation 5.2}$$

Where,

D_W – Weighted travel distance

d_{ij} – Network distance of unit i to sub-center j

W_{ij} – Weight or Force of attraction of Sub-center

Figure 5.5 shows the map of the estimated weighted travel distance for Ahmedabad city.

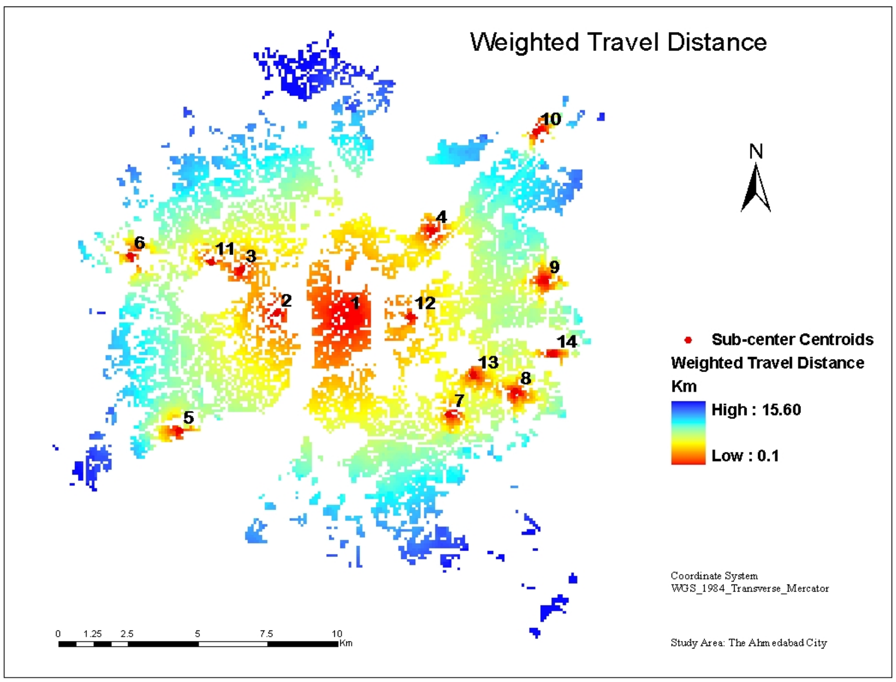


Figure 5.5: Weighted Travel Distance

5.5 Dispersion and Compactness Index

Dispersion for any city is the summation of product of unit's population and its distance to some reference point. For the purpose of inter-city comparisons normalized dispersion is computed which is the ratio of observed dispersion to the benchmark dispersion. A suitable benchmark form considered is a circular city of constant density; σ_B. Compactness is then computed by taking inverse of normalized dispersion. Following subsection explains computation of compactness for a mono-centric urban form using Zhang and Guindon (2006) method and section 5.5.2 explains computation of m-Compactness for a poly-centric urban form.

5.5.1 Dispersion and Compactness Index: Mono-centric Urban Form

Zhang and Guindon (2006) methodology followed for computing compactness index is discussed in detail in section 3.6.1. Euclidean distance to city centre (Sub-centre 1) was considered for each residential unit. Raster map depicting product of population and distance to city center for each residential unit is shown in figure 5.6.

