Geo-spatial modeling for competition-based accessibility to job locations for the urban poor: case study in Ahmedabad

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February, 2013

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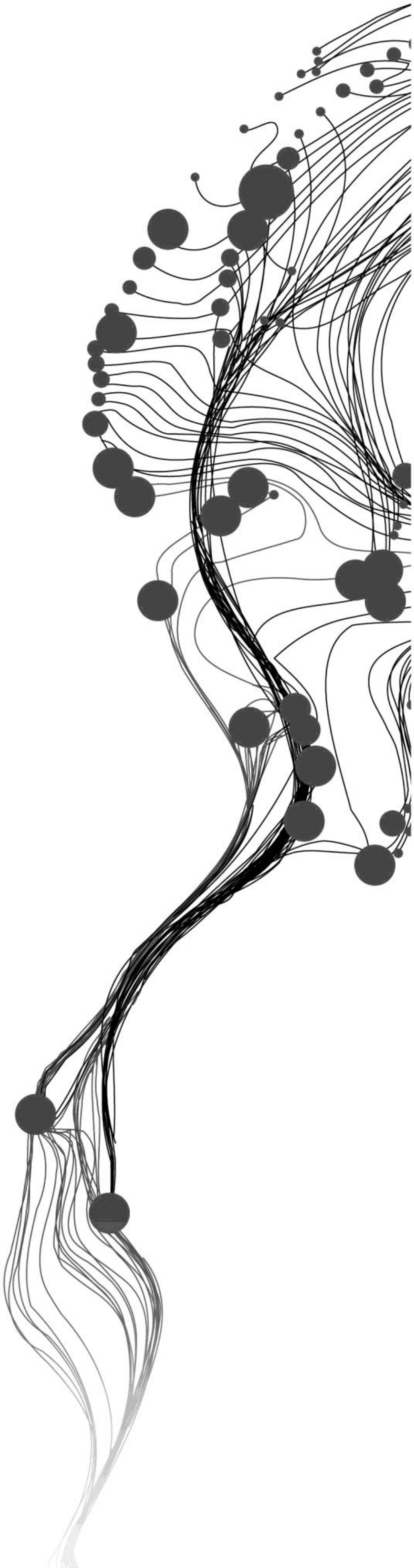

Geo-spatial modeling for competition-based accessibility to job locations for the urban poor: case study in Ahmedabad

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Enschede, The Netherlands, [February, 2013]

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfillment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: [Urban planning and management]

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ABSTRACT

With rapid urbanization, there are more and more socially excluded people living in mega cities around the world. Often, they can't conveniently access some of the essential social activities like jobs, healthcare services and so on because of the inadequate public transport or poorly transport planning. To solve the problem of insufficient transport supply is not too hard but it definitely not easy to make a reasonable planning scheme. Accessibility metrics can help planners to analyze where the socially excluded (in terms of transport) are living in the urban area. As such it is one of most important indicators to quantify the relationship between transport and land use. However, most accessibility measures used in practice ignore some important factors such as the competition for opportunities, the potential of destinations etc. This research provides a specific discussion about the drawbacks of some existing accessibility measures.

Cheng et al. (2012) proposed a competition-based model (i.e. Cheng's model) to measure job accessibility applied to Amsterdam, which considers travel cost, competition, diversity of jobs and a decay function. Based on Cheng's model, this research aimed to implement and adapt this model as an automation tool in the ArcGIS 10.1 environment with Python and apply it for the specific case of accessibility to the urban poor. This is done for Ahmedabad, India using the data from the World Bank project (Zuidgeest et al., 2012). Meanwhile, this research considers the travel fare as an important factor that determines the level of job accessibility of the urban poor. Using the provided 3D road network and Network Analyst tool, the Fare tool is developed and programmed to calculate the monetary expenditure of each route. Finally, this research analyzes and discusses the job accessibility for the urban poor in Ahmedabad with the fare and time decay function respectively.

As a case study, this research evaluates the public transport of Ahmedabad in relation to a housing project named SEWSH using the adapted and GIS-implemented version of Cheng's model. According to Cheng's model, this research finds that providing one more public transport mode can't enhance the job accessibility of all worker locations in Ahmedabad because the accessibility analysis involves the competition factors. One more travel mode such as the AMTS can help people to reach more employment locations comparing to only walking. But the competition also increases at the employment location because of more workers. Therefore, the method for interpreting the result of Cheng's model is proposed by this research. Based on the interpretation method, the results reveal that the AMTS (i.e. ordinary bus) is the most efficient travel mode for the poor people who live in slums/chawl area. In contrast the BRTS (i.e. Bus Rapid Transit) and MRTS (i.e. metro) only marginally contribute in the level of accessibility for these workers, which is not surprising given the difference in the extent of both systems as compared to the AMTS. Once workers live in SEWSH locations, most of their job accessibility increases. The BRTS and MRTS, moreover, further improve the job accessibility for them. In addition, the time decay function has the better effect on the improvement of job accessibility than that of fare decay function for the urban poor.

Key words: Job accessibility, Competition, Fare, Python, 3D road network, Decay function

ACKNOWLEDGEMENTS

First, I want to thank the Faculty of Geo-Information Science and Earth Observation of the University of Twente (ITC) and Chang'an University, because they provide this great opportunity for me to study in the Netherlands. The abroad study and life are my precious wealth, which doesn't only give me the rich knowledge, but also enrich my experience and broaden my horizon.

My sincere appreciations belong to my supervisors Dr. Ir. M.H.P. Zuidgeest and Dr. S. Amer. There is no doubt that I can't finish my thesis successfully without their help. Their regular feedbacks and meetings don't only give me the academic suggestions, but also have the encouragement for me. I have gained lots of useful knowledge from their patient and professional guidance.

I would like thanks to Ing. F.H.M.(Frans) van den Bosch, Talat Munsh, PhD Zhou Liang and Xiong Biao very much. Frans provided to me the useful data, including the 3D multi-modal road network and other relevant data. Without these data, it is impossible to finish my research. Talat Munsh gave me some introductions about the Ahmedabad. The local knowledge is very useful for my research. Zhou Liang and Xiong Biao helped me to figure out the programming ideas. They open my mind about how to design the programming process.

To all my friends in ITC, I thank to you because it is happy to study with you. You don't only encourage me, but also give me lots of helps when I'm in trouble. I can't forget the period of time studying and living with you in ITC.

My special thanks are for my parents and grandparents. You support me all the same time. Moreover, you give me the trust, encouragement, spirit and material support, with which I can do anything confidently. If the thesis were an award, half of its honour belongs to you. Without you, I can't go abroad and can't finish my MSc study in the Netherlands. My love belongs to you forever.

Chao Zhen
February, 2013

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LIST OF ACRONYMS

AMTS	Ahmedabad Municipal Transport Service
BRTS	Bus Rapid Transit System
MRTS	Mass Rapid Transit System
SEWSH	Socially and Economically Weaker Section Housing
ITC	Faculty of Geo-Information Science and Earth Observation in Twente University
AMC	Ahmedabad Municipal Corporation
CEPT	Centre for Environment Planning and Technology University
AUDA	Ahmedabad Urban Development Authority

1. INTRODUCTION

1.1. Background

During the recent decades, mega cities have come up around the world due to the fast growing urban population. This rapid urbanization has led to social exclusion in many developing countries. The socially excluded people "are not just poor, but that have additionally lost the ability to both literally and metaphorically connect with many of the jobs, services, and facilities that they need to participate fully in society"(Church et al., 2000, pg.197). Actually, the inadequate transport infrastructure mainly causes the social exclusion because it reduces the convenience of access to public transport for the urban poor (Wati, 2009), for whom a private motorized mode is too expensive. Moreover, the public transport alternatives are not planned for well enough.

Transport planning plays an important role in mitigating social exclusion in many cities. However, traditional transport planning has an evident shortcoming as well. It only focuses on the efficiency of the road network, while it ignores the interaction among people (e.g. competition among workers and employers etc) and infrastructure (e.g. road network, transport hubs etc). This biased planning idea, therefore, produces outcomes that don't fit the aim of reaching a sustainable urban transport development. Examples include the construction of a metro line for enhancing the accessibility of poor people, while they can't use it because of affordability problems, which is not considered or underestimated during the planning phase. So integration of social-economic interaction with traditional transport methods can help people to understand and plan transport systems better.

Low income people are living in the marginalized areas of cities such as Ahmedabad, India, and experience high levels of social exclusion. The main reason is that they don't have a good education background or working skills, which forces them to just get the low payment jobs. Moreover, the commuting expense of overcrowded public transport grows quickly due to the insufficient supply and increasingly high demand. This is a critical social problem. If too many people can't find a job for living, the society would be unstable happening conflicts.

In order to help excluded poor people, many cities in India, like Ahmedabad, have started improving the urban transport system to make the city more equitable and efficient. Meanwhile, the government tries to integrate urban development and transport planning together in order to get better outcome. For example, the government gives some priority policies for the urban poor to use the new constructed metro, bus rapid transit and some other basic infrastructure. At the same time, several slum improvement programs are being implemented such as the Basic Service to Urban Poor (BSUP) or Socially and Economically Weaker Section Housing (SEWSH) program. These projects aim at preventing the poor people to be excluded from the activities, which are the bases to improve their quality of life (Lucas, 2004).

1.2. Justification

Accessibility, which deal with measuring the convenience of people moving from one place to the other place, could help planners to make a useful framework for the integration of transport and land use planning (Bertolini et al., 2005). As Gutiérrez (2009) wrote, accessibility analysis enables one to identify which areas are poorly covered or good served by the urban facilities. However, the existing accessibility model is not good as the competition-based model proposed by (Cheng et al., 2012). (In the following parts, Cheng's model is the accessibility model from (Cheng et al., 2012)). That is because Cheng's model explicitly considers more factors, which are potential destinations, the diversity factors and the interaction among people (i.e. the competition on demand and supply side) comparing to other accessibility measures. The detailed comparison between Cheng's model and other commonly used accessibility measures is explained in the Chapter 2. Then, we can see that Cheng's model is more realistic due to involving several important factors, while the author didn't provide a specific explanation about how to interpret the results. Therefore, this research explores how Cheng's model can be used and improved in the context of studying accessibility for the urban poor in Ahmedabad. Meanwhile, the algorithms of Cheng's model are implemented in ArcGIS as a specialized tool. By this tool, it is easy to run various scenarios and use these results to find a reasonable interpretation method, which can help planners to formulate schemes enhancing accessibility for the urban poor.

1.3. Research problems

Ahmedabad is an upcoming mega city in India, where 25% of total population live in slums (Ahmedabad Municipal Corporation et al., 2006). The city experiences quite a few problems caused by the poor transport planning and management, in particular lack of infrastructure for pedestrians and cyclists as well as congested traffic due to traffic behaviour and capacity problems of its roads. Moreover, the large amount of poor people having a low income constrains them to access jobs because of the affordability problems for public transport. Obviously, social exclusion, which is caused by the insufficient public transport supply, doesn't only reduce the number of job opportunities for the urban poor, but also heavily limits Ahmedabad development.

To mitigate the high rate of social exclusion in the city, the local government planned to construct a Metro system linking the current Ahmedabad Municipal Transport Service (AMTS) and the Bus Rapid Transit System (BRTS). These programs are expected to impact on the travel behaviour of all people who live in the city, including the urban poor. So the key question is how to adopt accessibility metrics to measure the effect of these infrastructure projects on the ability of the urban poor to reach jobs and propose solutions for the urban poor to get more benefits from these infrastructure projects.

In order to measure the improvement of job accessibility for the urban poor produced by these projects, this research adapts Cheng's model for Ahmedabad. However, as the pervious part mentioned, Cheng's model may not be completely suitable for the case of Ahmedabad because this mode before was used to measure accessibility of workers in Amsterdam where has the different social-economic background compare to Ahmedabad. Therefore, Cheng' mode needs to be adapted. Then, Cheng's model is complemented with the inclusion of generalized cost (i.e. fare and travel time impedances) as the urban poor are expected to value fares very much because of their relatively low income. Finally, we interpret the results to guide policy making for sustainable transport planning.

1.4. Objectives

1. General objectives

1) To adapt and implement the accessibility model proposed by (Cheng et al., 2012) for the study of job accessibility of the urban poor in Ahmedabad.

2. Sub-objectives

1) Assess Cheng's accessibility model for its possible use in Ahmedabad
2) Adapt and improve Cheng's accessibility model for the urban poor in Ahmedabad.
3) Implement Cheng's accessibility model in the ArcGIS environment.
4) Investigate the implications of Cheng's accessibility model for the urban poor.

1.5. Research questions

These research questions related to the four sub-objectives are:

Sub-objective (1): assess Cheng's accessibility model for its possible use in Ahmedabad

1) How does Cheng's accessibility models work and compare to other such models?
2) What are the innovative points of Cheng's accessibility model?
3) What are the shortcomings of Cheng's accessibility models?

Sub-objective (2): adapt and improve Cheng's accessibility model for the urban poor in Ahmedabad.

4) How does the model involve the generalized cost (i.e. the fare and travel time impedance)?
5) What's the relationship between different types of urban poor and different jobs?
6) What are the related parameters of adapted Cheng's model?

Sub-objective (3): implement Cheng's accessibility model in the ArcGIS environment.

7) What are the key functions in ArcGIS to implement this model?
8) What are the limitations of ArcGIS to implement this model?
9) Which approach can solve these limitations?
10) What is the sequence of implementation?

Sub-objective (4): investigate the implications of Cheng's accessibility model for the urban poor.

11) How does the result evaluate the effect of infrastructure projects for the urban poor in Ahmedabad?
12) Which class of urban poor could have the lowest accessibility to job locations?
13) Which type of transport project is the most useful and convenient for the urban poor?
14) Which combination of travel modes is the most efficient way to increase the job accessibility for the urban poor in Ahmedabad?

1.6. Conceptual framework

The conceptual framework involves three parts, and concern the demand part (i.e. workers/the urban poor), the supply part (i.e. employers) and the physical infrastructure (i.e. public transport). These factors affect on job accessibility of the urban poor.

All of the factors are influenced by the urban form. As Lynch (1981) defined, urban form is the spatial arrangement of human activities, which produces spatial flows of persons, goods as well as information. Meanwhile, these social activities change the public facilities and people's decisions, which shape and modify the urban form. It means the spatial locations of the demand, supply and physical infrastructure are somehow determined by the urban form and there is also mutual influence between each other. Due to the different spatial distribution of demand and supply, people have to use the physical infrastructure to overcome the friction of distance. So transport mainly impacts on accessibility, which is the most important link between the demand and supply side.

Specifically, in this research, the characteristics of demand and supply are determined by the interaction of people (i.e. the competition factors) and the competition is influenced by the living environment, the character of jobs, the number of workers and jobs. For example, some people are willing to go further looking for a job because of the low competition and high salary etc. Then, their behaviours alter the intensity of competition of a certain job market. Obviously, these characteristics of demand and supply consist of the social-economic interaction, which should be one of the key elements of accessibility.

In terms of physical infrastructure, the fare, frequency, speed, categories and transfer of public transport are significant attributes for job accessibility of the urban poor. And these factors react the efficiency of the public transport and how difficult to access to this system.

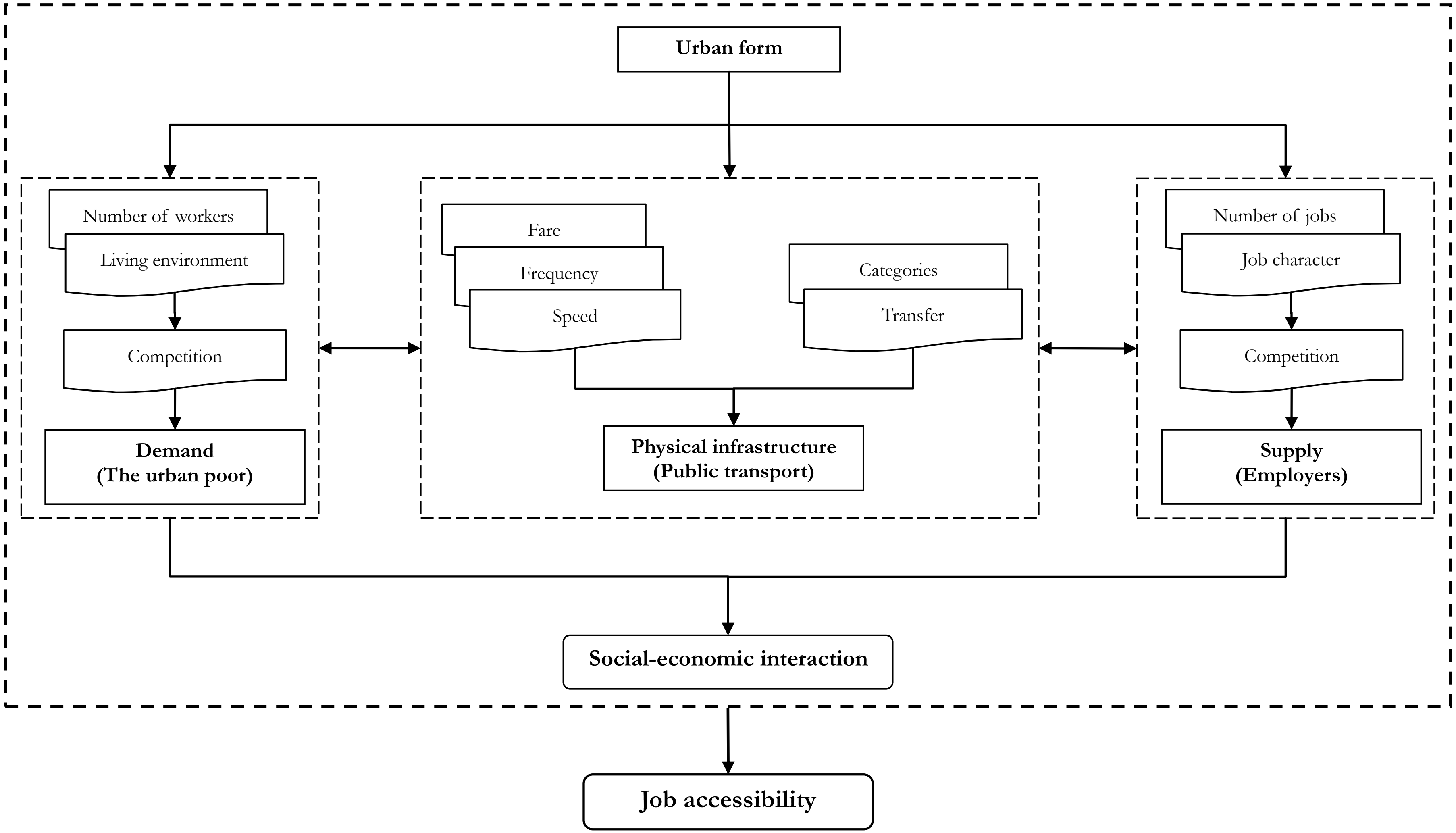


Figure 1 Conceptual framework

1.7. Research design

1.7.1. Research data

The data has been obtained from a World Bank project executed by ITC and CEPT University in Ahmedabad (Zuidgeest et al., 2012). Data used in this research is therefore limited to those data collected in that project. The focus is on the evaluation, implementation and interpretation of Cheng's model.

1.7.2. Research methods

1. Modelling accessibility and its components

The method is to adapt the main components of Cheng's model for Ahmedabad. The most important components of Cheng's model are travel cost, diversity factor, decay function and competition factors. For travel cost, the time impedance can be gotten from Network Analyst from ArcGIS 10.1 based on the 3D road network, while the fare requires the combination of related functions of ArcGIS to calculate, which is explained specifically in section 4.2. Moreover, Cheng's model doesn't consider the fare as a factor to influence accessibility but this research incorporates the fare into accessibility analysis. Then, the diversity function, decay function and competition factors are directly used from Cheng's model. But the beta parameter of decay function is calibrated by the related reports or literature about the travel behaviour of the urban poor in Ahmedabad.

2. Implementation method

1) Geoprocessing tools

ArcGIS has a package of powerful geoprocessing tools, which has hundreds of functions to deal with geographic data analysis. These functions can help researchers to know the spatial characters of urban development. Moreover, the Network Analyst function is the key method to know the efficiency of transport infrastructure. So this research adopts these tools to implement Cheng's mode in ArcGIS.

2) Python scripting

Even though it is feasible to work out the accessibility of Cheng's model by these geoprocessing tools, the computing processes are complicated and the speed is slow because of the ways of data storage structure and data reading by geoprocessing tools. In contrast, Python provides a good data management and calculation environment. And ArcGIS provides a module for Python scripting named Arcpy, which can combine geoprocessing tools with Python. So this research adopts Python to execute the core calculations and encapsulate related geoprocessing functions as a specialized tool for Cheng's model. And this specialized tool implements the algorithms of Cheng's model in the ArcGIS environment.

3. Interpretation method

This method includes statistical analysis and visualization methods to evaluate job accessibility, transport projects in Ahmedabad. And it is a way to explore how to use this accessibility model in urban planning.

1.8. Research matrix

<table>
<tr><th colspan="2">Data requirement</th><th>Model methods</th><th>Answered questions</th><th>Implementation methods</th><th>Answered questions</th><th>Interpretation method</th><th>Answered questions</th></tr>
<tr><td rowspan="3">Urban poor</td><td>Slum level</td><td rowspan="6">The decay function
Competition formulas</td><td rowspan="6">Questions 1), 2), 3), 4), 5), 6)</td><td rowspan="10">Geoprocessing tools
Python script</td><td rowspan="10">Questions 4),7), 8), 9), 10)</td><td rowspan="10">Statistical methods
Visualized methods</td><td rowspan="10">11), 12), 13, 14)</td></tr>
<tr><td>Spatial location</td></tr>
<tr><td>The number of workers</td></tr>
<tr><td rowspan="3">Jobs</td><td>Job types</td></tr>
<tr><td>Spatial location</td></tr>
<tr><td>The number of jobs</td></tr>
<tr><td rowspan="4">Public transport network dataset</td><td>Fare</td><td rowspan="4">3D multi-modal road network dataset</td><td rowspan="4">Questions 4), 7), 8), 10)</td></tr>
<tr><td>Speed</td></tr>
<tr><td>Transfer</td></tr>
<tr><td>Frequency</td></tr>
</table>

Table 1 Research matrix

1.9. Research phases

In order to achieve the research objectives, there are four major phases to be done.

1) The first phase is to assess the popular accessibility models, have an overview of the data and Ahmedabad. The strengths and weaknesses of Cheng's model can be found after the evaluation of other relevant accessibility models. The overview of data and Ahmedabad is the preparation for adapting Cheng's model.
2) The second phase aims at making Cheng's model fit for Ahmedabad. Specifically, the major components of Cheng's model (i.e. the diversity factor, the definition of the decay and competition function) are adapted for Ahmedabad. And the parameters of the decay and competition function are calibrated according to the context of Ahmedabad.
3) In the third phase, the algorithms of Cheng's model are implemented as a specialized tool in ArcGIS, which combines the geoprocessing functions with Python.
4) The fourth phase runs the accessibility tool developed by this research to analyze the job accessibility of the urban poor in Ahmedabad based on different research scenarios. And then the interpretation method is discussed and formulated to evaluate the transport and housing projects in Ahmedabad. Meanwhile, this research concludes how to use Cheng's model in urban planning.

