# GIS-BASED STOCHASTIC MODELING OF PHYSICAL ACCESSIBILITY BY USING FLOATING CAR DATA AND MONTE CARLO SIMULATIONS

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# GIS-BASED STOCHASTIC MODELING OF PHYSICAL ACCESSIBILITY BY USING FLOATING CAR DATA AND MONTE CARLO SIMULATIONS

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# ABSTRACT

## GIS-BASED STOCHASTIC MODELING OF PHYSICAL ACCESSIBILITY BY USING FLOATING CAR DATA AND MONTE CARLO SIMULATIONS

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The term physical accessibility has widely been used by geographers, economists and urban planners and basically reflects the relative ease of access to/from several urban/rural services by considering various travelling costs. Numerous accessibility measures, ranging from simple to sophisticated, can be found in the GIS based accessibility modeling literature. However, whether simple or sophisticated, one of the fundamental shortcomings of the current GIS-based accessibility measures is that they are generally calculated from a fixed catchment area boundary based on constant traveling costs such as Euclidian (bird-flight) distance costs or transportation network-based average speed costs (e.g. 50 km/h for main streets and 30 km/h for local streets, etc.). Although such deterministic approaches are widely used in GIS-based accessibility modeling literature, they are not realistic, especially due to highly variable speeds in road segments and uncertainty in the accuracy and reliability of the accessibility measures. Therefore, this dissertation provides a new stochastic methodology for GIS-based accessibility modeling process by using GPS-based floating car data and Monte Carlo Simulation (MCS) that could handle variations in traveling costs and consider all possible catchment area boundaries, instead of one average or maximum fixed catchment area boundary. The main contribution of the research is that; the proposed physical accessibility modeling could handle uncertainties in transportation costs, create significant improvement on accuracy and reliability of accessibility measures in terms of catchment area boundaries and support decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues. The proposed stochastic methodology is implemented to a case study on medical emergency service accessibility, in Eskisehir, Turkey and the results of the deterministic and stochastic accessibility models are compared. The main focus of the case study is not to evaluate a specific accessibility condition in a detailed manner but to provide a methodological discussion and comparison between the deterministic and stochastic accessibility modeling process. With the implementation to a case study, it is shown that; the results of the proposed methodology are more realistic than the conventional deterministic approaches.

**Keywords:** Physical Accessibility, Geographical Information Systems (GIS), Global Positioning Systems (GPS), Stochastic/Probabilistic Accessibility Modeling, Floating car data, Monte Carlo simulation, Service/Catchment Area, Location/Allocation, Supply/Demand.

# ÖZ

## HAREKETLİ ARAÇ VERİSİ VE MONTE CARLO BENZETİŞİMİ KULLANARAK FİZİKSEL ERİŞEBİLİRLİĞİN CBS'YE DAYALI STOKASTİK MODELLEMESİ

Ertuğay, Kıvanç
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Fiziksel erişebilirlik kavramı, coğrafyacılar, ekonomistler ve şehir plancıları tarafından oldukça yaygın bir şekilde kullanılmaktadır ve temel olarak çeşitli kentsel/kırsal servislere, farklı ulaşım maliyetlerini dikkate alarak erişme/erişilme kolaylığını yansıtmaktadır. Coğrafi Bilgi Sistemlerine (CBS) dayalı fiziksel erişebilirlik literatürüne bakıldığında basitten karmaşığa çok farklı erişebilirlik ölçülerine rastlanabilir. Fakat, ister basit, ister karmaşık olsun tüm fiziksel erişebilirlik ölçülerinde karşılaşılan temel eksiklik, tüm erişebilirlik ölçülerinin genel olarak sabit ulaşım maliyetlerine dayanan tek bir servis/etki alanına bağlı olarak hesaplanmasıdır. Örneğin; Öklid (kuş-uçuşu) mesafesi maliyetleri veya ulaşım ağına bağlı ortalama hız maliyetleri (bulvarlar için 90 km/saat veya anayollar için 50 km/saat hız vb. gibi). Benzeri deterministik yaklaşımlar, CBS'ye dayalı fiziksel erişebilirlik modellemesinde oldukça yaygın olarak kullanılmalarına rağmen özellikle yol kesimlerindeki oldukça değişken hız yapısı ve erişebilirlik ölçülerinin hassasiyet ve güvenirliğindeki belirsizlik dikkate alındığında gerçekçi değillerdir. Bu sebepten yola çıkılarak gerçekleştirilen tez Küresel Konum belirleme (KKB) ile toplanmış hareketli araç verisi ve Monte Carlo Benzetişimi kullanarak ulaşım ağı hız maliyetlerindeki değişkenlikleri yönetebilen ve sabit tek bir etki alanı yerine olası tüm etki/servis alanlarını dikkate alabilen olasılığa dayalı yeni bir erişebilirlik modellemesi yaklaşımı geliştirmektedir. Geliştirilen model; ulaşım maliyetlerindeki belirsizlikleri dikkate alabilmekte, fiziksel erişebilirlik ölçümlerinin hassasiyet ve güvenirliğini kayda değer ölçüde artırmakta ve erişebilirlik, yerseçimi ve servis analizleri üzerinde çalışan araştırmacı ve karar vericilere daha gerçekçi bir karar desteği sağlamaktadır. Önerilen fiziksel erişebilirlik modeli, Türkiye'nin Eskisehir ili kent merkezinde acil durum kuruluşları fiziksel erişebilirliği özelinde yapılan bir alan çalışmasında uygulanmış, elde edilen sonuçlar günümüzde kullanılan deterministik model ile karşılaştırmalı olarak tartışılmıştır. Alan çalışmasının temel amacı belli bir fiziksel erişebilirlik durumunun detaylı olarak ortaya konması değil, deterministik ve olasılığa dayalı yaklaşımların metodolojik olarak karşılaştırılması ve tartışılmasıdır. Yapılan alan çalışmasıyla olasılığa dayalı yaklaşımın geleneksel deterministik yaklaşımlara kıyasla çok daha gerçekçi sonuçlar verdiği ortaya çıkartılmıştır.

**Anahtar kelimeler:** Coğrafi Bilgi Sistemleri (CBS), Küresel Konum Belirleme (KKB), Olasılığa dayalı erişebilirlik modellemesi, Hareketli araç trafik verisi, Monte Carlo benzetişimi, Erişebilirlik, Servis alanı belirleme ve Yer seçim analizleri

TO MY DEAR FAMILY…

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# TABLE OF CONTENTS

**ABSTRACT** .......... **iv**

**ÖZ** .......... **vi**

**ACKNOWLEDGMENTS** .......... **ix**

**TABLE OF CONTENTS** .......... **xii**

**LIST OF TABLES** .......... **xv**

**LIST OF FIGURES** .......... **xvii**

**CHAPTERS**

**1. INTRODUCTION** .......... **1**

1.1. Introduction .......... 1
1.2. Organization of the research .......... 7

**2. THEORETICAL FRAMEWORK** .......... **8**

2.1. Introduction .......... 8
2.2. Definitions of accessibility .......... 8
2.3. Application areas of accessibility .......... 10
2.4. Components of accessibility .......... 11
  2.4.1. Activity element .......... 11
  2.4.2. Cost element .......... 12
2.5. Accessibility measures .......... 13
  2.5.1. Place accessibility measures .......... 13
    2.5.1.1. Travel time and distance measures .......... 14
    2.5.1.2. Cumulative-opportunity measures .......... 15
    2.5.1.3. Supply to demand ratio measures .......... 16
    2.5.1.4. Kernel density measures .......... 17
    2.5.1.5. Gravity-based measures .......... 18

2.5.1.6. Two-step floating catchment area (2SFCA) measures ......... 19
2.5.2. Individual accessibility measures .............................................. 20
2.5.2.1. Space-time measures .......................................................... 20
2.6. GIS-based accessibility modeling techniques ............................... 23
2.6.1. Zone-based technique ............................................................... 23
2.6.2. Isochronal (isochrone-based) technique .................................... 28
2.6.3. Raster-based technique ............................................................. 31
2.7. The role of GIS in physical accessibility modeling ....................... 38
2.7.1. The contribution of GIS into physical accessibility modeling ... 38
2.7.2. GIS-based accessibility modeling examples ............................. 40
2.7.3. The shortcoming of the current GIS-based accessibility modeling ........................................................................... 55

**3. METHODOLOGY ................................................................ 59**

3.1. Introduction ...................................................................... 59
3.2. Data collection .................................................................. 61
3.3. Data preperation ............................................................... 63
3.4. Monte Carlo simulations ................................................... 70
3.5. Model validation ............................................................... 74

**4. CASE STUDY: MEDICAL EMERGENCY SERVICE ACCESSIBILITY ............................................................ 75**

4.1. Introduction ...................................................................... 75
4.1.1. Case study area ............................................................ 75
4.1.2. Definition of medical emergency .................................. 77
4.1.3. Actors of medical emergency ........................................ 78
4.1.4. The work flow of medical emergency services .............. 79
4.2. Data collection .................................................................. 80
4.3. Data preperation ............................................................... 83
4.3.1. Determination of road segments with and without data ............ 83
4.3.2. Extraction of speed statistics ........................................ 84
4.3.3. Cost calibration ............................................................ 87
4.3.4. Integration of speed statistics with the road segments ............... 91

4.4. Monte Carlo simulations ................ 93
4.5. Comparison of deterministic and stochastic models ................ 94
4.6. Model validation ................ 105
4.7. The effect of catchment area boundaries on accessibility measures ................ 113

**5. CONCLUSION ................ 118**

5.1. Conclusion ................ 118
5.2. Sustainability of the proposed methodology ................ 121
5.3. Broader impacts ................ 122
5.4. Limitations and future research ................ 123

**REFERENCES ................ 125**

**APPENDIX A (PUBLICATIONS) ................ 134**

**CIRRICULUM VITAE ................ 151**

# LIST OF TABLES

TABLES

Table 2.1. Cell crossing time according to average speeds (Juliao 1999) ................. 35
Table 2.2. Average deterministic transportation network costs (average speed) used in calculation of traveling costs (Brabyn 2002) .................................... 46
Table 3.1. Speed statistics for each of the road segments (km/h) .............................. 67
Table 3.2. Speed statistics for each of the road types (km/h) (highway, boulevard, street etc.) ........................................................................................... 67
Table 3.3. Random costs of time in seconds calculated for each road segment ........ 72
Table 4.1. Comparison of cost statistics produced from direct extraction and interpolation-based extraction ............................................................. 87
Table 4.2. Calibration of probe vehicle speeds according to ambulance speeds. ...... 88
Table 4.3. Rush hour speed change according to transportation network hierarchies90
Table 4.4. Neighbourhoods of Eskişehir according to mean probability of having five minutes of medical emergency service accessibility........................... 102
Table 4.5. Deterministic model errors in terms of RMSE ....................................... 111
Table 4.6. Stochastic model errors in terms of probability scores........................... 112
Table 4.7. The results of the comparison ................................................................ 116

# LIST OF FIGURES

FIGURES

Figure 1.1. Euclidian distance based catchment area boundaries (Radke and Mu 2000) ... 4
Figure 1.2. Transportation network based catchment area boundaries ... 4
Figure 2.1. The space-time path (Miller 2003) ... 21
Figure 2.2. The space-time prism (Miller 2003 reproduced from Wu and Miller 2002) ... 22
Figure 2.3. Centroid of a zone ... 24
Figure 2.4. Retail employment distribution in Dallas/Fort Worth area and travel time between zones (Chen 2000) ... 25
Figure 2.5. Zone-based technique representations of accessibility (travel time/distance measure) ... 25
Figure 2.6. Zone-based technique representations of accessibility (cumulative opportunity measure) (Chen 2000) ... 26
Figure 2.7. Zone-based technique representations of accessibility (gravity measure) (Chen 2000) ... 26
Figure 2.8. The isochronal representation of accessibility ... 29
Figure 2.9. The simple representation of isochronal accessibility (Dodge and White 1995) ... 30
Figure 2.10. Catchment area of a medical centre in Makkah City, Saudi Arabia (Murad 2004) ... 31
Figure 2.11. The raster-based representation of accessibility (ESRI User Manuel 2010) ... 33
Figure 2.12. Road network data in raster format (Juliao 1999) ... 34
Figure 2.13. Accessibility of municipality towns in Portugal in raster-based technique (Juliao 1999) ... 36
Figure 2.14. Accessibility of highway nodes in Portugal in raster-based technique (Juliao 1999) ... 36

Figure 2.15. Accessibility of Lisbon in Portugal in raster-based technique (Juliao 1999)........................................................................................ 37
Figure 2.16. Extension of the catchment area in raster-based technique (Ebener et al. 2005)........................................................................................ 38
Figure 2.17. Healthcare accessibility for pedestrians by using raster-based technique (A-digital elevation model, B-landuse types C-accessibility results) (Ebener et al. 2005) ............................................................................. 38
Figure 2.18. 100, 200 and 300 meters of constant deterministic Eucledian-based buffers around each educational facility in London, UK (Boulos et al. 2001)........................................................................................ 41
Figure 2.19. Healthcare accessibility based on Eucledian-based distance in Yemen (Ghio et al. 2007) ....................................................................... 42
Figure 2.20. Accessibility to general practitioners in Gurgaon as Eucledian-distance based travel time/distance measure (Chapelet and Lefebvre 2005)...... 43
Figure 2.21. Attractiveness of different landuse types by considering their total area and their distance to a general practitioner in Gurgaon (Chapelet and Lefebvre 2005) .......................................................................... 43
Figure 2.22. Healthcare accessibility in Honduras as Thiessen/Voronoi based travel time/distance and cumulative opportunity measures (Black et al. 2004) ........................................................................................ 45
Figure 2.23. Road network showing constant average estimated traveling speeds (Brabyn and Skelly 2002) ........................................................ 47
Figure 2.24. Travel Distance in Kilometers to the Closest Hospital by Census Centroids (Brabyn and Skelly 2002)................................................ 47
Figure 2.25. Travel Time in hours to the Closest Hospital by Census Centroids (Brabyn and Skelly 2002) ........................................................ 48
Figure 2.26. Population more than 60 Minutes from a Hospital by District Health Board (Brabyn and Skelly 2002)......................................................... 48
Figure 2.27. The input GIS data used in the research (Nadine et al. 2006) ............... 49
Figure 2.28. 1 hour service areas for all hospitals (Nadine et al. 2006)..................... 49
Figure 2.29. 1 hour service areas for hospitals with ICU and Surgeon (Nadine et al. 2006)........................................................................................ 50

Figure 2.30. 1-hour service areas for hospitals with Obstetrician available with the estimates of the percentage of population that is served or not served (Nadine et al. 2006) .......... 50
Figure 2.31. Hospital locations data in Michigan (Messina et al. 2006) .......... 51
Figure 2.32. Population distribution data in Michigan (Messina et al. 2006) .......... 51
Figure 2.33. Community hospital accessibility for 30-minute travel time in Michigan for normal traffic conditions (Messina et al. 2006) .......... 52
Figure 2.34. Community hospital accessibility for 30-minute travel time in Michigan for rush hour traffic conditions (Messina et al. 2006) .......... 52
Figure 2.35. Dialysis centers in study area (Yang et al. 2006) .......... 53
Figure 2.36. A hypothetical example for two-step floating catchment area method illustrated by Luo and Wang (2003) .......... 54
Figure 2.37. A) Distribution of supply points by Kernel density method B) Distribution of demand points by Kernel Density method (Yang et al. 2006) .......... 54
Figure 2.38. Comparison of the accessibility results of 2SFCA measures with the Kernel density based measures (Yang et al. 2006) .......... 55
Figure 3.1. The flowchart of the methodology .......... 60
Figure 3.2. Determination of road segments with and without GPS data in ArcGIS model builder environment .......... 63
Figure 3.3. Interpolation-based extraction of speed statistics in ArcGIS Model builder environment .......... 64
Figure 3.4. Production of raster speed surface from GPS data by using IDW interpolation .......... 65
Figure 3.5. Direct extraction of speed statistics from the GPS-based floating car data in ArcGIS Model builder environment .......... 66
Figure 3.6. Integration of extracted speed statistics with the attribute table of the road data in ArcGIS Model builder environment .......... 68
Figure 3.7. Integration of speed statistics of mean and standard deviation with the transportation network data .......... 68
Figure 3.8. Results of distribution fitting tests applied to GPS-based floating car data .......... 70

Figure 3.9. Random costs for each road segment in GIS environment ...................... 72
Figure 3.10. Calculation of catchment area boundaries for each of the MCS-based random costs in ArcGIS model builder environment ........................... 73
Figure 4.1. The case study area, Eskisehir city ........................................................ 76
Figure 4.2. Digital transportation road network data with related hierarchies ........... 80
Figure 4.3. The location of medical emergency service stations on transportation road network ............................................................................................. 81
Figure 4.4. GPS-based floating car traffic-data collected by two-week fieldwork with 50-meter track intervals on August 2007 and February 2008 ............... 82
Figure 4.5. GPS-based floating car traffic-data collected by four medical emergency service vehicles with 50-meter track intervals in May 2008 ................ 83
Figure 4.6. Road segments with and without GPS data ............................................ 84
Figure 4.7. The GPS data information for the road segments in the attribute table of road data as Boolean information of 0 and 1 ....................................... 84
Figure 4.8. Raster speed surface produced from GPS-based floating car data by using IDW interpolation ................................................................... 85
Figure 4.9. The observed mean and standard deviation statistics for different road types extracted from the interpolation-based approach ......................... 86
Figure 4.10. Speed statistics of GPS-based floating car data according to different time intervals ........................................................................... 89
Figure 4.11. The local mean and standard deviation of speed integrated with the transportation network data ................................................... 92
Figure 4.12. Variation in pixel values with number of simulations ........................... 94
Figure 4.13. Deterministic modeling of accessibility for medical emergency services in Eskisehir ........................................................................... 95
Figure 4.14. Stochastic modeling of accessibility for medical emergency services in Eskisehir ........................................................................... 96
Figure 4.15. The overlay of stochastic and deterministic modeling of accessibility in GIS environment ................................................................... 98
Figure 4.16. Low, moderate and high probability regions of having five minutes of medical emergency service accessibility ............................................ 101

Figure 4.17. Neighbourhoods of Eskişehir according to mean probability of having five minutes of medical emergency service accessibility .................. 101
Figure 4.18. The five minutes accessibility in rush hour traffic conditions............ 105
Figure 4.19. Actual traveling time information in the GPS-based floating car data 106
Figure 4.20. Ambulance trips starting from medical emergency service stations and five minutes in length .......................................................... 107
Figure 4.21. Five minutes catchment area boundary estimation in deterministic models .......................................................................... 108
Figure 4.22. Five minutes probabilistic catchment area estimation in stochastic model (east station) ........................................................................ 109
Figure 4.23. Five minutes probabilistic catchment area estimation in stochastic model (south station) ....................................................................... 109
Figure 4.24. Five minutes probabilistic catchment area estimation in stochastic model (west station) ........................................................................ 110
Figure 4.25. Five minutes probabilistic catchment area estimation in stochastic model (north station) ....................................................................... 110
Figure 4.26. Deterministic model comparisons in seconds .................................... 111
Figure 4.27. The starting-ending cost calculation capabilities of ArcGIS network analyst.......................................................................................... 112
Figure 4.28. The 2000-year neighbourhood population of Eskisehir ...................... 114
Figure 4.29. Convertion of polygon-based population data into point-based centroids ........................................................................................... 115
Figure 4.30. The cumulative populations within five minutes medical emergency service/catchment area boundaries..................................................... 115

# CHAPTER 1

# INTRODUCTION

## 1.1. Introduction

The term physical accessibility has long been used by geographers, economists and urban planners and reflects the relative ease of access to/from several urban/rural services by considering several travelling costs (Halden et al. 2000, Makri 2002, McGrail and Humphreys 2009). Physical accessibility measures are generally concerned with equity and a better distribution of services in a territory and help to evaluate the proximity/availability of several services like health, education, recreation, emergency or trade etc. by considering various transportation types such as pedestrian, bicycle, car or public transport etc.

The accessibility measures help decision makers to

- identify regions that have inadequate or excessive service
- select appropriate sites for new or re-located services,
- test and improve the performance of the transportation system.

That is why, accessibility measures can be accepted as key variables for supporting supply/demand, location/allocation and service/catchment area related planning policies and strategies at national, regional, and local levels (Makri 2002, Juliao 1999, Kuntay 1990, Halden et al. 2000, Radke and Mu 2000).

Numerous accessibility measures, ranging from simple to sophisticated, can be found in the accessibility literature. While simple measures only consider proximity in terms of time and distance, sophisticated ones consider both proximity and availability including the size of supply and demand. Some of the most widely used accessibility measures in the literature are;

a) Travel time/distance measures, service/catchment areas (travel time or distance to nearest supply/demand calculated from Euclidian/Network-based costs) (see Ghio et al. 2007, Joseph et al. 2006, Fortney et al. 2000, Sylvie 2007, Brabyn 2002, O'Sullivan et al. 2000, Charreirea and Combierb 2008, Juliao 1999, Ebener et al. 2005),

b) Cumulative opportunity measures (consider the total amount of demand/supply inside the catchment areas) (see Chapelet and Lefebvre 2005, Boulos et al. 2001, Nadine et al. 2006, Black et al. 2004, Goulias 2007),

c) Population to provider ratio measures (supply to demand ratios, calculated inside the catchment areas) (see Luo 2004, Scott et al. 2006, Bagheri et al. 2006),

d) Kernel density measures (use the Gaussian kernel approach to calculate the density value of each demand/supply) (see Yang et al. 2006, Gibin et al. 2007 McGrail and Humphreys 2009),

e) Gravity-based measures (a combined indicator of accessibility and availability by considering the attractiveness of supply/demand) (see Kwan 1998, Chen 2000, Guagliardo 2004),

f) Two-step floating catchment area measures (2FCA) (repeat the process of catchment area calculation for both supply and demand points and consider both of the overlay areas (see Mitchel et al. 2008, Luo and Wang 2003, Luo 2004, Yang et al. 2006, Scott et al. 2006)

Since accessibility measures describe the characteristics of a location and need organization of huge and complex spatial data sets, accessibility modeling often lends itself to Geographical Information Systems (GIS) for analysis and presentation. GIS have unique capabilities to present spatially referenced information in a way, which aids decision-making and provides a powerful interface for handling, organizing, analyzing and presenting huge and complex spatial data sets. For example; data storage, management and manipulation capabilities for both graphical and attribute data, core data analyses capabilities such as buffer, overlay, proximity, shortest path, raster cost-distance etc., programming capabilities to handle current models or create new models and mapping and visualization capabilities to evaluate the results of the analyses (Black et al. 2004, Chen and Weng 1999, Chen 2000, Peters and Hall 1999).

In a more specific way, GIS can handle important steps in accessibility modeling like;

- storing road networks and origin/destination-based geographical databases,
- calculating costs between origins and destinations on transportation networks,
- building regulations of streets such as one-way streets, closed streets, overpasses and underpasses,
- considering the delays in intersections, and
- presenting results for a defined time or distance threshold (e.g. < 10 minutes or 10 kilometers) with several techniques such as zone, raster or isochronal technique with opportunity of different scales and various visualization alternatives etc. (MacFarlane 2005).

In spite of important contribution of GIS technology for physical accessibility measurement and evaluation (Makri 2002), there are still open research areas associated with the improvement of the current GIS-based accessibility modeling. Current GIS-based tools are generic tools and have some basic shortcomings in providing more realistic decision support for decision makers in accessibility measurement and evaluation (Kwan et al. 2003, NCGIA 1998, Ebener et al. 2005, Boulos et al. 2001).

Whether simple or sophisticated, one of the fundamental limitations of the current GIS-based accessibility measures is that they are generally calculated from a constant deterministic catchment area boundary (average or maximum catchment area boundary) based on unconstrained Euclidian distances or constrained transportation network costs. Euclidian distance based catchment area boundaries are simple boundaries and generally calculated from bird-flight distances such as buffer, Voronoi/Thiessen polygons etc (Figure 1.1).

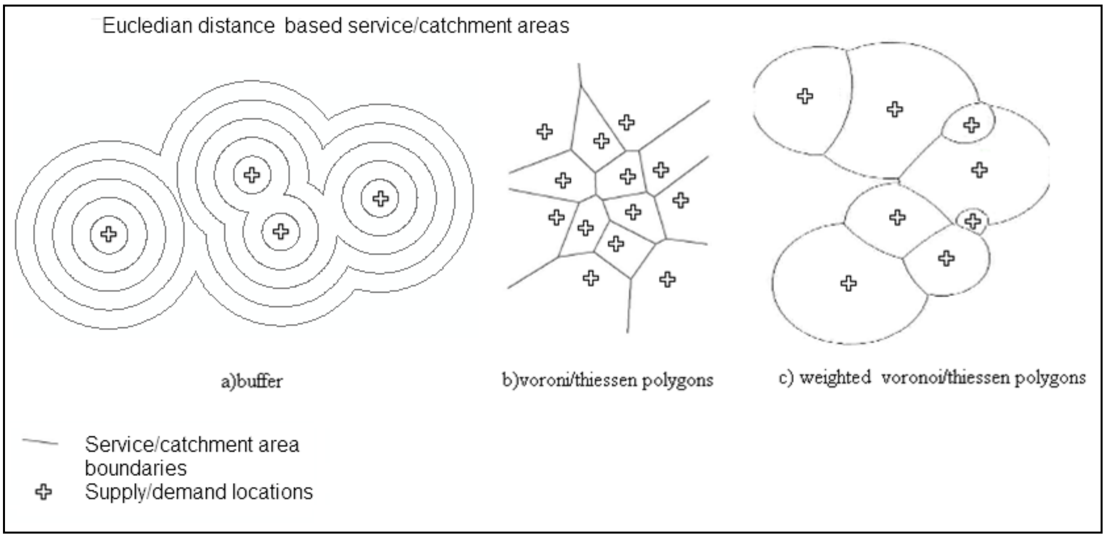

Figure 1.1. Euclidian distance based catchment area boundaries (Radke and Mu 2000)

Transportation network based catchment area boundaries are more complex and generally calculated from average or maximum speeds on classified road segments such as 120 km/h for highways, 50 km/h for main streets and 30 km/h for local streets, etc (Figure 1.2).