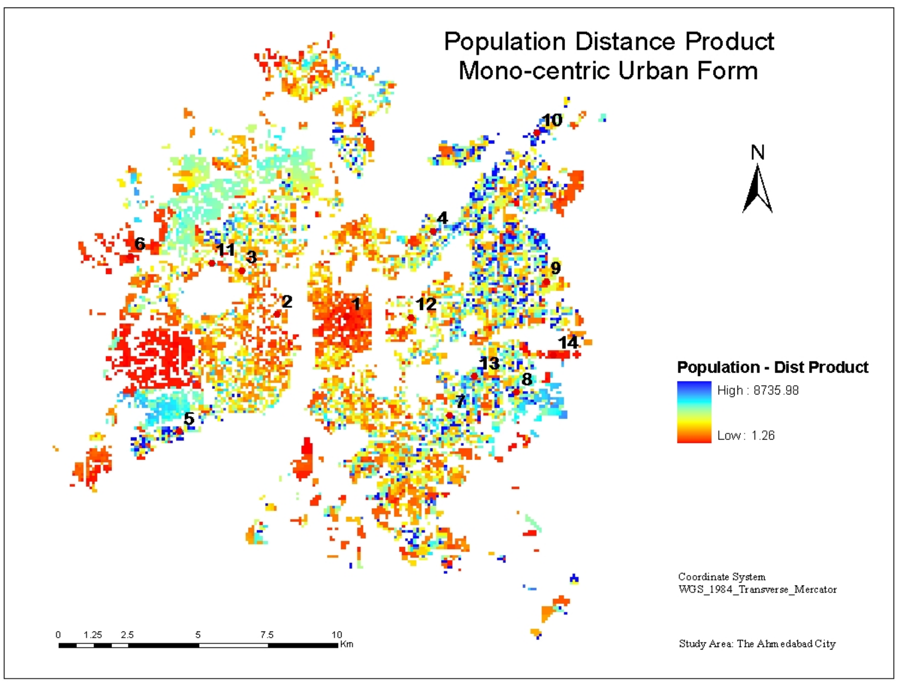


Figure 5.6: Product of Population and Distance: Mono-centric City

Dispersion is computed using following formula

$$D = \sum P_i \times R_i \quad \text{……………………..Equation 5.3}$$

Where, the summation is over all residential units. P_i is the unit's population and R_i is the distance of the unit from city center.

Observed dispersion for Ahmedabad city was – 13336600

Benchmark dispersion was computed using following formula –

$$D_B = \frac{2P^{1.5}}{3\sqrt{\pi\sigma_B}} \quad \text{………………..Equation 5.4}$$

Total Population of Ahmedabad city *P* – 2448719
Urban Land Area of Ahmedabad city – 15969 acer i.e. 159.69 km^2
Population Density of Ahmedabad city - 15334 persons / km^2

Constant Population Density σ_B – 16000 persons / km^2

Benchmark population density σ_B, considered in this study is a value within the range of population densities observed for major Indian cities.

Benchmark dispersion computed based on formula 5.2 – 11395233

Normalized dispersion is the ratio of observed dispersion to the benchmark dispersion. Thus normalized dispersion computed –
ND – Observed dispersion / Benchmark dispersion
= 13336600 / 11395233
= 1.17

Compactness computed – *C* = 1/ *ND* = 0.854

5.5.2 Dispersion and Compactness Index: Poly-centric Urban Form

Procedure for computing m-Compactness is same except that the distance to reference point is the weighted travel distance computed in section 5.4.2 in place of Euclidean distance to city centre. Raster map depicting product of population and weighted travel distance for each residential unit is shown in figure 5.7.