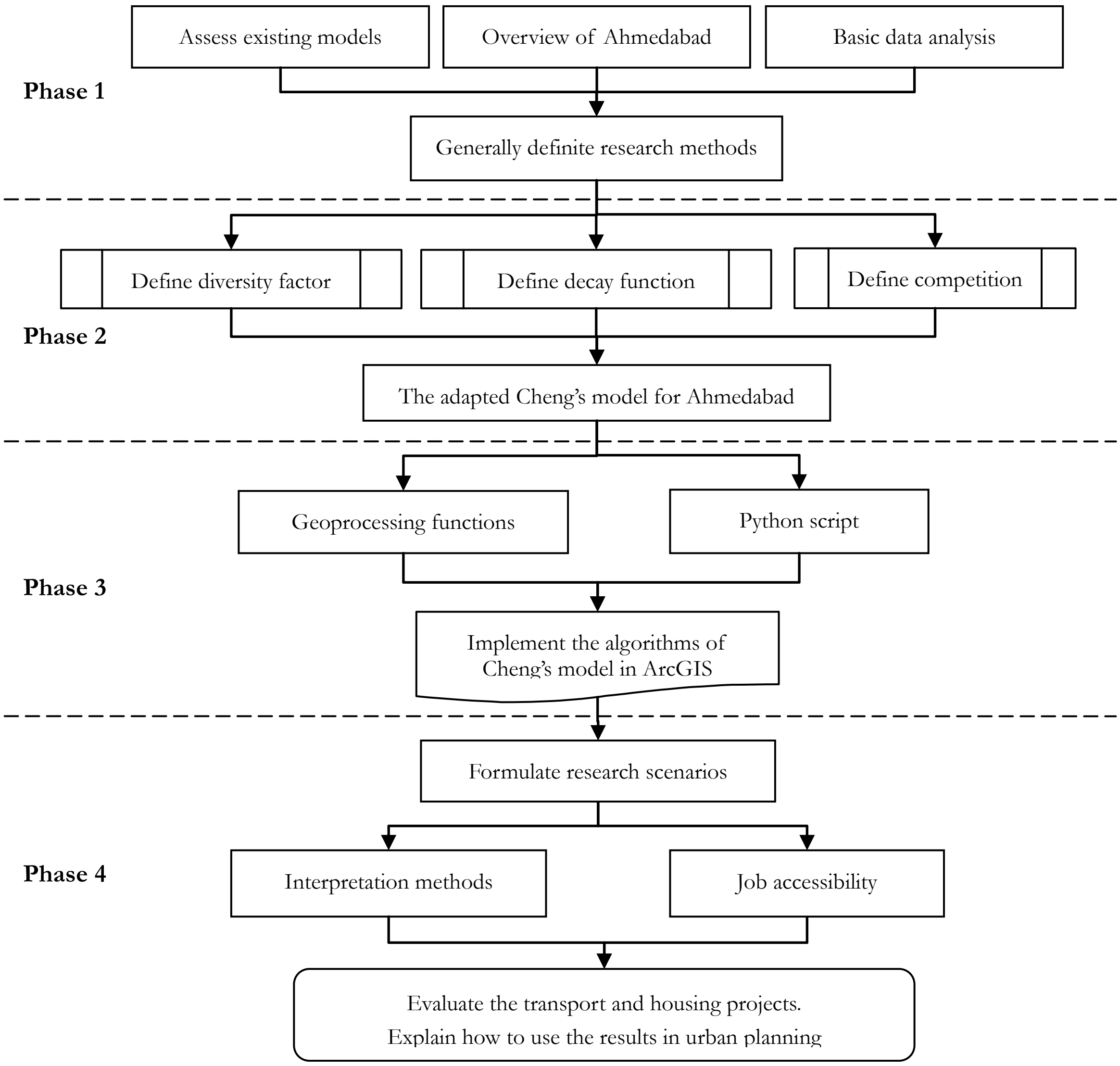


Figure 2 Research phases

1.10. Structure of thesis

This thesis includes six chapters. Below is a brief description of each chapter.

Chapter One: Introduction

This introductory chapter shows the background, research problems, objectives with the corresponding questions and research design etc.

Chapter Two: Review of related accessibility measures

Description of existing accessibility models and concepts, which are relevant for this thesis, are discussed. And there will be some specific arguments on the strength and weakness of these models.

Chapter Three: Study area and data

In this chapter, it provides the insight into the study area according to literature and includes a general description about the data used in this research.

Chapter Four: Implementation of Cheng's accessibility model in ArcGIS

This chapter specifies how to implement Cheng's model in ArcGIS. It displays how to use Python building Cheng's model in ArcGIS as an automation tool.

Chapter Five: Accessibility analysis and results

The contents of this chapter are about how to make Cheng's model adapt for the study area. Then, the result of job accessibility in Ahmedabad is discussed based on different research scenarios. And the interpretation method is formulated to evaluate the public transport and housing projects in Ahmedabad.

Chapter Six: Conclusions and Recommendations

This chapter provides some suggestions on how to use Cheng's accessibility model in urban planning. And according to the limitations of this research, there are also some recommendations for the further study.

2. REVIEW OF RELATED ACCESSIBILITY MEASURES

This chapter has five sections. The first section provides a basic description of the accessibility concept, which includes the definition, importance and components of accessibility. Second, Cheng's model is explained, especially for the competition factors. Third, it reviews and evaluates some related accessibility measures, including the primary measures and the competition-based measures. Fourth, the comparison between Cheng's model and other accessibility measures is provided. The fifth section discusses about the common problems of accessibility analysis.

2.1. Basic description of accessibility

2.1.1. Definition of accessibility

In a scientific forum, Hansen (1959) defined accessibility as "the potential of opportunities for interaction". From then on, there had been many different definitions about accessibility. Accessibility is "a property of individuals and space which is independent of actual trip making and which measures the potential or opportunity to travel to selected activities" (Morris et al., 1979, pg.92). And Geurs and van Wee (2004, pg.128) consider accessibility as "the extent to which the land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)." Accessibility can also be described as "the opportunities available to individuals and companies to reach those places in which they carry out their activities" (Gutiérrez, 2009, pg.410). Actually, these definitions are based on their researches but the core ideas are the same, which is to analyze the ease of access to activities. For this research, accessibility means the urban poor by public transport can get how many jobs when there is competition on the employer side and worker side.

Although the above definitions of accessibility don't include keywords like social and economic, absolutely, accessibility can't separate from these three words. The main parts of accessibility like travelling, opportunity or activity are strongly related to social-economic factors. For example, if researchers neglect the social-economic factors in job accessibility analysis, the results could be biased. In some residential locations, people can reach many job locations within a very short travel time, which means their accessibility is very high. Actually, the real job accessibility is quite low because of the high intensity of competition. So we should not only analyze the efficiency of infrastructure system (i.e. road network & public transport) in accessibility analysis. But unfortunately, Moseley (1978) found most of accessibility analysis paid more attention to physical analysis such as the spatial patterns, efficiency of public transport rather than social-economic factors.

2.1.2. Importance of accessibility

This research agrees that "accessibility is an important spatial characteristic and an significant link between transportation and land-use"(Hansen, 2009, pg.385). The mutual affect between land-use and transport infrastructure is via accessibility. Specifically, land-use pattern determines the locations of activities and residents. And the travel impedance (e.g. travel time/distance) depends on the efficiency of the transport system. The government or transport department, therefore, often improves the certain links of road network in order to increase the accessibility of some residential area. But after making transport better for some sites, residents are likely to sell the lands to businessmen for other different activities due to the high accessibility.

Accessibility, which is strongly related to social and economic factors, is a powerful tool or framework in urban planning (Gutiérrez, 2009; Straatemeier, 2008). Thus it helps planners to know the urban status quo and plan the future development well. For instance, in case of inequitable distribution like healthcare, planners have used different accessibility models to understand the reasons of inequity and optimize the healthcare source to achieve equity (Higgs, 2004). With regard to the economic aspect, land with high accessibility is more worthy such as the land in the urban centre.

2.1.3. Components of accessibility

Depending on the different definitions of accessibility, researchers proposed various accessibility models, while this research studies the model inclusion of the following three basic components, which are origins, destinations (as in opportunity locations) and transport (as in travel impedance).

1) Origins are often residential areas, mostly represented as point locations or zonal polygons. The number of origins in study area is influenced by the analysis scale a lot. If we want to calculate the accessibility at the level of individual, a point represents one person. And when the analysis scale is bigger not the level of individual, researchers often aggregate some places as one point like every street block being an origin. So the accessibility of every person requires more origins than the aggregated level of analysis.
2) Destinations, in which people carry out activities, can be different facilities (e.g. healthcare, job location, school etc), also represented as point locations. The other specification is the same as that of origin.
3) The transport refers to the generalized travel cost of different types of travel modes like car, metro, bicycle etc. Hence, the simulation of the road network is the key part for measuring accessibility. However, sometimes researchers don't use road network to get travel cost, while they adopt a Euclidean distance as the cost, although the straight distance is not close to reality. The Euclidean distance is simpler and more efficient for calculation compare to road network. And the straight lines are often used when the study area doesn't have developed road network or it is flat area. For building road network, there are two common approaches, which are vector-based and raster-based network. For vector method, it is hard to simulate walking because people don't only follow the road network to walk. By contrast, the raster-based approach can create spatially continuous accessibility surfaces (Hansen, 2009), which easily handles the walking simulation and deals with the road network without complete data (Ahlstrom et al., 2011).

2.2. Cheng's competition-based accessibility model

Actually, this research adopts the competition-based accessibility model from (Cheng et al., 2012) (i.e. Cheng's model). The detailed formulas are shown as follow:

$$D_j = -\frac{\sum_l Q_{lj} \times ln(Q_{lj})}{\ln(n)}, \quad Q_{lj} = \frac{E_{lj}}{E_j} \tag{1}$$

$$f(t_{kj}) = e^{-\beta \times t_{kj}} \tag{2}$$

$$P_{jk} = \frac{E_j{}^{D_j} \times f(t_{kj})}{\sum_s E_s{}^{D_s} \times f(t_{ks})} \tag{3}$$

$$Q_i = \frac{\sum_j E_j \times P_{ji} \times W_i \times f(t_{ij})}{\sum_k P_{jk} \times W_k \times f(t_{kj})} \tag{4}$$

Eq. (1) is to define the diversity of jobs at location j, which is derived from the entropy, E_{lj} is the number of l type jobs and E_{lj} is the total number of jobs at location j, n is the number of job types.

Eq. (2) is a negative exponential function for distance decay. t_{kj} is the travel time from residential location k to employment location j. β is a calibration parameter.
Eq. (3) represents the competition of employers for workers between location j and s. E_j is the total number of jobs at location j. E_s is the total number of jobs of all job locations. D_j and D_s are the diversity of jobs in location j and s respectively.
Eq. (4) is the final job opportunity Q_i allocated to residential location i. W_i and W_k are the number of workers at location i and k respectively, competing for jobs at location i.

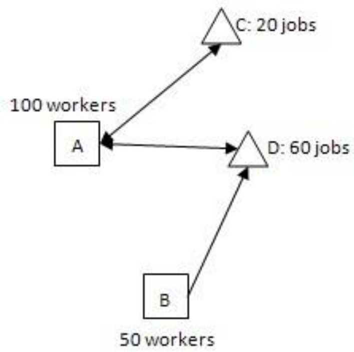


Figure 3 Example of Cheng's model

The basic components of Cheng's model are still the origins, destinations and transport but this model mainly defines the interaction among origins and destinations (i.e. two-side competition). According to the Oxford Dictionary, the word "competition" has two explanations. One is "a situation in which people or organizations compete with each other for something that not everyone can have." The other is "an event in which people competes with each other to find out who is the best at something." The competition factors of Cheng's model match the two definitions. Figure 3 is to explain the concrete calculations of two-side competition (i.e. Eq. (3) and (4)), which doesn't consider the diversity of jobs and decay function of Cheng's model in order to show the major calculations clearly. In Figure 3, the arrow direction is competition direction. Location B is so far away from job location C that no one from B finds a job in C. Then, the competition for worker location A between employers of C and D are 20/80=1/4 and 60/80=3/4 respectively. This calculation fits the second definition of competition in Oxford Dictionary (i.e. "an event in which people competes with each other to find out who is the best at something."). That is to compare which job location is better or more attractive. So the competition among employers can also be regarded as the attractiveness of a job location. For the competition among workers, the calculation follows the first definition of competition (i.e. "a situation in which people or organizations compete with each other for something that not everyone can have."). The competition among workers of A and B for jobs D is 60/(100 x 3/4+50) = 0.48. In other word, when workers from A or B look for jobs in D, everyone can get 0.48 jobs from statistical view. And 75 people from A will go to D for jobs because 100 x 3/4 =75 (i.e. the number of people from A multiplies the competition factors among employers). Likewise, 25 people from A will go to C and 50 people from B go to D. Finally, the accessibility of A is 0.48 x 75 +20 =56 and the result of B is 0.48 x 50 =24. It means that workers of A and B can get 56 and 24 jobs respectively. The job accessibility of A is higher than the accessibility of B.

2.3. Overview of commonly used accessibility measures

In order to compare Cheng's model to other accessibility models, the following sections review of some popular accessibility measures, which are related to Cheng's model.

2.3.1. Infrastructure-based measure

This method focuses on the efficiency of the road network, in which the locations of origins and destinations are required but other characteristics from origins and destinations are ignored. This measure requires data about physical infrastructure like the bus lines, cycling lanes and waiting time for public transport etc. With this kind of data, this method can, for example, reflect the congestion level and help researchers to find the most efficient transport corridor. So the infrastructure-based measure is easy to calculate and interpret. Yet, it lacks of the social-economic factors involved.

2.3.2. Cumulative measure

The contour or isochrones measure (Geurs & van Wee, 2004) (also called threshold measure) is frequently used in urban planning. The first step of this measure is to count the total number of reachable destinations in a certain travel distance or time from an origin by the possible transport modes (Lovett et al., 2002). Then, the total number of opportunities from every reachable destination for one origin is calculated. Here the origins and destinations are more important, especially the number of opportunities from destinations. For example, residents from A can reach 2 healthcare units via the fastest travel mode in 15 minutes and each healthcare unit has 3 practitioners, while people living in B can reach one healthcare unit by the same mode in 15 minutes and this healthcare unit has 7 practitioners. Consequently, residents of A and B can get 6 and 7 practitioners in 15 minutes respectively. We can say the accessibility of B to healthcare is higher than that of A in 15 minutes. In terms of transport component of this measure, the road network is not necessary because researchers can use Euclidean distance to represent the travel impedance.

This paragraph discusses about the strengths and weaknesses of cumulative measure. The strength of the cumulative measure is easy to calculate and interpret because it only counts the number of opportunities available for every origin. Moreover, the cumulative measure considers the character of destinations (i.e. the number of opportunities) comparing to the infrastructure-based measure. And the visualization is intuitive and meaningful. One of the major problems for cumulative measure is to give every destination equal weight in a certain travel distance or time threshold and it doesn't consider the opportunities outside of this threshold. Like the example of above paragraph, if there is another healthcare unit with 2 doctors away from A 16 minutes, which is a little more than defined time threshold (i.e. 15 minutes). In reality, people of A could get service from this 16-minute healthcare. Therefore, it is not exact that the accessibility of B to healthcare is higher than that of A.

2.3.3. Potential measure

The potential accessibility measure assigns the different weight for each destination depending on a distance decay function, which means the accessibility level of one origin is inversely proportional to the distance away from destinations. Obviously, the origins and destinations are also important. Like the cumulative measure, the number of opportunities of each destination is key factor to influence the final accessibility. For the transport part, it can be road network or Euclidean distance. And the common formula is demonstrated below:

$$A_i = \sum_{j=1}^{n} D_j f(c_{ij}) \qquad (5)$$

$$f(c_{ij}) = e^{-\beta c_{ij}} \qquad (6)$$

Where A_i is the accessibility of origin i, D_j is the total number of facilities or opportunities at location j, $f(c_{ij})$ is the general decay form and it can be power function, combination of power function with negative exponential function and so on, Although the decay function has many forms, most of researchers has chosen the negative exponential function because it is closer to people's travel behaviour (Handy & Niemeier, 1997). So the most common used decay function is $e^{-\beta c_{ij}}$, β is a calibration parameter, c_{ij} is the travel impedance (e.g. travel distance or time) from i to j.

In terms of the advantages and disadvantages of the potential measure, one of this method's advantages is to consider the opportunities of all destinations. The travel time can't limit the reachable destinations but the time can discount the opportunities from the destination. Another advantage is easy to calculate and interpret because it is to measure the probability of available opportunities from each destination for every origin. And the visualization is very simple. For the disadvantage, it is not easy to define the decay function because everyone has the different travel behaviours. Even though the negative exponential function is often used, sometimes the beta parameter is not meaningful in the function. For example, the travel time 30 minutes is equal to 0.5 hour, while it is evident that $e^{-\beta \cdot 30} \neq e^{-\beta \cdot 0.5}$. This example also proves that this kind of distance decay function is very sensitive to the unit of travel time.

2.3.4. Competition-based measure

Besides above primary measures, some researchers tried to incorporate the competition factor into accessibility model (for example, (Joseph & Bantock, 1982; Joseph & Philips, 1984; Weibull, 1976; Wilson, 1971)). Generally speaking, there are two categories of competition-based measures. One is constituted by a competition factor and decay function like Two-step Floating Catchment Area. This category always involves one side of competition. The other kind of competition-based measure is Singly/Doubly Constrained Gravity Model, which can simulate one or two sides of competition. Both of measures mainly study how the intensity of competition influences the accessibility. Comparing to primary measures, the competition-based measure is more realistic. However, it is not easy to interpret the results due to the competition factor involved. The following sections illustrate two most popular competition-based measures, which are (Two-step) Floating Catchment Area and Singly/Doubly Constrained Gravity Model.

1) Two -step Floating Catchment Area

The original version of this measure was to calculate the job to housing ratio (i.e. service or opportunities) (Peng, 1997), which can be considered as the intensity of competition on the demand side (i.e. the number of facilities or opportunities available for everyone). The centroid of the Floating Catchment Area (FCA) is the demand location (i.e. origin). And the FCA overcomes the drawback of fixed analysis zones, which is in other accessibility measures. Specifically, without FCA, researchers divide the study area into several zones, which are often partitioned by administrative boundaries or traffic analysis zones. This zoning method is criticized neglecting the cross boundary issue. For example, although people (i.e. demand) don't only look for a job (i.e. supply) in the analyzed area (e.g. traffic analysis zone or administrative district), researchers assume that people can only get the employment opportunities in one fixed zone. Obviously, they could go outside of the analyzed zone finding jobs. Thus, the FCA provides different catchment areas for every demand location depending on its character to solve the cross boundary problem. The results of FCA are opportunities to people ratios, which mean how many opportunities are gotten by everybody in the catchment area. Consequently, this model only takes account into competition on the demand side.

Following the FCA method, Radke and Mu (2000) proposed Two-step Floating Catchment Area (2SFCA), which was explained how to implement in ArcGIS by (Wang & Luo, 2005). There are two steps for calculation in the 2SFCA, which is to do the floating catchment area twice with a different centroid. The first computing centroid is supply location (i.e. destination). And then the demand side (i.e. origin) is chosen as the centre. Comparing to FCA, the 2SFCA considers the character of the supply side because it makes the supply as the centroid of catchment area to analyze the accessibility. Consequently, the two catchment areas can be different size. For example, physicians (i.e. supply) can go to further than the served people (i.e. demand). The catchment area, which the physician location is the centroid, is bigger than the other catchment area, which chooses the served people as the centroid. The result of first catchment area is the competition on the demand side (i.e. the number of physicians available for every person in this catchment area), while the second step result is not the competition on the supply side, which is only the sum of results from the first step in the second catchment area and doesn't make any comparison among different supply locations. So there is no competition on the supply side in 2SFCA. Due to this reason, researchers

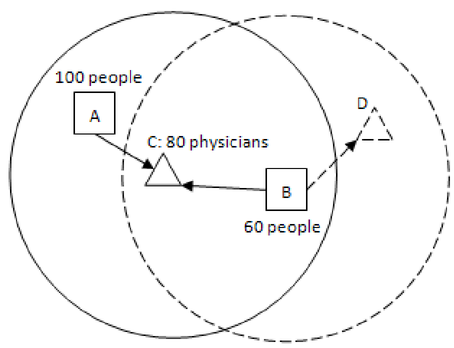


Figure 4 Example of 2SFCA

frequently use the 2SFCA to measure the accessibility to healthcare. Obviously, they assume that there is competition among people but no competition among the healthcares.

Figure 4 is an example of healthcare accessibility analysis by the 2FSCA. The location C has 80 physicians. In a certain travel time, 100 people from A and 80 people from B can reach location C to get the healthcare service. The ratio of physician to people at location C is 80/(100+60)=0.5 based on the algorithm of 2FSCA. It means every one can get 0.5 physicians in this catchment area from mathematical view. And this calculation fits the first definition from Oxford Dictionary (i.e. "a situation in which people or organizations compete with each other for something that not everyone can have."). Subsequently, using the same method calculates a ratio for location D, which is assumed to be 0.8. Finally, the residential location B is chosen as the centroid of the dashed catchment area within a threshold of travel time. So the accessibility of B is 1.3 (i.e. 0.5+0.8). This result is the average number of physicians available for everybody from location B.

This method also has some strengths and weaknesses. As the previous paragraphs mentioned, the strength of the 2SFCA is to involve one-side competition and overcome the cross boundary problem. Moreover, the result is easy to interpret, which reflects the number of opportunities available for every person. In terms of the weaknesses, the original 2SFCA has two limitations. First, the results are very sensitive to the size of catchment area because it assumes that people only can reach some facilities or get opportunities in the catchment area. Second, it is lack of competition on the supply side. The first limitation can be solved by a predefined the threshold or studying people's travel behaviour. For example, Luo and Whippo (2012) proposed a method to define a base value for population to get the reasonable catchment size. However, no one gave a method to add competition on the supply side.

2) Singly/Doubly Constrained Gravity Model

This measure, which is derived from Newton's law of gravitation, considers the characters of two sides (i.e. the number of people and opportunities from origins and destinations respectively). The origins and destinations are very important in the gravity measure and the travel cost is like potential measure, which can be Euclidean distance or the result from road network analysis. The formulas are shown below:

$$\mathrm{T}_{ij} = \mathrm{a}_i \mathrm{b}_j \mathrm{O}_i^{\alpha_i} \mathrm{D}_j^{\beta_j} f(c_{ij}) \tag{7}$$

$$\mathrm{a_i} = \left[\sum_{j=1}^{n} \mathrm{b_j D_j f(c_{ij})}\right]^{-1} \tag{8}$$

$$\mathrm{b_j} = \left[\sum_{i=1}^{m} \mathrm{a_i O_i f(c_{ij})}\right]^{-1} \tag{9}$$

Where T_{ij} is the travel flow from i to j, O_i is the number of activities at location i (e.g. the number of people) and it reflects the willingness or desire to go somewhere, D_j is the attractiveness of location j and it is often the number of activities or opportunities (e.g. the number of shops or jobs), α_i and β_j are the calibration parameters. In many versions of gravity model, we assume $\alpha_i = \beta_j = 1$ (Giuseppe Bruno & Improta, 2008). The travel impedance between i and j is c_{ij}.