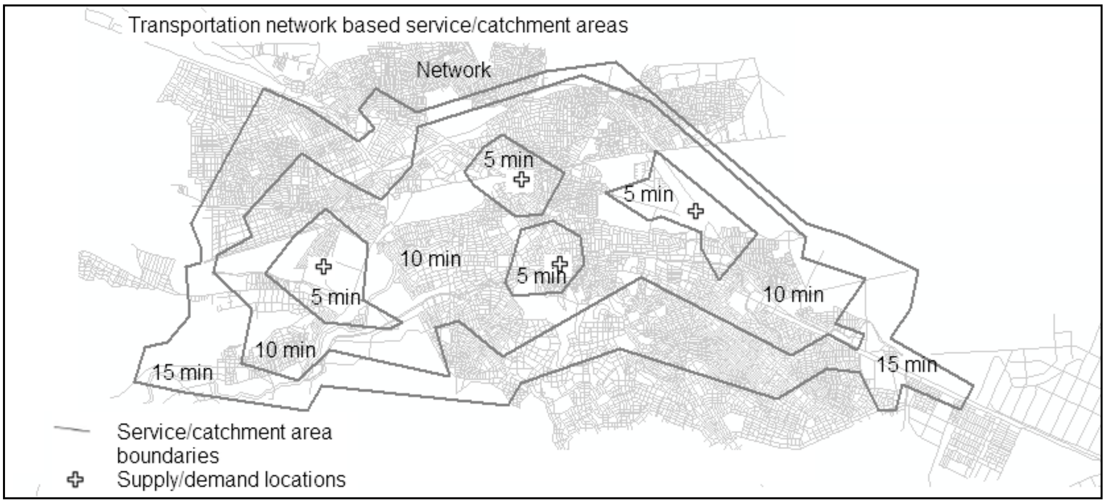

Figure 1.2. Transportation network based catchment area boundaries

Although Eucledian and transportation network based catchment area boundaries are widely used in GIS-based accessibility modeling literature (e.g. Emelinda et al. 1995, Juliao 1999, Ritsema van Eck and de Jong 1999, O'Sullivan et al. 2000, Fortney et al. 2000, Brabyn 2002, Makri 2002, Luo and Wang 2003, Luo

2004, Bixby 2004, Messina et al. 2006, Scott et al. 2006, Nadine et al. 2006, Sylvie 2007, Goulias 2007, Charreirea and Combierb 2008, Mitchel et al. 2008, McGrail and Humphreys 2009, Lotfi and Koohsari 2009, Vahidnia et al. 2009), such deterministic approaches are not realistic, especially due to highly variable speeds in road segments and uncertainty in the accuracy and reliability of the accessibility measures. Stochastic approaches, integrated with detailed traffic-data collection methods can be a solution for more accurate and reliable accessibility modeling, where speed variations of transportations costs can be taken into account in a probabilistic manner.

Although there are several traffic-data collection methods such as stationary traffic sensors (induction loops, optical systems), space and airborne techniques (observation from planes, satellites) and GPS-based floating car data (GPS probe vehicle data), GPS-based floating car data, is one of the most suitable traffic-data collection methods in terms of it's fast and cheap integrating capabilities in GIS. The GPS-based floating car data is obtained by recording position and speed from vehicle(s) moving in the traffic. The GPS-based floating car data, when integrated with GIS, can provide speed variations in transportation costs. Moreover, such data collection is relatively fast and cheap as well as providing accurate position and speed with availability to be integrated in GIS (Daoqin et al. 2009, D'Este et al. 1999, Mintsis et al. 2004, Quiroga 2000, Taylor et al. 2000, Zito et al. 1995, Derekenaris et al. 2001, Yutaka et al. 2000, Guillaume 2008, DAAD 2003).

Once the speed variations in the road network are obtained, it can be incorporated into the physical accessibility modeling by using simulation. The word simulation refers to analyzing the effect of varying inputs, on outputs of the modeled system. A simulation involves hundreds or thousands realization of the model outputs for all possible inputs and gives a probabilistic measure of the outputs. Monte Carlo Simulation (MCS) method is a well-known method to create the random realizations of a deterministic model (Metropolis and Ulam 1949, Hoffman 1998). By integrating MCS method into GIS-based accessibility modeling process, possible random transportation cost values can be used instead of constant deterministic costs. Hence, the probability of an accessibility outcome can be obtained in terms of all possible catchment area boundaries. By this way, accessibility can be expressed in terms of probability of having a certain accessibility measure instead of stating a deterministic accessibility measure. The probabilistic accessibility measures can take the uncertainties of transportation costs into account and enhance decision-making processes due to consideration of variability involved in the transportation cost parameters.

In the light of the above-mentioned facts, *the aim of this research* is to develop a new stochastic methodology for GIS-based accessibility modeling process by using GPS-based floating car data and MCS technique that could handle variations in traveling costs and consider all possible catchment area boundaries, instead of one average or maximum catchment area boundary. The main *contribution of the proposed stochastic methodology* is that; it provides additional information related with the accuracy and the reliability of the catchment area boundaries in accessibility modeling, which means better decision support for the decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues. The proposed stochastic model allows systematic treatment of uncertainties related with the catchment area boundaries and the crisp catchment area boundaries in the deterministic model turns into probabilistic catchment area boundaries providing decision makers to operate different levels of uncertainty in modeling of accessibility.

The proposed stochastic methodology is implemented to a case study on medical emergency service accessibility, and the results of the deterministic and stochastic accessibility models are compared. Although the case study is implemented on medical emergency service accessibility, the main focus of the case study is not to evaluate a specific accessibility condition in a detailed manner but to provide a methodological discussion and comparison between the deterministic and stochastic accessibility modeling process.

The proposed stochastic methodology can be implemented on modeling of any kind of accessibility measure, ranging from simple travel time measures to more sophisticated cumulative opportunity, gravity, two-step floating catchment area measures, etc. Moreover, the proposed stochastic methodology can easily be adapted to other kinds of accessibility related studies such as central business district accessibility, job accessibility, recreational accessibility, trade center accessibility or educational accessibility etc. by considering other several transportation modes such as pedestrian, bicycle, car or public transport etc.

## 1.2. Organization of the research

The dissertation is organized in five parts. Chapter 1 covers a detailed introduction including the motivation of the research, the primary aim of the research, the contribution/benefits of the research.

Chapter 2 provides an overview of the theoretical framework and relevant background about physical accessibility modeling in order to clarify the nature of GIS-based physical accessibility modeling. It includes a detailed review of the literature about definitions of accessibility, usage areas of accessibility, components of accessibility, accessibility measures, GIS-based accessibility modeling techniques the role of GIS in accessibility modeling.

In the light of the theoretical framework about physical accessibility modeling covered in Chapter 2, Chapter 3 introduces a new GIS-based stochastic accessibility model by integrating GPS-based floating car data collection and Monte Carlo simulations technique into physical accessibility modeling process. It includes detailed methodological flowchart of the proposed approach, which are data collection, data preparation, Monte Carlo simulations and model validation.

Chapter 4 describes the implementation of the proposed model with a case study on medical emergency service accessibility in Eskisehir, Turkey. It includes detailed explanation about the aim of the case study, case study area, data collection, implementation steps of the proposed accessibility model, the results of the proposed accessibility model, the validation of the model and effect of results on accessibility measures with methodological discussion and comparison between the deterministic and stochastic accessibility modeling process.

Finally, Chapter 5 concludes the research by giving detailed explanation about the benefits, broader impacts and limitations of the research.

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# CHAPTER 2

# THEORETICAL FRAMEWORK

## 2.1. Introduction

This chapter of the dissertation provides an overview of the theoretical framework and relevant background about physical accessibility modeling in order to clarify the nature of GIS-based physical accessibility modeling.

The chapter includes a detailed review of the literature about definitions of accessibility, usage areas of accessibility, components of accessibility (activity and cost elements), place accessibility measures (Travel time/distance, Cumulative opportunity, Population to provider ratio, Kernel density, Gravity measures, Two-step floating catchment area), individual accessibility measures (space-time), GIS-based accessibility modeling techniques (zone-based technique, isochrone-based, raster-based), the role of GIS in accessibility modeling (contribution of GIS technology into accessibility modeling, GIS-based accessibility modeling examples, and shortages of current GIS-based accessibility modeling).

## 2.2. Definitions of accessibility

The term accessibility is used by various disciplines and many different aspects and definitions of accessibility can be found in the literature.

Some of these different aspects are;

- Physical accessibility which is being able to reach a service/facility in spite of physical impedances
- Mental accessibility which is understanding and being able to use a given area and its facilities

- Social accessibility which is having friends and a job and being able to get to and from work, meet friends and participate in social activities
- Organizational accessibility which is having access to travel opportunities, information and service regarding a journey
- Financial accessibility which is being able to afford available public or private means of transport
- Virtual accessibility which is being able to access information and people without moving from a certain place, by using electronic facilities (Kwan 1998, Makri 2002).

The accessibility concept in this research is physical accessibility. Several definitions related with physical accessibility can be found in the accessibility literature. Kuntay (1976b) defines physical accessibility as the ability to reach from one place to another securely and comfortably by shortest way, simple route, appropriate speed, and ability to reach the intended location for a specific aim. Dong et al. (1998) defines physical accessibility as the ease and convenience of access to spatially distributed opportunities with a choice of travel. Joly (1999) defines the physical accessibility as a geographical concept in transportation planning and as a capacity term to reach customers, or a service for evaluation of projects. Chen (2000) defines physical accessibility as a significant index that reflects the ease for travelers to achieve desired movements in urban areas. Although there are several definitions about physical accessibility in the literature, they mostly point out a common direction. Physical accessibility is a term that reflects the relative ease of access to/from several services by considering several costs of travelling.

Kwan (1998) also emphasizes that physical accessibility can be handled either for people (individual accessibility) or for places (place accessibility) according to the aim of the study. This means that physical accessibility can be handled as a property of people defining how easily an individual can reach activity locations, or can be handled as an attribute of locations indicating how easily certain places can be reached by the people or services. In this regard, this research focus on places rather than individuals and handle accessibility as place accessibility as an attribute of locations indicating how easily urban places can be reached by several urban services such as medical emergency services (see chapter 2.5 for detailed explanation about place and individual accessibility measures).

## 2.3. Application areas of accessibility

The physical accessibility measures have long been used by geographers, economists and urban planners and directly or indirectly always been an important part of urban analyses. Accessibility measures are concerned with equity and a better distribution of services in the territory and can be accepted as key variables for the decision makers to test the accessibility level of several urban services and give vital clues for decision makers to define planning strategies. That is why accessibility measures, whether simple or sophisticated, are important variables that decision makers must consider in the early stages of their planning efforts (Makrí, 2001; Makrí and Folkesson, 1999; Juliao, 1999; Emelinda and Shashi, 1995).

Accessibility measures are widely used to check the benefits of urban plans as a planning control tool. They help to evaluate proximity and availability of several urban/rural services like health, education, recreation, emergency or trade etc. by considering several transportation types like pedestrian, bicycle, car, public transport etc. for a defined threshold of time or distance (e.g. 1 km, 5 minutes etc.) (Kuntay 1976ab, Kuntay 1990, Halden et al. 2000).

By the help of the accessibility measures, decision makers can;

- identify regions that have inadequate or excessive service
- select appropriate sites for new or re-located services,
- evaluate the performance of the transportation systems

That is why, accessibility measures can be accepted as key variables for the decision makers to support their supply/demand, location/allocation and service/catchment area related planning policies and strategies at national, regional, and local scales in different levels (Makri 2002, Juliao 1999, Halden et al. 2000, Radke and Mu 2000).

When medical emergency service accessibility is considered, physical accessibility measures reflect the emergency organization’s readiness to respond to an emergency in a coordinated, timely and effective manner and help decision makers, who are medical emergency service providers, to determine the extent to which a city is ready for any medical emergency. For example, physical accessibility of medical emergency services can be measured to check if urban/rural areas are highly accessible by medical emergency vehicles (ambulances) within five minutes of critical time threshold. The physical accessibility measures related with medical emergency services could directly help medical emergency service providers to identify critical urban/rural areas that have inadequate or overlapped service, select appropriate sites for new or re-located services and to evaluate the current state of the transportation network performance. As a few seconds of delay by medical emergency response units can directly mean loss of human life, medical emergency service accessibility can be considered as vital from planning policy and strategy development point of view at national, regional, and local levels (Badri et al. 1996, Peters and Hall 1999, Emelinda et al. 1995).

## 2.4. Components of accessibility

There are two fundemental components of accessibility in the literature, which are;

- Activity element and
- Cost element

The activity element of the accessibility usually includes the type of the traveler and distribution of various urban/rural services. All accessibility measures include representation of the activity and cost element, which need to be defined at a level of detail, according to the needs of the particular situation about accessibility.

The cost element of accessibility includes either un-constrained Euclidian distance-based costs (bird-flight distance-based costs) such as Buffer, Voronoi/Thiessen polygons etc. or constrained transportation network-based costs such as travel distance/travel time by considering transportation network and several transportation types (pedestrian, bicycle, car, public transport etc.) (Halden et al. 2000, Makrí 2001).

### 2.4.1. Activity element

The activity element of the accessibility generally consists of two elements, which are;

- Urban/rural services/facilities (supply points which are interested) and

- Type of the person/traveler (demand points)

Depending on the issue at hand, activity element in accessibility analyses is based on various urban/rural services which are interested, such as education/training facilities (like schools, colleges, universities, training centers), emergency facilities (like health centers, hospitals, police stations, fire brigades), or shopping/leisure facilities (like shops/shopping centers, cinemas/theatres, sports centers, outdoor activity opportunities, pubs/clubs) etc.

Type of person/traveler in accessibility analyses includes several factors such as employment status of the traveler (unemployed, retired, economically active etc.) or age of the traveler (adult, children etc.) or physical health of the traveler (healthy, disabled etc.) (Makrí and Folkesson 1999; Halden et all. 2000). For example, economically active people and shopping centers can create the activity elements of an accessibility research, in which accessibility level of economically active people to shopping centers are investigated.

### 2.4.2. Cost element

The cost element of accessibility usually comprises two basic elements, which are;

- Unconstrained Euclidian distance-based / bird-flight costs (such as Buffer, Voronoi/Thiessen polygons etc.) and
- Constrained transportation network-based costs (such as distance or time)

In representation of cost element in accessibility analyses, there are also several factors that must be considered in detail, which are;

- Time of the travel (rush hour, normal hour, etc.),
- Type of the travel (pedestrian, bicycle, car, public transport, etc.),
- Day of the travel (Sunday, Monday, etc.),
- Season of the travel (winter, summer, etc.),
- Characteristics of the travel (quality and capacity of the roads, the economy, comfort, cost and safety considerations)
- Type of the traveller (adult, children, normal, disabled etc.) or

- Mobility of the traveller[1] (Kuntay, 1976ab, Halden et al. 2000).

For example, a 5-minute accessibility of a bicycle vehicle is different from a car vehicle. Similarly, a 5-minutes accessibility of a car in rush hour time traffic conditions will be different from the normal time traffic conditions.

## 2.5. Accessibility measures

In general, accessibility measures can be handled either for places (place accessibility measures) or for people (individual accessibility measures).

### 2.5.1. Place accessibility measures

Place accessibility measures handle accessibility as an attribute of locations indicating how easily certain places can be reached by the people or services. At its simplest level, qualitative descriptions can be used to define the place accessibility of a location. Terms such as good accessibility, average accessibility or poor accessibility can be used as simple qualitative accessibility measures for describing the accessibility level of a location. These qualitative measures can be based on;

- average time and distance between locations,
- accessed population or facilities within a defined time/distance threshold, or
- amount, frequency or cost etc. of transportation supply (number of stations, number of bus lines, the variety of public transportation (e.g. rail/bus/light rail etc.), the frequency of public transportation, (e.g. 1 bus for every 15 minutes etc.), total length of motorways) (Halden et al. 2000).

The simple indicators of accessibility are useful indicators and have been widely used by providing a general approach. However, decision makers, who are

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[1] Mobility is a critical component of accessibility. The term mobility refers to the potential for movement. A number of factors affect mobility including the availability and cost of transportation infrastructure. For example, if two people have the same residential location, but one person has a car and the other does not, each person's access to employment and shopping activities may be very different (Transportation Statistics Annual Report, 1997).

supposed to deal with accessibility, location/allocation and service/catchment area related issues, usually need a more comparative and qualitative approach rather than quantitative accessibility measures in order to support their planning policies and strategies at national, regional, and local levels. Numerous qualitative accessibility measures ranging from simple to sophisticated can be observed in the accessibility modeling literature. While the simple accessibility measures only consider proximity in terms of time and distance without considering the transportation network, sophisticated accessibility measures could consider both proximity and availability considering the size of the supply and demand and the transportation network. Some of the most widely observed accessibility measures in the literature are;

- Travel time/distance measures (travel time or distance to nearest supply/demand calculated from Euclidian/Network-based costs),
- Cumulative opportunity measures (consider the total amount of demand/supply inside the catchment areas),
- Supply to demand ratio measures (population to provider ratios, calculated inside the catchment area boundaries),
- Kernel density measures (uses the Gaussian kernel approach to calculate the density value of each demand/supply),
- Gravity-based measures (a combined indicator of accessibility and availability by considering the attractiveness of the supply/demand) and
- Two-step floating catchment area measures (FCA) (repeat the process of catchment area calculation twice for both supply and demand points), etc. (Luo and Wang 2003, McGrail and Humphreys 2009, Guagliardo 2004, Bagheri et al. 2006,).

Although there are various accessibility measures ranging from simple to sophisticated, there is no best approach to measure accessibility. Different aims and situations can demand different measures and approaches (Makri 2002).

#### 2.5.1.1. Travel time and distance measures

The travel time and distance measures are simple and commonly used measure of accessibility. They help accessibility related decision makers to understand the minimum, maximum or average travel cost between several opportunities (supply and demand points) and to determine the catchment/service area boundaries. The travel time and distance measures are widely used in the accessibility modeling literature and can be considered as the fundamental elements of all kind of accessibility measures, ranging from simple to sophisticated (Makri 2002, Makri and Folkesson 1999).

The travel time/distance costs can be measured as several ways such as;

- average travel time/distance to opportunities or
- minimum travel time/distances to opportunities
- average travel time/distance to nearest opportunity or
- minimum travel time/distance to nearest opportunity etc.

The shorter the travel time/distance mean the higher the accessibility. The estimation of these measures can be performed in two different ways. One is the simple Euclidian costs (known as straight-line costs bird-flight costs or unconstrained costs) and the other is more complicated transportation network-based costs (constrained costs). While the Euclidian costs are calculated from Buffer, Voronoi/Thiessen polygons etc., the transportation network-based costs are generally calculated from average speeds on road segments such as 120 km/h for highways, 50 km/h for main streets and 30 km/h for local streets, etc. (See several examples; Ritsema van Eck and de Jong 1999, Makri 2002, Luo and Wang 2003, Bixby 2004, Lotfi and Koohsari 2009, McGrail and Humphreys 2009, Vahidnia et al. 2009).

#### 2.5.1.2. Cumulative-opportunity measures

Cumulative-opportunity measures are evaluations of accessibility in terms of number or proportion of available opportunities within certain catchment area boundary (a threshold of travel distance or time). These measures provide an idea of the range of various choices available to supply/demand points in urban/rural environment.

The cumulative opportunity measures usually calculated from major facilities or centers of population such as cities, districts, central business districts or several public services such as hospitals, schools, recreation, emergency services etc. The cumulative opportunities can be the total number of jobs, floor spaces, people or employees etc. within a defined service/catchment area boundary threshold of distance or time. For example, the total number of schools within 500 meters of districts, the total number of customers within 30 minutes of shopping centers or the total number of people within 15 minutes of city center are good examples of this kind of accessibility measures. (Makrí and Folkesson 1999, Halden et al. 2000, Kwan 1998).

The basic formulation for cumulative opportunity measure ($A_t$) is that;

$$A_t = \sum_t O_t \tag{1}$$

in which $t$ is the catchment threshold, and $O_t$ is the cumulative opportunity that can be reached within threshold t.

As, all potential opportunities, whether closer or further, within the defined deterministic threshold are weighted equally and all potential opportunities beyond the defined deterministic threshold are not taken into consideration, defining a threshold is a critical factor in the calculation of cumulative opportunity measures and directly affect the results of the cumulative opportunity measures (Makri 2002, Makri and Folkesson 1999, Makrí 2001).

#### 2.5.1.3. Supply to demand ratio measures

Supply to demand ratios, also known as provider to population ratios, are another type of accessibility measures, which are calculated within the bordered zones or geographical units such as states, countries, metropolitan statistical areas, districts, neighbourhoods or catchment/service area boundaries. As advanced GIS tools and expertise is not needed to calculate and required data sources are relatively easier to obtain, they are widely observed in the accessibility modeling literature as simple accessibility measures.

The supply to demand ratios basically need two types of data source which are supply and demand sources. The supply sources are generally some service provider related indicators, such as number of schools, jobs, hospital beds or doctors and the demand sources are generally the population related indicators such as number of children, employees, economically active people etc., and mostly obtained from the census files.

Although supply to demand ratios are useful for making comparisons between several zones as indicators of availability, they have several limitations such as;

- they do not account for any measures of distance or travel impedance,
- results are blind to accessibility variations within bordered zones,
- results and interpretations obtained from deterministic bordered zones can vary greatly depending on the size of the zone, which is also well-known to geographers and spatial analysts as the modifiable areal unit problem (Guagliardo 2004)

### 2.5.1.4. Kernel density measures

Kernel density measures are based on cells named pixels in raster environment. The value of each cell is represented by the help of a pre-defined kernel function which is generally a Gaussian kernel found in the GIS-based Spatial Analyst modules. The radius of the kernel reflects the catchment area boundary of the supply/demand locations.

There are mainly two types of data needed in the calculation of the kernel density measures, which are the location, and capacity of the demand and supply points. After the data is obtained, the density of the supply and demand is calculated separately according to the defined deterministic distance-based kernel size, which is a type of service/catchment area boundary. This calculation is performed in such a way that the cells near the kernel center receives higher values of supply or demand, and those near the kernel periphery receive lower values of supply or demand. A cell's value is inversely affected from its distance to the kernel’s center. In the case of kernels overlap, either partially or fully, cells in these overlapping zones receive a higher score that is the sum of contributions from all overlying kernels. That is why the summed kernels can be quite peaked.

After the density calculation of supply and demand, the supply to demand ratio is computed in order to represent accessibility. The higher accessibility values represent higher supply and lower demand zones and lower accessibility values represent lower supply and higher demand zones in the final map (Guagliardo 2004).

Although the kernel density measures give useful information about accessibility level to services, one of the biggest shortages of the measure is the usage of an unconstrained Euclidian distance-based kernel in determination of the catchment area boundary without considering the transportation network.

### 2.5.1.5. Gravity-based measures

Gravity-based measures represent accessibility of any location, by weighting the supply opportunities within a reasonable service/catchment area boundary according to their attraction (size, service capacity etc.) and evaluating each opportunity according to a measure of travel impedance (time or distance) (Kwan 1998, Makrí 2001, Guagliardo 2004).

Basic formulation for gravity model is that;

$$Ai = \sum_{j} \frac{S_j}{d_{ij}^{\beta}} \tag{2}$$

in which $S_j$ represents the attraction factor of the supplies (service size or capacity), $d_{ij}^{\beta}$ represents the impedance (time or distance) (Guagliardo 2004). Although the simple gravity base measure formulations do not consider the size of the demand, the more sophisticated ones also take the demand $V_j$ into consideration in such a way that;

$$Ai = \sum_{j} \frac{S_j}{d_{ij}^{\beta} V_j} \tag{3}$$

and

$$V_j = \sum_{k} \frac{P_k}{d_{kj}^{\beta}} \tag{4}$$

where $P_k$ is population size at point k (the centroid of a census tract or block) $d_{kj}^{\beta}$ is the distance between the demand point k and supply location j. The demand on provider location j is obtained by summing the gravity discounted demand influence of all population points within a reasonable catchment area boundary (Guagliardo 2004).

Although the gravity-based measures can be considered as more realistic in terms of considering attraction of the opportunities (supply/provider), demand (population) and transportation characteristics, they have still limitations in terms of using deterministic catchment area boundaries.