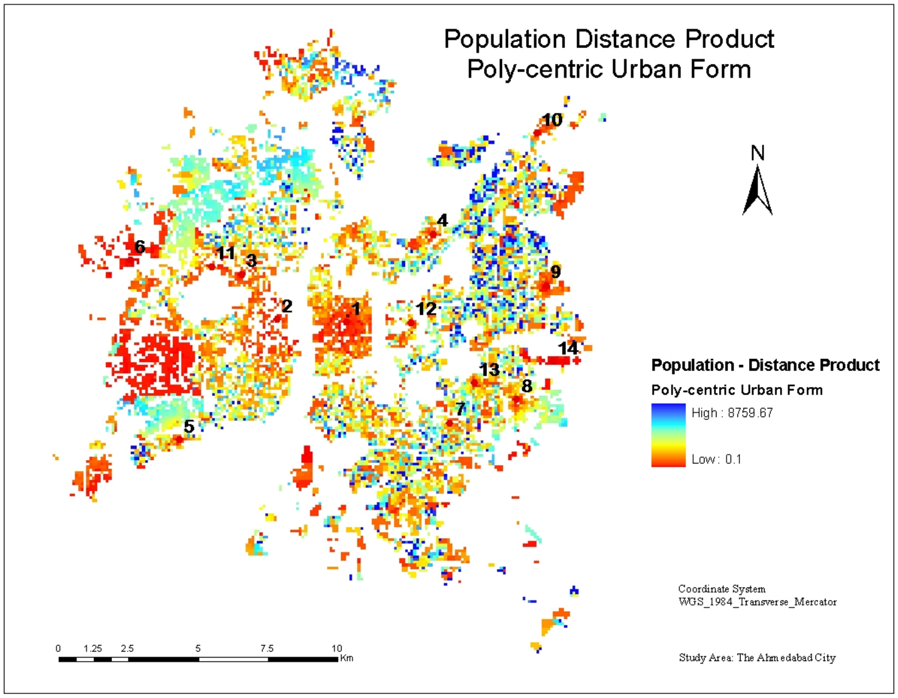


Figure 5.7: Product of Population and Distance: Poly-centric City

Dispersion is computed using following formula –

$$D = \sum P_i \times Dw \qquad \text{……………………Equation 5.5}$$

Where, the summation is over all residential units. P_i is the unit's population and D_W is the weighted travel distance of the unit.

Observed dispersion for Ahmedabad city was – 13045600

Benchmark dispersion as computed in section 5.5.1 – 11395233
Normalized dispersion
ND – Observed dispersion / Benchmark dispersion
= 13045600 / 11395233
= 1.144

m-Compactness – m*C* = 1/ *ND*
= 0.873

5.5.2 m-Compactness Computed for Each Residential Unit

To know the variation of compactness over the study area, m-Compactness was computed for each residential unit. Dispersion per unit area was computed by considering a circular city of constant density;

Constant Density; σ_B, considered - 16000 persons / Km^2

Benchmark dispersion (B_D) computed is - 11395233.

Area (A) of such benchmark form for the population (P) of Ahmedabad city, would be – P / σ_B = 2448719/ 16000 = 153.04 Km^2.

The dispersion per unit area then would be – B_D / A = 74459.18

Size of the residential units (grid cell) is 100m. Thus area of each unit would be – 0.1 * 0.1 Km^2 = 0.01 Km^2

Benchmark dispersion for each unit would be then - 74459.18 * 0.01 = 744.6

To compute normalized dispersion for each residential unit, Population distance product computed in section 5.5.2 was divided by unit benchmark dispersion of 744.60. Minimum dispersion value was limited to 0.1 as resolution of grid cell is 100m i.e. 0.1 Km

m-Compactness for each residential unit was then computed by taking inverse of unit normalized dispersion (1 / ND).

Figure 5.8 shows the map of m-Compactness computed for each residential unit.