The formulas are the Doubly Constrained Gravity Model, while the Singly Constrained Gravity Model needs to remove a_i or b_j depending on the modelling requirements. Some researchers thought this kind of gravity model fit for measuring accessibility (for example, Fotheringham (1986), Horner (2004)). When the number of people of each origin and the number of opportunities of every destination are fixed, we can use the Doubly Constrained Gravity Model. Like measuring job accessibility, workers (i.e. origin) compete for jobs (i.e. destinations) and employers compete for workers. So this case is good to use the doubly constrained model. For shopping accessibility, only the number of residents is fixed because we assume that there is no upper limitation for the shop's capacity. In other words, the more customers patronize, the better operating condition is. In this case, the Singly Constrained Gravity Model is adopted to measure the accessibility.

For the strengths and shortcomings of the gravity model, the strength is to consider the competition factors on the origin side and destination side, which makes the analysis more realistic. However, the shortcoming of the gravity measure is the complex and meaningless iterations. In some researches, there are hundreds of origins and destinations, which make the balancing process complex. Because it can cost lots of time to calculate in the computer. And the final results are not easy to interpret due to the iterative balancing process just being a mathematic operation, which doesn't have any real meanings and the calculation doesn't fit the two definitions of competition from the Oxford dictionary.

2.4. Comparison between Cheng's model and other accessibility measures

Comparing to other measures except the competition-based measures (i.e. Singly/Doubly Constrained Gravity Model and 2SFCA), Cheng's model is more realistic and reliable due to including the two-side competition, the diversity and decay function.

In terms of the comparison between Cheng's model and the other two competition-based models mentioned in section 2.3.4. First, Cheng's model involves the two-side competition comparing to the 2SFCA which only includes one-side competition. And the result of Cheng's model is the number of opportunities for each origin, while the result of 2SFCA is a relative value, which is the average number of opportunities for every origin. Second, Cheng's model has the transparent definition and calculation contrast with Singly /Doubly Constrained Gravity Model. Even though both models can include two sides of competition, it is obvious that Cheng's model avoids the meaningless iteration and has the clear definitions about the competition as section 2.2 explained. Third, Cheng's model is like a platform, which is flexible to change. Every function of this model can be adjusted according to research requirements. It is also easy to add new factors or parameters in Cheng's model. Like this research, it focuses on the urban poor in Ahmedabad, India. So the fare factor is incorporated into Cheng's model.

However, the calculation of Cheng's model costs more time due to more factors involved comparing to other accessibility measures. This research implements Cheng's model in ArcGIS to be an automation tool, which can make the calculation more convenient. For the decay function, Cheng's model uses the negative exponential function. As section 2.3.3 explained, this kind of decay function sometimes is meaningless (e.g. 30 minutes = 0.5 hours but $e^{-\beta \cdot 30} \neq e^{-\beta \cdot 0.5}$). But this problem can't be solved by this research. Another major limitation of Cheng's model is how to interpret because it involves several factors, which makes the interpretation of Cheng's model not as easy as other accessibility models, especially not like the models without competition factors. This is an important problem to be solved by this research.

2.5. Common problems of accessibility analysis

There are two common problems for all accessibility measures, which are somehow solved by this research. First, sometimes the results are often biased from the reality because of incomplete road network. The left picture of Figure 6 shows people from residential location can take a bus or drive a car on the road going to the shopping mall. Yet, there could be off-road path (i.e. the dashed lines in Figure 6), which costs less time than the road path. Although this problem can't be solved, this research mitigates this kind of problem by the complete 3D multi-modal road network as Figure 5 shows.

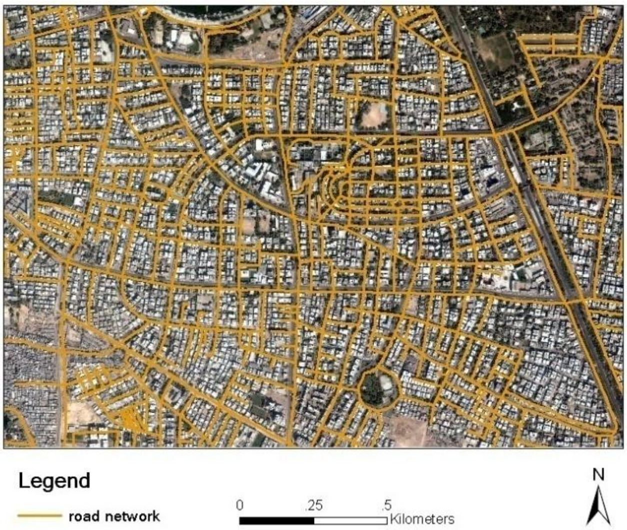


Figure 5 Road network and remote sensing image

Second, the intra-zone problem is shown in the right side of Figure 6. If the analysis is regional or national level, it is necessary to divide the study area into several zones in order to make sure the computer work out results. No matter which kinds of accessibility measures, origins and destinations are points, which frequently represents all of residents or opportunities in one analysis zone. The residential location (i.e. origin) in Figure 6 represents all the people in zone A. Thus, the final accessibility of everybody in A is the same as the accessibility of that point (i.e. origin), which is obviously not practical. The intra-zone problem is caused by the predefined boundaries, which aims at increasing the calculation speed. This problem can't be avoided unless the accessibility analysis is from the level of individual. Although this research doesn't analyze the accessibility for every single person but the predefined zones are reasonable (i.e. the aggregated cells discussed in section 5.1.1), which ensures the relatively high accuracy.

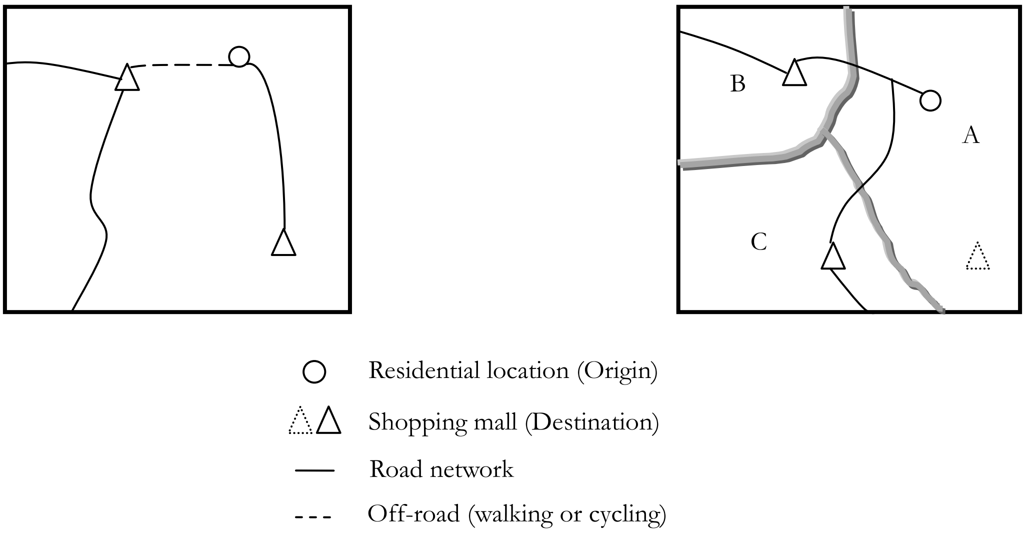


Figure 6 Example of common problems for accessibility measures

In conclusion, Cheng's model is more realistic than other accessibility measures but it can't be used for every case. If planners want to evaluate the efficiency of physical infrastructure or measure the accessibility with one-side of competition etc, Cheng's model is not suitable for them. The requirements of different cases are determined by the data and its context. So the next chapter introduces the background about the job accessibility in Ahmedabad and the relevant data used in this research.

3. STUDY AREA AND DATA

This chapter provides a description of Ahmedabad, particularly looking at job accessibility for the urban poor. Meanwhile, the data from the Word Bank project in Ahmedabad is discussed. Specifically, the road network data is produced by ITC staffs. And the housing data is from Ahmedabad Municipal Corporation (AMC) and Centre for Environmental Planning and Technology University (CEPT) in India. The employment data is from the Census Enumeration Block Data and ITC. This chapter also introduces the strengths and limitations of these data.

3.1. Overview of Ahmedabad

Ahmedabad is a district which contains several areas. The study area of this thesis is Ahmedabad Municipal corporation area. Ahmedabad is situated in the state of Gujarat, which was named as India's Guandong by The Economist magazine due to the fast economic growth. Moreover, the commercial centre of Gujarat is Ahmedabad city because it is famous for innovation, education and tourism. As Figure 7 shows, this city locates in the northern west part of India crossed by the River Sabarmati, which has the seventh largest metropolitan area and the fifth largest population around the whole country. The population of Ahmedabad is 6.35 million people living in this urban area and the population has been increased at 3.5 percent yearly for the last decades (Office of the Registrar General & Census Commissioner & Ministry of Home Affairs, 2011). The source of Figure 7 is from Google Earth, which can't guarantee the high spatial accuracy, but does give a general geographic description.

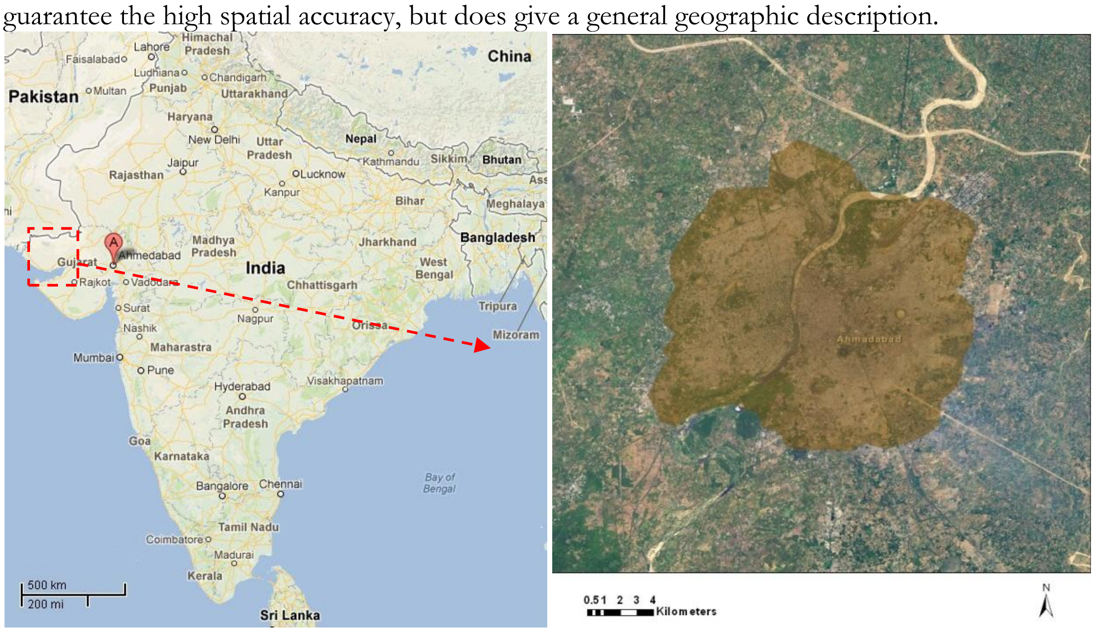


Figure 7 Geographic location of Ahmedabad

3.2. Housing for the urban poor

In Ahmedabad, there are two types of houses for the urban poor. One is called Chawl, which originally was used for the workers in textile mills. Before 1985, this city was known for the cotton textile industry and there were many mills, which were concentrated in the east of Ahmedabad. The owners of mills provided a single unit house with basic amenities for the workers. This kind of house was Chawl. In 1988, most of the mills were closed down but the Chawl was remained. From then on, unemployed people lived there with very low rent because the owner stopped to maintain the house. Later, some owners sold Chawl to unemployed people or low income people with a cheap price. These poor people began to share one single unit room with others in Chawl, which reduced the living cost but became crowed. The other kind of house for the poor is known as slum. UN-Habitat defines a slum as a group of individuals living in one crowded room who can't access to the safe water, sanitation facilities and lack of tenure security in the urban area. The slums of Ahmedabad often occupy some lands illegally and also lack of the basic amenities. Like the distribution of Chawls, most of slums locate in the east of Ahmedabad (Figure 8) but recent 5 years the western part of this city began to emerge many new slums. That was because the local government tried to stimulate commercial activities in the western side and lots of migrants settled there.

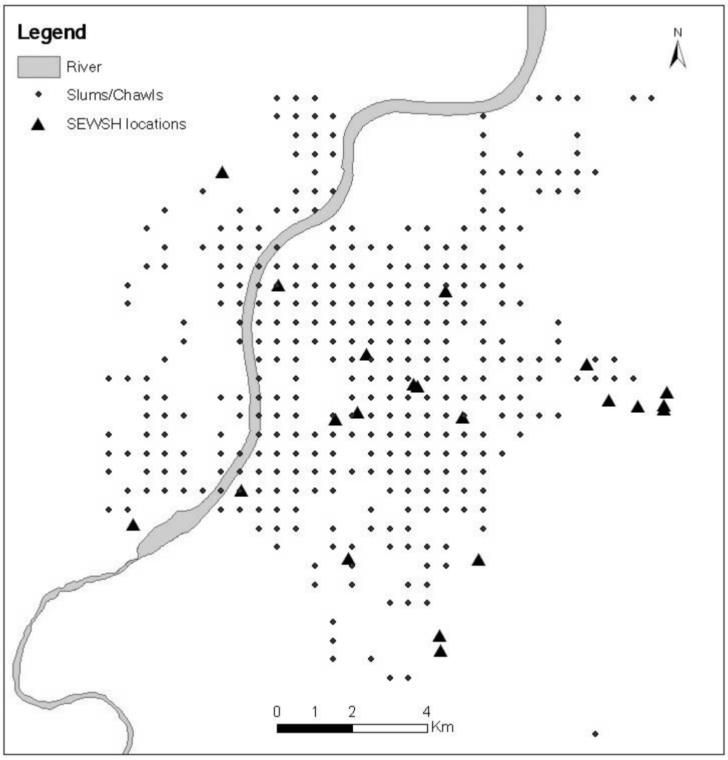


Figure 8 Original Slum/Chawls and SEWSH locations

Both house types have four kinds of architecture styles. The first one is Huts, which is made of available materials such as bricks, stones and branches etc. Second, it is named Kuttcha which is like Huts built by natural materials such a mud, grass or sticks but without bricks or stones. So Huts and Kuttcha are the temporary shelter for housing but some poverty people probably live there around 20 years because of the low income (Bhatt, 2003). Third, Semi-pucca is the huts either wall or roof with brick construction. The fourth one is Pucca, which is constructed by cement, concrete and bricks. Obviously, Pucca is more stable than other kinds of houses. The common points of these buildings are lack of the basic amenities. However, these buildings can stand the normal weather except the extreme weather.

The housing of the poor has been a problem all the time in Ahmedabad city even during its prosperous age. From 1961 to 1991, the percent of people living in slums or Chawls increased from 17.2 to 25.6. Moreover, Pandey (2002) revealed the ratio in The Times of Inida, which was 41% of people were living in ghettos. The population density of slums or Chawls is 3 to 8 times of the average level of Ahmedabad city (Kashyap, n.d.) The government, therefore, proposed a project named Socially & Economically Weaker Section Housing (SEWSH) to improve the living conditions for poor people. This project aims at moving the urban poor from slums or Chawls to the 21 SEWSH locations where offers the basic infrastructure including water supply, drainage and sanitation facilities. The left picture of Figure 9 is slums or Chawls and the right is the SEWSH buildings.

Figure 9 Slums/Chawls and SEWSH in Ahmedabad

3.3. Jobs for the urban poor

There are three classifications of every kind of job which are self-employed, regular and casual work in Ahmedabad. However, the available employment data doesn't have detailed explanation about job classifications. This research assumes that these job data are all the available opportunities for the urban poor, including self-employed, regular and casual work. Then, according to the quality of house, three poverty levels are determined and link the corresponding job types (see Table 10 in section 5.1.1). This classification generally matches the statistics data from AMC and National Sample Survey Office (NSSO). Absolutely, this research also measures the accessibility with the total number of jobs for the urban poor. The next paragraph is a brief description about the employment condition in Ahmedabad.

The large-scale cotton textile industry had been flourishing more than 30 years after 1950 in Ahmedabad city. During that time most of people went to mills as a worker. However, from 1985 to 1995 many mills were closed down and people started to do other kinds of jobs, which were small-scale or informal manufacturing like plastic, machinery and alloys. In addition, the macro economic reform boosted other forms of commercial activities such as trade, transport and so on in 1990s. Consequently, the tertiary sector has become better than ever before. According to NSSO, regular work of manufacturing has accounted for the largest percent of worker participation in this city after 1987, although almost every year this ratio declines. Mahadevia (2012) pointed at two interesting phenomena in this respect. First, from 2004 to 2010 the overall work participation and unemployment rates decreased together because female workers tend to do self-employed or home-based jobs and male workers work later in order to get higher education or the labour force shrunk. Second, if there are not enough opportunities of manufacturing jobs, most of women work in public administration or social service.

3.4. Urban transport in Ahmedabad

3.4.1. General condition of transport

Ahmedabad has a very developed road network, which links other big cities such as Delhi and Mumbai via national expresses or railways. For the public transport, the city operates the AMTS (i.e. the ordinary bus system) and the largest Bus Rapid Transit System (BRTS) in India, which has gotten some national and international awards. The first phase of metro construction, meanwhile, will be constructed in 2013 according to Gujarat Infrastructure Development Board.

The well connected transport system doesn't only stimulate the fast economic growth in Ahmedabad, but also brings the fast urbanization resulting in population growth. The Indian census data displays the population of Ahmedabad increases 27.8% from 2001 to 2011. The rapid development also brings the transport problems. From Figure 10, we can see the motor cycles, cars and auto rickshaws causing congestion on the main roads, which decreases the mobility for travelling and the efficiency of public transport. According to statistical information from the Planning Statistical Deparment (2007), the number of motor cycles is the largest part around all categories of vehicles on the road from 1987 to 2007. The second is motor car and third is auto rickshaw. But the sum of motor car and auto rickshaw is less than the number of motor cycle on the road. Along with the terrible road condition, the average speed of some major roads is just 10 km/h (Ahmedabad Municipal Corporation & Ahmedabad Urban Development Authority, 2006), which constrains the further development of the city.

Even though there are many travelling modes in this city, most of the urban poor walk and cycle to work in order to save money. Mahadevia et al. (2012) found that only 0.4 percent of poor people could take BRTS, while the middle class people often take BRTS. In contrast, most of the poor people go to work by cycling at least 10~12 kilometers daily (Bhatt, 2003). But the disorderly management of road transport is terrible for walking and cycling in the narrow and unsafe roads.

Figure 10 Crowded main roads in Ahmedabad

3.4.2. Data of road network

This research adopts a 3-dimensional network from the World Bank project. The left of Figure 11 is a 2D network and the right is 3D network. Obviously, the 3D network is more intuitive than 2D network. Because in planar network one line represents many bus lines or metro lines, while 3D network can show different bus lines on different heights. Most importantly, the stereoscopic network easily simulates the transfers among different public transport modes. The vertical lines between different public transport lines are the transfer links, which have their own travel impedance. So when running the Network Analyst of ArcGIS, the routes can't change frequently among different travel modes[1], which is the same as people's travel behaviour in reality.

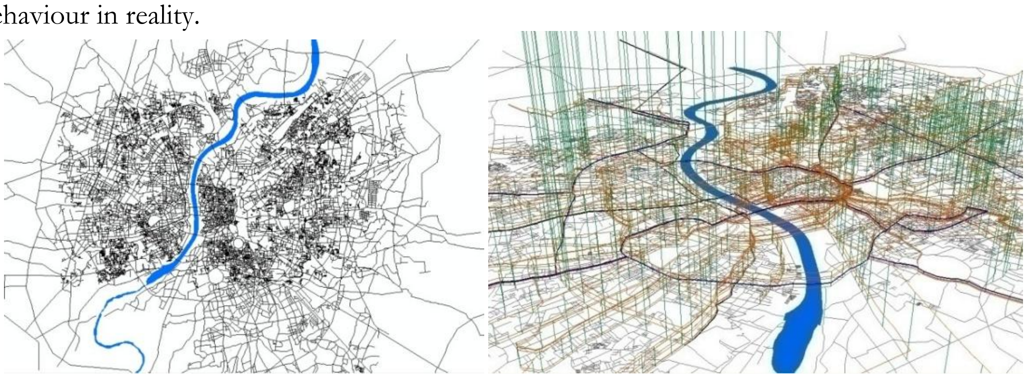


Figure 11 2D and 3D road network

[1] This conclusion is from Ing. F.H.M. (Frans) van den Bosch, who is the practice teacher in ITC

4. IMPLEMENTATION OF CHENG'S ACCESSIBILITY MODEL IN ARCGIS

This previous chapter introduced the study area and data, which are the important factors for implementing Cheng's model. This chapter describes how Cheng's model was implemented in ArcGIS using Python. The main reasons of choosing Python programming are convenience and ease of understanding. ArcGIS provides the Arcpy module for Python scripting and support to call the Geoprocessing functions from Toolbox in Python style. This chapter is divided into four sections. The first section is the general description about implementation of Cheng's model, including the reasons of implementation, basic ideas and the preparation. The second section is to design a tool getting the fare for every travelling route. The third section is to explain the implementation of Cheng's model. The fourth section is the explanation of the result of Cheng's model based on a simple example.

4.1. General description about implementation

4.1.1. Implementation reasons

The first reason for implementing Cheng's model in ArcGIS as an automation tool is due to the complex calculation processes. If the several scenarios are calculated by Cheng's model using the independent functions of ArcGIS manually, it is possible to produce some mistakes because of the carelessness. Most importantly, the manual operations take a lot of time and create useless intermediate files, which are produced by the Geoprocessing functions of ArcGIS like Summarize, Spatial Join etc. Moreover, this research needs to run Cheng's model more than 30 times based on many scenarios in order to figure out the job accessibility of the urban poor in Ahmedabad and interpret the result of Cheng's model (The section 5.2 discusses about the specific scenarios). Therefore, the implementation of Cheng's model is very important.

The other reason for programming in ArcGIS with Python is the efficient and flexible calculation. Obviously, ArcGIS is good at analyzing the spatial problems by the hundreds of Geoprocessing functions, while these functions require loading many relative properties that are useless for computing Cheng's model. In contrast, the dictionary or list of python is very simple data structure, which is good at computation. For example, when ArcGIS calculates the values of one field from an attribute table, it loads the properties of the attribute table and every field properties of this table when the user opens the table. However, if the values of that field are stored in dictionary or list in Python, the calculation only needs to load the properties of these values. Moreover, the structure of the attribute table of ArcGIS is fixed and the calculation functions of ArcGIS must obey the table structure, especially the Field Calculator function. But the calculations in Python are flexible. If some values of a field are divided by the other values of the same field, ArcGIS can't implement this calculation, while Python can finish this calculation quickly by the list or dictionary. This research, therefore, improves the data calculation processes with the data structure of Python and all the important calculations are finished in Python but the spatial analysis depends on the Geoprocessing functions of ArcGIS.