#### 2.5.1.6. Two-step floating catchment area (2SFCA) measures

The two-step floating catchment area (2SFCA) measures, which are recently developed accessibility measures, are improved version of supply to demand ratio measures. There are two key differences between supply to demand ratio measures and the 2SFCA measures. Firstly, 2SFCA measures use time and distance-based catchment area boundaries rather than administrative zones such as districts or neighbourhoods. Secondly, 2SFCA measures could consider accessibility differences in intersection zones by summing the population-to-provider ratios in the study area. 2SFCA measures consider the idea that the populations only use services within their catchment area. The size of the catchment area boundary is generally calculated from average or maximum traveling costs of time or distance, where all services within that boundary are considered accessible, and all other services out of the boundary are considered not accessible to the population.

The first step of calculating 2SFCA is to define a catchment area boundary for a defined time or distance threshold and determine the total demand that falls within the service/catchment area boundary for each of the service providers (supply). The division of the total potential populations (demand) within the defined catchment area boundary to the supply of the each service providers gives the service/catchment area-based population-to-provider ratios. The second step of calculating 2SFCA is to determine all available services (supply) for each of the populations (demand) that are within the catchment area boundary for a defined time or distance threshold. The final step of calculating 2SFCA is to sum all of the population-to-provider ratios, calculated in the second step, for each of the overlay areas.

2SFCA measures produce more realistic accessibility measures when compared with the supply to demand ratios (population-to-provider ratios), however they are still unrealistic in terms of using deterministic catchment area boundaries (McGrail and Humphreys 2009).

### 2.5.2. Individual accessibility measures

Unlike place accessibility measures which handle accessibility as an attribute of locations, individual accessibility measures handles accessibility as a property of people, defining how easily an individual can reach locations considering the spatio-temporal constraints of the people and activities such as schedule, mobility, budget, time constraints etc. Individual accessibility measures are more sensitive to personal traveling abilities to reach activity locations considering space and time instead of assuming that all individuals in one place have the same level of accessibility (Hägerstrand 1970, Lenntorp 1976, Kwan 1998, Pirie 1979, Makri and Folkesson 1999).

The most widely used individual accessibility measures in the literature are known as space-time measures. All types of space-time measures are developed based upon Hägerstrand’s (1970) time-geographic framework which can be considered as an effective tool for understanding individual movement to reach service and activity locations in the environment. When compared with the research on place accessibility measures, the research on individual accessibility measures has slowly growed, mainly because of the lack of strong geocomputational platforms and georeferenced individual-level traveling data. Only from 1990s, GIS-based researches and technologies reprovide popularity in the field and several researchers have worked on individual accessibility measures (Neutens et al. 2007, Dong et al. 2006, Kwan 1998, Miller 2003, Kwan 2004).

#### 2.5.2.1. Space-time measures

The theory of individual space-time measures was first introduced by Hägerstrand (1970). Space-time measures model the accessibility of individuals by using the volume and projected area of the space-time prism as indicators of physical accessibility. Hägerstrand (1970) defines three types of constraints, which could shape of an individual’s space-time prism:

- Capability constraints
- Coupling constraints

- Authority or steering constraints

Capability constraints limit the activities of individuals through their own biological necessities such as eating or sleeping and physical capabilities such as the resources they can command. For example, individuals eating and sleeping characteristics can be different from each other or individuals with private automobiles can generally travel faster through space than individuals who walk or rely on public transportation. Coupling constraints relate to where, when, and for how long individuals have to join other people, service and activity locations in space and time. Authority or steering constraints relate to the institutional context and refer to laws and regulations, which defines that specific locations are only accessible at specific times for specific people and for specific activities (Hägerstrand 1970, Neutens et al. 2007, Kwan 1998, Miller 2003).

The basic conceptual item in the space- time framework is the space-time path, which traces the movement of an individual in space and time. In addition to tracing movement in geographic space from location to location, it also traces simultaneous movement from time to time (Figure 2.1). The path is vertical when the individual is stationary in space (but always moving in time) and the path is horizontal when the individual is moving in space and in time. The slope in the path indicates how fast individual is moving by using a potential transportation mode such as pedestrian, bicycle, car or public transport etc (Hagerstrand 1970, Lenntorp 1976, Miller 2003)

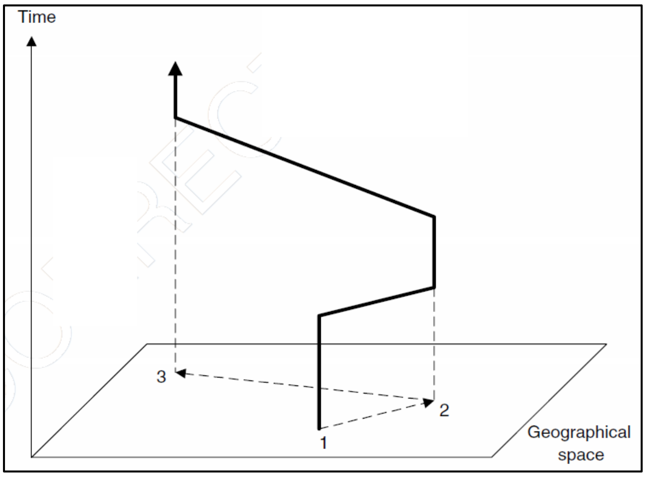


Figure 2.1. The space-time path (Miller 2003)

A space-time prism (STP) is an extension of the space-time path that defines a potential accessibility space considering individual constaints (Figure 2.2). In this regard, a person must be at a given location (e.g. work) until time t1 and then must return to work again at time t2. If an average travel velocity is assigned for the individual's free time budget between t1 and t2, a potential path space (PPS) showing all locations in space and time that the person can occupy can be calculated. If the person wants to visit an activity location in his or her free time budget, its space-time path must intersect with the potential path space. Projecting the PPS to the two-dimensional geographic plane forms the potential path area (PPA). This area defines the set of geographic locations that the person can occupy.

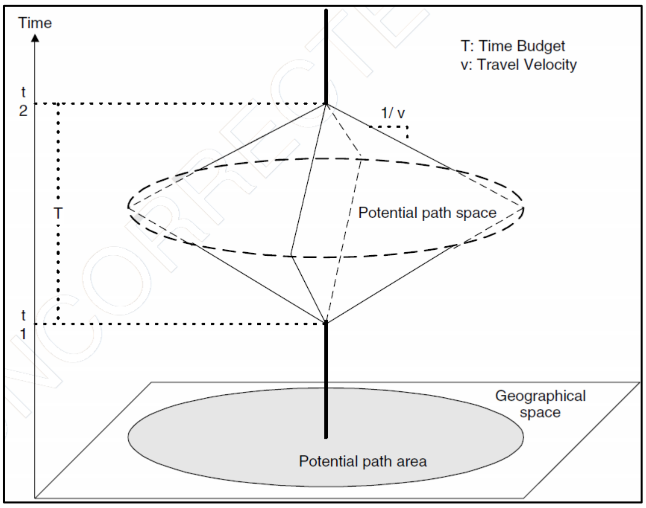


Figure 2.2. The space-time prism (Miller 2003 reproduced from Wu and Miller 2002)

Hägerstrand's time-geographic framework has inspired a great deal of researchers in their studies such as Lenntorp 1976, Lenntorp 1999, Kwan 1998, Miller 2003, Kwan 2004, Dong et al. 2006, Neutens et al. 2007. Although the framework provides as an effective infrastructure for understanding individual movement to reach service and activity locations, the major problem with space-time measures is that they depend on large amounts of individual information about completed trips and activities, which makes it difficult to use space-time measures in large-scale projects (Pirie 1979, Kwan 1998).

## 2.6. GIS-based accessibility modeling techniques

The literature on GIS-based accessibility modeling techniques can generally be divided into three, which are;

- Zone-based technique
- Isochronal (isochrone-based) technique
- Raster-based technique (Makrí and Folkesson 1999, Juliao 1999, Chen 2000).

The techniques are slightly different from each other and they have similar running steps, which are;

- data acquisition and integration phase,
- traveling cost calculation phase and
- visualization phase

Data acquisition and integration phase contain preparation of geographical information, which are mainly socio-economic, transportation and land use information. Traveling cost calculation phase contains calculation of cell crossing time in raster environment or calculation of the Eucledian/transportation network-based impedances in vector environment. Visualization phase is the last step in accessibility modeling and contains presentation of the calculated accessibility measures.

### 2.6.1. Zone-based technique

In zone-based technique, calculated accessibility measures are represented inside the defined bordered zones such as states, countries, metropolitan areas, districts, neighbourhoods or any catchment/service areas. Determination of the size of the bordered zones is generally determined by the aim, the obtained data and the detail needs of the study. While a national or regional scale accessibility study generally requires a coarse zone representation such as state, country or district boundaries, a local scale accessibility study can require a smaller zone representation such as neighbourhood or parcel boundaries. However, it must also be taken into consideration that the data is more difficult to obtain for the smaller zones such as parcels and neighbourhoods when compared to coarse zones such as districts and countries (Halden et al. 2000).

In zone-based accessibility modeling technique, travelling cost calculation between supply and demand points are usually based on the zone centroids, which are geometric center of zones. In GIS environment, zonal centroids are generally used as representatives of the bordered zones (Figure 2.3) and help to calculate traveling costs between supply and demand points. Although zone-based technique has an advantage of easier comparison of accessibility scores between the bordered zones, two main disadvantages of the technique are that the whole area inside the zones are represented with the same accessibility value and a constant catchment area boundary (average or maximum catchment area boundary) based on deterministic traveling costs such as Euclidian distance costs or constant transportation network-based costs are used to model accessibility.

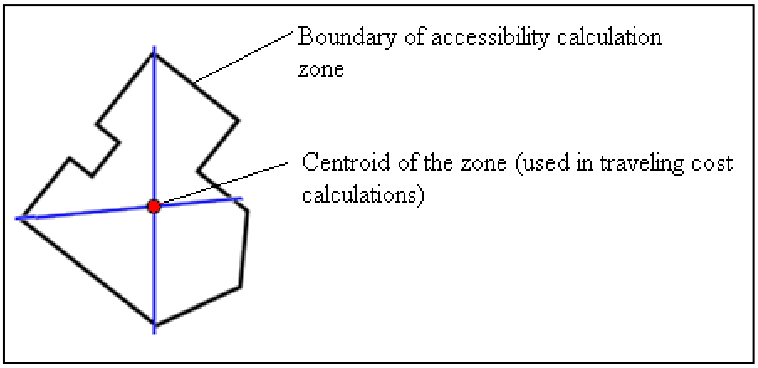
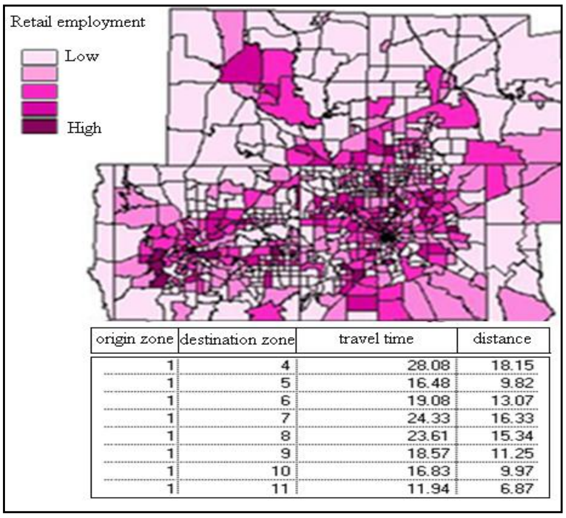


Figure 2.3. Centroid of a zone

Chen (2000)'s study is one of the examples of the zone-based technique for modeling of accessibility by GIS. By using the data of shopping opportunities (number of retail employment in each neighbourhood and travel time data between neighbourhoods (Figure 2.4), Chen (2000)'s study model shopping accessibility of Dallas/Fort Worth region by car and public transit during off-peak hours. The retail employment distribution boundaries are used as zone elements and different accessibility measures such as travel time and distance (Figure 2.5), cumulative opportunity (Figure 2.6) and gravity (Figure 2.7) are measured and compared.



| origin zone | destination zone | travel time | distance |
|---|---|---|---|
| 1 | 4 | 28.08 | 18.15 |
| 1 | 5 | 16.48 | 9.82 |
| 1 | 6 | 19.08 | 13.07 |
| 1 | 7 | 24.33 | 16.33 |
| 1 | 8 | 23.61 | 15.34 |
| 1 | 9 | 18.57 | 11.25 |
| 1 | 10 | 16.83 | 9.97 |
| 1 | 11 | 11.94 | 6.87 |

Figure 2.4. Retail employment distribution in Dallas/Fort Worth area and travel time between zones (Chen 2000)

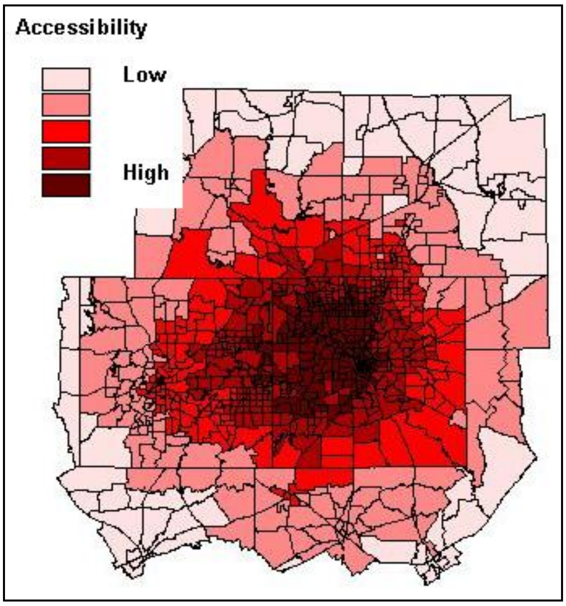


Figure 2.5. Zone-based technique representations of accessibility (travel time/distance measure)

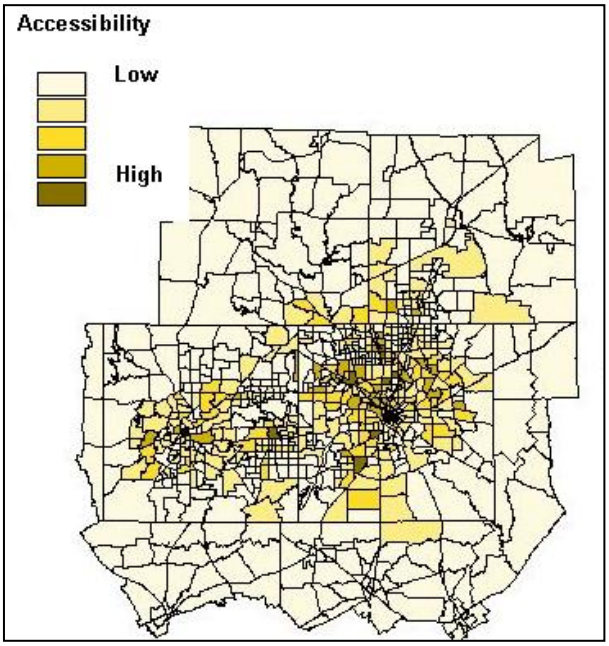


Figure 2.6. Zone-based technique representations of accessibility (cumulative opportunity measure) (Chen 2000)

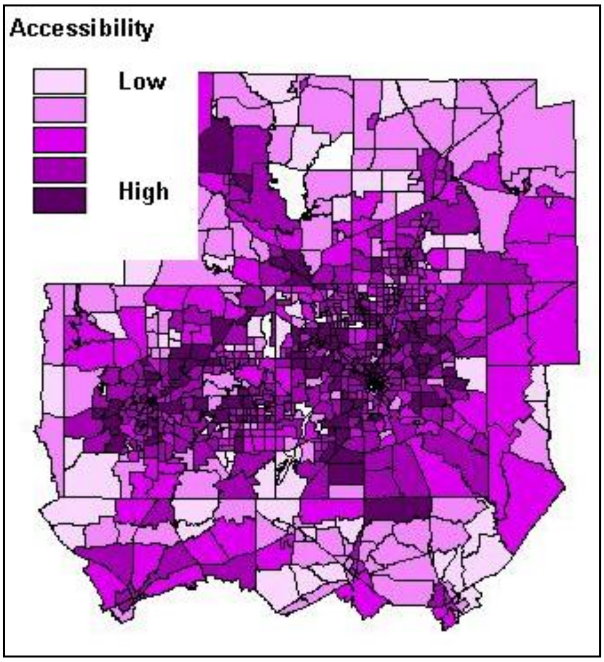


Figure 2.7. Zone-based technique representations of accessibility (gravity measure) (Chen 2000)

The shopping accessibility as travel distance/time measure is calculated with the following equation;

$$A_i = \sum_j t_{ij} \tag{5}$$

where $t_{ij}$ is the minimum total travel time between the centroids of zones i and j by auto and by transit in off peak hours. The calculated minimum travel cost values are used to model accessibility as a travel time distance measure in zone-based technique.

The shopping accessibility as cumulative opportunity measure is calculated with the following equation;

$$A_i = \sum_{t_{ij<T}} R_j \tag{6}$$

where i is the origin zone, j is the destination zone, $R_j$ is the retail employments in destination zone, $t_{ij}$ is the travel time between zones i and j, T is the time threshold which is set as 30 minutes for auto and 45 minutes for transit in the study. The cumulative retail employments, with traveling time less than the time threshold of 30 and 45 minutes, is used to represent shopping accessibility for each zone as cumulative opportunity measure

The shopping accessibility as gravity-based measure is calculated with the following equation;

$$Ai = \left[ \frac{1}{j} \sum_{j=1}^{j} \frac{\log R_j}{\log H_{ij}} \right] \tag{7}$$

where $R_j$ is the retail employment in zone j, J is the total number of zones in the area, $H_{ij}$ is the transportation impedance element. The cumulative retail employments, divided by the transportation impedance without any defined threshold, is used to represent shopping accessibility for each zone as gravity-based measure.

Kwan (1998)’s study for Franklin County, Ohio is another example of GIS-based accessibility modeling in zone-based technique. In Kwan (1998)’s study, zone-based accessibility is modeled as a cumulative opportunity and gravity measure for 20, 30, and 40 minutes of time thresholds by using digital transportation network data of Franklin County and parcel boundaries data including various kinds of shopping and retail facilities such as restaurants, personal business establishments, banks, entertainment, outdoor activities, educational institutions and office buildings.

In calculation of travel time and distances between land parcels, the parcel boundaries are converted into point-based centroids and all point-to-point distances between land parcels are measured in terms of shortest travel time (minutes) by considering the Franklin County transportation network. Seven road classes in the digital street network are classified into three major categories in order to simplify the computational process in the study. Travel impedances are assigned to the transportation network as constant average traveling speeds such as;

- 55 miles per hour for controlled access freeways,
- 25 miles per hour for state highways and municipal arterials without access control and
- 15 miles per hour for other city streets

The travel time is further adjusted upward 25 percent to take the delays at traffic lights and turns into account.

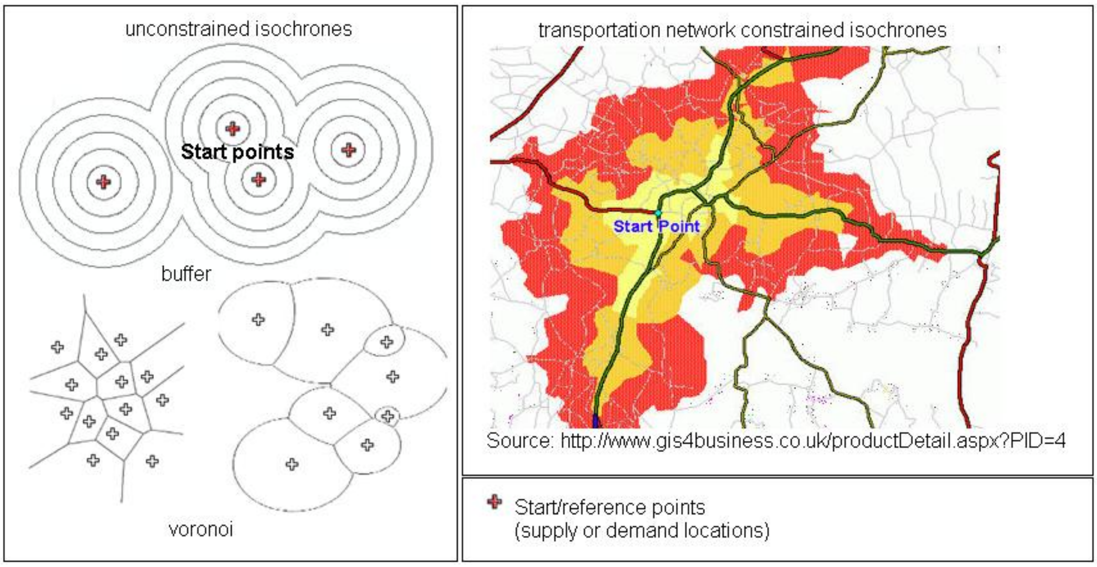
In calculation of the weighted sum of shopping opportunities in a particular parcel for the gravity measure, each of the parcel area is multiplied by a building height factor. The building height factor is set to 1 except that; a value of 0.5 is assigned to multi-storey retail structures, a value of 2 is assigned to walk up commercial buildings with three or more stories and elevator commercial buildings with three or more stories, a value of 4 is assigned to non downtown locations and a value of 10 is assigned to downtown locations.

### 2.6.2. Isochronal (isochrone-based) technique

In isochronal technique, accessibility measures are represented in terms of isochronal polygons, which are also known as the catchment or service area polygon boundaries. Isochronal polygon boundaries connect equal travel time or distance points away from one or more reference points (e.g. supply or demand).

Isochrone-based accessibility polygon boundaries are calculated from either constant average transportation network-based traveling costs such as 120 km/h for highways, 50 km/h for main streets and 30 km/h for local streets, etc. or unconstrained Eucledian distance based costs (straight-line/bird-flight based distances) such as buffer, voronoi (thiessen) polygons without considering the transportation network.

When an origin is defined as a reference point such as a demand or supply location, isochronal polygon boundaries can be drawn by connecting all points in all directions for an equal threshold of time or distance (Figure 2.8).



Source: http://www.gis4business.co.uk/productDetail.aspx?PID=4

Figure 2.8. The isochronal representation of accessibility

The buffer and voronoi-based isochrononal polygon boundaries have regular shape because of their unconstrained structure. However, transportation network-based isochronal polygon boundaries are constrained by the transportation network and can have irregular shape as the costs in a transportation network can provide traveling faster in some directions and traveling slower in other directions (Transportation Statistics Annual Report, 1997).

Isochronal technique can be used in calculation of several accessibility measures ranging from simple to sophisticated. For example,

- 10 minutes catchment area polygon boundary of supply/demand points can be calculated as a travel time/distance type of measure or

- Total number of cumulated supply/demand points within 10 minutes catchment area boundary can be calculated as a cumulative opportunity type of measure or
- Total number of weighted supply/demand points within 10 minutes catchment area boundary can be calculated as a gravity type of measure etc.

Dodge and White (1995)'s study in is an example of isochrone-based representation of accessibility for public services. The study calculates isochronal accessibility in terms of an unconstrained/bird flight distance measure and tries to understand how far people have to travel to reach a healthcare service in Wales. For this reason, 5 km buffer is created as a catchment area boundary around every supply points of healthcare services and critical zones are found where accessibility to the clinics could be a problematic. (Figure 2.9)

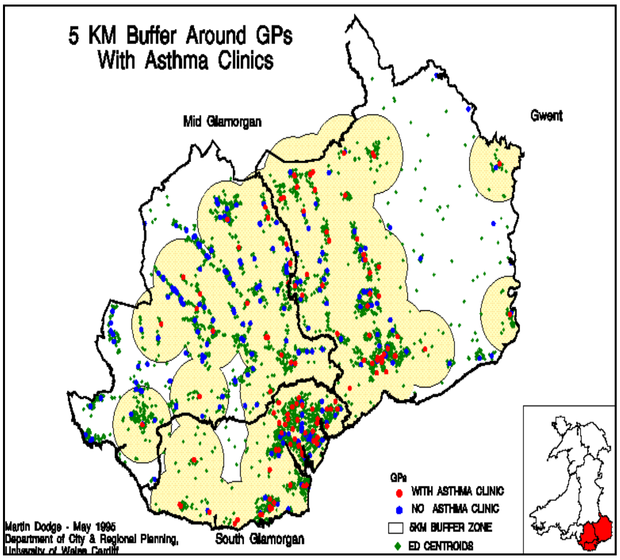


Figure 2.9. The simple representation of isochronal accessibility (Dodge and White 1995)

Murad (2004)'s study also investigates catchment area boundaries of a medical center in Makkah City, Saudi Arabia in isochronal technique. By using a road network that shows all types of roads in the study area and a medical center location in point format, a transportation network-based service/catchment area is defined in ArcGIS Network analyst software environment and supply/demand opportunities inside the service/catchment area are analysed (Figure 2.10). Then the outputs are used to define the priorities in health care plans, shortages in actual catchment area and the need for additional healthcare resources.