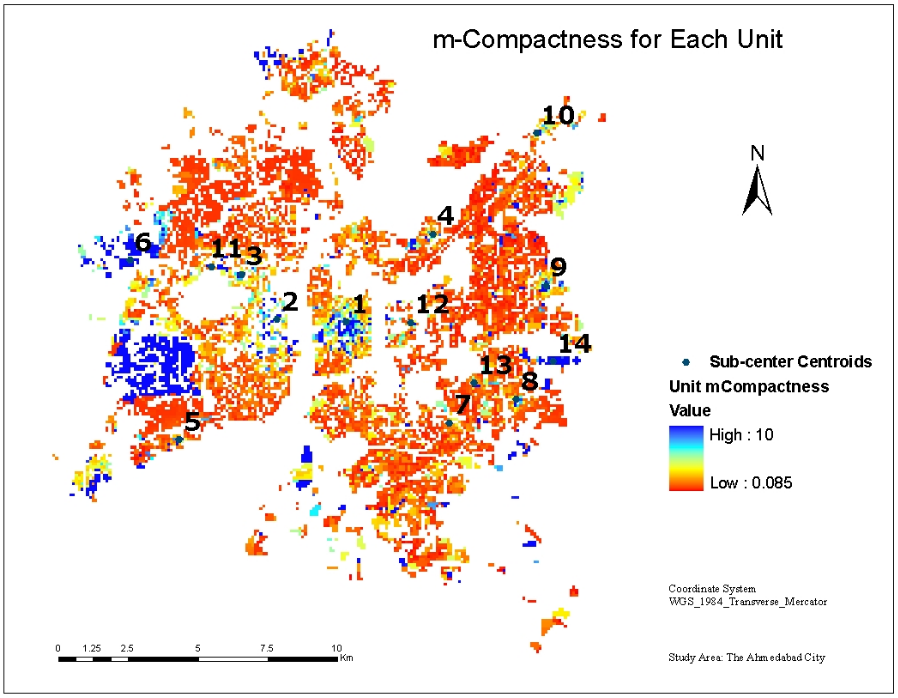


Figure 5.8: m-Compactness for Each Residential Unit

The m-Compactness for each residential unit was then considered in examining the causality between work trips and urban form in the next chapter.

5.6 Summary

Compactness indices for Ahmedabad city were computed using both, Zhang and Guindon (2006) methodology considering Euclidean distance to city centre and m-Compactness considering weighted travel distance. m-Compactness computed for each residential unit is considered in the following chapter to examine the causality between work trips and compact urban form.

6. Compactness Index and Travel Behaviour

6.1. Travel Characteristics and Household Survey Data

Travel time, trip length and transport mode are some of the indicators of travel behaviour. To find the relation between M-Compactness and travel behaviour, household survey data made available primarily from the PhD work of Munshi (2007) was used.

Sampling unit of the surveyed data are persons from randomly selected households. Each sampling location represents a house hold. The aim of the analysis is to find a relation between compactness index values or computed weighted distances and work trip lengths and the choice of the mode hence only samples with work as the trip purpose were selected from the entire survey data set.

Urban work trips are known to depend on urban form with respect to its landuse. However, the causality is still debated among scientists, engineers, planners (Sriram, 2008). To examine the causality between work trips and urban form, 4481 individuals were selected from the entire survey data set with work as trip purpose. The locations of the households are shown in the map in figure 6.1. Visual check reveals that the sampling units are random and well distributed over the study area.

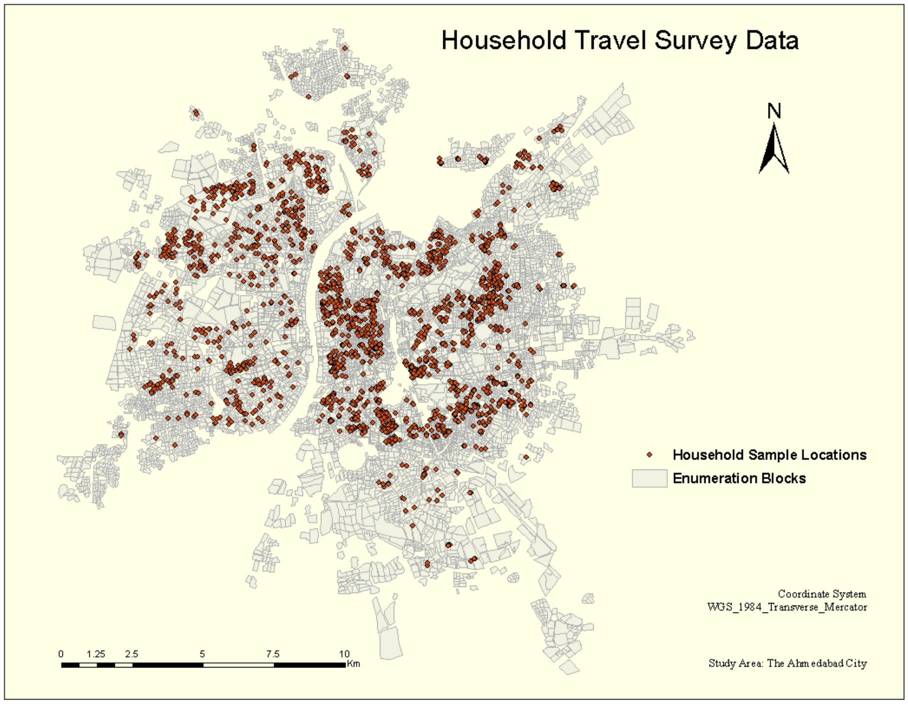


Figure 6.1: Household Travel Survey Data

6.1.1. Modal Split

Modal share, or Modal split, describes the percentage of travellers using a particular type of transportation. The modal share and the number of samples are shown in table 6.1.