4.1.2. Implementation ideas

For implementation of Cheng's model, this research uses three tools, which are Network Analyst, Fare tool and Competition tool. The Network Analyst function of ArcGIS is used to compute the travel time based on the 3D multi-modal road network. The Fare tool and Competition tool are developed by Python and Geoprocessing functions of ArcGIS to calculate fares and job opportunities. Even though it is rather straightforward to integrate Network Analyst, the Fare tool and Competition tool into one package, this research keeps every tool as an independent package. That is because Network Analyst already has a user-friendly interface. If we put these three functions together via Python, there will be too many parameters on the interface, which could make users confused. The following descriptions are the relation between the specific tool and formulas of Cheng's model.

The following formulas are Cheng's model, which are the same as section 2.2 explained. Before implementing these equations into ArcGIS 10.1 by Python, there are some basic explanations about these formulas.

$$D_j = -\frac{\sum_l Q_{lj} \times ln(Q_{lj})}{\ln(n)}, \quad Q_{lj} = \frac{E_{lj}}{E_j} \tag{1}$$

$$f(t_{kj}) = \mathrm{e}^{-\beta \times t_{kj}} \tag{2}$$

$$P_{jk} = \frac{{E_j}^{D_j} \times f(t_{kj})}{\sum_s {E_s}^{D_s} \times f(t_{ks})} \tag{3}$$

$$Q_i = \frac{\sum_j E_j \times P_{ji} \times W_i \times f(t_{ij})}{\sum_k P_{jk} \times W_k \times f(t_{kj})} \tag{4}$$

Eq. (1) is to calculate the diversity of jobs in employment location j. For its implementation in ArcGIS, the Field Calculator function is feasible and efficient.
Eq. (2) is the time decay function, while this research adopts this function as a fare decay function. So the t_{kj} is treated as the travel impedance (i.e. travel time or the fare) from worker location k to job location j. The travel time can be calculated by the Network Analyst of ArcGIS, while the fare can't be gotten from one function of ArcGIS directly. So this research creates the Fare tool in ArcGIS to calculate fares.
Eq. (3) and (4) is to define the competition on jobs/employers and workers respectively, which have been discussed specifically with an example in section 2.2. For their implementation, this research develops the Competition tool, which is major part of Cheng's model.

4.1.3. Preparation

The preparation for implementing Cheng's model in ArcGIS is to run the Network Analyst because the attribute table of the result reveals that workers of every location go to which employment locations. Depending on this result, we can use Cheng's model to compute the job accessibility of the urban poor. So the first step of preparation is to run Network Analyst function, which can quickly find the shortest routes and calculate the corresponding travel time for each worker location to job locations based on Dijkstra's algorithm (ESRI, 2010). And then the Fare tool can calculate fares for the results of Network Analyst. Both the travel time and fares are the input of the Competition tool. The diversity of jobs (i.e. Eq. (1)) calculated by the Field Calculator function is also the input of the Competition tool.

Following this section, the subsequent two sections illustrates how to program the Fare tool and Competition tool, including the design thoughts and specific functions of ArcGIS as well as Python used. The specific Python codes are shown in the appendix.

4.2. Programming of the Fare tool

4.2.1. Design thoughts of the Fare tool

The fare data of public transport in Ahmedabad is not a linear function. The fare is determined by the number of stops or stations passed by one travel mode as Figure 12 shows. In this case, this research combines the characteristics of 3D multi-modal road network with the fare structure to design the Fare tool.

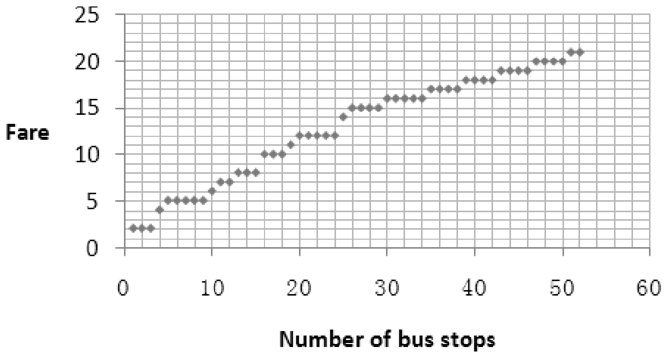


Figure 12 Fare structure

As the section 3.4.2 explained, each line of 2D road network can be several travel modes, while every line of the 3D network is one specialized route of a public transport mode, which provides the key point to get the fare for each route. Specifically, the different public transport is represented by the lines with different heights and their stops or stations intersect with the corresponding lines. For example, there are two different bus lines, which are bus 1 and bus 100. The bus 1 and its stops are 1 meter high and the bus 100 and its stops are 100 meters high in the 3D multi-modal road network. Absolutely, the stops of bus 1 and bus 100 should intersect with the bus line 1 and bus line 100 respectively. This spatial relation is helpful to calculate fare for each shortest route. Figure 13 is the example to illustrate why only 3D results are useful for the fare calculation. If the road network is 2D dataset, the result is the planar line like the left side of Figure 13, which intersects with 4 bus stops. However, we can't identify this route taking how many buses because there are no labels for the different bus stops. The right side of Figure 13 is produced by the 3D road network. In this figure, according to the different heights of two bus lines, it is obvious that this route uses two buses and passes two stops of bus 1 and two stops of bus 100. Therefore, the 3D result provides the height as the label for different bus lines and its stops.

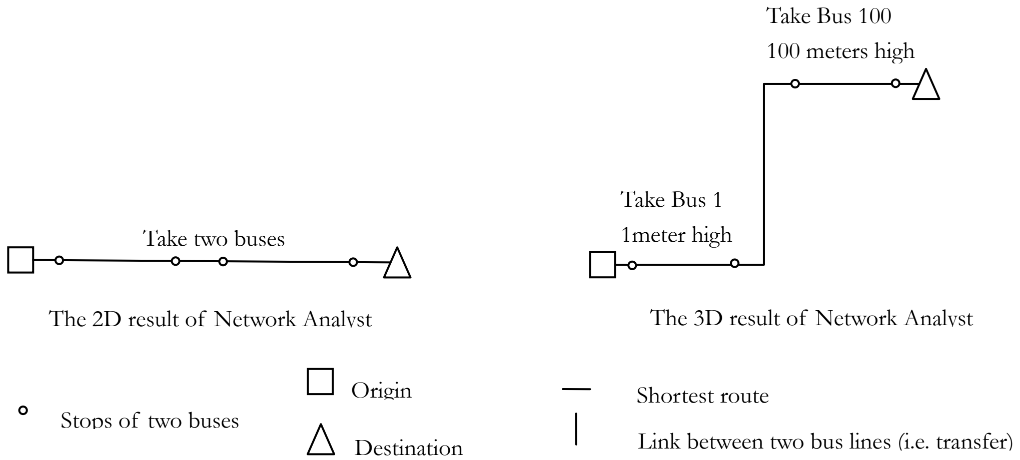


Figure 13 Comparison between the 2D result and the 3D result of Network Analyst

The outcomes of Closest Facility from Network Analyst based on 3D multi-modal road network are also 3D lines, while the results of OD Cost Matrix function based on 3D road network, which can also analyze the multi origins and destinations problem, are planar straight lines like the 2D result of Figure 13. This is the reason OD Cost Matrix is not useful for the fare analysis.

4.2.2. Functions used in ArcGIS for the Fare tool

This section describes which functions are used to implement the above ideas in ArcGIS. There is an example for explaining specific processes. The right picture of Figure 14 is a simple result from the Closest Facility analysis. The red dots are the stops or stations and the lines are the final routes. The important thing is to analyze the relation between 3D points and 3D lines by a suitable Geoprocessing functions. The

Intersect and Spatial Join functions are useless because both of them are based on the planar coordinate, which could produce biased results for 3D analysis. It means these functions judge the spatial relations between points and lines depending on the XY coordinates ignoring the Z coordinate (i.e. Height). For example, each line intersects with two red dots from 3D view in the left picture of Figure 14, while from 2D view (i.e. look right above the 3D figure.) every line intersects with four points. Specifically, ArcGIS has only one function to analyze the spatial relations between 3D points and 3D lines, which is Selection By Location and one of its methods is named Intersect 3D.

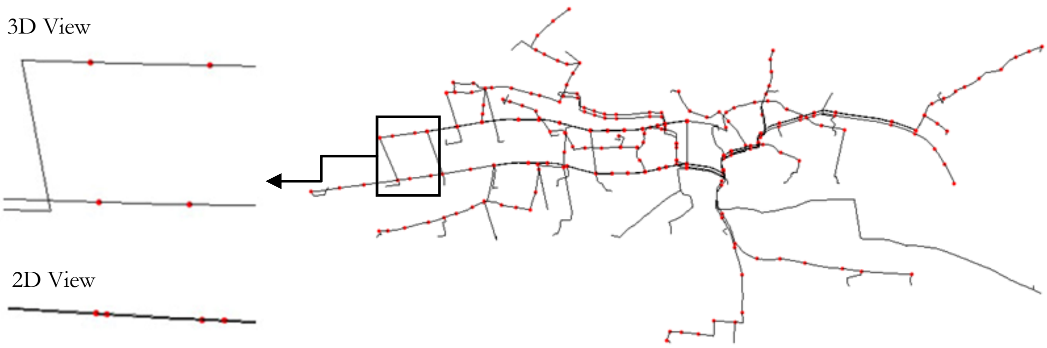


Figure 14 Example of Closest Facility

Figure 15 is the interface of the Fare tool, which can handle three kinds of travel modes (i.e. AMTS, BRTS and MRTS) because in Ahmedabad these three kinds of public transport are paid by the travellers.

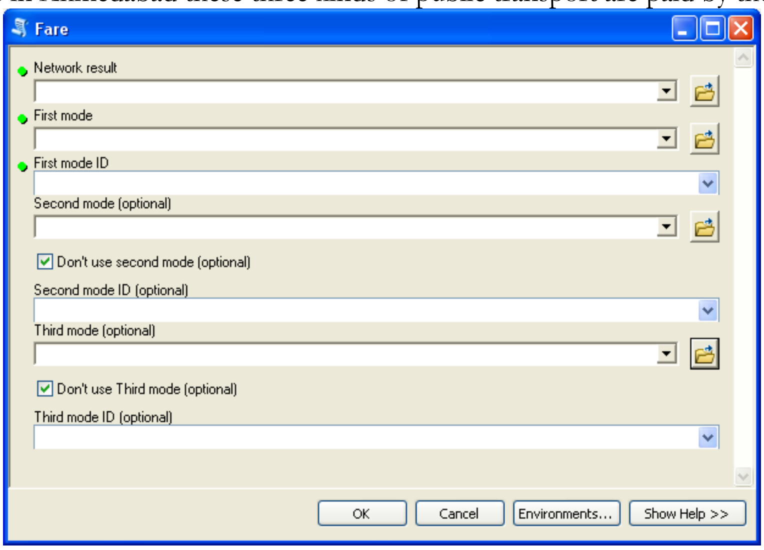


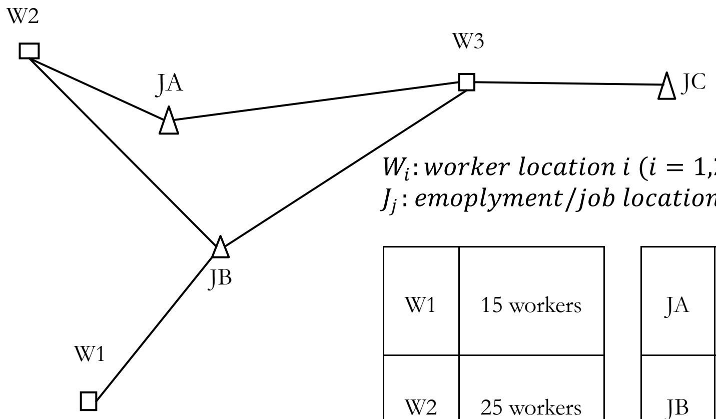
Figure 15 Interface of the Fare tool

4.3. Programming of the Competition tool

4.3.1. Design thought of the Competition tool

As section 4.1.2 explained, the Competition tool is to implement the Eq. (3) and Eq. (4) in ArcGIS, which are the core parts of Cheng's model. Like the Fare tool, the input data of Competition tool is the result of Network Analyst. The only difference about the input data is that the Fare tool only requires the result from Closest Facility, while the input data of the Competition tool can be produced by the Closest Facility or OD Cost Matrix function from the Network Analyst. That is because the Competition tool doesn't analyze the 3D spatial relations discussed in section 4.2.2 and this tool only needs the travel time from every origin (i.e. worker location) to all reachable destinations (i.e. employment location). Consequently, the planar straight lines of OD Cost Matrix result are feasible to be the input for the Competition tool. Before illustrating the implementation processes, it is better to show the example of Figure 16, which could make the following explanations clear.

In Figure 16, every employment location has different kinds of jobs. The lines of Figure 16 are the shortest route from every worker location to reachable job locations. These shortest routes can be produced by the Network Analyst of ArcGIS (Closest Facility or OD Cost Matrix). The attribute table of these shortest routes is Table 2 for the example in Figure 16. In this attribute table, The Name field means each worker location goes to which employment location. So the left words of hyphen are the labels of worker locations and the right side of words are the labels of employment locations. The Time field of Table 2 is the travel time of every route. Subsequently, it is the descriptions about implementation of Eq. (3) and Eq. (4). The first phase is to implement Eq. (3) and the second phase is to implement Eq. (4).



$W_i: worker\ location\ i\ (i = 1{,}2{,}3)$
$J_j: emoplyment/job\ location\ j\ (j = A, B, C)$

W1	15 workers
W2	25 workers
W3	30 workers

JA	100 jobs	Retail: 20
		Bank: 10
		Industry: 70
JB	40 jobs	Logistics: 25
		Bank: 15
JC	20 jobs	Industry: 20

Figure 16 Example of competition model

OID *	Shape *	Shape_Length	Name	Time
1	Polyline	16412.524414	W1-JB	5
2	Polyline	20635.090648	W2-JA	10
3	Polyline	33406.570672	W2-JB	20
4	Polyline	28704.337147	W3-JA	15
5	Polyline	26935.209322	W3-JB	30
6	Polyline	22882.798705	W3-JC	10

Table 2 Results of Network Analyst

1. First phase

For the implementation of Eq. (3), the key point is to know which employment locations compete for one worker location. And then, according to the Eq. (3), we can find which job location is better or more attractive for this worker location. For example, employers of JA (i.e. 100 jobs) and JB (i.e. 40 jobs) compete for workers of W2. If the results of diversity of jobs (i.e. Eq. (1)) and decay function (i.e. Eq. (2)) are considered as 1, the competition factor of JA and JB is 5/7 and 2/7 respectively. As the section 2.2 explained, the competition factor can also be treated as the attractiveness of a job location.

2. Second phase

The results of the first phase (i.e. Eq. (3)) are the input for the implementation of Eq. (4), which is divided into three steps. Table 3 is the results of the Competition tool for Figure 16. The following illustrations are based on Table 3.

1) First, it is to calculate how many workers of each worker location are attracted by every employment location, which is the part of the numerator of Eq. (4) (i.e. P_{ji} x W_i x $f(t_{ij})$). Specifically, the number of workers (i.e. W_i) multiplies the corresponding result of Eq. (3) (i.e. P_{ji}) and decay function (i.e. Eq. (2)). If we still use the above example in which the result of decay function is 1, the job location JA and JB

attract 17.857 (i.e. 25 x 5/7) workers and 7.143 workers (i.e. 25 x 2/7) from worker location W2 respectively.

2) The second step is to calculate the competition among workers. The key point is to know which worker locations compete for one employment location. So we can calculate the total number of attracted workers for each job location, which is the sum of first step based on the dominator of Eq. (4). Then, the number of jobs of every employment location is divided by the corresponding sum. For instance, workers of W2 and W3 look for jobs at location JA and JA actually attracts 17.857 workers from W2 and 18.75 workers from W3. The total number of attracted workers at JA is 36.607 (i.e. 17.857+18.75). The competition among workers at JA is the number of jobs (i.e. 100) divided by the total number of workers (i.e. 36.607). The result is the number of available jobs for every worker.

3) The third and last step of implementing Eq. (4) is to use the number of attracted workers of every worker location (i.e. the result of the first step) multiplying the corresponding result of the second step. Finally, summarize the total number of job opportunities for every worker location (see Table 4). In Table 4, the FREQUENCE field is the number of reachable destinations for every worker location, which only reflects the efficiency of physical infrastructure. And the SUM_Opport field is the final job opportunities for each worker location computed by Cheng's model.

Name	Time	WID	JID	jobs	Djobs	Jcomp	workers	Dworkers	Att_worker	Wcomp	Opport
W2-JA	10	W2	JA	100	100	.714286	25	25	17.857143	2.731707	48.780488
W3-JA	15	W3	JA	100	100	.625	30	30	18.75	2.731707	51.219512
W1-JB	5	W1	JB	40	40	1	15	15	15	1.349398	20.240964
W2-JB	20	W2	JB	40	40	.285714	25	25	7.142857	1.349398	9.638554
W3-JB	30	W3	JB	40	40	.25	30	30	7.5	1.349398	10.120482
W3-JC	10	W3	JC	20	20	.125	30	30	3.75	5.333333	20

Table 3 Job opportunities when diversity and decay factor are 1

Explanation of Table 3: WID is the labels of worker location and JID is the labels of job locations. Djobs and Dworkers are the discounted jobs and workers. The discounted jobs and workers are equal to the number of jobs and workers because the result of decay function is 1 in this example. Jcomp is the competition among jobs. Att_worker is the number of attracted workers and Wcomp is the competition among workers. Opport is the job opportunities for each worker location.

WID	FREQUENC	SUM_Opport
W1	1	20.240964
W2	2	58.419042
W3	3	81.339994

Table 4 Final job opportunities

In order to make the above explanation clearer, Table 5 is the relations between the fields of Table 3 and the components of Cheng's model. This table also shows every component of Cheng's model is implemented in which phase.

Field name	Components of Cheng's model	Explanation and Phase
Djobs	${E_j}^{D_j} \times f(t_{kj})$	The number of discounted jobs (First phase)
Jcomp	$P_{jk} = \frac{{E_j}^{D_j} \times f(t_{kj})}{\sum_s {E_s}^{D_s} \times f(t_{ks})}$	The competition among jobs/employers (First phase)
Dworkers	$W_i \times f(t_{ij})$	The number of discounted workers (Second phase, first step)
Att_worker	$P_{ji} \times W_i \times f(t_{ij})$	The number of attracted workers (Second phase, first step)
Wcomp	$\frac{\sum_j E_j}{\sum_k P_{jk} \times W_k \times f(t_{kj})}$	The competition among workers (Second phase, second step)

Opport	$Q_i = \frac{\sum_j E_j \times P_{ji} \times W_i \times f(t_{ij})}{\sum_k P_{jk} \times W_k \times f(t_{kj})}$	The final job opportunities (Second phase, third step)

Table 5 Relations between the table fields and components of Cheng's model

4.3.2. Functions used in ArcGIS for the Competition tool

Based on the design thought of the Competition tool, this section explains which functions of ArcGIS and Python used for programming this tool. There are three aspects in this section, which are preparation, the first phase and second phase of design thought.

1. Preparation

Before starting to implement two phases of design thought mentioned in section 4.3.1, it is necessary to finish the preparation for the following implementation. Specifically, the preparation is to copy the related data (i.e. the number of jobs, the number of workers and the diversity of jobs) from other feature classes to the attribute table of Network Analyst. That is because the attribute table of Network Analyst has the relation between worker locations and job locations (i.e. people from worker locations look for jobs in which employment locations and employers from job locations look for workers in which worker locations). This relation is the key point to calculate Cheng's model. Therefore, this research chooses the attribute table of Network Analyst as the base table and all related factors (e.g. the diversity of jobs, two-side competition etc) and the final results are shown in this table like Table 3. For the preparation, the Field Calculator, Add Field and Join field function are adopted. The Field Calculator function is used with Python to extract the labels of worker and job locations. For example, the values of WID field of Table 3 are extracted from the Name field. The Add Field function is to create new fields in the attribute table of Network Analyst like the WID field of Table 3. The Join field function is to copy the number of jobs and workers into the attribute table such as the jobs and workers field in Table 3.

2. The first phase of design thought

This phase is to calculate the competition among jobs by Python. The SearchCursor function from Arcpy module of ArcGIS can transfer the number of jobs in Python. According to the first phase of section 4.3.1 explained, this phase should make sure the attribute table sorting by the labels of worker locations in order to know which employment location look for workers from the same worker location. In Python, the list can keep this order. Then, the result of competition among jobs is calculated in Python and this result is copies into the attribute table by UpdateCursor function from Arcpy module. In Table 3, the Jcomp field is the result of this phase.

3. The second phase of design thought

The second phase has three steps as section 4.3.1 shown. For the first step, the Field Calculator is used to calculate the number of attracted workers (e.g. Att_worker field of Table 3). The second step is to compute the competition among workers, which is similar to the calculation of competition among jobs because both competitions need to be calculated in sequence. The data of this phase is necessary to sort by the labels of job locations (see the second phase of section 4.3.1). The SearchCursor function copies the number of workers in Python. And the list of Python keeps the required order. Then, the competition among workers is calculated in Python and this result is also copied into the attribute table by UpdateCursor function (e.g. Wcomp field of Table 3). The third step is computed by the Field Calculator and Statistics function of ArcGIS. The number of jobs multiplying the corresponding competition among workers is done by the Field Calculator. The Statistics function produces the final result like Table 4.

All of the above functions are encapsulated into one package, which is the Competition tool. Figure 17 is the interface of this tool in ArcGIS

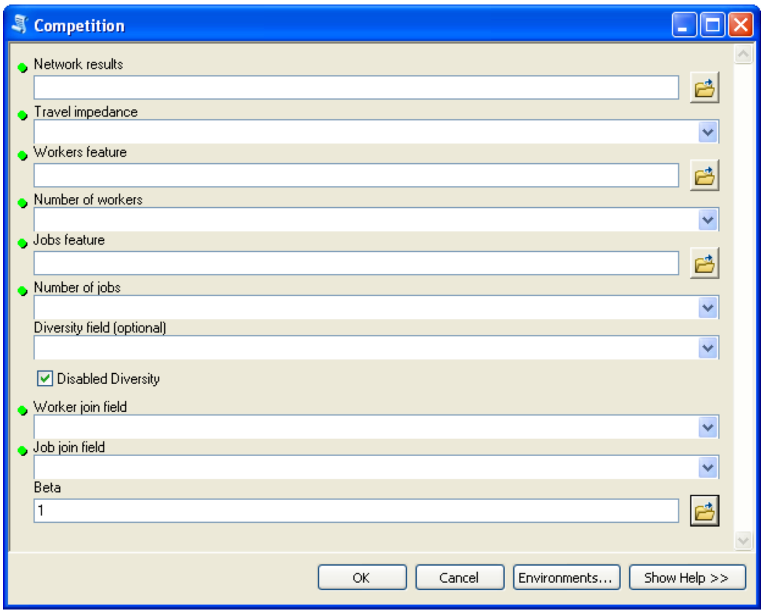


Figure 17 Interface of the Competition tool

4.4. Interpretation of the results

This section has three parts to explain how the components of Cheng's model influences the final job opportunities based on the example of Figure 16. The first part discusses the effect of the decay function. The second part is about the effect of diversity factor, which was treated as an elastic factor in Cheng's model. And the third part is to explain how the competition factors influence the result of Cheng's model. Then, this research gives a brief explanation about how to use the results of Cheng's model in urban planning.