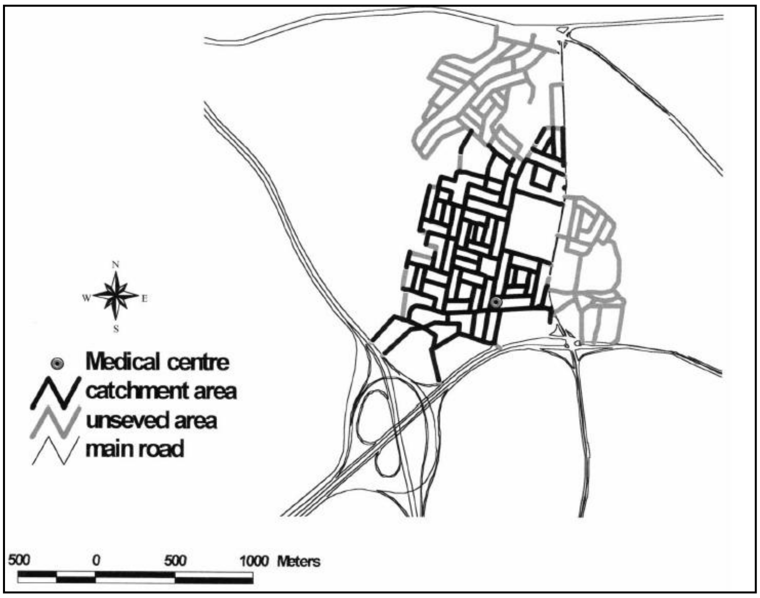


Figure 2.10. Catchment area of a medical centre in Makkah City, Saudi Arabia (Murad 2004)

Although isochronal-based technique is widely used in accessibility modeling literature, one of the weaknesses of the isochronal technique is that accessibility measures are highly sensitive to traveling time/distance based costs and user defined thresholds. Slight changes in traveling costs and user-defined thresholds can create significant changes in catchment area polygon boundaries and hence directly affect the amount of supply and demand opportunities. Considering several costs and thresholds can provide more realistic decision support for decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues.

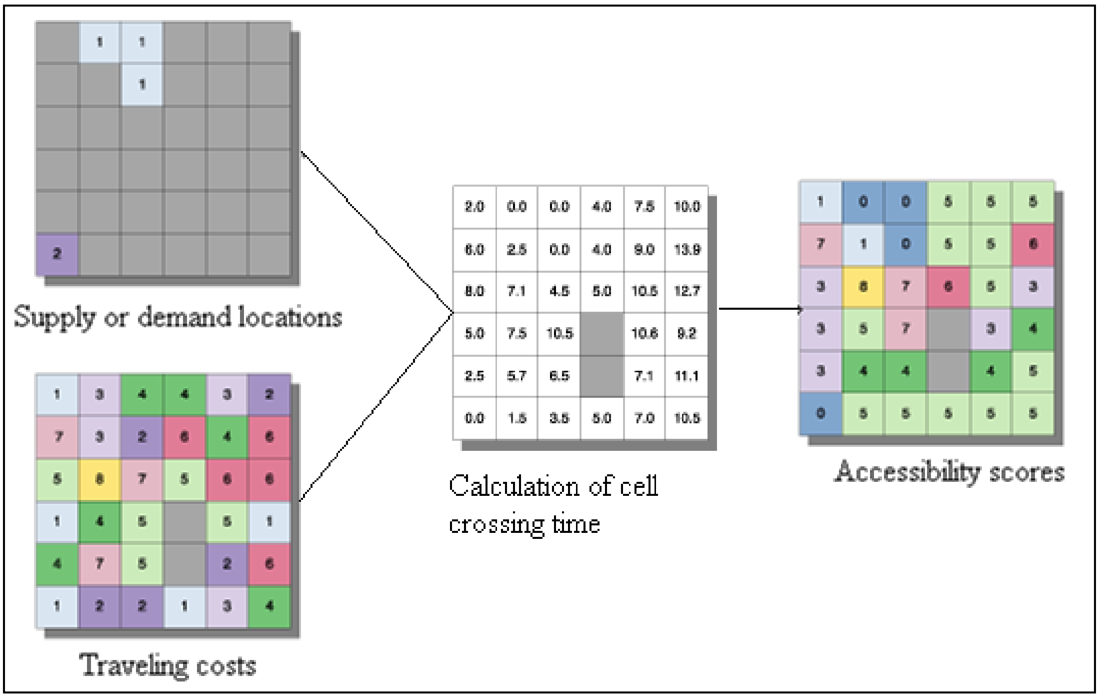
### 2.6.3. Raster-based technique

Pixel, which is also called cell, can be defined as the smallest unit in raster environment. In raster-based technique, accessibility measures are represented by raster-based pixels instead of vector-based polylines or polygons. The supply and demand locations and the transportation network are the main inputs of raster-based technique. By considering traveling costs in the transportation network, each pixel in raster environment generally gets an accessibility score, which is based on its proximity to nearest supply or demand opportunity.

There are three main phase in raster-based modeling of accessibility, which are;

- data acquisition and integration
- cost surface preparation
- accessibility modeling and visualization

Data acquisition and integration phase includes preparation of data in which supply/demand locations and transportation network data are obtained and converted into a common raster format. Cost surface preparation phase includes determination of traveling costs for each of the individual pixel on the transportation network and calculation of cell crossing costs. Finally, accessibility modeling and visualization phase includes measurement and representation of accessibility scores in raster-based environment by considering, supply/demand locations, traveling costs and cell crossing time (Figure 2.11).



|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | 1 | 1 |  |  |  |
|  |  | 1 |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
| 2 |  |  |  |  |  |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 1 | 3 | 4 | 4 | 3 | 2 |
| 7 | 3 | 2 | 6 | 4 | 6 |
| 5 | 8 | 7 | 5 | 6 | 6 |
| 1 | 4 | 5 |  | 5 | 1 |
| 4 | 7 | 5 |  | 2 | 6 |
| 1 | 2 | 2 | 1 | 3 | 4 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 2.0 | 0.0 | 0.0 | 4.0 | 7.5 | 10.0 |
| 6.0 | 2.5 | 0.0 | 4.0 | 9.0 | 13.9 |
| 8.0 | 7.1 | 4.5 | 5.0 | 10.5 | 12.7 |
| 5.0 | 7.5 | 10.5 |  | 10.6 | 9.2 |
| 2.5 | 5.7 | 6.5 |  | 7.1 | 11.1 |
| 0.0 | 1.5 | 3.5 | 5.0 | 7.0 | 10.5 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 5 | 5 | 5 |
| 7 | 1 | 0 | 5 | 5 | 6 |
| 3 | 8 | 7 | 6 | 5 | 3 |
| 3 | 5 | 7 |  | 3 | 4 |
| 3 | 4 | 4 |  | 4 | 5 |
| 0 | 5 | 5 | 5 | 5 | 5 |

Figure 2.11. The raster-based representation of accessibility (ESRI User Manuel 2010)

Raster-based technique is generally prefered in regional studies, which does not necessitate high spatial accuracy. Because of pixel-based structure of the raster-based technique, working in raster environment reduces the geometrical accuracy of accessibility measures. However, it enables continuous representation of accessibility scores and opens a wide range of new raster analysis capabilities.

Juliao (1999)'s study is an example of raster-based representation of accessibility. The study calculates accessibility scores of municipality towns, highway nodes and city centre in Portugal and gives a detailed explanation of covered steps in terms of raster-based representation of accessibility.

In the data acquisition and integration phase, the basic data of supply and demand points and the transportation network are all converted into raster format. First, transportation network is classified according to the road types, which are Main highway (IP), Main lane (IP2), Complementary highway (IC), Complementary lane (IC2), National Road, Regional Road, Municipal Road etc. Then, all of the data are converted into raster format with a pixel dimension of 100 meters (Figure 2.12).

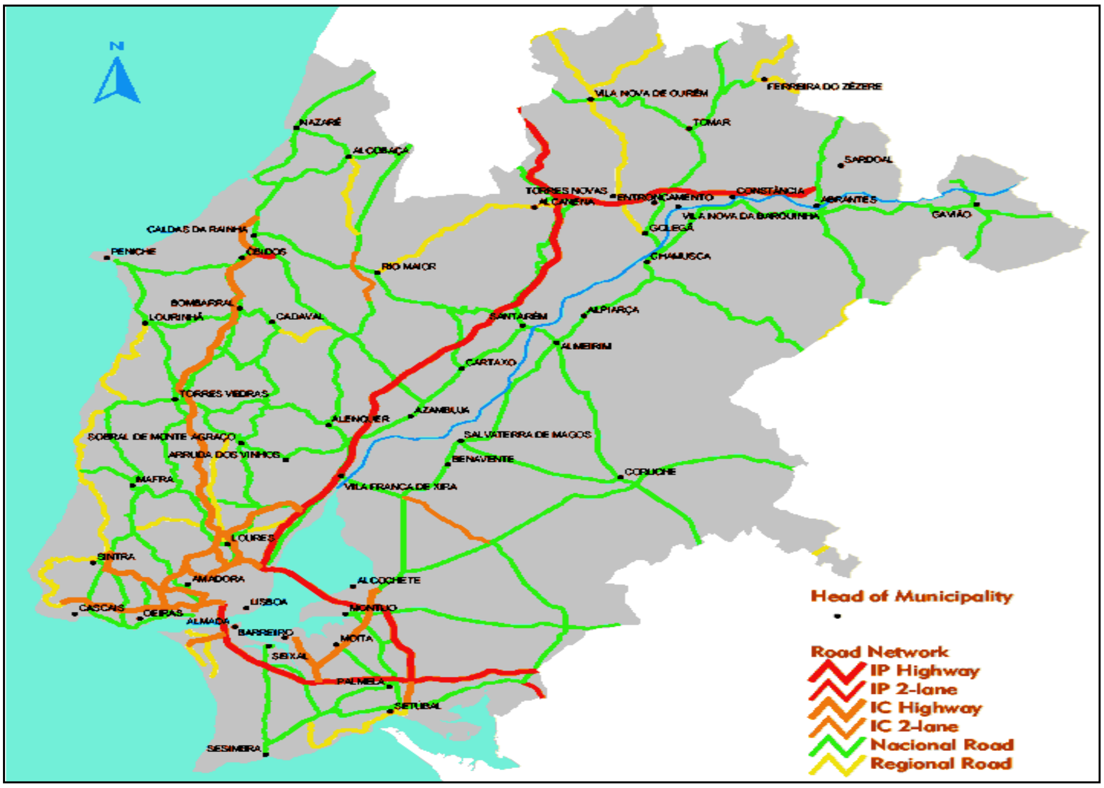


Figure 2.12. Road network data in raster format (Juliao 1999)

In the cost surface preperation phase, cell-crossing time for each of the pixel is calculated by using the following equation;

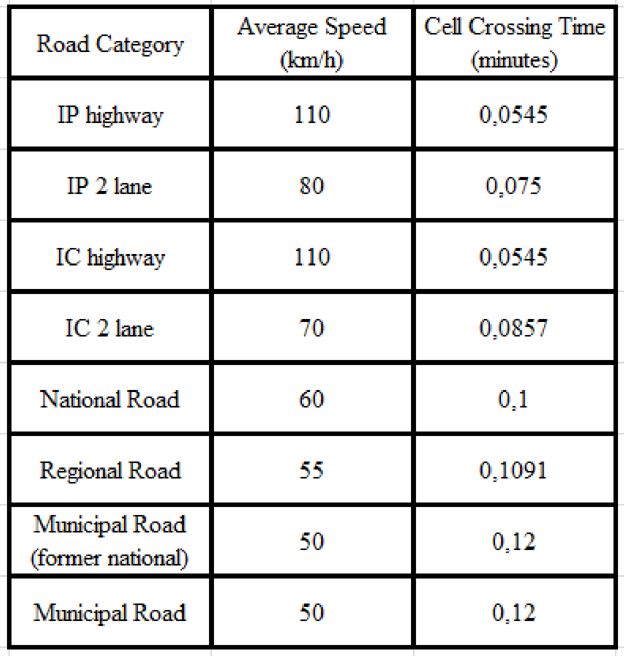
$$CCT = \frac{P * 60}{TS * 1000} \tag{8}$$

where CCT is the cell crossing time in minutes, P is the pixel size and TS is the average traveling speed in kilometers per hour (km/h) according to classified road segments in the transportation network. For example if a vehicle is travelling in road type Main Lane (IP2), cell-crossing time (CCT) is calculated as in below equation;

$$CCT = \frac{P * 60}{TS * 1000} = \frac{100 * 60}{80 * 1000} = \frac{6}{80} = 0.0750 \tag{9}$$

With the same logic, entire cell crossing times according to average speeds are calculated by considering different road categories in the transportation network (Table 2.1).

Table 2.1. Cell crossing time according to average speeds (Juliao 1999)



| Road Category | Average Speed (km/h) | Cell Crossing Time (minutes) |
|---|---|---|
| IP highway | 110 | 0,0545 |
| IP 2 lane | 80 | 0,075 |
| IC highway | 110 | 0,0545 |
| IC 2 lane | 70 | 0,0857 |
| National Road | 60 | 0,1 |
| Regional Road | 55 | 0,1091 |
| Municipal Road (former national) | 50 | 0,12 |
| Municipal Road | 50 | 0,12 |

To fill the gaps between road infrastructures and to have accessibility scores for the whole territory, an average walking speed of 6 Km/h is used as an average pedestrian speed outside of the transportation network.

In the accessibility modeling and visualization phase, supply/demand locations and cell crossing time are used to calculate several accessibility maps in Portugal for different time thresholds. These are accessibility map of the municipality towns (Figure 2.13), accessibility map of the highway nodes (Figure 2.14) and accessibility map of the city centre Lisbon (Figure 2.15).

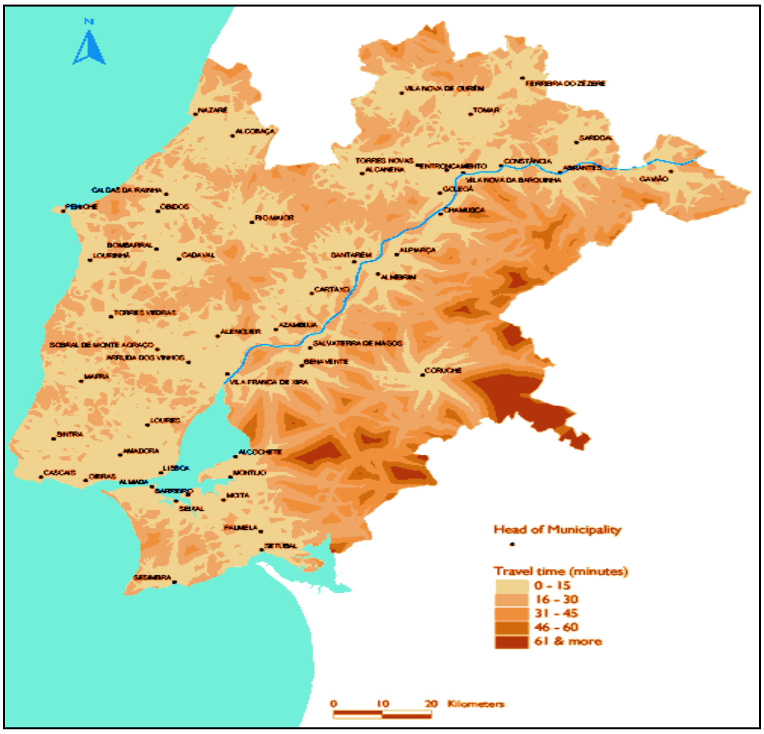


Figure 2.13. Accessibility of municipality towns in Portugal in raster-based technique (Juliao 1999)

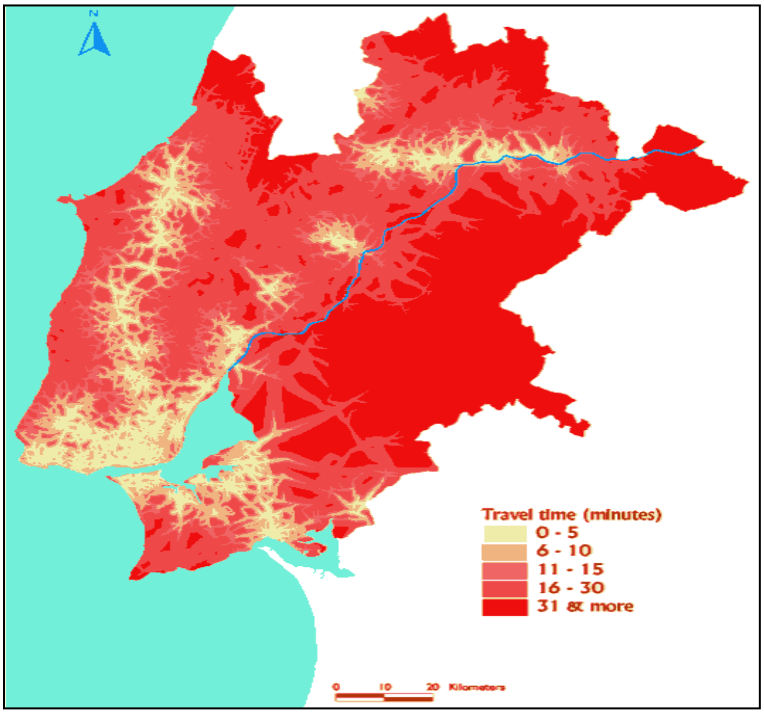


Figure 2.14. Accessibility of highway nodes in Portugal in raster-based technique (Juliao 1999)

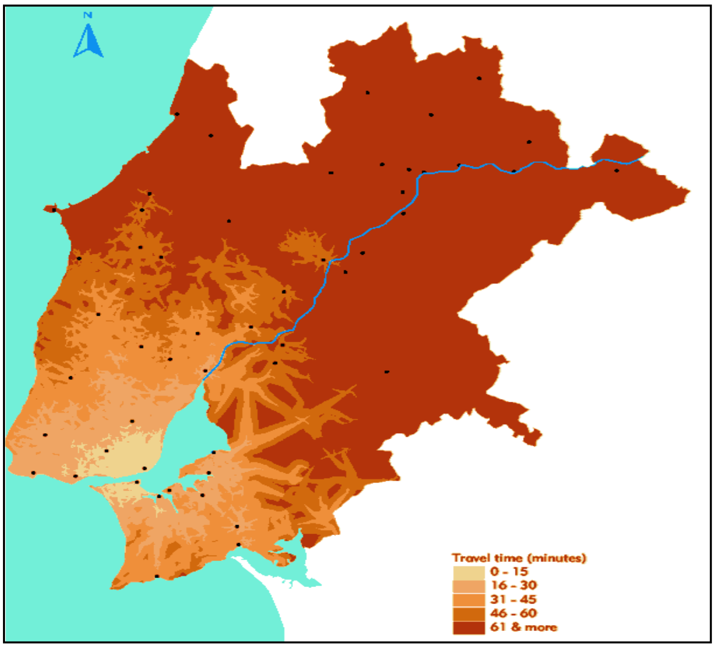


Figure 2.15. Accessibility of Lisbon in Portugal in raster-based technique (Juliao 1999)

Ebener et al. (2005)'s study is another research example for raster-based technique that models healthcare accessibility for pedestrians. According to the study, most of the accessibility modeling research involve vector approach, which relies on high quality road network and supply/demand information. However, an advantage of raster-based technique is that they do not restrict traveling by physical road network and provide a continuous accessibility environment with a free travel across the terrain (Figure 2.16). With this in mind, healthcare accessibility for pedestrians is analysed for 180 minutes of threshold time by using two different types of traveling costs, which are called isotropic (do not consider effect of slope and landcover in calculation of traveling costs) and anisotropic (consider the effect of slope and landcover in calculation of traveling costs). In isotropic approach, a fixed average travelling speed is used. In anisotropic approach several average travelling speeds considering different landuse and slope type are assigned and the accessibility map results are compared (Figure 2.17).

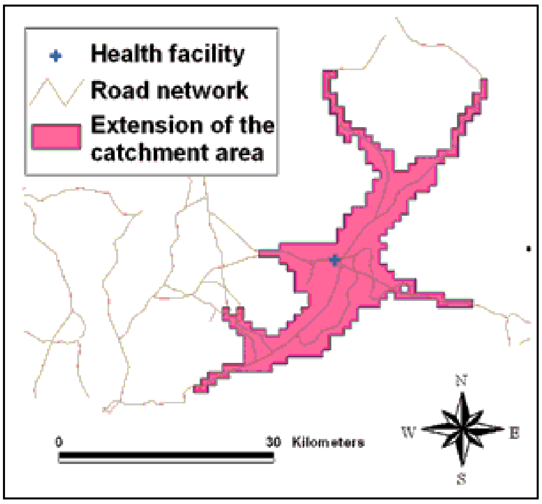


Figure 2.16. Extension of the catchment area in raster-based technique (Ebener et al. 2005)

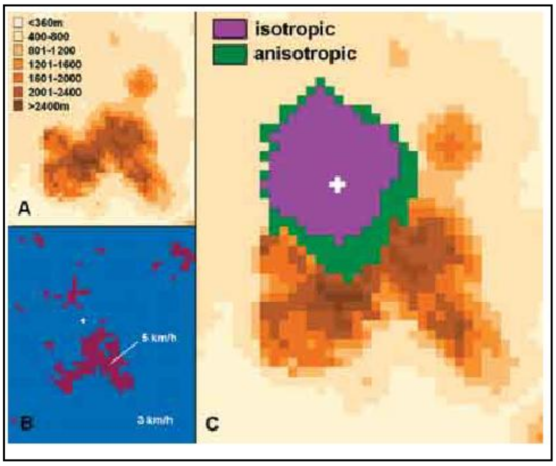


Figure 2.17. Healthcare accessibility for pedestrians by using raster-based technique (A-digital elevation model, B-landuse types C-accessibility results) (Ebener et al. 2005)

## 2.7. The role of GIS in physical accessibility modeling

### 2.7.1. The contribution of GIS into physical accessibility modeling

Since physical accessibility measures describe the spatial characteristics of a location and need large amount of computation and organisation between huge and complex spatial data sets, accessibility modeling often and unavoidably lends itself to Geographical Information Systems technologies in terms of data collection, manipulation, programming, topology, analysis and presentation related issues.

As GIS have unique capabilities to handle spatial data and operations related to positions on the Earth's surface, with an integrated database of basic transportation, land-use and socio-economical data, GIS could provide a powerful interface and infrastructure for the decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues. As accessibility measures such as transportation, landuse and/or socio-economical data, accessibility modeling needs a GIS environment.

The general support of GIS in accessibility modeling can be summarized as below;

- Data collection related supports (GIS have capabilities to capture, store, integrate and convert spatial and attribute data). For example,
    - GIS can support storing complex transportation network, supply/demand or origin/destination related datasets in a common raster or vector environment
- Data manipulation related supports (GIS have capabilities to select, query, calculate, update, classify spatial and attribute data). For example,
    - GIS can support classification of transportation network data according to road type or road capacity and classification of supply/demand or origin/destination locations data according to their weight, importance etc.)
    - GIS can support calculation of new information from classified datasets by using attribute table data (e.g. calculation of traveling time on main road segments by using road length and average speed data)
- Spatial analysis related supports (GIS have capabilities to operate vital raster and vector based spatial analysis functions such as proximity (buffer, voronoi, density etc.), spatial overlay (union, intersect, zonal statistics etc.) and network analysis (shortest path, service area, cost distance, etc.) For example;
    - GIS can support calculating proximity between origin/destination locations or performing network analyses, (e.g. creating 1 kilometers Eucledian distance buffer or

    creating 5 minutes transportation network based service area boundary

- Topology related supports (GIS can handle accessibility related topological relationships between nodes, arcs, polygons, centroids etc. and help to understand how transportation network or supply/demand segments connect and relate to each other). For example;
    - GIS can support building traffic regulations of streets such as one-way streets, closed streets, overpasses, underpasses, delays in intersections
    - GIS can support detecting cumulative number of opportunities inside catchment area boundaries
- Programming related supports (GIS have capabilities to create, edit, and manage current models or create new models by providing a specific programming environment). For example,
    - GIS can support developing a new toolbox / user-interface that handles stochastic modeling of accessibility)
- Mapping and presentation related supports (GIS have capabilities to present accessibility maps with opportunity of different scales (1/1000, 1/5000 etc.), different data classification methods (natural breaks, quantile, equal interval, standard deviation etc.), different dimension (in 2D or 3D dimension), various color choices (red, yellow etc.) and various figure choices (square, circle etc.)). For example,
    - An accessibility map can be presented 5, 10, 15, 20 minutes of accessibility of fire brigades in 3D with different colors)

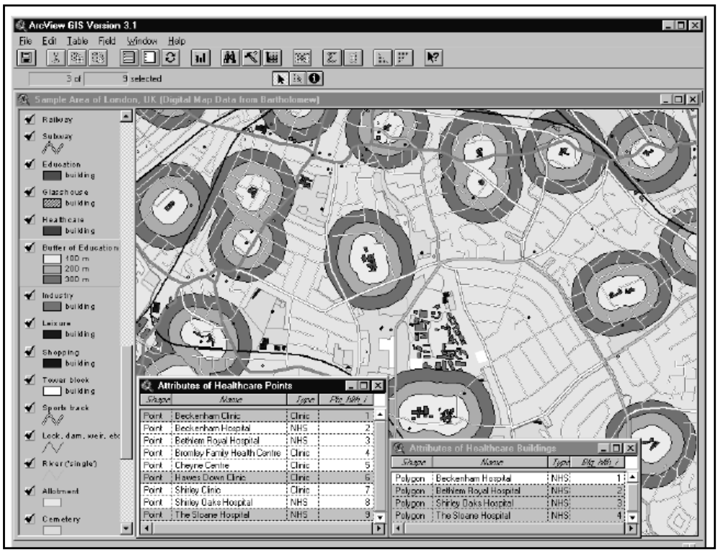
(Black et al. 2004, Peters and Hall 1999, MacFarlane 2005, Ebener et al. 2005)

### 2.7.2. GIS-based accessibility modeling examples

As physical accessibility modeling unavoidably lends itself to a GIS platform, many GIS-based accessibility modeling research can be observed in the literature, especially in the last decades. This part of the research summarizes some of the main and widely observed GIS-based accessibility modeling research examples in the literature.