Table 6.1: Modal Split

Mode	Work Trips	
	No. of Samples	%
Walk	860	19.20
Bicycle	827	18.50
Two Wheeler (Motorscooter)	1879	41.90
Car (Private Automobile)	81	1.80
Bus and Other	834	18.60
Total	4481	100

Modal split reveals the highest share of two wheelers. Almost half, nearly 44% of the people are using private mode that is motorscooters and cars. The walk and bicycle together contribute 38% while bus and other transport mode contribute only 19%. The figures show that people are more inclined towards private modes, especially motorscooters rather than other transport modes for their daily work trips.

6.1.2. Modal Split and Work Trip Length

Trip length is the distance a commuter is travelling in his daily trip. Average trip lengths for different modes and number samples are shown in table 6.2.

Table 6.2: Modal Split and Work Trip Length

Mode	No. of Samples	Average Work Trips Length Km
Walk	860	1.25
Bicycle	827	3.96
Two Wheeler (Motorscooter)	1879	5.67
Car (Private Automobile)	81	6.14
Bus and Other	834	5.29
Overall	4481	4.46

Car trips show the highest average work trip length of 6.14 Km. As presumed, walking trips show the least average work trip length of 1.25 Km. Bicycles trips also show low value of trip length, 3.96 Km. Bus and other mode show trip length of 5.27 Km whereas two wheelers having largest modal split share show almost as high average trip length as for cars of 5.67 Km.

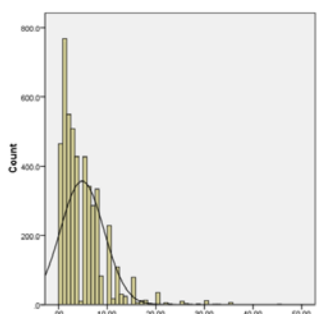
6.2. Compactness and work trip lengths

The hypothesis is that there is a negative correlation between work trip lengths and m-Compactness.

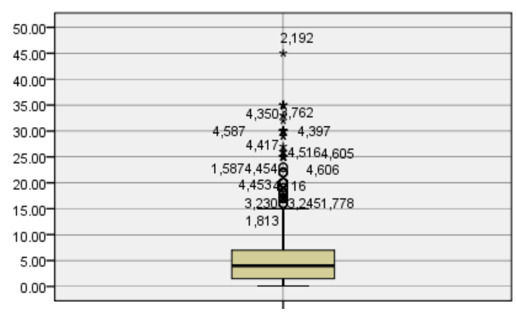
The null hypothesis (H_o) and alternate hypothesis (H_a) would be:
H_o: There is no relation between work trip lengths and m-Compactness.
H_a: There is a relation between work trip lengths and m-Compactness.

The sampling unit was house. In analysis, values of weighted travel distances for analysis unit (grid cell) and average work trip length of sampled units within grid cell were considered.

SPSS statistical software and regression analysis were used to test above hypothesis. The assumption for regression analysis is that the data is normally distributed. The outliers were detected using boxplot as shown in figure 6.2.



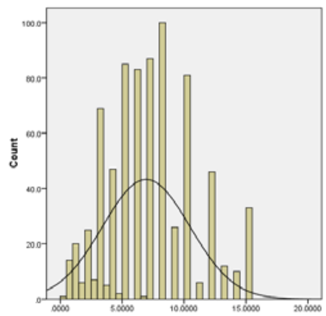
Work Related Trip Lengths



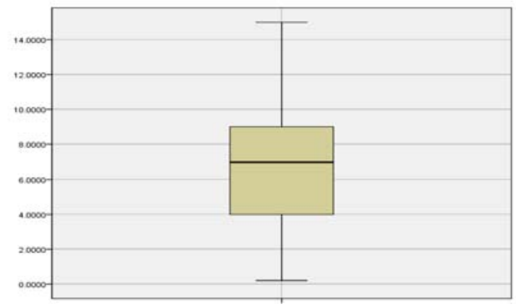
Work Related Trip Lengths

Figure 6.2: Histogram and Boxplot– Work Trip Lengths

The histogram and boxplot were re-plotted as shown in figure 6.3.