4.4.1. The effect of decay function in Cheng's model

Cheng's model distributes the existing opportunities to each worker location and doesn't have some opportunities remained. The decay function is one of the factors to influence the distribution of job opportunities. Table 6 is the result of Cheng's model when beta is 0.5 and the diversity factor is 1. Table 3 and Table 6 are the same example, while the only difference is beta value. The beta value of previous one is 0 and the later one is 0.5. We can see that W2 and W3 location can get 48.78 and 51.22 jobs from JA respectively in Table 3. Their sum is still equal to the number of jobs in JA (i.e. 100 jobs). For Table 6, W2 and W3 gets 97.21 jobs and 2.79 jobs from JA respectively. The sum is still equal to the number of jobs at JA location. So the decay function can change the distribution of jobs in Cheng's model.

Name	Time	WID	JID	jobs	Djobs	Jcomp	workers	Dworkers	Att_worker	Wcomp	Opport
W2-JA	10	W2	JA	100	.673795	.997312	25	.168449	.167996	578.62364	97.206397
W3-JA	15	W3	JA	100	.055308	.290975	30	.016593	.004828	578.62364	2.793603
W1-JB	5	W1	JB	40	3.2834	1	15	1.231275	1.231275	32.48657	39.999901
W2-JB	20	W2	JB	40	.001816	.002688	25	.001135	.000003	32.48657	.000099
W3-JB	30	W3	JB	40	.000012	.000064	30	.000009	0	32.48657	.000000
W3-JC	10	W3	JC	20	.134759	.708961	30	.202138	.143308	139.55940	20

Table 6 Job opportunities when diversity factor is 1 but the beta of decay function is 0.5

4.4.2. The effect of diversity factor in Cheng's model

According to the equation (1) (i.e. diversity of jobs), if an employment location has one kind of jobs, the number of this type jobs is equal to the total number of jobs at this location (i.e. $E_{lj} = E_j$). This diversity of jobs (i.e. D_j) at this employment location is zero and $E_j^{D_j}$ (in Eq. (3)) is 1. In contrast, if another employment location has many types of jobs but the number of every type of jobs is equal, the diversity of jobs (i.e. D_j) is

1 at this job location and ${E_j}^{D_j}$ is equal to E_j. Cheng et al. (2012, pg.3) explained the diversity as an elastic factor and "the elasticity is between one (each additional type of job will affect the probability that a worker from i will be attracted by j) and zero (no additional type of jobs will affect the probability of a worker from i to be assigned to j)."

The diversity function is the elasticity, which only influences the distribution of jobs. For example, Table 7 is the result with diversity factor, which is calculated from Eq. (1). W2 can get 53.63 jobs from location JA and W3 has 46.37 jobs from the same job location. Their sum is still equal to the number of jobs at JA location (i.e. 100).

Name	Time	WID	JID	jobs	Djobs	Div	Jcomp	workers	Dworkers	Att_worker	Wcomp	Opport
W2-JA	10	W2	JA	100	40.145789	.8018	.777664	25	25	19.44159	2.758095	53.62175
W3-JA	15	W3	JA	100	40.145789	.8018	.560511	30	30	16.81532	2.758095	46.37825
W1-JB	5	W1	JB	40	11.477804	.6615	1	15	15	15	1.576916	23.653745
W2-JB	20	W2	JB	40	11.477804	.6615	.222336	25	25	5.55841	1.576916	8.765148
W3-JB	30	W3	JB	40	11.477804	.6615	.160252	30	30	4.807552	1.576916	7.581107
W3-JC	10	W3	JC	20	20	1	.279238	30	30	8.377128	2.387453	20

Table 7 Job opportunities when diversity factor is not 1 but decay factor is 1.

4.4.3. The effect of competition factors

The section explains which factors determine the two-side competition and how the two-side competition affects on the job opportunities. Actually, the competition factors are determined by the Network Analyst, the number of workers, the number of jobs, diversity factor and decay function. The Network Analyst impacts on the number of reachable employment locations for each worker location. But it doesn't mean that more reachable job locations could provide more job opportunities because of the competition factor in Cheng's model. If we still use the example of Figure 16 but the road network is improved for W1 and W2. W1 can reach two more job locations (i.e. JA and JC) and W2 can reach one more job location (i.e. JC). The improvement is only for W1 and W2 worker locations and other things of this example don't change (see Table 8 and the diversity and decay factors are 1). From the view of accessibility analysis without competition, the job accessibility of W1 and W2 should increase because they can reach more job locations, while the result of Cheng's model shows that the job accessibility of W2 decreases from 58.42 (see Table 4) to 57.14 (see Table 9). And only the job accessibility of W1 increases from 20.24 (see Table 4) to 34.29 (see Table 9) after improvement of the road network (Table 4 is the result based on the original road and Table 9 is the result based on the improved road network).

W1 and W2 have the different variations after the road network improved due to a series of changes. First, the improvement of road network enhances the mobility for workers and employers. So from Table 3 and Table 8, we can see that the job competition factor (i.e. Jcomp field) of JA to W2 and JB to W2 decline (i.e. from 0.714 to 0.625 and from 0.286 to 0.25) because there is one more worker location (i.e. JC) compete for workers from W2 with JA and JB. In other word, the attractiveness of JA and JB decrease due to one more employment location going to W2. Therefore, the number of attracted workers (i.e. Att_worker field) from W2 by JA and JB also declines, which influences the competition among workers (i.e. Wcomp field) according to Eq. (4). The values of Wcomp field are the average number of jobs for every worker location. If the value of Wcompe is bigger, more job opportunities are offered for every worker. In Table 3, JA and JB can provide 2.732 and 1.349 jobs for every worker who lives in W2. However, in Table 8, both of JA and JB can provide 2.286 jobs for every worker at location W2. This value could increase or decrease after improvement the road network. Actually, this value (i.e. the competition among workers is shown in Wcomp field) is affected by all the related worker locations and job locations. That is because Wcomp is calculated from the number of attracted workers (i.e. Att_worker field), which is determined by the number of workers and competition among jobs (i.e. Jcomp).

In a word, the JA and JB provide a fewer of jobs for W2 comparing to the result of original road network, although JC can provide new jobs for W2 but the number of new jobs is less than the decreased number of jobs. For W1, the number of jobs gotten from JB is fewer, while JA and JC can supply more new jobs than the decreased jobs.

Name	Time	WID	JID	jobs	Djobs	Jcomp	workers	Dworkers	Att_worker	Wcomp	Opport
W1-JA	15	W1	JA	100	100	.625	15	15	9.375	2.285714	21.428571
W1-JB	5	W1	JB	40	40	.25	15	15	3.75	2.285714	8.571429
W1-JC	20	W1	JC	20	20	.125	15	15	1.875	2.285714	4.285714
W2-JA	10	W2	JA	100	100	.625	25	25	15.625	2.285714	35.714286
W2-JB	20	W2	JB	40	40	.25	25	25	6.25	2.285714	14.285714
W2-JC	20	W2	JC	20	20	.125	25	25	3.125	2.285714	7.142857
W3-JA	15	W3	JA	100	100	.625	30	30	18.75	2.285714	42.857143
W3-JB	30	W3	JB	40	40	.25	30	30	7.5	2.285714	17.142857
W3-JC	10	W3	JC	20	20	.125	30	30	3.75	2.285714	8.571429

Table 8 Job opportunities based on the improved road network

WID	FREQUENC	SUM_Opport
W1	3	34.285714
W2	3	57.142857
W3	3	68.571429

Table 9 Final job opportunities based on the improved road network

4.4.4. Conclusion and interpretation method

According to the above analysis, we can conclude that the result of Cheng's model is an absolute value, which is the number of jobs for every worker location. And it is difficult to compare the results of Cheng's model based on different scenarios because several factors affect the final result. Like the previous example, after the improvement of road network, the job accessibility analyzed from the models without competition factors should increase but for Cheng's model the job accessibility could increase or decrease. In fact, this kind of variation is close to reality and reasonable. The more reachable destinations don't mean people could have more job opportunities. Maybe more people can reach one job location, which could make the intensity of competition higher and reduce the job opportunities for everyone.

Due to the above reasons, this research proposes a method to interpret the result of Cheng's model in urban planning. It is to count the variation of job accessibility of worker locations among different scenarios. Like the example of Table 9 comparing to Table 4, the job accessibility of two worker locations decrease and one worker location increase after improving the road network. So this improvement is not good for the whole system because more worker locations' accessibility decrease. This is an easy and good way to evaluate the urban planning projects when there is competition involved.

This chapter provided the explanation of implementing Cheng's model and the primary idea about interpretation. So the next chapter discusses about how to use the developed Fare tool and Competition tool in Ahmedabad. The detailed interpretation method is shown in next chapter.

5. ACCESSIBILITY ANALYSIS AND RESULTS

In this chapter, the competition-based accessibility measure for Ahmedabad (i.e. Cheng's model) is demonstrated. First, we discuss the data preparation, which is about how to aggregate data, calculate the beta parameter of decay function and other related descriptions. The second section provides the scenarios in this research. The third section explains how to interpret the result of Cheng's. The fourth section shows some discussions about which factors influence job accessibility of the urban poor in Ahmedabad according to the interpretation.

5.1. Data preparation

5.1.1. Locations of employment and potential workers

The base data of employment and slum locations is 100 x 100m grid cells, which is collected by AMC and CEPT University. Each cell is one job or slum location and the centroid of a cell represents the specific origin or destination. The spatial units are the key point to influence the accuracy of accessibility measure (Apparicio et al., 2008). And the unit size also determines the feasibility of calculation in a computer. Like the base data, there are 12078 job locations and 1752 worker locations. With such amount of data it is difficult to work out results by the computer because of around 12 million OD lines and let alone the 3D routes of Closest Facility analysis. In order to reduce the burden for computation and keep acceptable accuracy, this research aggregates the 100 x 100m cell into 500 x 500m for slum locations (i.e. the right side of Figure 18). For the employment locations, the spatial unit is aggregated into 1000 x 1000m (i.e. the left side of Figure 18). In reality, the distribution of employment locations is always concentrated in one place. For example, Cheng et al. (2012) chose only 45 major employment locations to analyze the competition-based job accessibility (i.e. Cheng's model) in Amsterdam. Consequently, this research makes the spatial unit of employment larger, while there are still 255 job locations, which has the relative high accuracy compare to (Cheng et al., 2012).

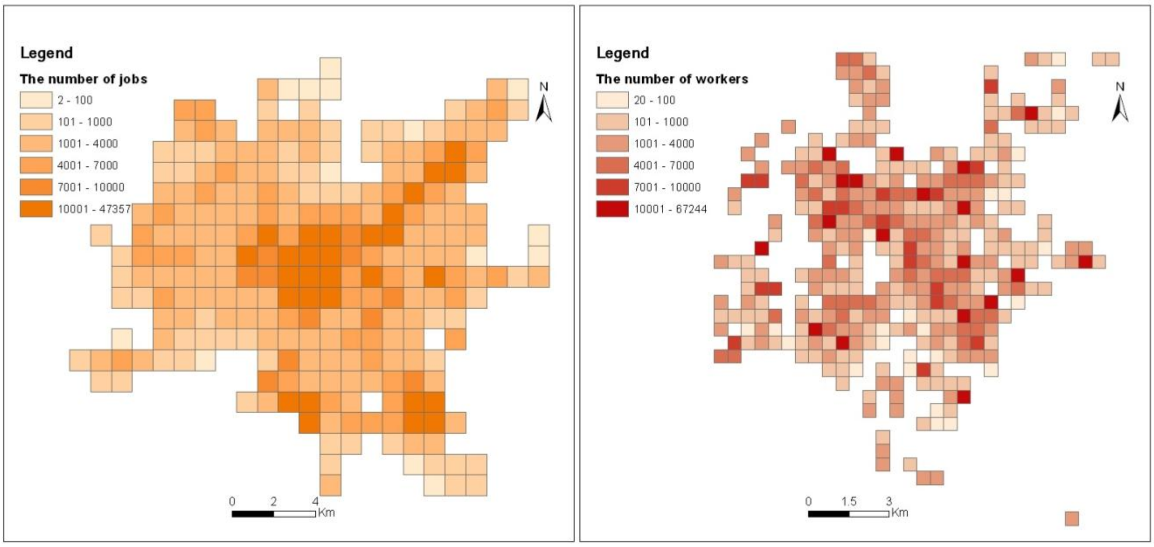


Figure 18 Aggregated number of jobs and workers

The base data has four types of slum or Chawl. And depending on the quality of houses (see Section 3.2) the urban poor is classified into three classes as Table 10 shows. Based on the suggestions from Talat Munshi[2] and (Ray, 2010), six kinds of job sectors are reclassified into three categories and every category of jobs corresponds to a certain level of poverty people (Table 10). Specifically, all kinds of job locations are 255.

2 An associate Professor in CEPT University

Either the very poor or middle poor people, there are 251 employment locations for them and 255 employment locations for the least poor. The number of worst quality of houses (i.e. Huts & Kutccha) is 351 and the worse houses (i.e. Semi-pucca) are 318 as well as the bad houses are 261. Then, this number of potential workers estimation is from the World Bank project (Zuidgeest et al., 2012), which assumes there are 2 potential workers in every kind of house. This research also has the data about 21 SEWSH (see Section 3.2) locations where people living can find all kinds of jobs.

House type	Poverty degree	Job type
Huts & Kutccha	Very poor	Transport & Storage, Small-scale industry
Semi-pucca	Middle poor	Retail, Medium-scale industry
Pucca	Least poor	Government sector, education jobs, jobs in hotels & boarding, office & commercial jobs, Large-scale industry

Table 10 Relationship between house and job type

5.1.2. Decay function and diversity factor

1) Time decay function

The time decay function is taken from the World Bank project. The report from that project mentions that when travel time is 30 minutes from worker location to employment location, 31% of workers are willing to go there, represented by taking 0.03838 as the beta parameter in the negative exponential function (Figure 19).

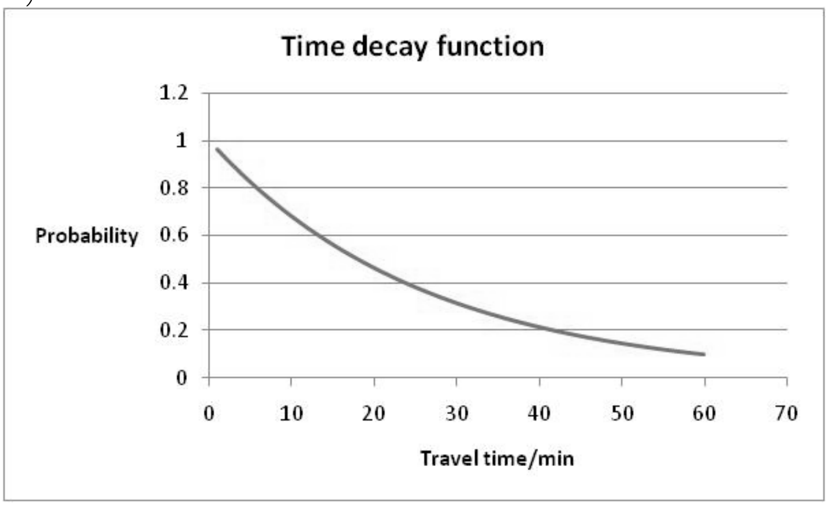


Figure 19 Time decay function

2) Fare decay function

For fare decay function, it is also the negative exponential function. As (Mahadevia et al., 2012) found, poor people in Ahmedabad wanted to spend less than 5 per cent of their total household expenditure on transport and 65% of households preferred not to spend anything on transport. Thus, this beta parameter is 0.52491 because only 35% of poor people could take public transport for travelling (Figure 20).

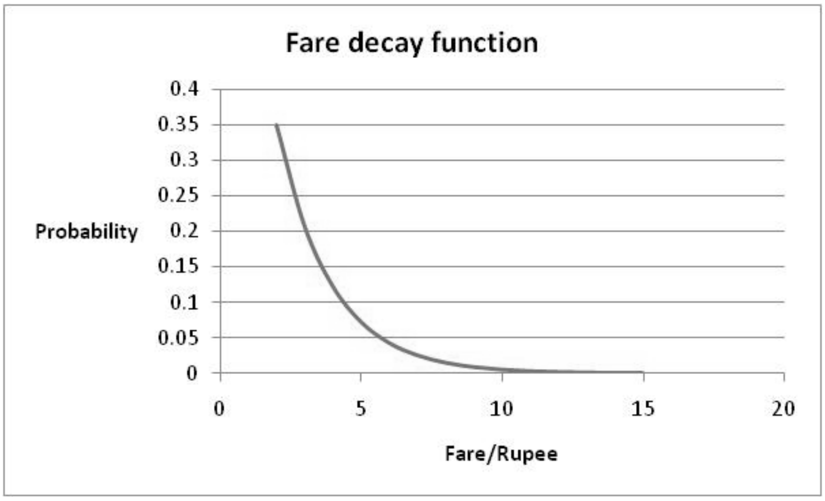


Figure 20 Fare decay function

The detailed fare structure of AMTS is in section 4.2.1. For BRTS and MRTS, both of them are under construction in Ahmedabad. According to the BRTS report (Ahmedabad Municipal Corporation et al., 2008), the fare of BRTS will be increased by 125% based on the fare of AMTS. Since Bus Rapid Transit is often regarded as the on-the-road metro because the character of BRT is very similar to the metro. Therefore, this research assumes that the MRTS has the same fare structure as that of BRTS in Ahmedabad.

3) Diversity factors

The diversity factors are 1 and there are two reasons. First, any scenario has the same number of job types for each employment location. So the diversity factor could have a little impact on the final results. And this research considers that the diversity of jobs is not an important factor to attract the workers, while the number of jobs is the key to attract poor people. Second, even though the diversity factor is treated as the elasticity for the attractiveness of a job location, the diversity is calculated by Eq. (1) derived from the entropy, which are not like factors like competition, decay function having the social meanings.

5.1.3. Road network

As section 3.4.2 shown, the road network of this research is 3D. And there are five travel modes in this network, which are walking, cycling, bus (AMTS), Bus Rapid Transit (BRTS) and metro (MRTS). Figure 21 is the current and under constucted public transport systems in Ahmedabad. This figure is made by the 2D view in order to show the network of every public transport clearly. The AMTS has a very developed network comparing to the BRTS and MRTS. Table 11, which is also from the World Bank project, is the related properties of every travel mode. The Access means that people spend how much time on waiting for a public transport and the Egress is the get-off time. The access and egress time are the impedance of links between two different travel modes.

Mode	**Speed** (km/h)	**Access** (min)	**Egress** (min)
Walking	3.5	N/A	N/A
Cycling	12	N/A	N/A
AMTS	15 - 20	10	1
BRTS	25	5	2
MRTS	35	3.75	2

Table 11 Properties of road network

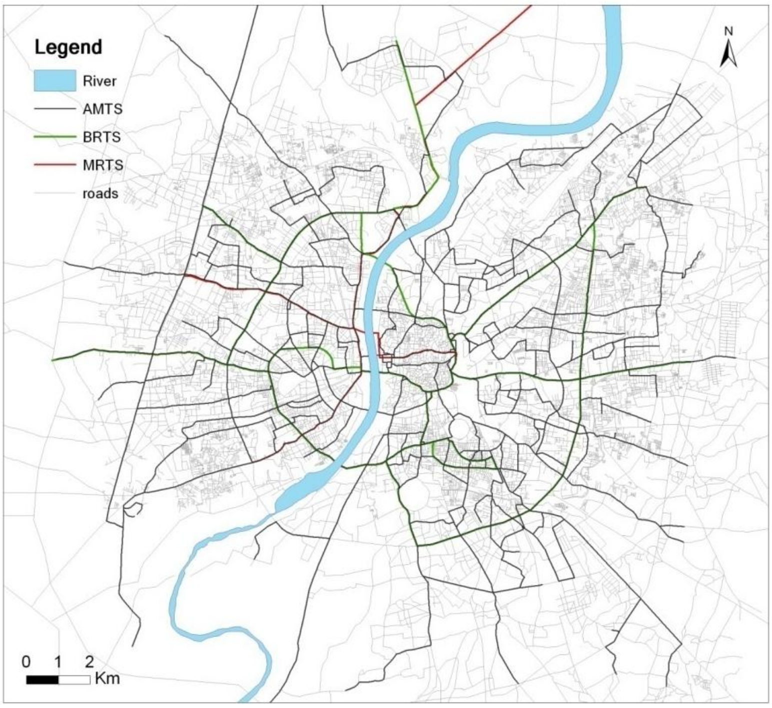


Figure 21 Public transport systems in Ahmedabad

5.1.4. Travel time threshold

There are two reasons for defining a travel time threshold. First, according to the decay function of Cheng's model, if the travel time is too large, the effect will be less, which affects the final results little. So it is not necessary to analyze those locations, which are too far away from the worker location. Second, Bhatt (2003) found the urban poor in Ahmedabad cycling10-12 km every day go to work. In other words, the poor people could travel around 60 minutes for commuting daily. Consequently, this research defines a travel time threshold for the urban poor, which is reasonable and good to increase the efficiency of calculation.

The travel time threshold is 60 minutes. But the time threshold of Network Analyst should be less than 60 minutes because of the intra-zone problem. Figure 22 shows the intra-zone problem in this research. In the Network Analyst, it is assumed that all of people living in the square cell have the same results as people in the centroid. In order to measure the accessibility objectively, the average intra-zone travel distance (i.e. Maximum intra-zone distance/2) and walking speed are used to compute the intra-zone travel time. This time is 20 minutes, including the travelling time in slum cell and employment cell. So the travel time threshold for Network Analyst is 40 minutes.