Boulos et al. (2001), Ghio et al. (2007), Chapelet and Lefebvre (2005) and Black et al. (2004) are some of the GIS-based examples that model accessibility as Eucledian-distance based travel distance measure and cumulative opportunity measure.

Boulos et al. (2001)’s study calculates healthcare accessibility for educational facilities in London, as Eucledian-distance based travel distance and cumulative opportunity measure by using isochronal technique. 100, 200 and 300 meters of constant deterministic Eucledian-based buffers are created around each educational facility as a travel distance measure and number of health services inside each of the buffer area is calculated as a cumulative opportunity measure in ArcView GIS software environment (Figure 2.18).



| Shape | Name | Type | Plc_fdth_i |
|---|---|---|---|
| Point | Beckenham Clinic | Clinic | 1 |
| Point | Beckenham Hospital | NHS | 2 |
| Point | Bethlem Royal Hospital | NHS | 3 |
| Point | Bromley Family Health Centre | Clinic | 4 |
| Point | Cheyne Centre | Clinic | 5 |
| Point | Hawes Down Clinic | Clinic | 6 |
| Point | Shirley Clinic | Clinic | 7 |
| Point | Shirley Oaks Hospital | NHS | 8 |
| Point | The Sloane Hospital | NHS | 9 |

| Shape | Name | Type | Blg_fdth_i |
|---|---|---|---|
| Polygon | Beckenham Hospital | NHS | 1 |
| Polygon | Bethlem Royal Hospital | NHS | 2 |
| Polygon | Shirley Oaks Hospital | NHS | 3 |
| Polygon | The Sloane Hospital | NHS | 4 |

Figure 2.18. 100, 200 and 300 meters of constant deterministic Eucledian-based buffers around each educational facility in London, UK (Boulos et al. 2001)

Ghio et al. (2007)’s study is another example that measure healthcare service accessibility as Eucledian-distance based travel distance and cumulative opportunity measure by using isochronal technique. In order to find out the average distance to a healthcare facility from a populated area and the critical areas that should be targeted for a new facility (a mobile clinic), a GIS-based buffer analysis is performed and unserved or limitedly served populations in Yemen that currently fall outside of a suitable buffer distance to healthcare services are analysed (Figure 2.19).

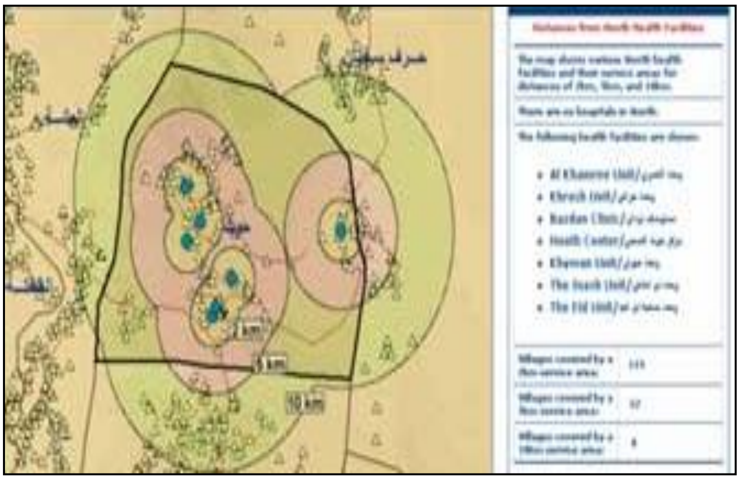


Figure 2.19. Healthcare accessibility based on Eucledian-based distance in Yemen (Ghio et al. 2007)

Chapelet and Lefebvre (2005)'s study calculates accessibility to general practitioners as Eucledian-distance based travel time/distance measure. By using a raster-based cost distance function in GIS environment, the study develop an analytical methodology for showing the attractiveness of different landuse types by considering their total area and their distance to a general practitioner in Gurgaon (e.g. 75% of commertial areas are at less than 600 meters from a general practitioner or 10% of industrial areas are at less than 1 km from a doctor etc) (Figure 2.20, Figure 2.21).

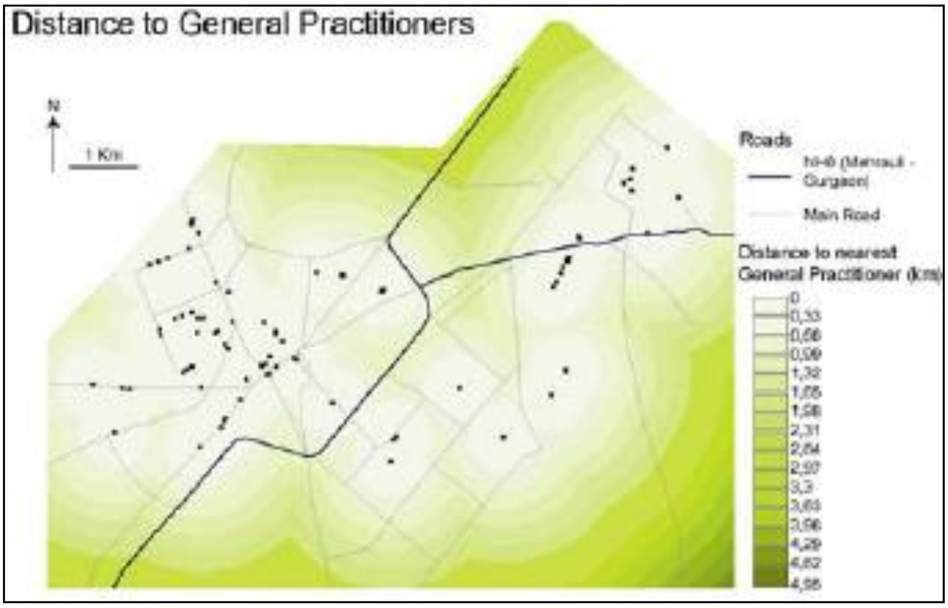


Figure 2.20. Accessibility to general practitioners in Gurgaon as Eucledian-distance based travel time/distance measure (Chapelet and Lefebvre 2005)

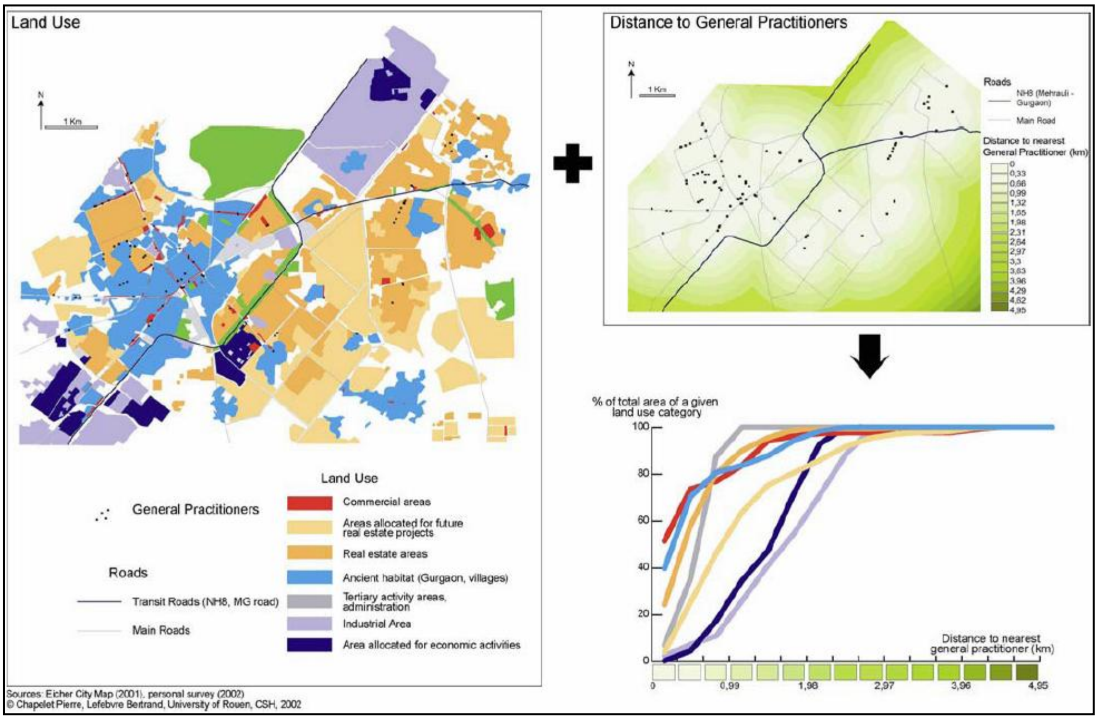


Figure 2.21. Attractiveness of different landuse types by considering their total area and their distance to a general practitioner in Gurgaon (Chapelet and Lefebvre 2005)

Black et al. (2004)'s study calculates healthcare accessibility in Honduras as Eucledian-distance based travel time/distance and cumulative opportunity measure. By using Thiessen/Voronoi polygons as a catchment area boundary, accessibility to healthcare facilities (CESAMO's) are calculated by considering several input data which are; population and populated places (towns and villages), land cover, road network, digital elevation model (DEM), municipality boundaries, healthcare facilities (CESAMO's) and number of physicians.

In order to detect critical settlements in terms of healthcare accessibility, several travel time/distance and cumulative opportunity measures are calculated for each populated place (towns and villages).

These measures are;

- Available physicians inside each Thiessen polygon catchment area
- Distance (kilometers) to the nearest CESAMO
- Traveling time (minutes) to the closest road segment by walking (In calculation of traveling costs by walking, average speed of 5 kilometer per hour, weighted by the slope, is used)
- Traveling time (hours) to the closest CESAMO by car (In calculation of traveling costs by car, the road types are used. For primary roads average speed of 100 kilometers per hour weighted by the slope, for secondary roads average speed of 70 kilometers per hour weighted by the slope, and for Rodera's roads average speed of 20 kilometers per hour,weighted by the slope is used (Figure 2.22).

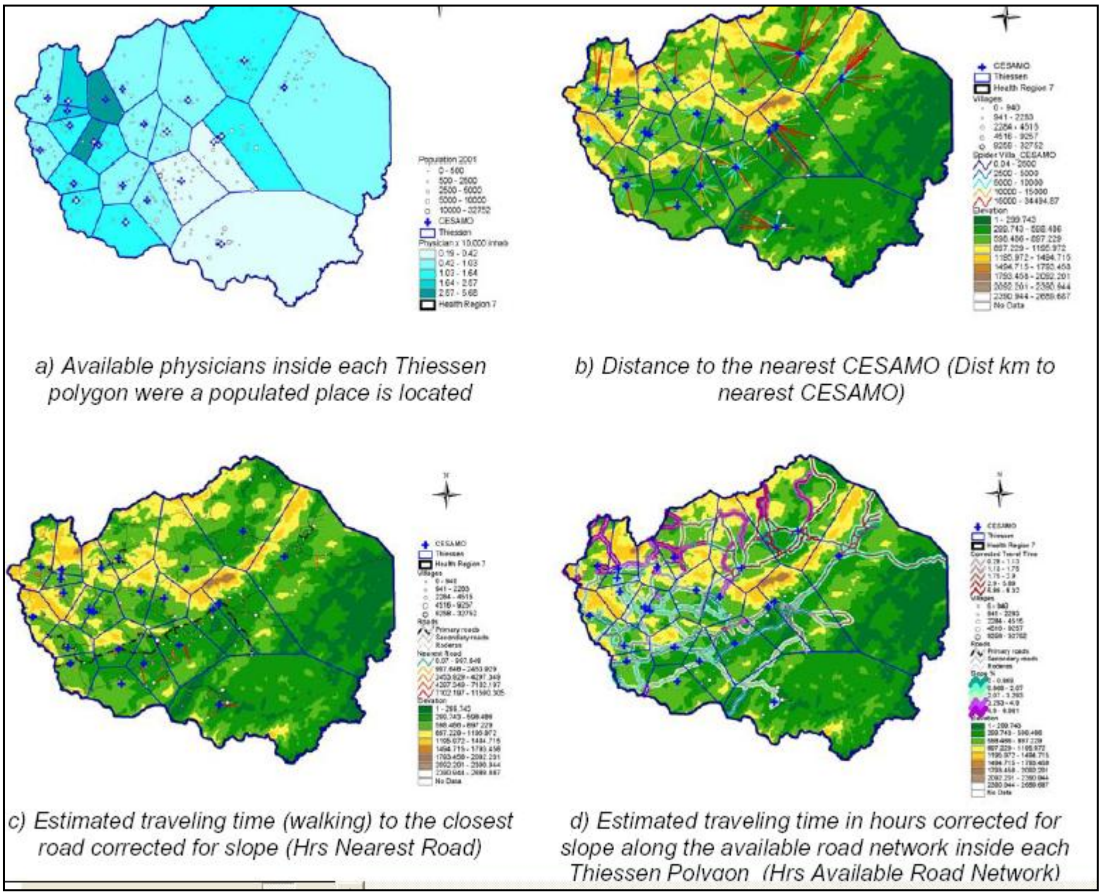
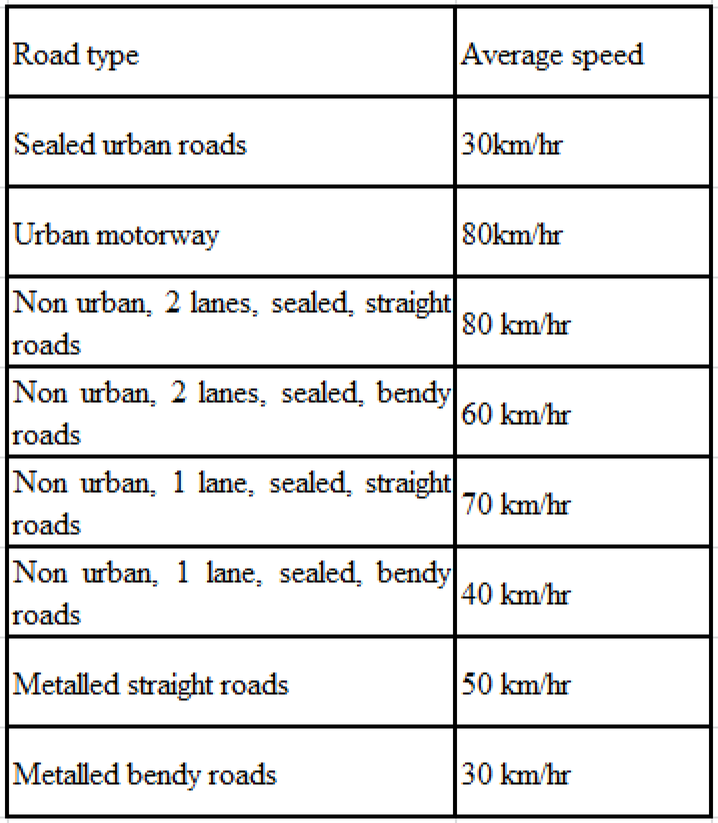


Figure 2.22. Healthcare accessibility in Honduras as Thiessen/Voronoi based travel time/distance and cumulative opportunity measures (Black et al. 2004)

Brabyn (2002), Brabyn and Skelly (2002), Nadine et al. (2006) and Messina et al. (2006) are some of the GIS-based accessibility modeling examples that model accessibility as a transportation network based travel time/distance and cumulative opportunity measure.

Brabyn (2002) models physical accessibility of General Practitioners (GPs) as a transportation network based travel time/distance measure in zone-based technique. By considering average deterministic transportation network costs, Brabyn (2002) calculates minimum travel time and distance from the centroids of the population blocks to the closest GP in New Zealand. In calculation of average constant transportation network costs, roads are classified according to types and an average traveling speed is assigned for each of the pre-determined road classes (Table 2.2).

Table 2.2. Average deterministic transportation network costs (average speed) used in calculation of traveling costs (Brabyn 2002)



| Road type | Average speed |
|---|---|
| Sealed urban roads | 30km/hr |
| Urban motorway | 80km/hr |
| Non urban, 2 lanes, sealed, straight roads | 80 km/hr |
| Non urban, 2 lanes, sealed, bendy roads | 60 km/hr |
| Non urban, 1 lane, sealed, straight roads | 70 km/hr |
| Non urban, 1 lane, sealed, bendy roads | 40 km/hr |
| Metalled straight roads | 50 km/hr |
| Metalled bendy roads | 30 km/hr |

Similarly, Brabyn and Skelly (2002) estimates physical accessibility of New Zealand public hospitals as a transportation network based travel time/distance measure in zone-based technique. By using average deterministic transportation network costs in the digital road network data (Figure 2.23), minimum traveling distance and time between census centroids and closest hospital are calculated as a travel time/distance measure (Figure 2.24, Figure 2.25) and population more than 60 minutes from a hospital are calculated as a cumulative opportunity measure (Figure 2.26) in a GIS environment.

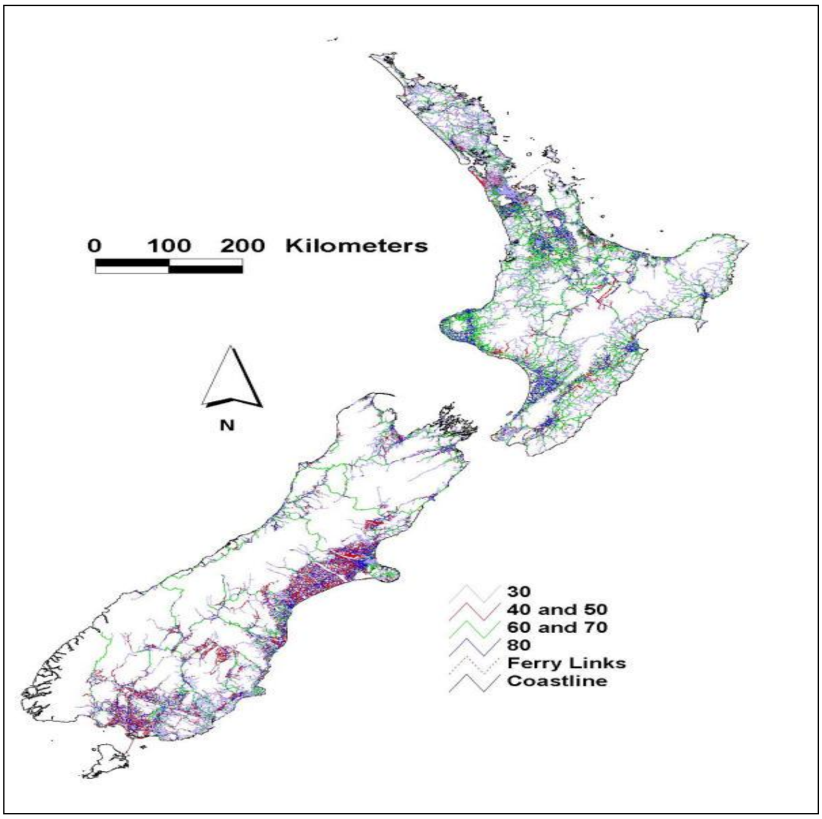


Figure 2.23. Road network showing constant average estimated traveling speeds (Brabyn and Skelly 2002)

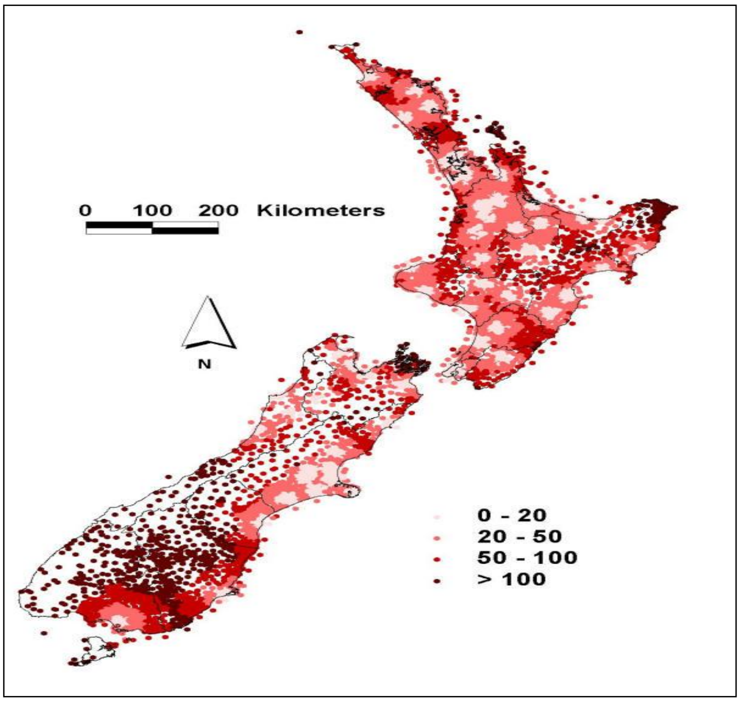


Figure 2.24. Travel Distance in Kilometers to the Closest Hospital by Census Centroids (Brabyn and Skelly 2002)

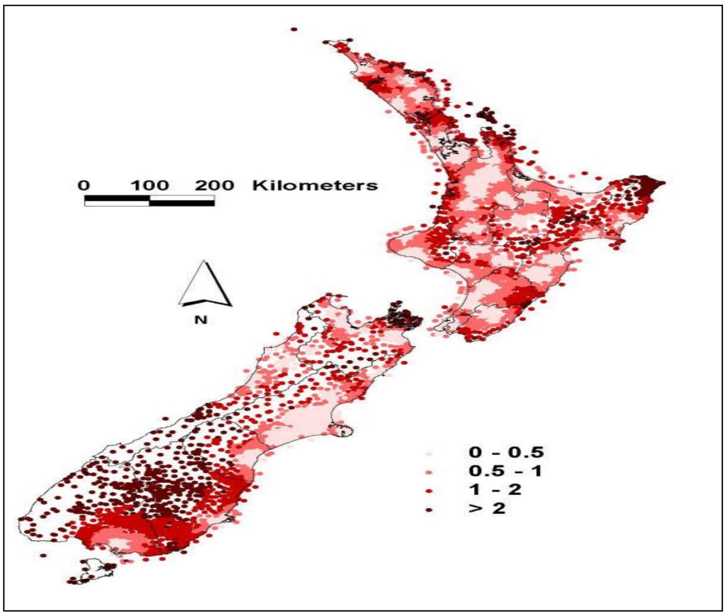


Figure 2.25. Travel Time in hours to the Closest Hospital by Census Centroids (Brabyn and Skelly 2002)

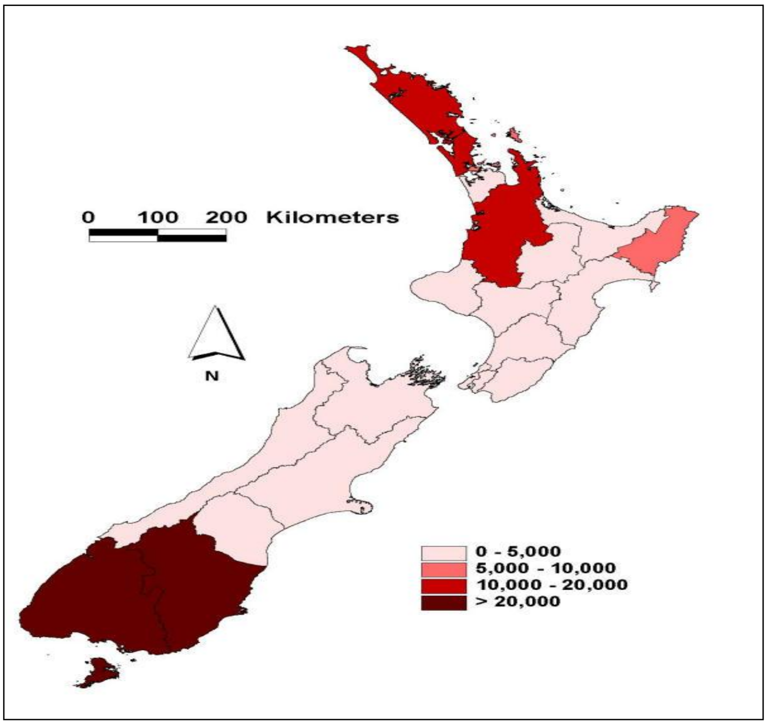


Figure 2.26. Population more than 60 Minutes from a Hospital by District Health Board (Brabyn and Skelly 2002)

Nadine et al. (2006) is an example that measure healthcare service accessibility as transportation network based travel time/distance and cumulative opportunity measure by using isochronal technique. The hospital locations, populated census blocks and digital road network data of British Columbia are used as input data (Figure 2.27) and alternate accessibility scenarios are modeled for different type of healthcare services (e.g. all hospitals, hospitals with critical care etc.) and for different travel time thresholds (e.g. 30 minutes, 1 hour) including the estimates of percentage of population that is served or not served (Figure 2.28, Figure 2.29, Figure 2.30).