Work Trip Lengths



Work Trip Lengths

Figure 6.3: Re-plotted Histogram and Boxplot– Work Trip Lengths

Data appears reasonably normal from the visual check. Histogram does not appear to have a perfect bell-shaped pattern but there is more data in the middle and less toward the two extremes. Additionally, half of the data are above and half below the mean. Based on these observations the assumption of normality appears reasonable and regression analysis could be conducted.

The significance level was set at 0.01. Work trip length was set as dependent and m-Compactness as independent or predicator. The results of the analysis are shown below.

Table 6.3: m-Compactness and Work Trip Length

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.053[a]	.003	.002	2.9108459

Table 6.4: ANOVA in Regression

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	30.920	1	30.920	3.649	.056[a]
	Residual	11142.026	1315	8.473		
	Total	11172.946	1316			

Table 6.5: Coefficients in Regression

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.833	.096		50.102	.000
	mcompac	-.061	.032	-.053	-1.910	.056

The summary table 6.3 provides values of R and R_2 for the model. Value of R is 0.053 which is very low and is insignificant (sig > 0.01). The value of R^2 is 0.003 that means weighted distance can account for 0.30% of the variation in work trip lengths. ANOVA table 6.4 shows that F ratio is 3.649 and associated p-value is 0.056 which is greater than 0.01. The Coefficients table 6.5 gives estimates of slope and intercept and a t-test of null hypothesis that they are zero.

Since the p-value, the observed significance of 0.056 is more than 0.01 we accept null hypothesis (H_o). We fail to reject null hypothesis and can not accept alternate hypothesis. There is not enough evidence to prove a relation between work trip lengths and m-Compactness

Compactness for a polycentric city is based on the weighted distance to subcenters. Considering the available surveyed data and having failed to prove relation between m-Compactness and work travel distance, weighted distances were considered in the analysis.

6.3. Weighted Travel Distance and Work Trip Lengths

The hypothesis is that there is a positive correlation between work trip lengths and weighted trip distances.

The null hypothesis (H_o) and alternate hypothesis (H_a) would be:

H_o: There is no relation between work trip lengths and weighted trip distances.

H_a: There is a positive correlation between work related trip lengths and weighted trip distances.

The significance level was set at 0.01. Work trip length was set as dependent and weighted distance as independent or predicator. The results of the analysis are shown below.

Table 6.6: Weighted Travel Distance and Work Trip Length

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.619a	.384	.383	2.7715183
a. Predictors: Weighted Distance				

Table 6.7: ANOVA in Regression

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3652.390	1	3652.390	475.490	.000a
	Residual	5868.524	764	7.681		
	Total	9520.914	765			

Table 6.8: Coefficients in Regression

Model		Un-standardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.516	.311		1.657	.098
	Wt_Dist	1.286	.059	.619	21.806	.000
a. Dependent Variable: Work Trip Length						

The summary table 6.6 provides values of R and R_2 for the model. Value of R is 0.619 which shows that there is a positive relation between weighted distance and work trip length ($p < 0.01$). The value of R_2 is 0.384 that means weighted distance can account for 38.40% of the variation in work trip lengths. ANOVA table 6.7 shows that F ratio is 475.490 and associated p-value is 0.000 which is less than 0.01. The Coefficients table 6.8 gives estimates of slope and intercept and a t-test of null hypothesis that they are zero.

Since the p-value that is observed significance of 0.000 is less than 0.01 we reject null hypothesis (H_o). That means there is very little doubt that a significant amount of the variation in work trip lengths is explained by weighted distance. The dispersion is the product of population and weighted distance and compactness is the inverse of dispersion. Hence it can be inferred that the work trip distance could be explained by compactness index.