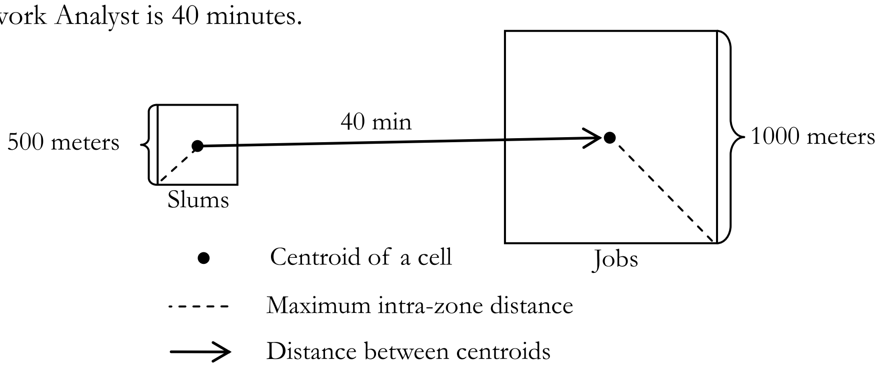


Figure 22 Intra-zone problem

5.1.5. Dwelling places change from Slums/Chawls to SEWSH

As section 3.2 mentioned, the government of Ahmedabad builds the SEWSH, which has better living environment and conditions. The 21 SEWSH locations are the new houses for the urban poor. Some poor people could change their living places from Slums/Chawls to SEWSH. However, if the job accessibility analysis is only for the 21 SEWSH locations, it must be biased from the reality using Cheng's model. That is because the poor people living in SEWSH don't only compete for jobs with themselves, they but also compete with the people who still live in Slums/Chawls. Therefore, if we want to measure the job accessibility of SEWSH, it is necessary to know which Slums/Chawls' poor people change their dwelling places to SEWSH. This research assumes that the dwelling changes for the poor people from Slums/Chawls to SEWSH depend on the Euclidean distance and the nearest Slums/Chawls to one SEWSH location has the highest priority. Due to the limited capacity of SEWSH, some poor people from Slums/Chawls will change their dwelling places as SEWSH but there are still remained poor people who still live in Slums/Chawls. Based on this assumption, the job accessibility analysis of SEWSH can reflect the effect of this housing project.

Figure 23 shows the results of dwelling changes. Compare to Figure 8, some Slums/Chawls locations nearby SEWSH locations disappear in Figure 23 (i.e. the hollow points) because all of the urban poor from these Slums/Chawls locations move to live in SEWSH. The poor people of some locations are divided into two parts. Some of them move to live in SEWSH and the remained people are still living in Slums/Chawls because of the limited capacity of SEWSH. Finally, the 353 worker locations and 21 SEWSH locations are merged together as 357 worker locations. The workers from 35 Slum/Chawl locations move to live in SEWSH locations. There are 17 Slums/Chawls disappeared after rearranging the worker locations. All of workers from the 17 locations move to live in SEWSH.

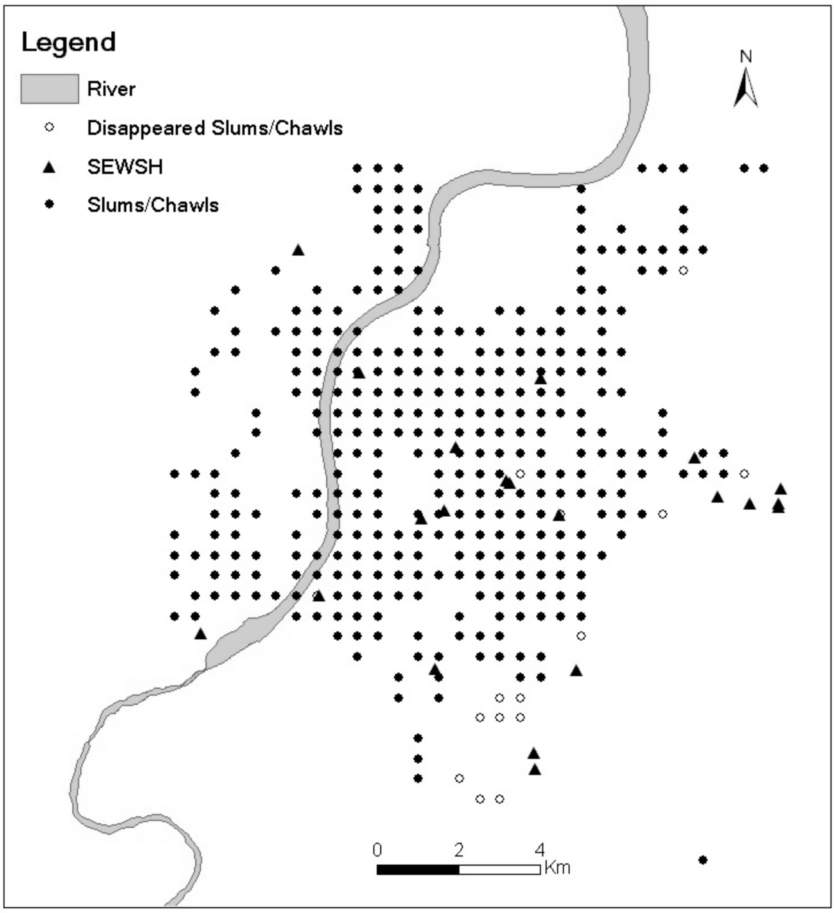


Figure 23 Slums/Chawls and SEWSH locations after changing dwelling places

5.2. Explanation about research scenarios

One of the research goals is to figure out the job accessibility of the urban poor in Ahmedabad and evaluate the effect of AMTS, BRTS, MRTS and SEWSH projects. This research defines the following the scenarios matrix (i.e. Table 12). For the combinations of travel modes, there are four options in this matrix and each combination has five kinds of workers to analyze according to the worker classification in section 5.1.1 and the dwelling changes described in section 5.1.5. The time and fare decay functions are also involved in the scenarios of three combinations of travel modes (i.e. except only walking).

Combination of travel modes	Worker classification	Decay function
Walking	Very poor	Only time decay function used
	Middle poor	
	Least poor	
	All poor[3]	
	Slums/Chawls to SEWSH[4]	
Walking AMTS	Very poor	Time and fare decay function used
	Middle poor	
	Least poor	
	All poor	
	Slums/Chawls to SEWSH	
Walking AMTS BRTS	Very poor	Time and fare decay function used
	Middle poor	
	Least poor	
	All poor	
	Slums/Chawls to SEWSH	
Walking AMTS BRTS MRTS	Very poor	Time and fare decay function used
	Middle poor	
	Least poor	
	All poor	
	Slums/Chawls to SEWSH	

Table 12 Research scenario matrix

According to this scenario matrix and previous data preparation, the following explanations are about the job accessibility and evaluation of the relevant projects.

5.3. Explanation about the Interpretation

This section has two parts. First, one specific example is chosen to do the detailed analysis, which can figure out how Cheng's model measures the job accessibility for the urban poor in Ahmedabad. Second, based on the first example, a method is proposed to interpret the result of Cheng's model. Before analyzing the results, some abbreviations are explained in Table 13.

Abbreviation	Explanation
W	Only walking
WA	Walking and AMTS used
WAB	Walking, AMTS, BRTS used
WABM	Walking, AMTS, BRTS and MRTS used

Table 13 Explanation about abbreviations

[3] All poor: All worker locations except SEWSH without changing the dwelling places
[4] Slums/Chawls to SEWSH: All worker locations after changing the dwelling places include SEWSH

5.3.1. Specific example exploration

This section analyzed the job accessibility for all worker locations (i.e. only Slums/Chawls except SEWSH) to all job locations when the combination of travel modes changes from W to WA. In order to formulate the interpretation method, this research selects one specific worker location from the result. This example is about worker location 1421, which job accessibility grows a lot from W to WA (i.e. from 1366 to 33928). Table 14 is the result by only walking. The workers from 1421 can reach 4 job locations, which are 369, 331, 368 and330. And only workers from 1421 go to these four job locations. Thus, the values of Opport are equal to that of All_job field because no one from other worker locations competes with workers from 1421 for jobs at these four job locations. And the final job opportunities are the sum of Opport field, which is 1366.

Name	Total_Time	WID	JID	All_job	Djobs	Jcomp	All_poor	Dworkers	Att_worker	Wcomp	Opport
1421 - 369	5.50823	1421	369	294	237.976966	.309490	1260	1019.901283	315.649127	.931414	294
1421 - 331	14.600186	1421	331	302	172.443886	.224264	1260	719.46787	161.350657	1.8717	302
1421 - 368	17.601468	1421	368	431	219.326999	.285236	1260	641.187978	182.889595	2.356613	431
1421 - 330	23.194254	1421	330	339	139.185093	.181011	1260	517.325125	93.641385	3.620194	339

Table 14 Results of worker location 1421 by walking

After using walking and AMTS together (i.e. WA), workers from 1421 can reach 8 job locations as Table 15 shown. Besides the previous four job locations, workers of this location can get new jobs from other employment locations (i.e. 444, 481, 443 and 555), which is the main contribution for job accessibility increasing.

Name	Total_Time	Shape_Length	WID	JID	All_job	Djobs	Jcomp	All_poor	Dworkers	Att_worker	Wcomp	Opport
1421 - 369	5.50823	321.313466	1421	369	294	237.976966	.015438	1260	1019.901283	15.745437	13.902385	218.899124
1421 - 331	14.600186	851.677504	1421	331	302	172.443886	.011187	1260	719.46787	8.04861	37.522009	302
1421 - 368	17.601468	1026.752222	1421	368	431	219.326999	.014228	1260	641.187978	9.12303	47.243074	431
1421 - 330	23.194254	1352.998126	1421	330	339	139.185093	.009029	1260	517.325125	4.671087	72.574114	339
1421 - 444	27.234526	2969.907562	1421	444	2380	836.808009	.054286	1260	443.016005	24.049547	25.05127	602.471685
1421 - 481	32.53428	4469.385148	1421	481	21701	6225.742385	.403880	1260	361.478061	145.993912	17.904694	2613.976284
1421 - 443	38.385911	4151.455356	1421	443	29391	6735.804532	.436970	1260	288.765735	126.181821	232.925787	29391
1421 - 555	38.93594	7932.829257	1421	555	3777	847.52806	.054981	1260	282.733745	15.545095	1.937478	30.118278

Table 15 Results of worker location 1421 by walking and AMTS

For the previous four job locations (i.e. 369, 331, 368 and330), only job location 369 attracts another three worker locations as Table 16 shows, which are 2097, 2172 and 2247. So some jobs from 369 are distributed to other worker locations by WA, while these jobs originally belong to worker location 1421 by walking (i.e. W). The workers from 1421 get fewer jobs from 369 when the combination of travel modes changes from W to WA. But workers from 1421 can get much more jobs from other job locations by WA.

Specifically, the number of job opportunities for 1421 worker location is determined by the number of attracted workers and the competition among workers according to Eq. (4) (The specific explanation is the third step of second phase in section 4.3.1). It is interesting that the competition among workers (i.e. Wcomp field) in job location 369 doesn't cause the job accessibility decreasing for 1421 worker location because the Wcomp by W is 0.93 and Wcomp by WA is 13.90. So this increase from 0.93 to 13.90 means more jobs for every worker at location 1421 and it can't cause the decrease of job accessibility. The main reason to cause the job opportunities decreasing for 1421 location is the number of attracted workers (i.e. Att_worker field) at job location 369 declining from 315.65 (see Table 14) to 15.75 (see Table 15). It means that fewer workers want to find jobs at job location 369, which results from the attractiveness of 369 (i.e. Jcomp field/competition among jobs) decreasing from 0.309 (see Table 14) to 0.015 (see Table 15). So the 369 employment location offering fewer jobs for worker location 1421 is caused by the two-side competition and the two-side competition is determined by the Network Analyst, which influences how many worker locations compete for one job location and vice versa.

Name	Total_Time	Shape_Length	WID	JID	All_job	Djobs	Jcomp	All_poor	Dworkers	Att_worker	Wcomp	Opport
1421 - 369	5.50823	321.313466	1421	369	294	237.976966	.015438	1260	1019.901283	15.745437	13.902385	218.899124
2097 - 369	38.767674	7123.360392	2097	369	294	66.39863	.001691	12964	2927.863407	4.951317	13.902385	68.83511
2172 - 369	38.730381	7872.698727	2172	369	294	66.493736	.001625	568	128.464088	.208780	13.902385	2.902541
2247 - 369	37.918089	8231.512146	2247	369	294	68.599381	.001878	552	128.798838	.241917	13.902385	3.363226

Table 16 Results of job location 369 by walking and AMTS

Through this detailed analysis, we can see it is very complex to interpret the result for every worker location. The result interpretation, therefore, should be from the overall view for all worker locations like section 4.4.4 concluded. In 353 worker locations, 214 locations can get more jobs and other 139 locations lose some opportunities from W to WA. The AMTS can improve 60.6% of worker locations' job accessibility. For the improved worker locations (i.e. 214 locations), they can get 233562 more jobs by WA. The number of their job opportunities increases 43.4% by WA comparing to the number of their jobs by W (i.e. 537681).

5.3.2. Interpretation method

Based on the previous section analysis and the conclusion from section 4.4.4, this research formulates the following equations for interpretation:

$$V = A_{i,j,k} - A_{i',j',k'} \tag{10}$$

$$Pv = \mathrm{V}/A_{i',j',k'} \tag{11}$$

$$PI = n_{i,j,k-i',j',k'}/N_{i',j',k'} \tag{12}$$

Eq. (10): V is the accessibility difference of every worker location between two different scenarios, A is the number of job opportunities of every worker location from different scenarios, i and i' are the five kinds of worker locations (i.e. Worker classification of Table 12), j and j' are the four combinations of travel modes (i.e. Combination of travel modes in Table 12), k and k' are two different decay functions (i.e. Decay function of Table 12). So $i,\ j,\ k,\ i',\ j',\ k'$ indicate which scenario is analyzed.
Eq. (11): Pv is the percent of variation of job accessibility for every worker location between two different scenarios. The other variables are the same as Eq. (10)
Eq. (12): PI is the percent of improvement of job accessibility for all analyzed worker locations, n is the number of positive V or Pv, N is the total number of analyzed worker locations, $i,j,k-i',j',k'$ is the label of comparison between which two scenarios, $i,\ j,\ k,\ i',\ j',\ k'$ are the same as Eq. (10)

If the result of equation (10) or (11) is positive for one worker location, the job accessibility of second scenario (i.e.$A_{i,j,k}$) is higher than the job accessibility of first scenario (i.e. $A_{i',j',k'}$) and vice visa. The number of positive value V or Pv is more, the better of second scenario is. The core ideas about job accessibility analysis in Ahmedabad are the above explanations.

5.4. Accessibility results

Although there are lots of results produced based on the scenarios (i.e. Table 12), this research chooses the important and useful results discussed in this section, which is divided into four parts. The first part is about the job accessibility of all workers and jobs, which finds out the effect of different public transport modes on all poor people. The second part is about the job accessibility for three classes of poor people. The third part is about the effect of SEWSH. It is to analyze the job accessibility if the poor people change their dwelling places as section 5.1.5 shown.

5.4.1. Job accessibility of all worker locations

This section has two parts, which are about the job accessibility of all worker locations. The first part is to compare the job accessibility among different transport scenarios and find the best combination of travel modes to improve the job accessibility for the urban poor. The second part is to compare the differences between fare and time decay function for the job accessibility of all the worker locations.

1) The best travel mode for improving job accessibility

In order to find the most efficient travel mode for improving accessibility, this section compares three combinations of travel modes with two different decay functions. Figure 24 is the job accessibility from

Cheng's model when the time decay function is used. The left top map is the results by W[5] and the right top map is the results by WA. The biggest map is about the comparison between the above two maps. Specifically, the comparison formula is from Eq. (10) and Eq. (11):

$$Pv = (A_{All\ poor\ ,WA,Time\ decay} - A_{All\ poor\ ,W,Time\ decay})/A_{All\ poor\ ,W,Time\ decay} \quad (13)$$

The biggest map shows the accessibility of some worker locations decrease, while other locations increase from W to WA. We can't judge whether the WA is better than W by the map. Consequently, according to the interpretation method from section 5.3.2, this research makes Table 17, which is the Percent of improvement from Eq. (12). And there are three scenarios in this table, which are changing the combination of travel modes from W to WA (only using time decay function), and from WA to WABM (using time decay and fare decay function separately). The combination of travel modes changes from W to WA or from WA to WABM, the Percent of improvement of three scenarios is around 60% and there is a little difference. So we can't find which combination of travel modes is the best for improving job accessibility. But most of worker locations can get more job opportunities when the AMTS, BRTS and MRTS are provided.

Scenarios	Percent of improvement (PI)
W-WA (time decay)	60.6%
WA-WABM (time decay)	59.5%
WA-WABM (fare decay)	61.3%

Table 17 Comparison among W, WA and WABM for all worker locations

Explanation of Table 17 and Table 18:

W-WA: the scenario changes from W to WA, which is the effect of AMTS. W is the first scenario and WA is the second one.

WA-WANM: the scenario changes from WA to WABM, which measures the effect of BRTS and MRTS. WA is the first scenario and WABM is the second one.

In the following sections, W-WA and WA-WABM has the same meaning as them in Table 17

In order to find the most efficient combination of travel modes, Table 18 shows the total number of jobs increase for the worker locations where job accessibility improved. It is evident that no matter which kind of decay function, the AMTS is most efficient public transport and it can make the jobs increase 43.4% comparing to the number of jobs accessed by only walking (i.e. W). For BRTS and MRTS, although both travel modes can improve the job accessibility, the effect is not good as that of AMTS. That is because the number of jobs only increases around 3.5% when the combination of travel modes changes from WA to WABM.

	Total number of increased job opportunities	Increased percent
W-WA (time decay)	233562	43.4%
WA-WABM (time decay)	21044	3.5%
WA-WABM (fare decay)	24138	3.6%

Table 18 Number of increased job opportunities between different combinations of travel modes

[5] W, WA, WAB and WABM are explained in Table 13 at the beginning of section 5.3

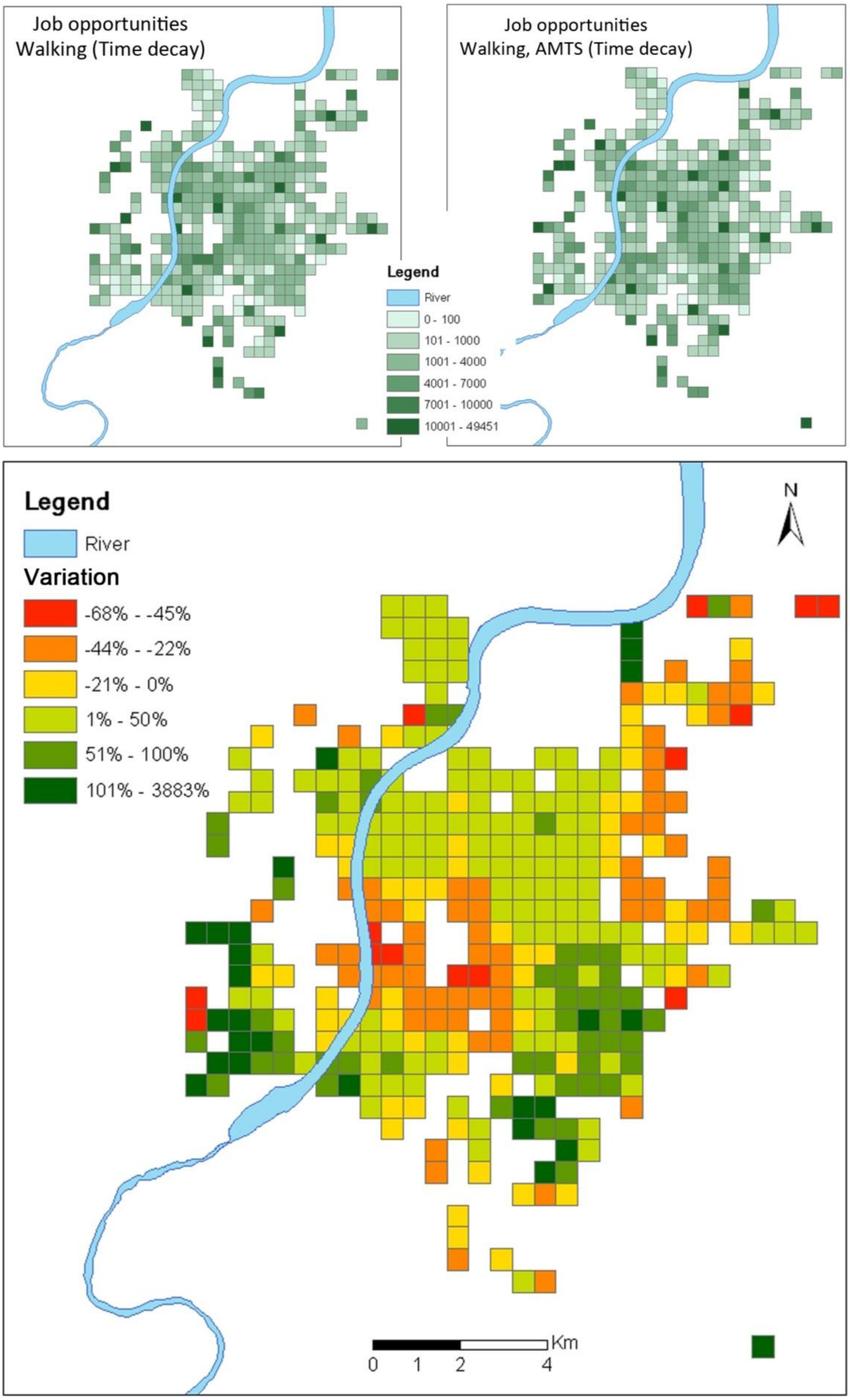


Figure 24 Comparison job opportunities of only walking with that of walking and AMTS[6]

[6] Variation is defined as the equation (13) in section 5.4.1

2) The effect of time and fare decay function

The top two maps of Figure 25 are the job opportunities with time and fare decay function using all travel modes (i.e. WABM). The biggest picture is the difference between the top two maps and it is also calculated by the equation (10) and (11).

$$Pv = (A_{All\ poor\ ,WABM\ ,Fare\ decay} - A_{All\ poor\ ,WABM\ ,Time\ decay})/A_{All\ poor\ ,WABM\ ,Time\ decay} \tag{14}$$

Like previous section shown, we can't evaluate the effect of two decay functions only through Figure 25. So we use the equation (12) (i.e. PI). There two kinds of combinations of travel modes (i.e. WA and WABM) generating the fare. So the comparisons have two formulas:

$$PI_{WA} = n_{All\ poor\ ,WA,Fare\ decay\ -All\ poor\ ,WA,Time\ decay} / N_{All\ poor\ ,WA,Time\ decay} \tag{15}$$

$$PI_{WABM} = n_{All\ poor\ ,WABM\ ,Fare\ decay\ -All\ poor\ ,WABM\ ,Time\ decay} / N_{All\ poor\ ,WABM\ ,Time\ decay} \tag{16}$$

The Percent of improvement values of these two scenarios (i.e. PI_{WA} and PI_{WABM}) are around 43.0%. It means around 43.0% of worker locations can get more jobs when change the time decay function as fare decay function. So 57% of worker locations lose some job opportunities because the time and fare decay function have different effects for distributing jobs. And we can conclude that more than 50% of worker locations are sensitive to the fare.