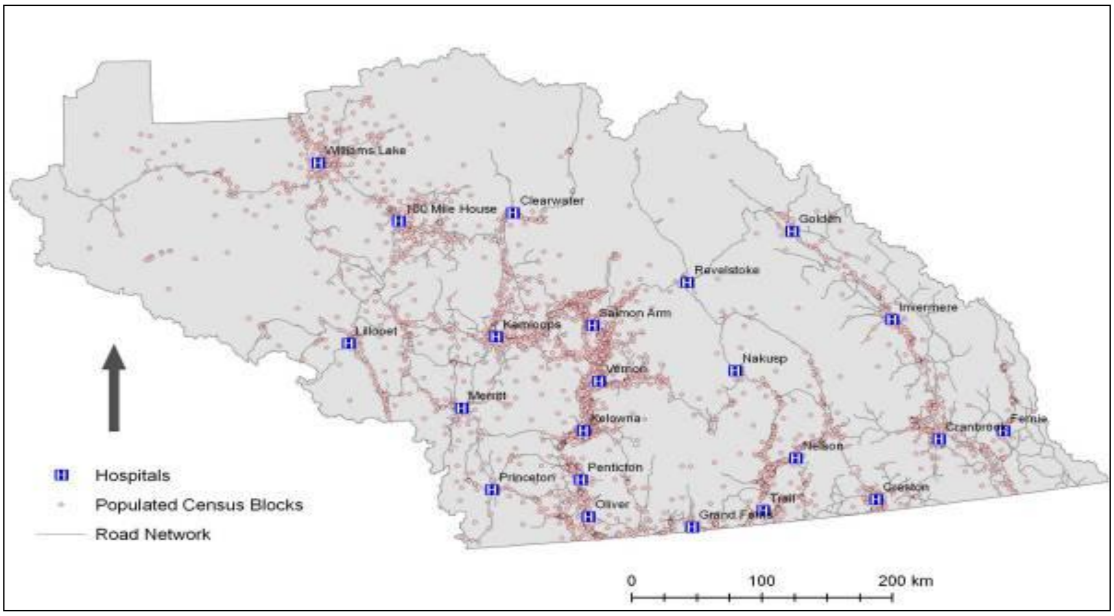


Figure 2.27. The input GIS data used in the research (Nadine et al. 2006)

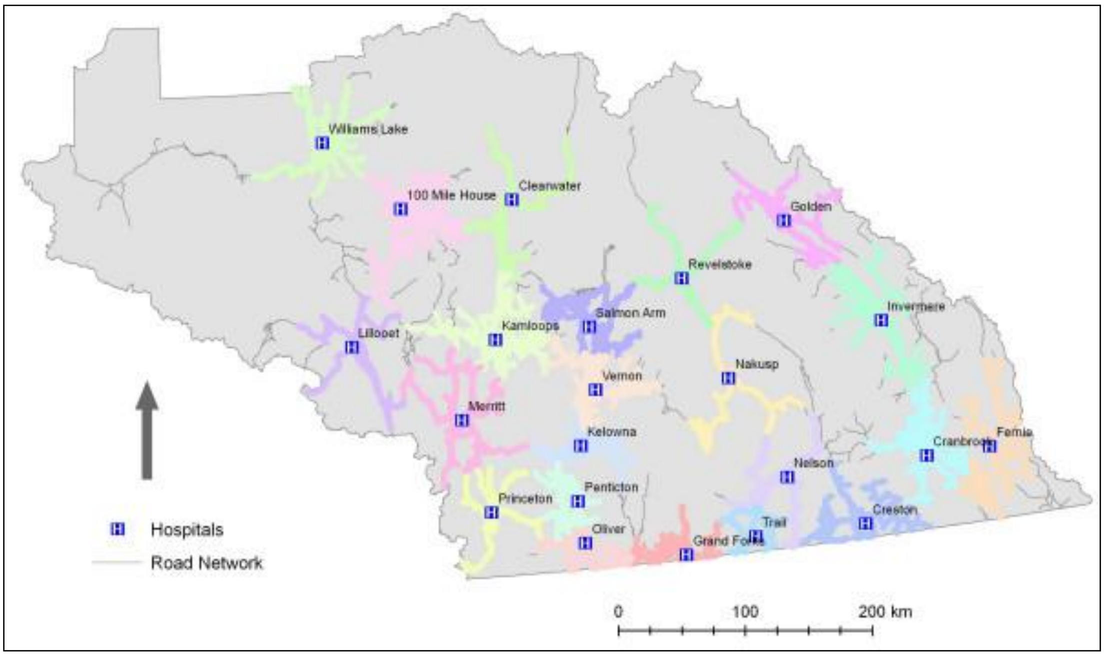


Figure 2.28. 1 hour service areas for all hospitals (Nadine et al. 2006)

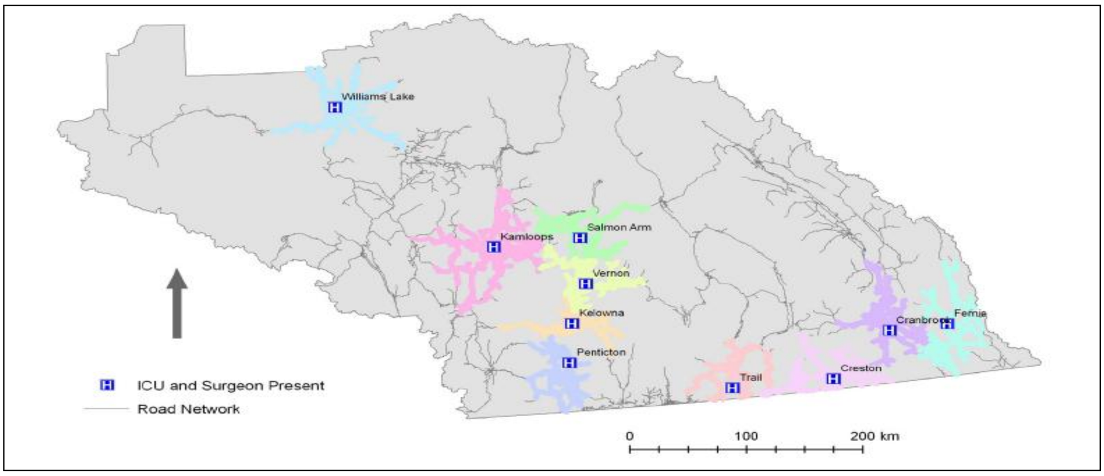
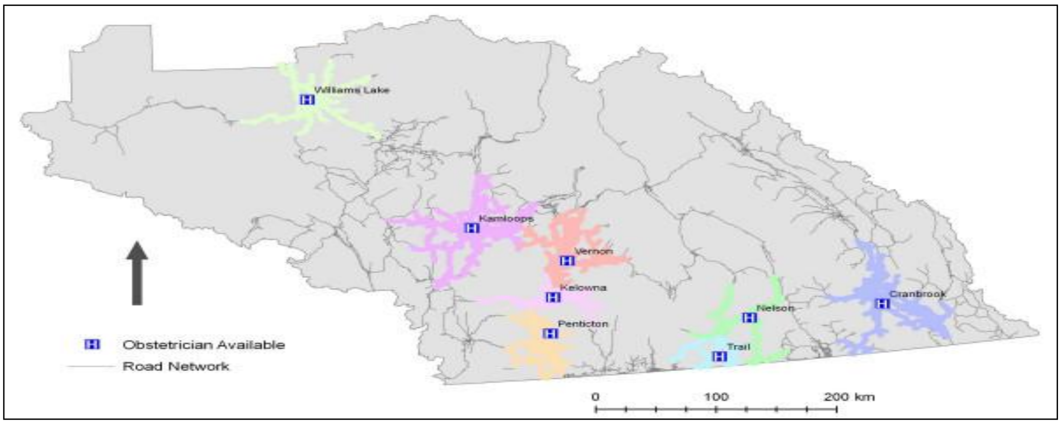
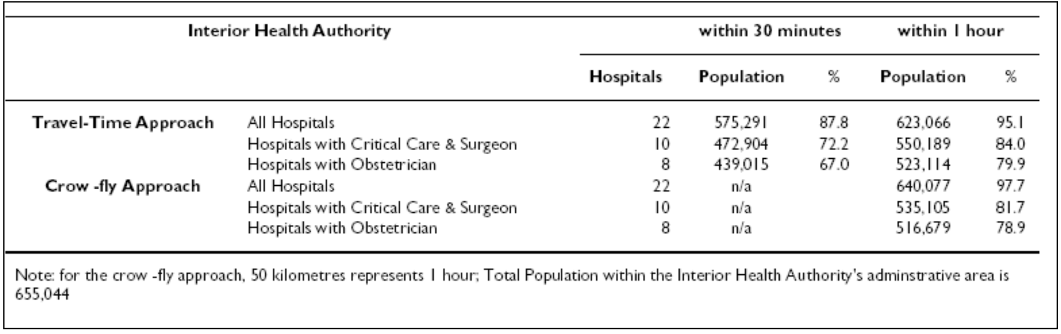


Figure 2.29. 1 hour service areas for hospitals with ICU and Surgeon (Nadine et al. 2006)





| Interior Health Authority | | within 30 minutes | | | within 1 hour | |
|---|---|---|---|---|---|---|
| | | Hospitals | Population | % | Population | % |
| **Travel-Time Approach** | All Hospitals | 22 | 575,291 | 87.8 | 623,066 | 95.1 |
| | Hospitals with Critical Care & Surgeon | 10 | 472,904 | 72.2 | 550,189 | 84.0 |
| | Hospitals with Obstetrician | 8 | 439,015 | 67.0 | 523,114 | 79.9 |
| **Crow -fly Approach** | All Hospitals | 22 | n/a | | 640,077 | 97.7 |
| | Hospitals with Critical Care & Surgeon | 10 | n/a | | 535,105 | 81.7 |
| | Hospitals with Obstetrician | 8 | n/a | | 516,679 | 78.9 |

Note: for the crow -fly approach, 50 kilometres represents 1 hour; Total Population within the Interior Health Authority's adminstrative area is 655,044

Figure 2.30. 1-hour service areas for hospitals with Obstetrician available with the estimates of the percentage of population that is served or not served (Nadine et al. 2006)

Messina et al. (2006) model accessibility to community hospitals as transportation network based travel time/distance and cumulative opportunity measure by using raster based technique. The aim of the study is to identify relatively remote locations from existing community hospitals and provide accessibility related decision support to policy makers in Michigan. For this aim, by using hospital locations data (Figure 2.31) and population distribution data (Figure 2.32), under-served population locations, which are within maximum 30 minute travel time to suitable hospitals and total population inside the under-served locations are modeled for normal and rush hour traffic conditions (Figure 2.33, Figure 2.34). In calculation of time cost for normal traffic conditions, speed limits defined by classified road segments are used (range from 40.2 to 112.7 kilometers per hour). In calculation of time cost for rush hour traffic conditions, all speed limits are reduced by 25%.

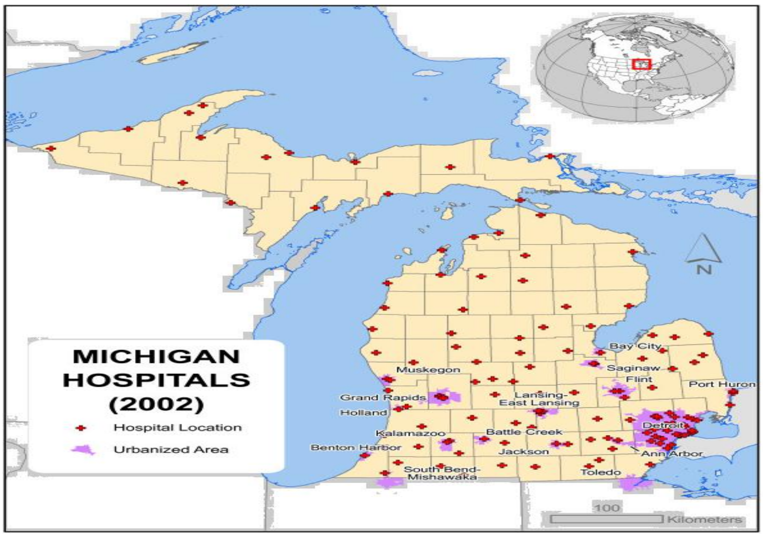


Figure 2.31. Hospital locations data in Michigan (Messina et al. 2006)

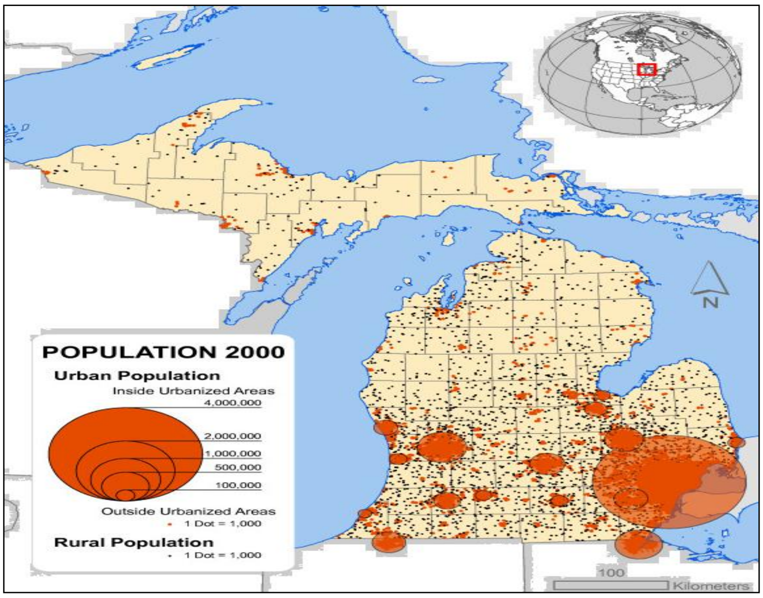


Figure 2.32. Population distribution data in Michigan (Messina et al. 2006)

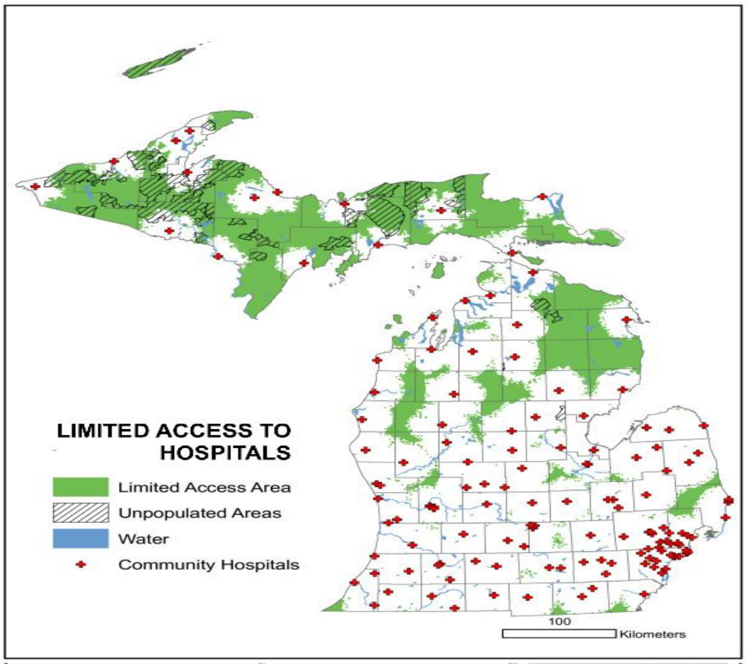


Figure 2.33. Community hospital accessibility for 30-minute travel time in Michigan for normal traffic conditions (Messina et al. 2006)

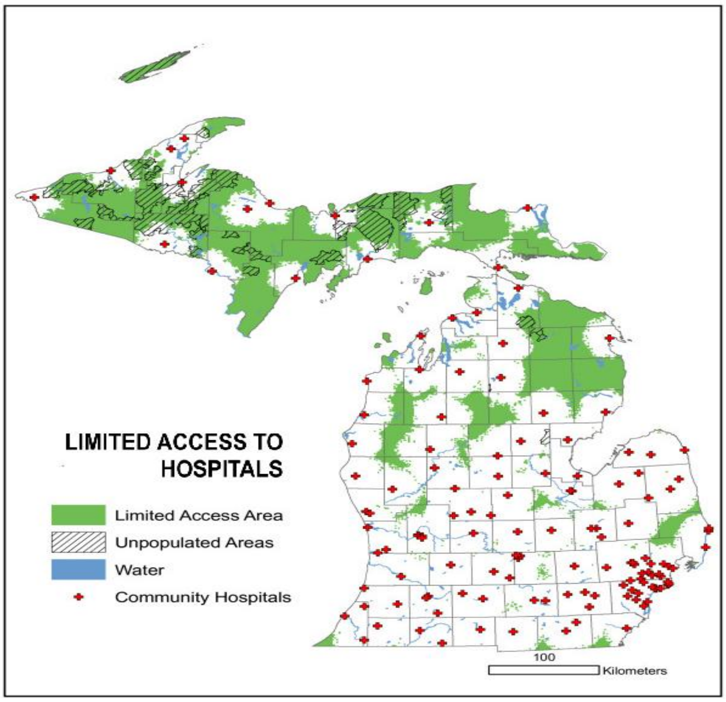


Figure 2.34. Community hospital accessibility for 30-minute travel time in Michigan for rush hour traffic conditions (Messina et al. 2006)

Yang et al. (2006)'s model accessibility as two-step floating catchment area (2SFCA) and kernel density measure for dialysis centers in Cook county, USA (Figure 2.35).

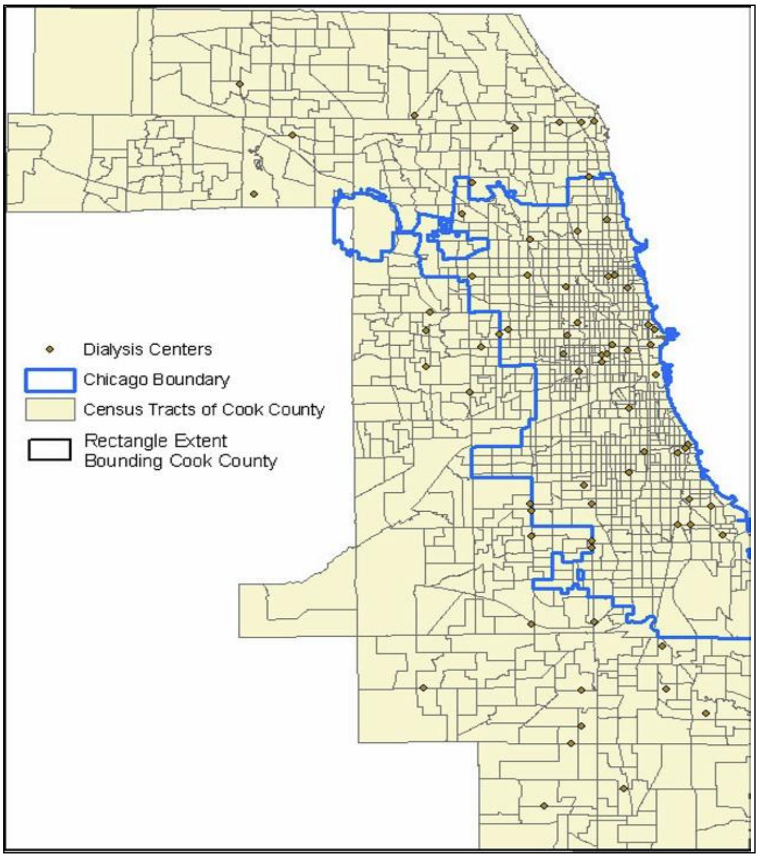


Figure 2.35. Dialysis centers in study area (Yang et al. 2006)

In calculation of 2SFCA measure scores, isochrone and zone-based accessibility modeling techniques are used. For each census tract within a 30-minute service area, a supply to demand ratio is computed by dividing the number of stations in each dialysis center by the sum of all population that requires dialysis treatments (Figure 2.36). Demand is calculated for each census tract by multiplying the 2000-year census tract population by a constant factor, 0.12%, which is the percent of population that requires dialysis treatments observed for Chicago in 2000. Supply is calculated as the number of stations in each dialysis center.

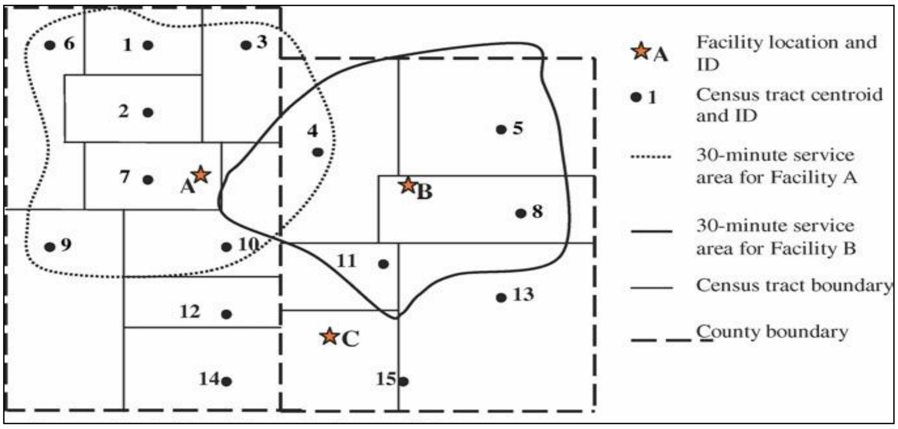


Figure 2.36. A hypothetical example for two-step floating catchment area method illustrated by Luo and Wang (2003)

In calculation of Kernel density measure scores, raster and zone-based accessibility modeling techniques are used. First, by defining suitable kernel radii as a Eucledian-based service area boundary, kernel density surfaces are created for both demand and supply locations (Figure 2.37). Then, supply to demand ratio surface was created for each census tract by dividing the supply density surface by the demand density surface.

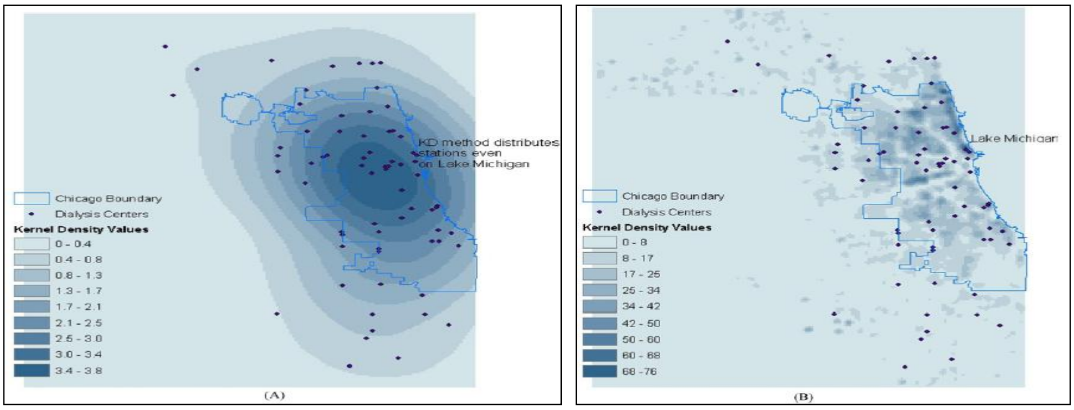
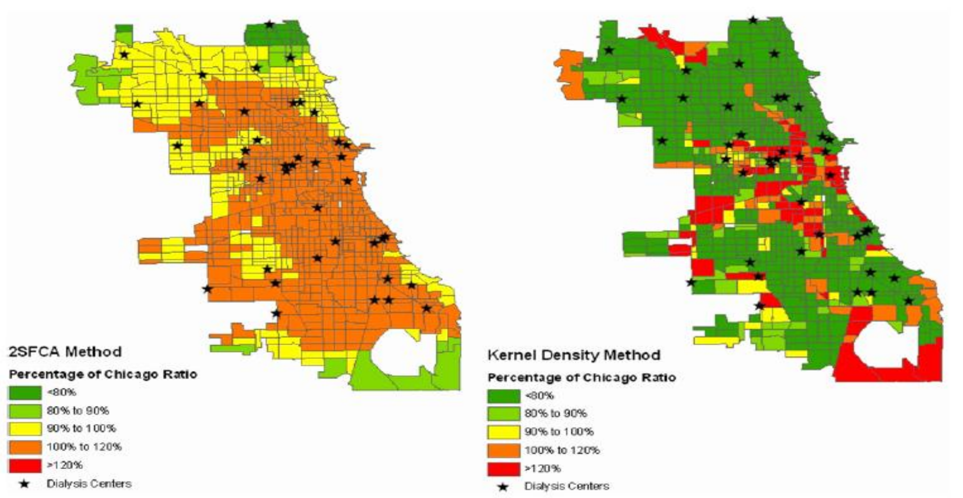


Figure 2.37. A) Distribution of supply points by Kernel density method B) Distribution of demand points by Kernel Density method (Yang et al. 2006)

Finally, accessibility scores of 2SFCA measures are compared with the Kernel density based measures by using a zone-based technique (Figure 2.38).



|  | 2SFCA | KD |
|---|---|---|
| Software | Unix ArcInfo Station | PC ArcGIS and Spatial Analyst |
| Population-weighted point | Yes | Yes |
| Population data | Tract-level | Block-level |
| Distance | Network | Euclidean |
| Study area | Cook County | Cook County |
| Dialysis Center data | Street Address | Street Address |
| Radius of patient residence | Not applicable | 1 km |
| Radius of facility service area | 30-min car travel time | 20 km |
| Cell size | Not applicable | 30 m × 30 m |
| Number of cells |  | 5.19 million |

Figure 2.38. Comparison of the accessibility results of 2SFCA measures with the Kernel density based measures (Yang et al. 2006)

Although there are numerous GIS-based accessibility measures, ranging from simple to sophisticated, the common point of them is that; they are all calculated from deterministic catchment area boundaries based on fixed/constant traveling costs such as Euclidian distance costs or constant transportation network based costs.