6.4. Weighted Travel Distance and Transport Mode

The sampling unit was house. For each analysis unit (grid cell), values of weighted travel distance and majority of transport mode of sampled units within grid cell were considered in the analysis.

The hypothesis is that weighted travel distance has effect on mode of transport. High values of weighted travel distances could be associated with

Private vehicle use that is two wheelers and cars while lower values of weighted travel distances are associated with walking or bicycling.
The null hypothesis (Ho) and alternate hypothesis (Ha) would be:
H_o: There is a no effect of weighted travel distances on transport mode.
H_a: Weighted travel distances have effect on transport mode.

SPSS statistical software and one-way ANOVA analysis were used to test above hypothesis. The assumptions for ANOVA analysis are –
- Populations are normally distributed
- Populations have equal variances
- Samples are randomly and independently drawn.

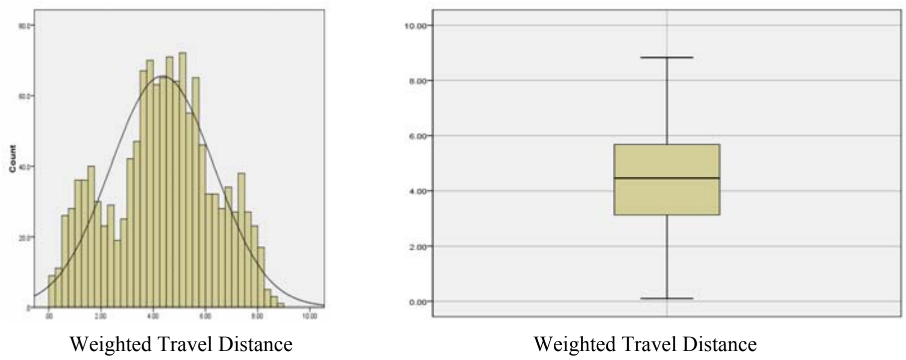


Figure 6.4: Histogram and Boxplot of Weighted Travel Distance

The samples are randomly and independently drawn and visual check oh histogram and boxplot revealed that the populations are normally distributed. Levene's test showed high value of probability (.195 > 0.05) that means the populations have equal variances.

Table 6.9: Codes used for transport modes

Mode Code	Transport Mode
1	Walk / Bicycle
2	Two Wheelers
4	Car
10	Bus and Other

The sampling unit was house. In analysis, values of weighted travel distances for analysis unit (grid cell) and majority of transport mode of sampled units within grid cell were considered. The significance level was set at 0.05. The results of the analysis are shown below.

Table 6.10: Test of Homogeneity of Variances.

Weighted Travel Distance			
Levene Statistic	df1	df2	Sig.
1.569	3	1302	.195

Test of Homogeneity of Variances is Levene's test to test the null hypothesis that the variances of the groups are the same. If test is significant that is the value of sig. is less than 0.05 then the variances are significantly different and that would be violation of one of the assumptions of ANOVA. Luckily, for five groups the variance are similar hence high probability value (.195 > 0.05).

Table 6.11: one-way ANOVA

Weighted Travel Distance					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	167.963	3	55.988	14.592	.000
Within Groups	4995.790	1302	3.837		
Total	5163.753	1305			

There is a significant effect of weighted distance on transport mode, $F(3, 1302) = 14.93$, $p < 0.05$.

However, the ANOVA analysis simply indicates a difference between group means, but it does not reveal difference among groups. In order to find out difference among groups, Tukey test was performed. The Tukey Test is a post hoc test designed to perform a pair wise comparison of the means.