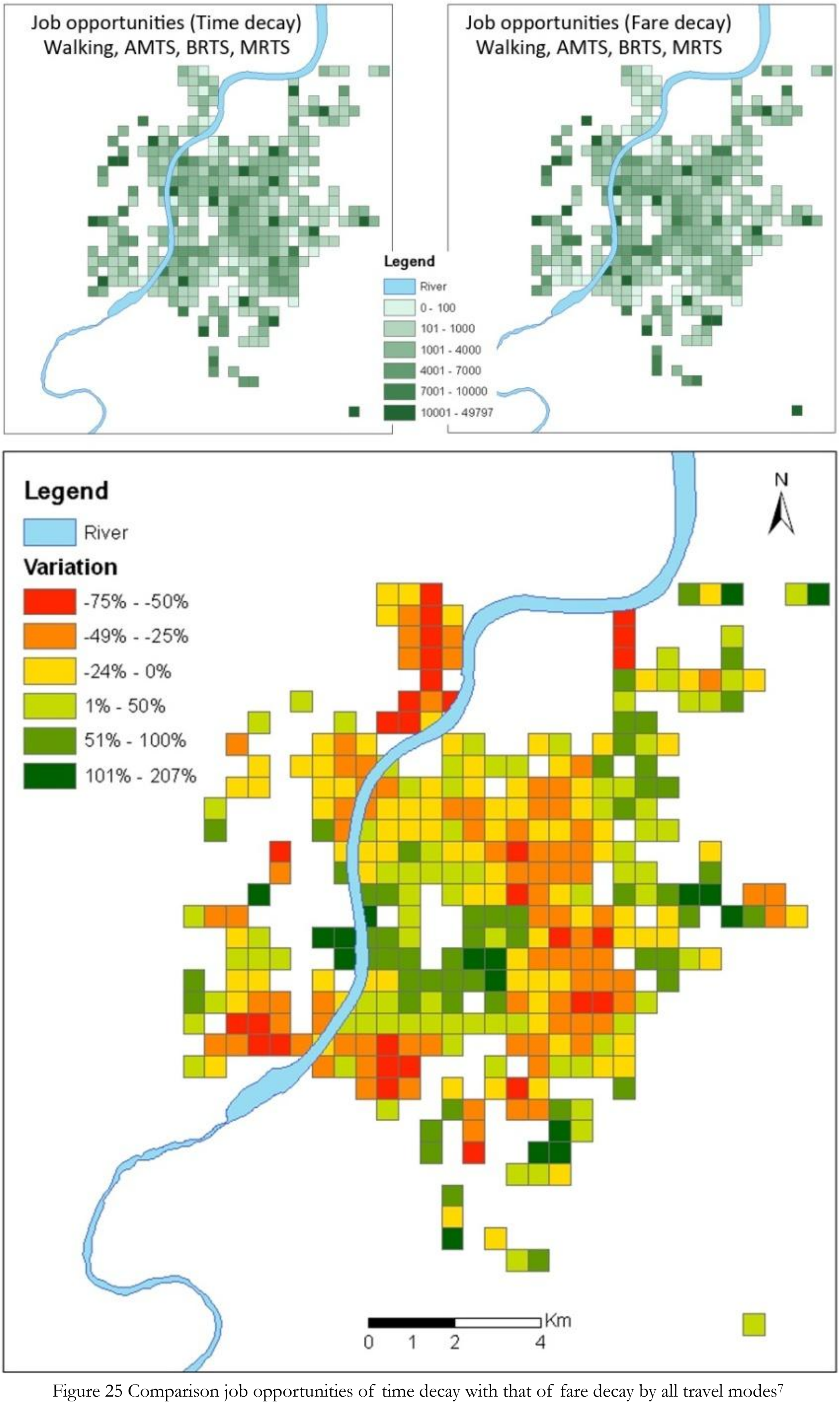


Figure 25 Comparison job opportunities of time decay with that of fare decay by all travel modes[7]

[7] Variation is defined as the equation (14) in section 5.4.1.

5.4.2. Job accessibility of three levels of poor people

The following explanation chooses the average number of reachable job locations and job opportunities to analyze accessibility in Ahmedabad. It can show which class of poor people has more jobs.

From the left side of Figure 26, we can see that if there is one more travel mode, the number of reachable employment locations increases. The significant increment is between W and WA, while there is a little increment among WA, WAB and WABM. For one certain combination of travel modes, the number of reachable job locations has tiny variations among three levels of poor people.

Let's explore the detailed information from the right side of Figure 26. The average number of job opportunities grows obviously between W and WA. From WA to WAB, the increment is a little, while there is no significant variation between WAB and WABM. For the three different categories of poor people in one combination of travel modes, the very poor people has the least job chances and the other two kinds of people (i.e. the middle poor and least poor) can get much more opportunities. Moreover, the least poor people have more jobs than that of the middle poor people.

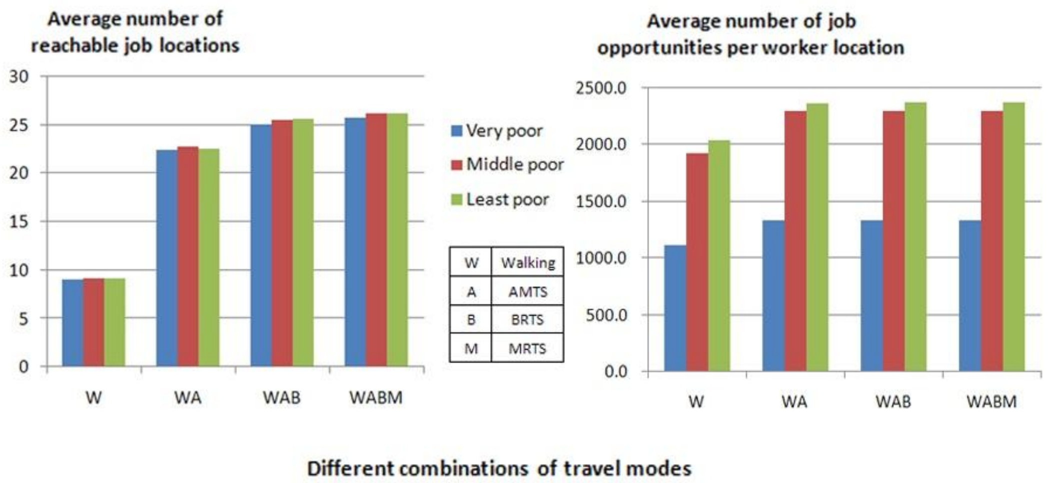


Figure 26 Average job opportunities for three levels of poor people

The above analysis is somehow like the cumulative analysis and there are two reasons. First, the number of reachable job locations doesn't include the competition and decay factor. Second, the average number of job opportunities for every worker location doesn't reflect the competition and decay factor. That is because the competition and decay factor can be reflected by the job accessibility of every single worker location so the sum of jobs is like the cumulative measure. The average number of job opportunities is from the sum of all the jobs divided by the number of worker locations. So the above analysis is like cumulative measure, which is to show the difference about the number of jobs among three classes of poor people.

And then the following sections discuss the job accessibility of three levels of poor people with competition and decay factor. The key point is also to use the interpretation method in section 5.3.2. The first part is the comparison among W, WA and WABM using time decay function. The second part is about the effect of fare decay function for three levels of poor people and the comparison between time and fare decay function for the three classes of poor people

1) The effect of different travel modes with time decay function

Figure 27 is the job accessibility variation between different combinations of travel modes. This figure shows the Percent of improvement for three levels of poor people by different combinations of travel modes with time decay function. Table 19 is the specific explanation about Figure 27.

Scenarios	Bar color in Figure 27	Equations
W-WA	Blue bar	$PI_{blue} = n_{Very\ poor,WA,Time\ decay - Very\ poor,W,Time\ decay} / N_{Very\ poor,W,Time\ decay}$
	Red bar	$PI_{red} = n_{Middle\ poor,WA,Time\ decay - Middle\ poor,W,Time\ decay} / N_{Middle\ poor,W,Time\ decay}$
	Green bar	$PI_{green} = n_{Least\ poor,WA,Time\ decay - Least\ poor,W,Time\ decay} / N_{Least\ poor,W,Time\ decay}$
WA-WABM	Blue bar	$PI_{blue} = n_{Very\ poor,WABM,Time\ decay - Very\ poor,WA,Time\ decay} / N_{Very\ poor,WA,Time\ decay}$
	Red bar	$PI_{red} = n_{Middle\ poor,WABM,Time\ decay - Middle\ poor,WA,Time\ decay} / N_{Middle\ poor,WA,Time\ decay}$
	Green bar	$PI_{green} = n_{Least\ poor,WABM,Time\ decay - Least\ poor,WA,Time\ decay} / N_{Least\ poor,WA,Time\ decay}$

Table 19 Explanations about Figure 27

For the scenario of W-WA, the very poor people has the largest Percent of improvement (i.e.71.8%), while it is 64.1% but still the largest one in the scenario of WA-WABM. In both of scenarios, the Percent of improvement for the middle poor and least poor are a little over 61%. We can find that AMTS, BRTS and MRTS can improve most of the poor people's job accessibility a lot, because all the values of Figure 27 are more than 50%.

The Percent of improvement of very poor people in the scenario of W-WA is higher than the Percent improvement of the very poor in the scenario of WA-WABM. So the AMTS is the most efficient travel mode to improve the job accessibility for the very poor people. For the middle poor, the Percent of improvement doesn't increase or decrease when the scenario changes from W-WA to WA-WABM. And the least poor is the same as the middle poor people. The AMTS has the same affect of BRTS and MRTS on the urban poor except the very poor people.

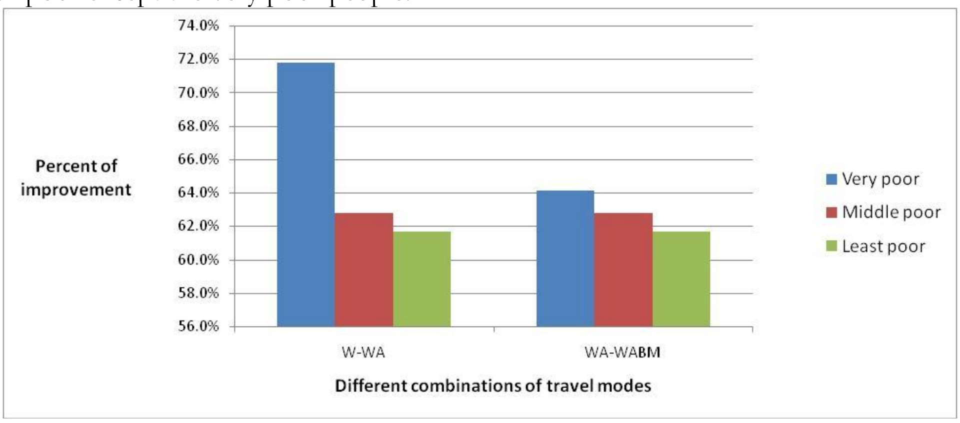


Figure 27 Improvement of job accessibility for different poor classes with time decay function

Although AMTS, BRTS and MRTS can help the most of worker locations to increase the job accessibility, AMTS can bring more job opportunities comparing to BRTS and MRTS. Figure 28 is the percent of increased job for three classes of people when the combination of travel modes is changed. In this figure, the percent of increased job of W-WA is much larger than that of WA-WABM.

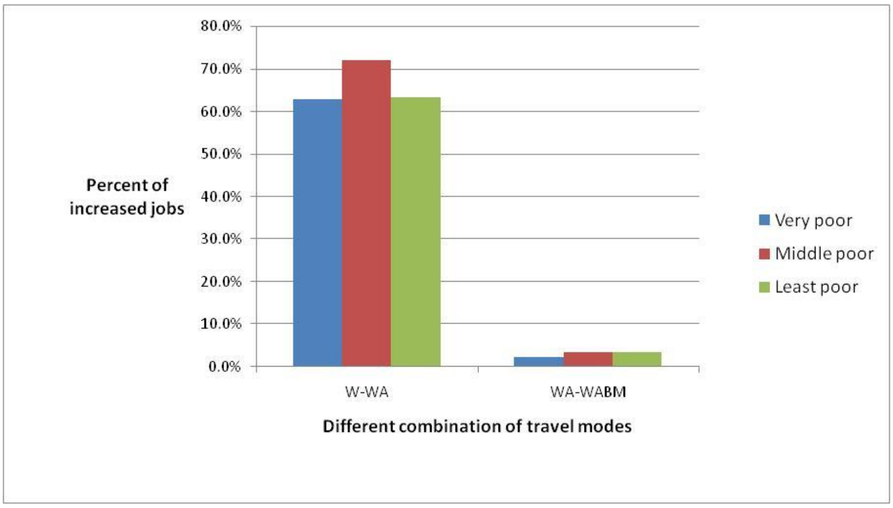


Figure 28 Percent of increased jobs for three levels of poor people

2) The effect of different travel modes with fare decay function

The previous part discussed about the job accessibility variation with time decay function for the three categories of poor people. Then, the job accessibility variation with fare decay function is shown in this part. Table 21 is calculated from the interpretation Eq. (12) (i.e. the Percent of improvement). Table 20 is the specific equations for calculating Table 21.

Scenarios	Poor level	Equations
WA-WABM	Very poor	$PI_1 = n_{Very\ poor,WABM,Fare\ decay - Very\ poor,WA,Fare\ decay} / N_{Very\ poor,WA,Fare\ decay}$
	Middle poor	$PI_2 = n_{Middle\ poor,WABM,Fare\ decay - Middle\ poor,WA,Fare\ decay} / N_{Middle\ poor,WA,Fare\ decay}$
	Least poor	$PI_3 = n_{Least\ poor,WABM,Fare\ decay - Least\ poor,WA,Fare\ decay} / N_{Least\ poor,WA,Fare\ decay}$

Table 20 Explanation about Table 21

In Table 21, the Percent of improvement of the three levels of poor is around 58% and the difference is a little among these three classifications. So we can conclude that BRTS and MRTS can improve most of three levels of poor people's job accessibility. However, BRTS and MRTS can bring few of new jobs for those locations where the job accessibility is improved. As Table 22 shows, the percent of increased job is only around 4%.

Poor level	Percent of improvement (WA-WABM)
Very poor	59.0%
Middle poor	58.0%
Least poor	56.3%

Table 21 Improvement of job accessibility for three levels of poor people with fare decay function

	Very poor	Middle poor	Least poor
Percent of increased jobs (WA-WABM)	3.7%	4.2%	3.9%

Table 22 Percent of increased jobs for three levels of poor people

3) The effect of time and fare decay function

In order to figure out the difference between time and fare decay function, Figure 29 shows that the Percent of improvement comparing time decay function to fare decay function. The Percent of improvement value is still calculated by the interpretation equation (12) and Table 23 is the specific formulas for Figure 29.

Scenarios	Bar color in Figure 29	Equations
WA	Blue bar	$PI_{blue} = n_{Very\ poor,WA,Fare\ decay - Very\ poor,WA,Time\ decay} / N_{Very\ poor,WA,Time\ decay}$
	Red bar	$PI_{red} = n_{Middle\ poor,WA,Fare\ decay - Middle\ poor,WA,Time\ decay} / N_{Middle\ poor,WA,Time\ decay}$
	Green bar	$PI_{green} = n_{Least\ poor,WA,Fare\ decay - Least\ poor,WA,Time\ decay} / N_{Least\ poor,WA,Time\ decay}$
WABM	Blue bar	$PI_{blue} = n_{Very\ poor,WABM,Fare\ decay - Very\ poor,WABM,Time\ decay} / N_{Very\ poor,WABM,Time\ decay}$
	Red bar	$PI_{red} = n_{Middle\ poor,WABM,Fare\ decay - Middle\ poor,WABM,Time\ decay} / N_{Middle\ poor,WABM,Time\ decay}$
	Green bar	$PI_{green} = n_{Least\ poor,WABM,Fare\ decay - Least\ poor,WABM,Time\ decay} / N_{Least\ poor,WABM,Time\ decay}$

Table 23 Explanation about Figure 29

In Figure 29, the PI (i.e. Percent of improvement) of the very poor is the least one in the scenario of WA and WABM. For the middle poor and least poor, the PI is similar and larger. According to this result, the very poor people values the fare more other classes of poor people. But the fare decay function still has the negative effect on the approximate half (i.e. around 55%) of middle poor and least poor worker locations.

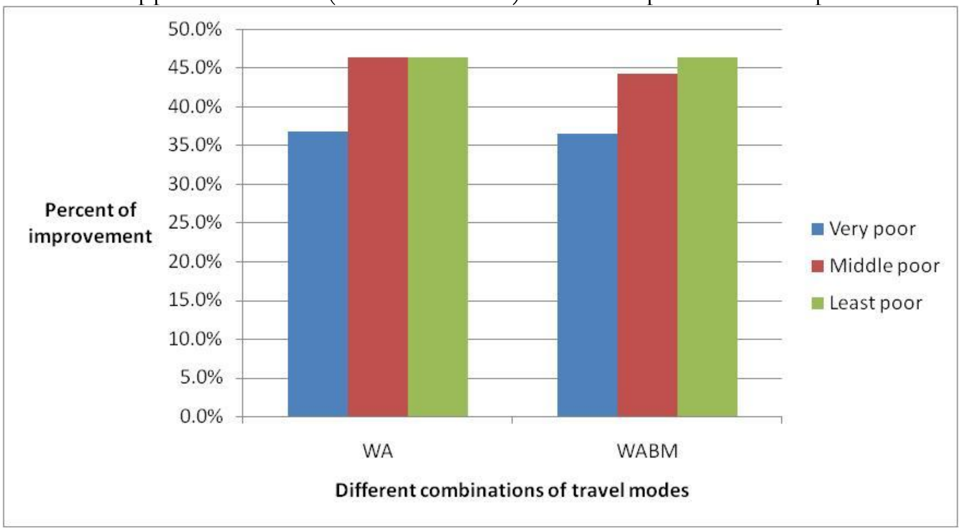


Figure 29 Improvement of job accessibility for three levels of poor people with fare decay function

5.4.3. Job accessibility of SEWSH locations

This section studies the job accessibility with the rearranged worker locations as section 5.1.5 described (i.e. some workers' dwelling places are changed from Slums/Chawls to SEWSH). First, it is to illustrate three kinds of results and related terms used in this section:

(a) The job accessibility of original Slums/Chawls:

This result is the job accessibility of Slums/Chawls without changing dwelling places. The accessibility analysis doesn't include SEWSH locations but involves all of Slums/Chawls. This result has been discussed in the previous sections. This section only chooses the result of 35 Slums/Chawls in which some workers or all of workers change their living places as SEWSH. These job accessibility results are for the comparison discussed in the following section.

(b) The job accessibility (i.e. opportunities) of SEWSH

This analysis adopts the rearranged worker locations. The worker locations include SEWSH and a part of Slums/Chawls, in which not all of workers and none workers move to live in SEWSH. So the rearranged worker locations don't involve some Slums/Chawls where all of workers move to live in SEWSH. This research assumes that these Slums/Chawls are disappeared as Figure 23 shown in section 5.1.5.

(c) The job accessibility of remained Slums/Chawls

For modifying worker locations from Slums/Chawls to SEWSH, only a part of workers of some Slums/Chawls changes their dwelling places as the SEWSH. This kind of Slums/Chawls is denoted as the remained Slums/Chawls. Therefore, the job accessibility analysis for the remained Slums/Chawls also uses the rearranged worker locations.

Furthermore, in order to compare the job accessibility of SEWSH to the job accessibility of the remained and original Slums/Chawls, this research defines the comparative indicator:

$$C_i = O_i / W_i \tag{17}$$

Eq. (17): C_i is the comparative indicator at location i, O_i is the number of job opportunities of the worker location i calculated by Cheng's model, W_i is the number of workers at worker location i. The reason for defining the comparative indicator is that one SEWSH can have workers, who live in different original Slums/Chawls. In this case, it is hard to evaluate the effect of SEWSH. For example, there are 150 workers living at location A and their job accessibility is 100 opportunities. For worker location B, it has 200 workers and the accessibility is 500 jobs. After the SEWSH 1 built up, 100 workers of A change their houses as SEWSH 1 and all the workers of B (i.e. 200) also move to live in SEWSH 1. The job accessibility of SEWSH 1 is 600 opportunities. We can't use the original job accessibility of A (i.e. 100 jobs) and B (i.e. 500 jobs) to compare to the job accessibility of SEWSH 1 because the number of workers are different for SEWSH, location A and B.

However, if we adopt the comparative indicator (i.e. formula (17)), it is easy to show the effect of changing living places, because this indicator reflects the number of jobs for every worker. The comparative indicator of original A and B is 0.67 (i.e. 100/150) and 2.5 (i.e. 500/200) respectively, while the indicator of SEWSH 1 is 2 (i.e. 600/(100+200)), which is higher than that of A and lower than of that of B. So workers of A had better move to live in SEWSH, which can increase the job accessibility of every worker from 0.67 to 2. By contrast, for workers of B, moving to live in SEWSH 1 is not good because the comparative indicator decreases from 2.5 to 2.

Subsequently, this research adjusts the interpretation Eq. (10) and (12) for analyzing the effect of SEWSH. And the following formulas combine the comparative indicator with the interpretation equations.

$$V_{SR} = C_{SEWSH,j,k} - C_{Remained\ ,j',k'} \tag{18}$$

$$V_{SO} = C_{SEWSH,j,k} - C_{Original\ ,j',k'} \tag{19}$$

$$PI_{SR} = n_{SEWSH,j,k-Remained\ ,j',k'} / N_{\text{Remained}\ ,j',k'} \tag{20}$$

$$PI_{SO} = n_{SEWSH,j,k-Original\ ,j',k'} / N_{\text{Original}\ ,j',k'} \tag{21}$$

Eq. (18) and (19): both of V_{SR} and V_{SO} are the comparative indicator difference between two different scenarios. j and j' are the four combinations of travel modes, k and k' are two different decay functions, $C_{SEWSH,j,k}$ is the comparative indicator of SEWSH location, $C_{Remain\ ed,j',k'}$ is the comparative indicator of the remained Slums/Chawls locations (i.e. where a part of remained poor people doesn't change their dwelling places to SEWSH). C_{SEWSH} and $C_{Remained}$ are calculated with the rearranged dwelling places for the urban poor. $C_{Original\ ,j',k'}$ is the comparative indicator for the original Slums/Chawls locations, which is calculated without changing dwelling places (i.e. it only analyzes the job accessibility for original Slums/Chawls except SEWSH).

Eq. (20) and (21): PI_{SR} and PI_{SO} are the percent of improvement of job accessibility for the changed worker locations, $n_{SEWSH,j,k-Remained\ ,j',k'}$ and $n_{SEWSH,j,k-Original\ ,j',k'}$ is the number of positive V_{SR} and V_{SO} respectively, $N_{\text{Remained}\ ,j',k'}$ is the number of remained Slums/Chawls (i.e. the value is 18 as section 5.1.5 explained), $N_{\text{Original}\ ,j',k'}$ is the number of original Slums/Chawls (i.e. the value is 35 as section 5.1.5 explained).

1) The job accessibility comparison between SEWSH and the remained Slums/Chawls

According to the above definitions, if the V_{SR} is a positive value, which means the job accessibility of SEWSH is better than the accessibility of corresponding remained Slums/Chawls and vice versa. So more positive values of V_{SR} is, the better of SEWSH is. In other words, if the Percent of improvement (i.e. PI_{SR}) is bigger, the effect of SEWSH is better.