### 2.7.3. The shortcoming of the current GIS-based accessibility modeling

Although there are important contributions of GIS technology for physical accessibility measurement and evaluation (see Makri 2002, Black et al. 2004, Peters and Hall 1999, MacFarlane 2005), current GIS-based accessibility modeling have some fundamental shortcoming in providing more realistic decision support for decision makers in accessibility measurement and evaluation (Kwan et al. 2003, NCGIA 1998, Ebener et al. 2005, Boulos et al. 2001, Pourvakhshouri and Mansor, 2003).

These fundamental shortcoming can be grouped into three main categories, which are;

- Constant traveling cost usage in accessibility modeling
- Deterministic service/catchment area boundaries
- The lack of an integrated toolbox

### Constant traveling cost usage in accessibility modeling

Whether simple or sophisticated, one of the fundamental shortcomings of the current GIS-based accessibility measures is that they are generally based on fixed traveling costs such as Euclidian distance costs(e.g. bird-fligh distances) or constant transportation network based costs(e.g. rough average speed data obtained from generalized traffic observations such as 50 km/h for main streets and 30 km/h for local streets, etc.). Although such costs are widely used in GIS-based accessibility modeling because of their simplicity, they are not realistic, especially when considered highly variable speeds in road segments and have uncertainty about the accuracy and reliability of the accessibility measures (Halden et al. 2000).

Detailed traffic-data collection techniques integrated with GIS can be a key component for more accurate and reliable accessibility modeling, where speed variations of transportations networks can be taken into account in a more realistic manner. There are several traffic-data collection methods such as stationary traffic sensors (induction loops, optical systems), space and airborne techniques (observation from planes, satellites) and GPS-based floating car data (GPS probe vehicle data) etc. When compared to other techniques, GPS-based floating car data collection, which is based on recording position and speed from vehicle(s) moving in the traffic, is relatively fast and cheap as well as providing accurate position and speed with availability to be integrated into GIS.

GPS-based floating car traffic-data can provide speed information in a continuous manner with several detail and complexity depending on the track intervals (e.g. every 10 seconds or every 50 meters etc.), day and time preferences (e.g. annual, seasonal, time-based variations (rash hours, normal hours, weekdays or weekends etc), methodology (e.g. data collection from whole transportation network or only the main road segments etc.) and accuracy (e.g. ranging from meters to centimeters based on the used GPS instrument) (See several examples and detailed explanation; Zito et al. 1995, D’Este et al. 1999, Quiroga 2000, Taylor et al. 2000, Derekenaris et al. 2001, Mintsis et al. 2004, Daoqin et al. 2009, Yutaka et al. 2000, Guillaume 2008, DAAD 2003).

### Deterministic service/catchment area boundaries

In calculation of physical accessibility measures, current GIS-based accessibility modeling tools generally consider a deterministic catchment area boundary, which is basically a most likely or average catchment area boundary, based on fixed travelling costs. Handling a deterministic service/catchment area boundary can be considered as a critical shortage from accuracy and reliability point of view and can directly affect/mislead accessibility, location/allocation and service/catchment area related strategy development and decision making process (Makri 2002, Makri and Folkesson 1999, Makrí 2001).

On the other hand, simulation-based stochastic approaches, incorporated into accessibility modeling, can help to overcome this problem. The word simulation refers to analyze the effect of varying inputs, on outputs of the modeled system. A simulation involves hundreds or thousands evaluations of the model for all possible inputs and gives a probabilistic measure of the outputs.

Monte Carlo Simulation (MCS) method is a well-known method to create the random realizations of a deterministic model (Metropolis and Ulam 1949, Hoffman 1998). By integrating MCS method into GIS-based accessibility modeling process, possible random transportation cost values can be used instead of constant deterministic costs. Hence, the probability of an accessibility outcome can be obtained in terms of all possible catchment area boundaries. By this way, accessibility can be expressed in terms of probability of having a certain accessibility measure instead of stating a deterministic accessibility measure.

The simulation-based stochastic approaches in accessibility modeling can take the uncertainties of transportation costs into account and enhance accessibility related decision-making processes due to consideration of variability involved in the transportation cost parameters. By converting static transportation input cost values into possible random inputs, decision maker can have sense of the likelihood of the result and understand the probability of a given outcome. For example, it can be said that there is only a 75% probability that the place x have 15 minutes emergency service accessibility as originally predicted when compared with the deterministic model (Metropolis, N. and Ulam, S., 1949).

### The lack of an integrated toolbox

Although accessibility measures are key variables for the decision makers in their strategical decision-making process, current GIS-based accessibility modeling tools have a general-purpose structure and can only provide a scattered support for many accessibility related process. For example, modeling of traveling time and distance, cumulative opportunity, gravity, supply to demand, kernel density or 2sfca-based accessibility measures in isochrone, raster and zone-based techniques are not directly applicable by a toolbox and requires huge effort, experience and time, which prevent accessibility measures to be used by a broader environment.

As success of GIS is related with how well it supports the needs of the decision maker (Keenan, 1998; Muller 1993), lack of an integrated toolbox can be considered as an important factor from accessibility modeling point of view and can directly improve accessibility modeling and strategical decision making capabilities of the decision makers. An integrated toolbox can incorporate decision maker’s expert knowledge with specialized modeling capabilities, database management tools and graphical display capabilities and could provide better decision support in a more simple, flexible and comparable environment (Zerger and Smith, 2003; Fabbri, 1998; Densham, 1991; DeSilva, 2001).

# CHAPTER 3

# METHODOLOGY

In the light of the theoretical framework and relevant background about physical accessibility modeling covered in Chapter 2, Chapter 3 introduces a new stochastic methodology for GIS-based accessibility modeling process by using GPS-based floating car data and Monte Carlo Simulation (MCS) that could handle variations in traveling costs and consider all possible catchment area boundaries, instead of one average or maximum fixed catchment area boundary.

The main benefit of the proposed physical accessibility modeling methodology is that it could handle uncertainties in transportation costs, provides additional information related with the accuracy and the reliability of the catchment area boundaries, create significant improvement on accuracy and reliability of accessibility measures and better support decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues.

The proposed stochastic modeling methodology allows systematic treatment of uncertainties related with the catchment area boundaries and the crisp catchment area boundaries in the deterministic model turns into probabilistic catchment area boundaries providing decision makers to operate different levels of uncertainty in modeling of accessibility.

## 3.1. Introduction

The proposed GIS-based stochastic accessibility model consists of four major parts, which are; (1) Data collection, (2) Data preperation (3) Monte Carlo simulation and (4) Model validation (Figure 3.1).

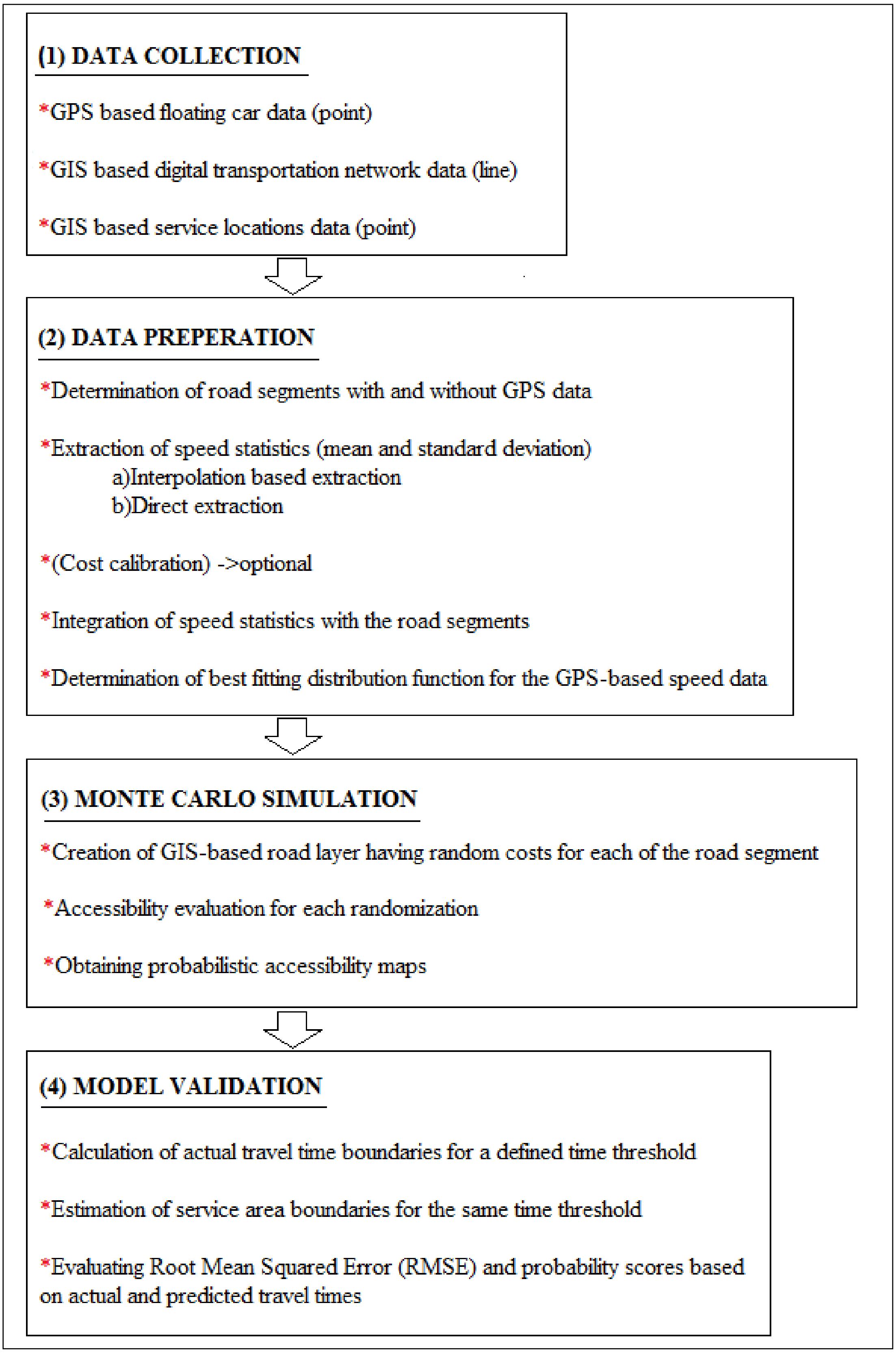


Figure 3.1. The flowchart of the methodology

Data collection involves obtaining GPS-based floating car data (speed data), digital transportation network and service locations. Data preparation consists of determining road segments, extracting speed statistics, and assigning speed statistics to road segments and finding the best fitting probability distribution function for speed data. Monte Carlo simulation includes creation of GIS-based road layers with random costs in each road segment, calculation of accessibility for each randomization and obtaining probabilistic accessibility maps. Finally, the results are validated by comparing simulation outputs with the actual data.

For an effective use of the methodology in Figure 3.1, an integrated toolbox is also developed in ArcGIS model builder environment in order to support the proposed stochastic accessibility modeling process.

The fundamental steps of the proposed methodology are published in Taylor & Francis, International Journal of Geographical Information Science, Volume 25, Issue 9, 2011, with DOI: 10.1080/13658816.2010.528419. The related manuscript is also given in the Appendix A.

### 3.2. Data collection

There are three basic data needed in the model:

- GPS-based floating car data (GPS-based probe vehicle data), which is in the form of point objects (includes location, speed and time information with a predefined time or distance interval). GPS-based floating car data is generally collected in log file format and needs to be converted to a point data having attributes of x and y coordinates, speed and time at that point
- GIS-based digital transportation network data, which is in the form of line objects. It includes the road lengths/widths and location of road segments/junctions and basic classification of roads according to their types such as Highways, Boulevards, Main Street etc.
- GIS-based service locations data, which is in the form of point objects and includes the location of the services

The GPS-based floating car data is obtained by recording position and speed from vehicle(s) moving in the traffic. It is needed in the model in order to take speed variations on road segments into account. Although there are several traffic-data collection methods such as stationary traffic sensors, like induction loops and optical systems, space and airborne data collection techniques like observation from planes and satellites, GPS-based floating car data technique is relatively the fastest and the cheapest traffic-data collection technique among the others. Compared with conventional traffic-data collection techniques, the GPS-based technique provides accurate position, speed, and easy integration capabilities with GIS. GPS data can provide speed variations in a continuous manner. The level of detail and complexity depends on preferred track intervals (e.g. every 10 seconds or every 50 meters etc.), day and time preferences (e.g. annual, seasonal, time-based variations, rush hours, normal hours, weekdays or weekends etc), methodology (e.g. data collection from whole transportation network or only the main road segments etc.) and accuracy (e.g. ranging from meters to centimeters based on the used GPS instrument). Examples and detailed explanation of such data collection can be found in Zito et al. 1995, D'Este et al. 1999, Quiroga 2000, Taylor et al. 2000, Derekenaris et al. 2001, Mintsis et al. 2004, Daoqin et al. 2009.

The GPS-based floating car data can generally be obtained from the transportation department of municipalities. The detail and complexity of the GPS data and the considered traffic conditions in the model (seasonal variations, rush hour variations, etc) are mostly based on the aim, the budget and required level of detail. For example, a study, which requires accurate determination of catchment area boundaries in rush hour time, could need a GPS data collected in long term (1 year or more) from the entire road segments for rush hour time with frequent track intervals. However, a GPS data collected only from the main street segments with large track intervals without considering a specific time or seasonal period could be enough for another study, which does not require high accuracy and reliability in determination of catchment area boundaries.

Although the proposed stochastic model in this thesis uses GPS-based floating car data, data from the other traffic-data collection methods such as induction loops, optical systems etc. can also be integrated into the proposed model and provide complementary traffic profile information, where it is not possible or partly possible to obtain GPS-based floating car data.

The GIS-based digital transportation network and GIS-based service locations are the other basic data needed for modeling of accessibility and can be obtained from the related department of municipalities like department of transportation and/or department of planning.

### 3.3. Data preperation

Data preperation is a vital step to be able to perform Monte Carlo simulations and mainly composed of five major steps (Figure 3.1). The first step in data preperation is determination of road segments with and without GPS data. The second step is extraction of speed statistics from the GPS-based floating car data. The third step is the cost calibration phase. The fourth step is the integration of extracted speed statistics with the attribute table of the road segments. Finally, the fifth step involves finding the best fitted probability distributions for the speed data.

In the first step, the road segments that have GPS data information is obtained by buffer, overlay, selection, add field, and calculate field capabilities of GIS in ArcGIS model builder environment (Figure 3.2). In Figure 3.2, the blue circles represent inputs, the yellow rectangles represent used GIS function and green circles represent the outputs in the model.

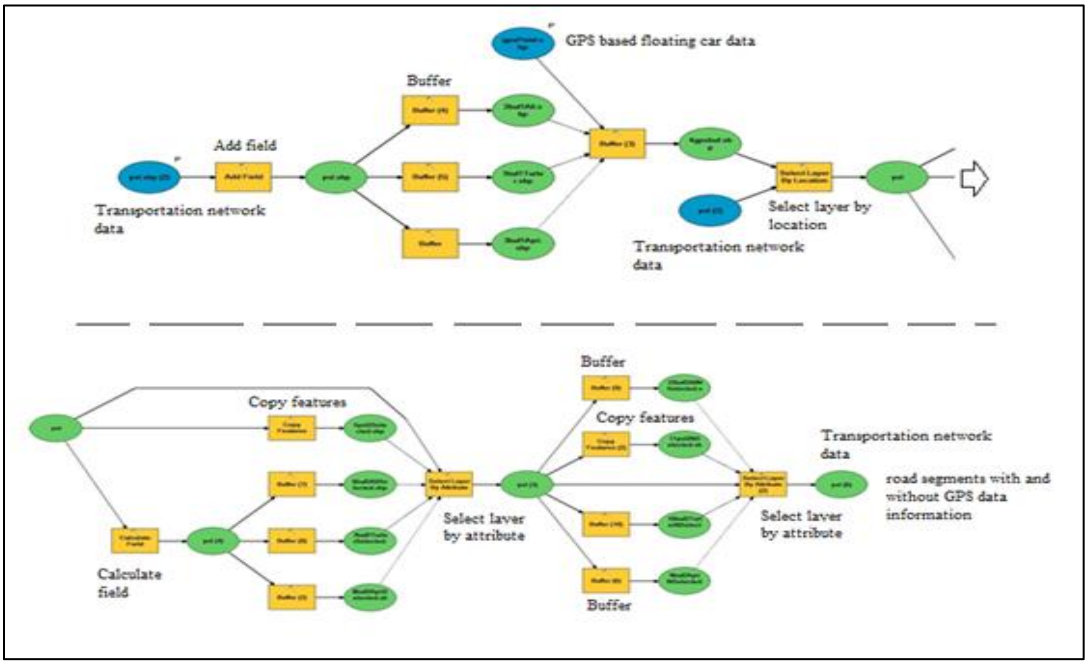


Figure 3.2. Determination of road segments with and without GPS data in ArcGIS model builder environment

The GPS data information for the road segments are added into the attribute table of road data in Boolean format (0 and 1). A GPS_data field is added to road attribute table and filled with 1 for the road segments that have GPS data and filled with 0 for the road segments that do not have GPS data (Figure 3.2).

In the second step, the speed statistics namely mean and standard deviation is extracted from the GPS-based floating car data in order to integrate with the road attribute table. In this step, two alternative approaches is performed and compared, one of which is extraction of speed statistics from the GPS-based floating car data by using interpolation and the second is the direct extraction of speed statistics from the GPS-based floating car data.

In extraction of speed statistics by interpolation, a continuous speed surface is created from the GPS-based floating car data in ArcGIS Model builder environment by using the spatial interpolation and overlay (zonal statistics) capabilities of GIS (Figure 3.3).

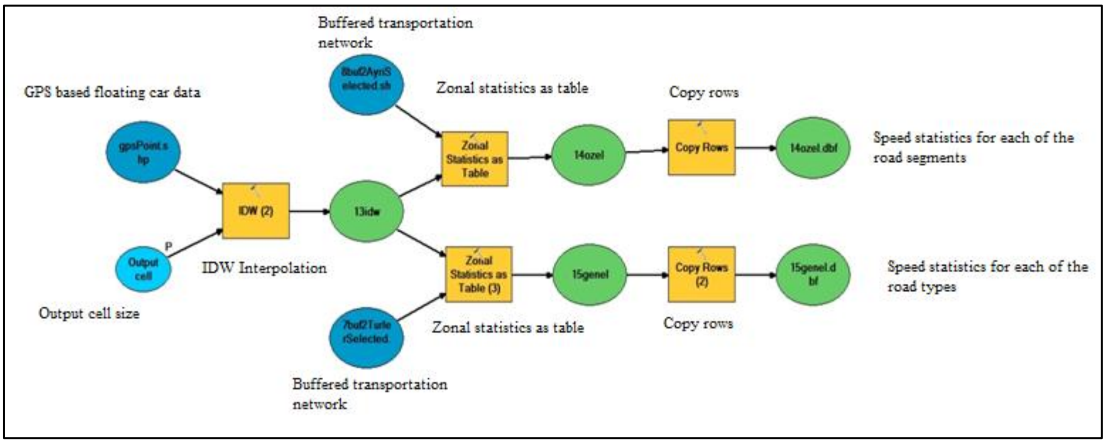


Figure 3.3. Interpolation-based extraction of speed statistics in ArcGIS Model builder environment

The inverse distance weighted (IDW) interpolation technique is used in the generation of speed surface. The aim of the interpolation is to fill the speed gaps between the known GPS points and create a continuous speed surface for the road segments that have GPS data. The IDW technique is mainly based on the assumption that the unknown cells are more alike to closer cells than those are farther. During the interpolation process, the road segments in the transportation network that have GPS data are buffered according to their road widths and used as a boundary/mask object in the interpolation process. Using a boundary/mask object for the road segments that have no GPS data is a vital step in the interpolation process, as the speed surface is created for only the street segments that have GPS-based floating car data (Figure 3.4).

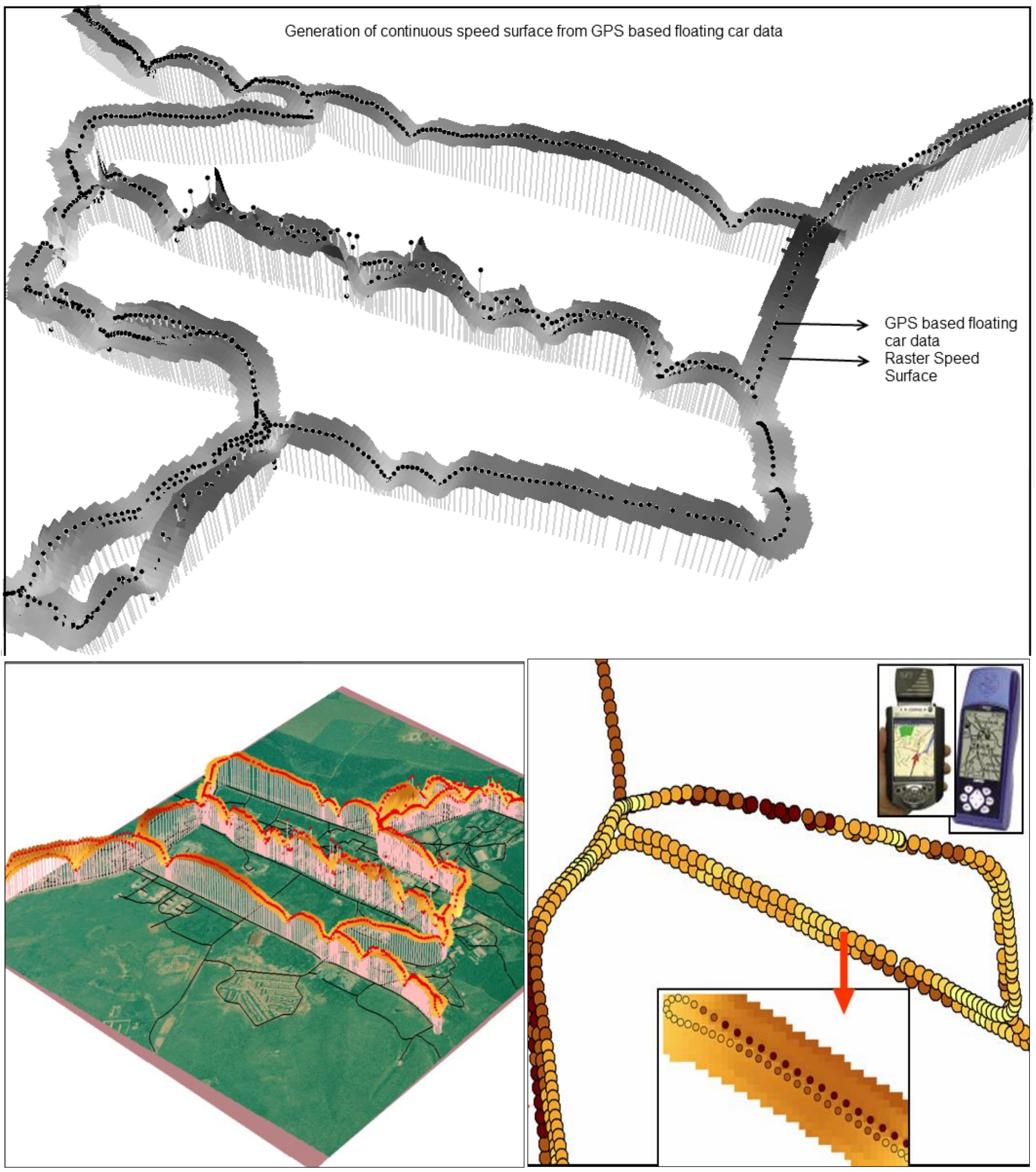


Figure 3.4. Production of raster speed surface from GPS data by using IDW interpolation

In direct extraction of speed statistics from the GPS-based floating car data, the speed statistics are directly extracted from the GPS data without any interpolation process in ArcGIS Model builder environment by using the selection, buffer, and overlay (spatial join and identity) capabilities of GIS (Figure 3.5).