Table 6.12: Multiple Comparisons; Tukey Post-hoc Test

Weighted Travel Distance						
(I) Mode	(J) Mode	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-.71803	.11475	.000	-1.01323	-.42283
	4	-1.06920	.40817	.044	-2.11918	-.01923
	10	-.13990	.19952	.897	-.65315	.37333
2	1	.71803	.11475	.000	.42283	1.01323
	4	-.35117	.40781	.825	-1.40021	.69787
	10	.57812	.19878	.019	.06678	1.08947
4	1	1.06920	.40817	.044	.01923	2.11918
	2	.35117	.40781	.825	-.69787	1.40021
	10	.92930	.43926	.149	-.20064	2.05924
10	1	.13990	.19952	.897	-.37333	.65315
	2	-.57812	.19878	.019	-1.08947	-.06678
	4	-.92930	.43926	.149	-2.05924	.20064
*. The mean difference is significant at the 0.05 level.						

Table 6.12 shows the results of the post hoc Tukey test. Mean weighted travel distance for mode 1 that is walk / bicycle is significantly different than mode 2 that is two wheelers (*sig.* < 0.05) and also significantly different than mode 4 that is car (*sig.* < 0.05). Also, the difference in means of weighted distances of mode 2 that is two wheelers and mode 10 that is bus and other is significant (sig. < 0.05). Table 6.13 below shows mean values of weighted travel distance for different transport modes.

Table 6.13: Multiple Comparisons; Tukey HSD

Mode Code	Transport Mode	Means of Weighted Travel Distance
1	Walk / Bicycle	3.99
2	Two Wheelers	4.70
4	Car	5.06
10	Bus and Other	4.13

Based on the ANOVA and Tukey analysis we reject null hypothesis (H_o). That means the hypothesis that weighted travel distance has effect on mode of transport is accepted. Also, high values of weighted travel distances are associated with Private vehicle use that is two wheelers and cars while lower values of weighted travel distances are associated with walking or bicycling.

6.5. Summar y

In summary the statistical analysis conducted showed no evidence of relation between m-Compactness and travel behaviour that is work trip length and choice of mode. Hypothesis testing for weighted travel distance showed that the work trip lengths could be explained by weighted travel distance. Also, weighted travel distance has effect on mode of transport and high values of weighted travel distances are associated with Private vehicle use that is two wheelers and cars while lower values of weighted travel distances are associated with walking or bicycling.

The limitation of the analysis is that the socio-economic parameters such as household income which are very influential, especially on modal split, were not considered and were not controlled in the analysis.

7. Result Discussion and Conclusion

7.1. Result and Discussion

General objective of the research was to quantify urban form based compactness indicator. Formulation and methodology was mainly based on quantification methodology developed by Zhang and Guindon (2006). Limitations of the previous methods of quantifications were identified and taking in to consideration the modern urban spaces effects of poly-centrism on compactness were studied.

Subcenters within Ahmedabad city were successfully identified adopting the criterion used by Giuliano and Small (1991). Network distances for each residential unit were successfully computed deploying Network Analyst and Spatial Analyst extensions of ArcGIS 9.3 software. Huff probabilistic gravity model was utilized to estimate trip attraction potentials of sub-centers. Weighted travel distances based on trip attraction potential of Sub-centers and their respective distances from residential unit, were computed. Dispersion and compactness index based on weighted travel distance and population were computed and compared for mono-centric and poly-centric urban forms. Statistical analysis was used to examine the causality between work trips and compactness.

7.2. Discussio n

There is not much difference in compactness index values computed using Zhang and Guindon (2006) method for mono-centric urban form and proposed m-Compactness for poly-centric urban form, as was expected. A value of 0.854 was computed based on Zhang and Guindon (2006) methodology whereas methodology developed in this study produced almost same value of 0.873. Both index values imply that the city is comparatively compact. Transport related problems could be attributed to other aspects such as insufficient infrastructure or inefficient transport system and not the sprawl.

Unpredictably, the research failed to establish causal relationship between m-Compactness and travel behaviour that is work trip lengths and modal split. But weighted distance computed was found to be significantly related to work trips and also with choice of mode.

In general compactness index is a measure of urban land use efficiency. An attempt was made to compute compactness values for every residential unit in the study area represented by a grid cell of 100m resolution. The research failed to establish causality between m-Compactness and travel behaviour but new approach and quantification methodology was derived. The methodology developed needs critically evaluation and more research need to be conducted from analytic formulation point of view.

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