Figure 30 is the Percent of improvement for comparing the effect of SEWSH to remained Slums/Chawls. For the time decay scenario (i.e. the black bar in Figure 30), all of the values are above 50%. Thus, the SEWSH locations are better to improve accessibility comparing to the remained Slums/Chawls. Meanwhile, we can find the black bar increases from using W to using WA and there is no variation between the scenario of WA and WABM. However, for the scenario of fare decay function (i.e. the grey bar in Figure 30), the Percent of improvement decreases from using WA to using WABM. Then, we can conclude that the AMTS is the most efficient one to improve the job accessibility, because for the scenario of time or fare decay function, adding BRTS and MRTS as two more travel modes doesn't increase the Percent of improvement. The other conclusion is that the urban poor are very sensitive to the fare decay function due to the Percent of improvement decreasing between WA and WABM with fare decay function.

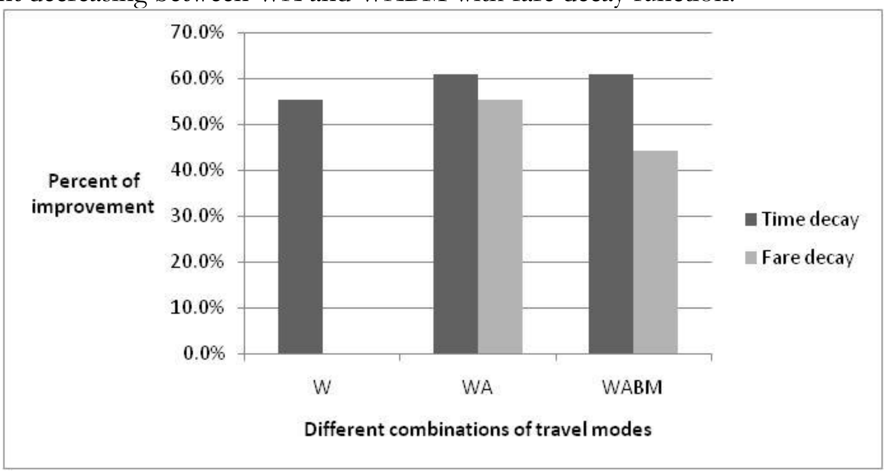


Figure 30 Comparison between SEWSH and remained Slums/Chawls[8]

[8] The walking is not related to fares so the W doesn't have the scenario of fare decay function.

2) The job accessibility comparison between SEWSH and the original Slums/Chawls

Like V_{SR}, if V_{SO} is the positive value, the job accessibility of SEWSH is higher than the accessibility of corresponding original Slums/Chawls and vice versa. The more positive values of V_{SO} indicate the effect of SEWSH better for improving job accessibility. Figure 31 is about the job accessibility of SEWSH and the 35 original Slums/Chawls based on the Eq. (21)

Figure 31 shows the Percent of improvement (i.e. PI_{SO}) by W is the largest in the scenario of time decay function. There is a little decrease between W and WA for the black bar, because the spatial distribution of SEWSH locations is relative dispersion comparing to the 35 original Slums/Chawls. So workers of SEWSH can reach more employment locations. Meanwhile, the competition on workers and jobs is not high due to limited walking speed. However, when using AMTS analyzes the job accessibility, the two-side competition changes a lot because more people can reach one employment location. So the competition factors and SEWSH spatial locations lead to the job accessibility decreasing. For the scenario of fare decay function (i.e. grey bar), the Percent of improvement is the same between WA and WABM. But the Percent of improvement in the scenario of fare decay function is much lower than that of time decay function. Similarly to the previous interpretation, the urban poor are very sensitive to the fare. The other important conclusion is that SEWSH is a good housing project to improve the job accessibility for the urban poor and this housing project has a synergy with BRTS and MRTS because the Percent of improvement increases when the combinations of travel modes change from WA to WABM in the scenario of time decay function.

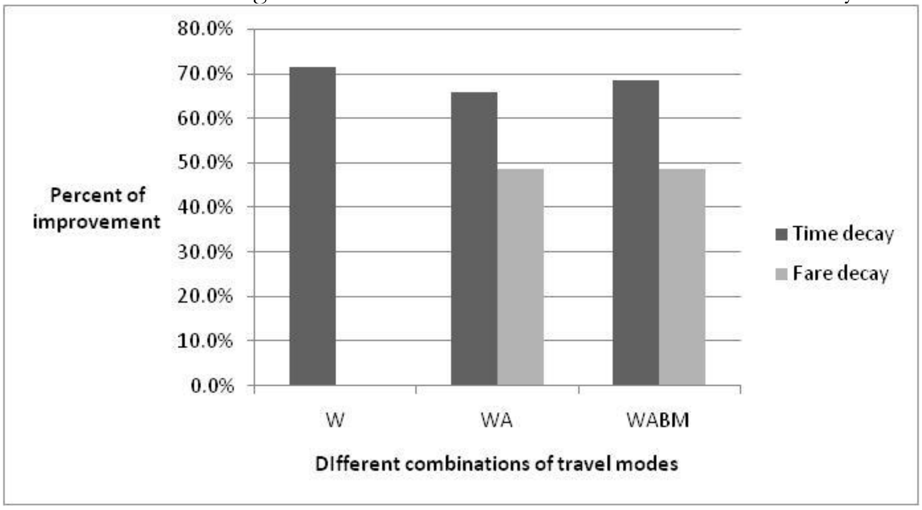


Figure 31 Comparison between SEWSH and original Slums/Chawls[9]

In a word, if the time decay function is used, people living in SEWSH can get better job accessibility by any kind of combination of travel modes comparing to living in Slums/Chawls. However, when the fare decay function is adopted, the job accessibility of most SEWSH locations decreases a lot. Particularly, adding BRTS and MRTS in the fare decay scenario reduces the job opportunities for most of SEWSH locations. By contrast, in the time decay scenario BRTS and MRTS can further improve the most of SEWSH locations' accessibility. So the urban poor value the fare more than travel time based on the result.

[9] The walking is not related to fares so the W doesn't have the scenario of fare decay function.

6. CONCLUSIONS AND RECOMMENDATIONS

The general conclusions are given in this chapter. They include the findings about the Python scripting in ArcGIS and describe the results of using Cheng's model for urban planning. Following, this chapter provides some recommendations for the further studies, including a discussion on the contents of the programming, the improvement of Cheng's model and the competition-based job accessibility analysis.

6.1. Conclusion

This research aimed at implementing and adapting Cheng's model in ArcGIS for the case of measuring competition-based job accessibility in Ahmedabad. The implementation uses the results from a Network Analyst application in ArcGIS as an input. The Network Analyst generates the least-impedance routes and travel times for multi-origins and multi-destinations in the study area. The attribute table of the Network Analyst result also provides a base to show all the important factors and outcomes of the calculations (see Section 4.3.2).

For the implementation part, Python integrates its computational strength with geoprocessing tools in ArcGIS. There are two tools designed by this research. One is the Fare tool, which calculates the route-based fare for each route in the Network Analyst of ArcGIS. The other is the Competition tool, which calculates the job opportunities available for each worker location depending on Cheng's model. Python is used to calculate the fare in combination with the 3D road network, which provides a specific spatial relationship between public transport stops and final routes (i.e. 3D intersection between points and lines). As such a stereoscopic analysis is performed. Besides, ArcGIS 10.1 only has one function to detect the 3D relation between points and lines, which is the Selection By Location. In contrast, the Competition tool doesn't require any spatial relation analysis, which could be programmed outside of the ArcGIS environment.

The model is applied to the study area of Ahmedabad in India, using data obtained from a World Bank supported project. According to the employment and housing data, the poor people are divided into three classes and each level corresponds to one job category. Subsequently, the job accessibility for every poor people class and all the urban poor are analyzed for each possible combination of travel modes (i.e. walking, AMTS, BRTS and MRTS) using both a time and fare decay function. After comparison the job accessibility for three poor classes, it appears that most jobs can be accessed by the least poor people. The AMTS is the most efficient way to improve job accessibility for residents who are living in the slum or chawl areas. The fare decay function can't improve the job accessibility for most poor people when change the time decay function as the fare decay function. As such, the job accessibility of very poor decreases more than the other two poor people classes.

Using the SEWSH locations as a case study for calculating competition-based accessibility for the urban poor, when people change their dwelling places from Slums/Chawls to SEWSH, most of these people can get more jobs than before. The BRTS and MRTS appear to be the most efficient modes to increase job accessibility for workers who live in SEWSH. So the BRTS, MRTS and SEWSH match very well and constructing them will improve job accessibility for the urban poor to a large extent.

6.2. Recommendations

6.2.1. Recommendations for programming

In terms of programming, it is better to find a more efficient way to program the Fare tool, which can improve the analysis speed for 3D points and lines. However, the current method is not the most efficient method to deal with fares. Obviously, the 3D road network takes a lot of time to be built. Most accessibility research is based on 2D data, raster data and Euclidean distance. Most importantly, depending on the programming ideas of this research, it is not feasible to get the fare data from the 2D Network Analyst. Therefore, it is recommended that finding a method to calculate the fare from planar road network when the fare is counted by the number of passed stops or stations.

6.2.2. Recommendations for accessibility analysis

There are four recommendations for further studies for Cheng's model and the job accessibility application to Ahmedabad.

First, this research doesn't combine cycling with AMTS, BRTS and MRTS. It just assumes that after taking bus or metro people walk to their final destinations. Although this assumption is reasonable in Ahmedabad because the crowded public transport don't have any room for a bicycle, it is possible to allow people bring bicycles to metro, which will be constructed in several years. So it is worth to consider cycling as in the combination of travel modes.

Second, the decay function needs improvement. This research only measures the job accessibility with time and fare decay function independently. However, it doesn't fit the reality very well because poor people don't only care about time or fare, they trade-off between fare and travel time for commuting. Further study, therefore, can focus on how to integrate fare and time into one decay function based on survey data.

Third, other factors should be considered to quantity the attractiveness of employment (i.e. competition among jobs) and define the two different decay functions for workers and employers. For the attractiveness of employment location, in Cheng's model it is determined by the number of jobs, the diversity of jobs and the decay function. However, the real attractiveness of job locations is also influenced by the income, working environment and so on. So in a further study it should be analyzed how to incorporate other useful factors in Cheng's model. For the decay function, it is another way to involve other social-economic factors and it is better to define two different decay functions. One function is for workers, which could include gender, age and other factors. The other function is for employers, which can also include other useful factors.

Fourth, Cheng's model is created for job accessibility analysis but it is possible to explore how to use it in other research like searching optimal location for shops and supermarket. This model aims at distributing the number of something from one kind of location to another type of location, including the impact of competition, travel cost, diversity and decay function. Obviously, these factors are the important components for competitive facilities. So it is feasible to use it for other location problems.

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APPENDICE 1 PYTHON CODES OF THE FARE TOOL

```
import arcpy
Infc=arcpy.GetParameterAsText(0) #Network Analyst result
First=arcpy.GetParameterAsText(1) #First travel mode
FirstID=arcpy.GetParameterAsText(2) #The field is to identify different buslines or travel modes
Second=arcpy.GetParameterAsText(3) #Second travel mode
CheckS=arcpy.GetParameterAsText(4) #Disabled second travel mode
SecondID=arcpy.GetParameterAsText(5) #Unique ID of second travel mode
Third=arcpy.GetParameterAsText(6) #Third travel mode
CheckT=arcpy.GetParameterAsText(7) #Disabled Third travel mode
ThirdID=arcpy.GetParameterAsText(8) #Unique ID of third travel mode

fare={0:0,1:2,2:2,3:2,4:4,5:5,6:5,
      7:5,8:5,9:5,10:6,11:7,12:7,
      13:8,14:8,15:8,16:10,17:10,
      18:10,19:11,20:12,21:12,22:12,
      23:12,24:12,25:14,26:15,27:15,
      28:15,29:15,30:16,31:16,32:16,
      33:16,34:16,35:17,36:17,37:17,
      38:17,39:18,40:18,41:18,42:18,
      43:19,44:19,45:19,46:19,47:20,
      48:20,49:20,50:20,51:21,52:21,
      53:21}

#Transfer Name field to dictionary {'Name':[value]}
#key_list keeps the order sorted by 'Name'
def dictionary(Infc,diction):
    rows=arcpy.SearchCursor(Infc)
    for i in rows:
        x=i.getValue('Name')
        diction.setdefault(x,[])
    return diction
diction={}
dictionary(Infc,diction)
key_list=sorted(diction.keys())

#Transfer all ID of different travel modes to dictionary
def dictionary1(Infc,diction,ID):
    rows=arcpy.SearchCursor(Infc)
    for i in rows:
        x=i.getValue(ID)
        diction.setdefault(x,[])
    return diction

dict1={}
dictionary1(First,dict1,FirstID)
Alist=sorted(dict1.keys())
```

```
if CheckS=='false':
    dict2={}
    dictionary1(Second,dict2,SecondID)
    Blist=sorted(dict2.keys())
else:Blist=[]
if CheckT=='false':
    dict3={}
    dictionary1(Third,dict3,ThirdID)
    Clist=sorted(dict3.keys())
else:Clist=[]

#Tranfer the corresponding StopsID for one route to dictionary
if FirstID!='Busl':
    arcpy.AddField_management(First,"Busl","TEXT")
    Expre='['+FirstID+']'
    arcpy.CalculateField_management(First,"Busl",Expre)

if CheckS=='false' and SecondID!='Busl':
    arcpy.AddField_management(Second,"Busl","TEXT")
    Expre='['+SecondID+']'
    arcpy.CalculateField_management(Second,"Busl",Expre)

if CheckT=='false' and ThirdID!='Busl':
    arcpy.AddField_management(Third,"Busl","TEXT")
    Expre='['+ThirdID+']'
    arcpy.CalculateField_management(Third,"Busl",Expre)

#Tranfer useful stops data into python dictionary
def stopid(diciton,key_list,Infc,Mode):
    for i in key_list:
        a="\"Name\"="+"'"+i+"'"
        b=arcpy.SelectLayerByAttribute_management(Infc,"NEW_SELECTION",a)
        c=arcpy.SelectLayerByLocation_management(Mode,"INTERSECT_3D",b)
        d=arcpy.SearchCursor(c,None,None,None,"Busl A")
        for j in d:
            diction[i].append(j.Busl)
    return diction

stopid(diction,key_list,Infc,First)
if CheckS=='false':
    stopid(diction,key_list,Infc,Second)
if CheckT=='false':
    stopid(diction,key_list,Infc,Third)

arcpy.SelectLayerByAttribute_management(Infc,"CLEAR_SELECTION")
arcpy.SelectLayerByAttribute_management(First,"CLEAR_SELECTION")
if CheckS=='false':
    arcpy.SelectLayerByAttribute_management(Second,"CLEAR_SELECTION")
```

```
if CheckT=='false':
    arcpy.SelectLayerByAttribute_management(Third,"CLEAR_SELECTION")

#define a function like COunter in python 2.7
def cou(x):
     res={}
     for i in set(x):
          res.setdefault(i)
          res[i]=x.count(i)
     return res

#Calculate fare
fare_dict={}
for keys in key_list:
    fare_dict.setdefault(keys)

for i in key_list:
     multi_dict=dict(cou(diction[i]))
     list_sum=[]
     for j in multi_dict:
            fare_key=multi_dict[j]
            if j in Alist:
                list_sum.append(fare[fare_key])
            elif j in Blist:
                list_sum.append(fare[fare_key]*1.25)#calculate BRT fare for every route
            elif j in Clist:
                list_sum.append(fare[fare_key]*1.25)#calculate MRT fare for every route
            elif j==None:
                list_sum.append(0)#walking doesn't take money
        fare_dict[i]=sum(list_sum)

#return fare to Network result
arcpy.AddField_management(Infc,"fare","DOUBLE")
rows=arcpy.UpdateCursor(Infc,None,None,None,"Name A")
for i in rows:
    i.fare=fare_dict[i.Name]
    rows.updateRow(i)
```

APPENDICE 2 PYTHON CODES OF THE COMPETITION TOOL

```
import arcpy
Infc=arcpy.GetParameterAsText(0) #Network Analyst result
Time=arcpy.GetParameterAsText(1) #Travel time
Inworker=arcpy.GetParameterAsText(2) #Worker feature class
Workers=arcpy.GetParameterAsText(3) #The number of workers (field)
Injob=arcpy.GetParameterAsText(4) #Job feature class
Jobs=arcpy.GetParameterAsText(5) #The number of jobs (field)
Dive=arcpy.GetParameterAsText(6) #Diversity of jobs
Check=arcpy.GetParameterAsText(7) #Disabled Diversity factor
Wjoin=arcpy.GetParameterAsText(8) #Unique key of worker feature
Jjoin=arcpy.GetParameterAsText(9) #Unique key of job feature
Beta=arcpy.GetParameterAsText(10) #beta value of decay function

#Create the fields for JID and WID (i.e. job ID & worker ID)
arcpy.AddField_management(Infc,"WID","TEXT")
arcpy.AddField_management(Infc,"JID","TEXT")
arcpy.CalculateField_management(Infc, "JID", "select( !Name! )", "PYTHON_9.3", "def select(x):\\n
y=x.split('-')\\n      return y[1].strip() ")
arcpy.CalculateField_management(Infc, "WID", "select( !Name! )", "PYTHON_9.3", "def select(x):\\n
y=x.split('-')\\n      return y[0].strip() ")

#Calculate the discounted jobs, ignoring the diversity of jobs
arcpy.JoinField_management(Infc,"JID",Injob,Jjoin,Jobs)
arcpy.AddField_management(Infc,"Djobs","DOUBLE")
if Check=='true':
    dist_decay='decay'+'(!'+Jobs+'!,!'+Time+'!,'+Beta+')'
    arcpy.CalculateField_management(Infc, "Djobs", dist_decay,"PYTHON_9.3","def decay(x,y,beta):\\n
from math import exp\\n      return x*exp(-beta*y)")

#If there is diversity factor, tranfer diversity field to Network Analyst result
if Check=='false':arcpy.JoinField_management(Infc,"JID",Injob,Jjoin,Dive)

#Store the attribute table in this way: {key:[v1,v2]}
diction={}
dict_dive={}
key_list=[] #for the SelectLayerByAttribute_management function
def dictionary(Infc,diction):
    rows=arcpy.SearchCursor(Infc) ##
    for i in rows:
        x=i.getValue('WID')
        diction.setdefault(x,[])
    return diction

dictionary(Infc,dict_dive)
dictionary(Infc,diction) #call the defined function "dictionary"
key_list=sorted(diction.keys()) #Ensure the order of key_list is sorted by WID
```

```
#Consider diversity of jobs
if Check=='false':
    arcpy.AddField_management(Infc,"Div","DOUBLE")
    Expre='['+Dive+']'
    arcpy.CalculateField_management(Infc,"Div",Expre)
    arcpy.DeleteField_management(Infc,Dive)
    arcpy.AddField_management(Infc,"Pjob","DOUBLE")
    Pow_jobs="math.pow( !"+Jobs+"!, "+"!Div! )"
    arcpy.CalculateField_management(Infc, "Pjob", Pow_jobs, "PYTHON_9.3", "")
    dist_decay='decay'+'(!'+'Pjob'+'!,!'+Time+'!,'+Beta+')'
    arcpy.CalculateField_management(Infc, "Djobs", dist_decay,"PYTHON_9.3","def decay(x,y,beta):\\n
from math import exp\\n     return x*exp(-beta*y)")
    arcpy.DeleteField_management(Infc,"Pjob")

#Tranfer the data from attribute to dictionary (i.e. Djobs field)
for i in key_list:
    a="\"WID\"="+"'"+i+"'"
    b=arcpy.SelectLayerByAttribute_management(Infc,"NEW_SELECTION",a)
    c=arcpy.SearchCursor(b,None,None,None,"WID A")
    for j in c:
        diction[j.WID].append(j.Djobs)

#Calculate competition between jobs (i.e. competition for workers)
comp_list=[]
for i in key_list:
    total=sum(diction[i])
    for j in range(len(diction[i])):
        if total==0:
            comp_list.append(0)
        else:
            comp=diction[i][j]/total
            comp_list.append(comp)

#Put the competition factor back to attribute table
#length of rows is equal to that of comp_list
arcpy.AddField_management(Infc,"Jcomp","DOUBLE")
arcpy.SelectLayerByAttribute_management(Infc,"ClEAR_SELECTION")
rows=arcpy.UpdateCursor(Infc,None,None,None,"WID A")
j=-1
for i in rows:
    j+=1
    while j < len(comp_list):
        i.Jcomp=comp_list[j]
        rows.updateRow(i)
        break
##############################################################
#Begin to calculate the competition between workers
#Calculate the discounted workers
```

```
arcpy.JoinField_management(Infc,"WID",Inworker,Wjoin,Workers)
arcpy.AddField_management(Infc,"Dworkers","DOUBLE")
dist_decay='decay'+'(!'+Workers+'!,!'+Time+'!,'+Beta+')'
arcpy.CalculateField_management(Infc, "Dworkers", dist_decay,"PYTHON_9.3","def decay(x,y,beta):\\n
from math import exp\\n      return x*exp(-beta*y)")
arcpy.AddField_management(Infc,"Att_worker","DOUBLE")
Expression='[Dworkers]*[Jcomp]'
arcpy.CalculateField_management(Infc,"Att_worker",Expression)

#{job_key:[jobs]}
dict_job={}
dict_attworker={}
rows=arcpy.SearchCursor(Infc)##
for i in rows:
    x1=i.getValue('JID')
    y1=i.getValue(Jobs)
    dict_job.setdefault(x1,[y1])
    dict_attworker.setdefault(x1,[])

job_list=sorted(dict_job.keys())

#Tranfer the data from attribute to dictionary
for i in job_list:
    a1="\"JID\"="+"'"+i+"'"
    b1=arcpy.SelectLayerByAttribute_management(Infc,"NEW_SELECTION",a1)
    c1=arcpy.SearchCursor(b1,None,None,None,"JID A")
    for j in c1:
        dict_attworker[j.JID].append(j.Att_worker)

#Caluclate the competition between workers (i.e. Wcomp)
for i in job_list:
    m=sum(dict_attworker[i])
    n=dict_job[i][0]
    if m==0:
        dict_job[i].append(0.0)
    else:
        p=n/m
        dict_job[i].append(p)

#return the worker competittion (Wcomp) factors to attribute table
arcpy.SelectLayerByAttribute_management(Infc,"ClEAR_SELECTION")
arcpy.AddField_management(Infc,"Wcomp","DOUBLE")
for i in job_list:
    a2="\"JID\"="+"'"+i+"'"
    b2=arcpy.SelectLayerByAttribute_management(Infc,"NEW_SELECTION",a2)
    c2=arcpy.UpdateCursor(b2,None,None,None,"JID A")
    for j in c2:
        j.Wcomp=dict_job[i][1]
```

```
        c2.updateRow(j)

#caluculate opportuntities for each worker location getting from the corresponding job location
arcpy.SelectLayerByAttribute_management(Infc,"ClEAR_SELECTION")
Expression='[Att_worker]*[Wcomp]'
arcpy.AddField_management(Infc,"Opport","DOUBLE")
arcpy.CalculateField_management(Infc,"Opport",Expression)
#Summarize the final result
arcpy.Statistics_analysis(Infc, "result", "Opport SUM", "WID")
```