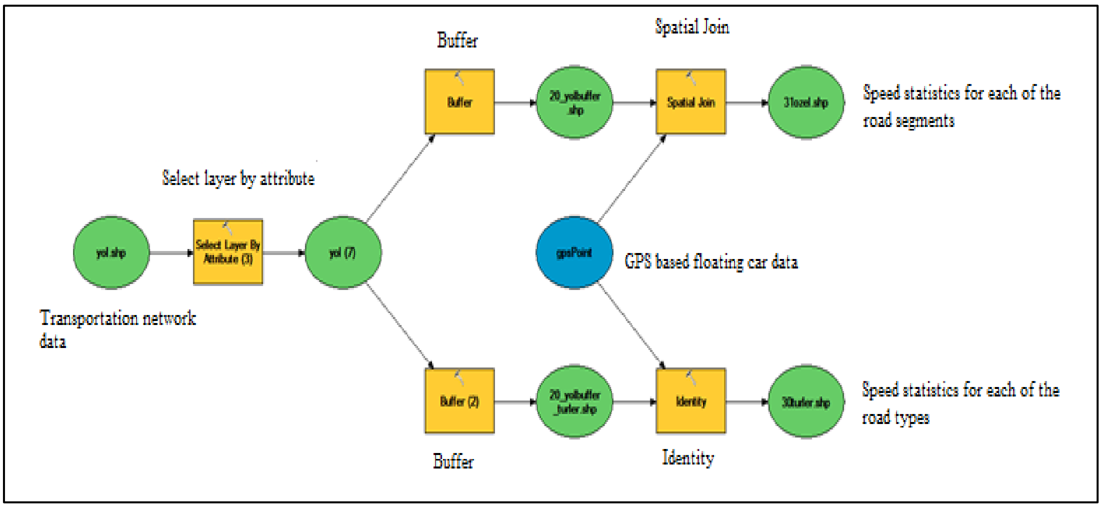
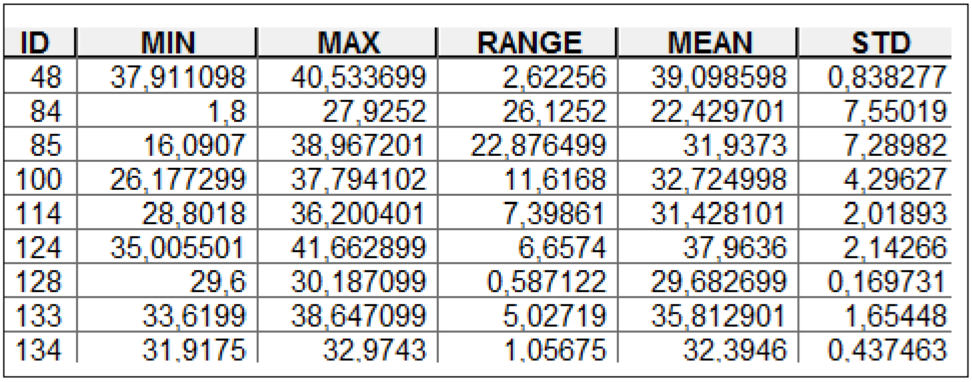


Figure 3.5. Direct extraction of speed statistics from the GPS-based floating car data in ArcGIS Model builder environment

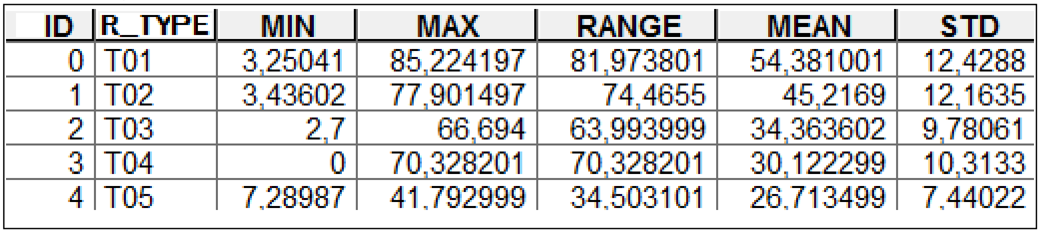
The outputs of the second step are the two-dbf database tables including speed statistics extracted from the GPS-based floating car data. The first table contains speed statistics for each of the road segments, (ID is the unique id for the road segments, MIN is the minimum speed, MAX is the maximum speed, RANGE is the difference speed between minimum and maximum speed, MEAN is the speed mean, STD is the speed standard deviation) and the second table contains speed statistics for each of the road types such as highway, boulevard, street etc (ID is the unique id for each road type, R_TYPE is the type of the road, MIN is the minimum speed, MAX is the maximum speed, RANGE is the difference speed between minimum and maximum speed, MEAN is the speed mean, STD is the speed standard deviation). Examples of obtained tables are given in Table 3.1 and Table 3.2.

Table 3.1. Speed statistics for each of the road segments (km/h)



| ID | MIN | MAX | RANGE | MEAN | STD |
|---|---|---|---|---|---|
| 48 | 37,911098 | 40,533699 | 2,62256 | 39,098598 | 0,838277 |
| 84 | 1,8 | 27,9252 | 26,1252 | 22,429701 | 7,55019 |
| 85 | 16,0907 | 38,967201 | 22,876499 | 31,9373 | 7,28982 |
| 100 | 26,177299 | 37,794102 | 11,6168 | 32,724998 | 4,29627 |
| 114 | 28,8018 | 36,200401 | 7,39861 | 31,428101 | 2,01893 |
| 124 | 35,005501 | 41,662899 | 6,6574 | 37,9636 | 2,14266 |
| 128 | 29,6 | 30,187099 | 0,587122 | 29,682699 | 0,169731 |
| 133 | 33,6199 | 38,647099 | 5,02719 | 35,812901 | 1,65448 |
| 134 | 31,9175 | 32,9743 | 1,05675 | 32,3946 | 0,437463 |

Table 3.2. Speed statistics for each of the road types (km/h) (highway, boulevard, street etc.)



| ID | R_TYPE | MIN | MAX | RANGE | MEAN | STD |
|---|---|---|---|---|---|---|
| 0 | T01 | 3,25041 | 85,224197 | 81,973801 | 54,381001 | 12,4288 |
| 1 | T02 | 3,43602 | 77,901497 | 74,4655 | 45,2169 | 12,1635 |
| 2 | T03 | 2,7 | 66,694 | 63,993999 | 34,363602 | 9,78061 |
| 3 | T04 | 0 | 70,328201 | 70,328201 | 30,122299 | 10,3133 |
| 4 | T05 | 7,28987 | 41,792999 | 34,503101 | 26,713499 | 7,44022 |

The cost calibration is an optional step in the model. If cost calibration for speed is needed in the model due to emergency cases, seasonal variations, rush hour variations etc, cost calibration process can be performed by using field editing and calculating capabilities of GIS just before the integration step of the model.

The fourth step in the data preperation part of the model is the integration of extracted speed statistics with the attribute table of the road segments. This step covers the integration of extracted speed statistics with the attribute table of the road data by using select, join and calculate field capabilities of GIS (see Figure 3.6 and Figure 3.7).

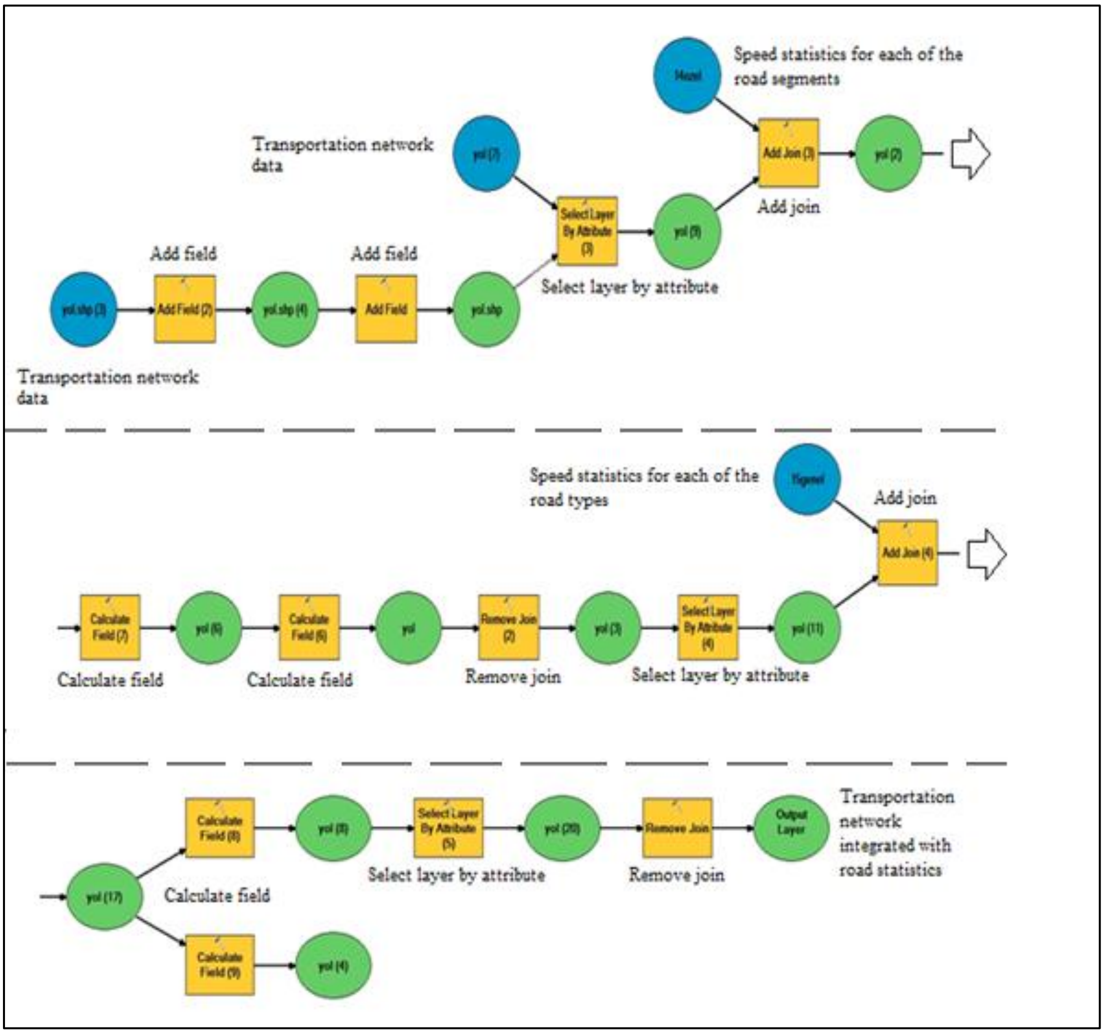
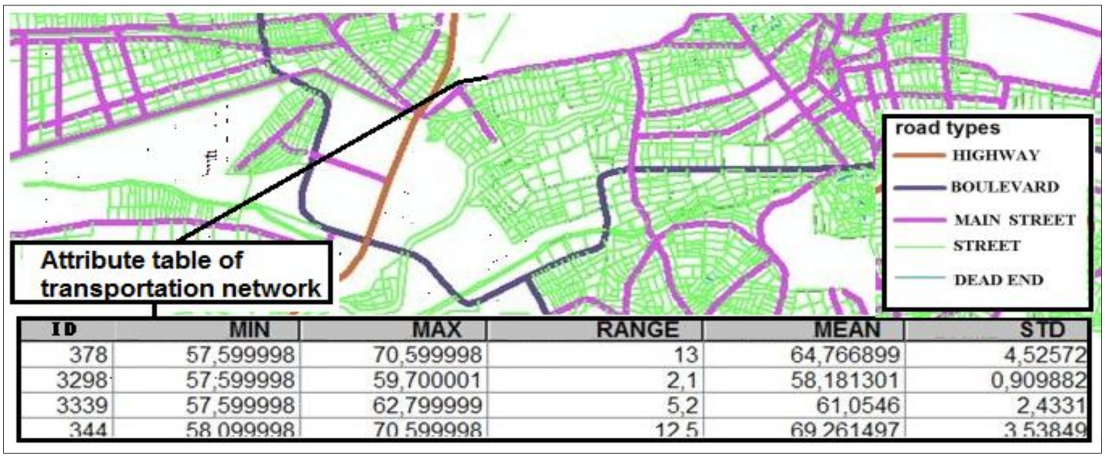


Figure 3.6. Integration of extracted speed statistics with the attribute table of the road data in ArcGIS Model builder environment

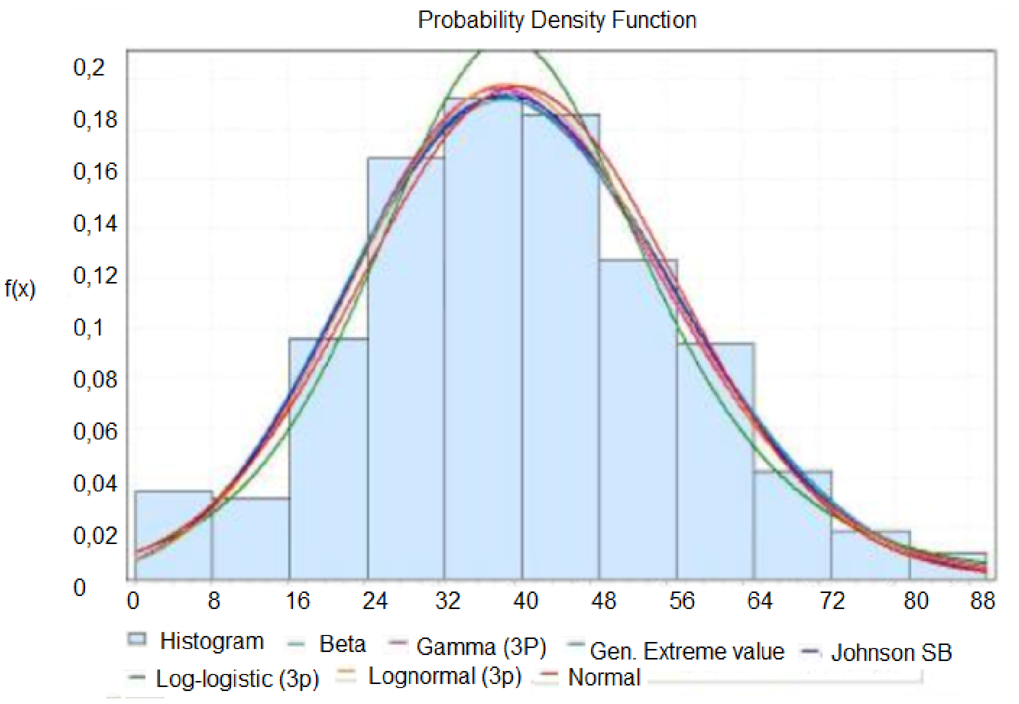


| ID | MIN | MAX | RANGE | MEAN | STD |
|---|---|---|---|---|---|
| 378 | 57,599998 | 70,599998 | 13 | 64,766899 | 4,52572 |
| 3298 | 57,599998 | 59,700001 | 2,1 | 58,181301 | 0,909882 |
| 3339 | 57,599998 | 62,799999 | 5,2 | 61,0546 | 2,4331 |
| 344 | 58,099998 | 70,599998 | 12,5 | 69,261497 | 3,53849 |

Figure 3.7. Integration of speed statistics of mean and standard deviation with the transportation network data

For each of the road segments that have GPS-based floating car data, speed statistics for each of the road segments are extracted and joined with the transportation network data. For each of the road segments that do not have GPS data, speed statistics for each of the road types (highway, boulevard, street etc.) are extracted and joined with the transportation network data.

As a final step, GPS-based floating car data is statistically analyzed by using Easy Fit distribution fitting software. Several probability density functions are tested and ranked by using the goodness of fit tests of Kolmogorov-Smirnov, Anderson-Darling, Chi-Squared. The results showed that the best fitting probability density functions for the speed data are Generalized Extreme Value, Normal, Weitbull, Johnson, Beta, Log-Logistic and Log-Normal probability density functions. As the results are significantly close to the normal distribution, the normal distribution is used as input distribution function to produce random costs in MCS (Figure 3.8).



Goodness of Fit Test Summary

| Distribution | Kolmogorov Smirnov | | Anderson Darling | | Chi-Squared | |
|---|---|---|---|---|---|---|
| | Statistics | Rank | Statistics | Rank | Statistics | Rank |
| Gen. extreme value | 0.02287 | 1 | 1,4709 | 1 | 19,647 | 1 |
| Normal | 0,02428 | 2 | 2,8255 | 5 | 22,752 | 2 |
| Weibull (3p) | 0,02606 | 3 | 1,5343 | 2 | 24,182 | 4 |
| Johnson SB | 0,02655 | 4 | 1,5938 | 3 | 23,109 | 3 |
| Beta | 0,02755 | 5 | 2,1099 | 4 | 30,57 | 7 |
| Log-logistic (3p) | 0,03034 | 6 | 2,9752 | 6 | 29,083 | 6 |
| Lognormal (3p) | 0,04334 | 7 | 5,3722 | 7 | 28,672 | 5 |

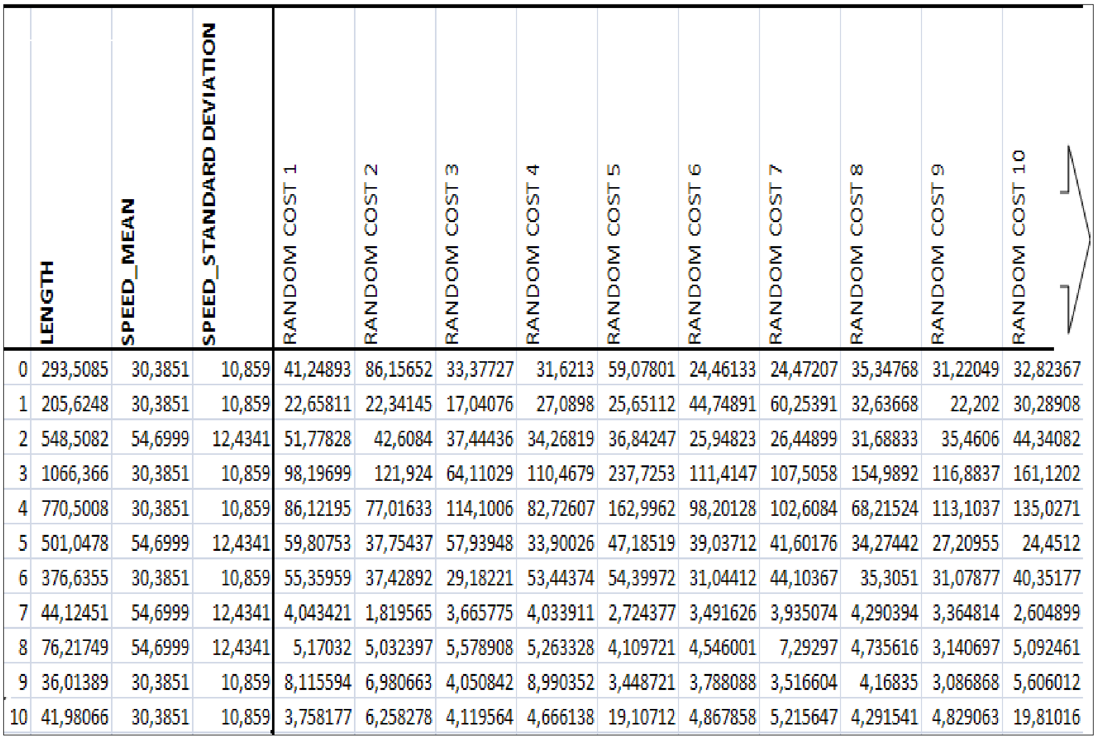
Figure 3.8. Results of distribution fitting tests applied to GPS-based floating car data

## 3.4. Monte Carlo simulations

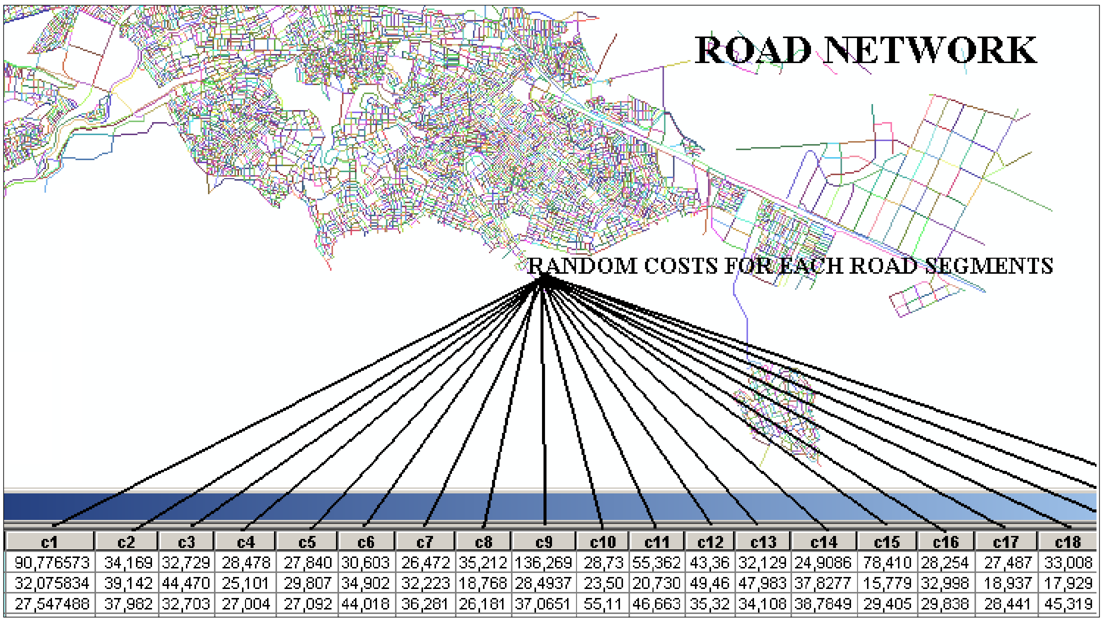
Stochastic transportation cost calculation approaches can be incorporated into the accessibility analyses by using simulation. The word simulation refers to analyze the effect of varying inputs, on outputs of the modeled system. A simulation involves hundreds or thousands realizations of the model outputs for all possible inputs and probabilistic measure of the outputs can be obtained from realizations. Monte Carlo Simulation (MCS) method is a well-known method to create the random realizations of a deterministic model (Metropolis and Ulam 1949, Hoffman 1998). By integrating MCS method into GIS-based accessibility modeling process, possible random transportation cost values can be used instead of constant deterministic costs. Hence, the probability of an accessibility outcome can be obtained in terms of all possible catchment area boundaries. By this way, accessibility can be expressed in terms of probability of having a certain accessibility measure instead of stating a deterministic accessibility measure. The probabilistic accessibility measures can consider the uncertainties in transportation costs and enhance decision-making processes due to consideration of variability involved in the transportation cost parameters.

In the light of the above mentioned framework, the best fitting distribution function (normal distribution), the extracted speed statistics (speed_mean and speed_standard deviation) and the length of the road segments (length) are used as input variables in ArcGIS Model builder programming environment and random time costs for each road segment is produced (Table 3.3, Figure 3.9).

Table 3.3. Random costs of time in seconds calculated for each road segment



| | LENGTH | SPEED_MEAN | SPEED_STANDARD DEVIATION | RANDOM COST 1 | RANDOM COST 2 | RANDOM COST 3 | RANDOM COST 4 | RANDOM COST 5 | RANDOM COST 6 | RANDOM COST 7 | RANDOM COST 8 | RANDOM COST 9 | RANDOM COST 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 293,5085 | 30,3851 | 10,859 | 41,24893 | 86,15652 | 33,37727 | 31,6213 | 59,07801 | 24,46133 | 24,47207 | 35,34768 | 31,22049 | 32,82367 |
| 1 | 205,6248 | 30,3851 | 10,859 | 22,65811 | 22,34145 | 17,04076 | 27,0898 | 25,65112 | 44,74891 | 60,25391 | 32,63668 | 22,202 | 30,28908 |
| 2 | 548,5082 | 54,6999 | 12,4341 | 51,77828 | 42,6084 | 37,44436 | 34,26819 | 36,84247 | 25,94823 | 26,44899 | 31,68833 | 35,4606 | 44,34082 |
| 3 | 1066,366 | 30,3851 | 10,859 | 98,19699 | 121,924 | 64,11029 | 110,4679 | 237,7253 | 111,4147 | 107,5058 | 154,9892 | 116,8837 | 161,1202 |
| 4 | 770,5008 | 30,3851 | 10,859 | 86,12195 | 77,01633 | 114,1006 | 82,72607 | 162,9962 | 98,20128 | 102,6084 | 68,21524 | 113,1037 | 135,0271 |
| 5 | 501,0478 | 54,6999 | 12,4341 | 59,80753 | 37,75437 | 57,93948 | 33,90026 | 47,18519 | 39,03712 | 41,60176 | 34,27442 | 27,20955 | 24,4512 |
| 6 | 376,6355 | 30,3851 | 10,859 | 55,35959 | 37,42892 | 29,18221 | 53,44374 | 54,39972 | 31,04412 | 44,10367 | 35,3051 | 31,07877 | 40,35177 |
| 7 | 44,12451 | 54,6999 | 12,4341 | 4,043421 | 1,819565 | 3,665775 | 4,033911 | 2,724377 | 3,491626 | 3,935074 | 4,290394 | 3,364814 | 2,604899 |
| 8 | 76,21749 | 54,6999 | 12,4341 | 5,17032 | 5,032397 | 5,578908 | 5,263328 | 4,109721 | 4,546001 | 7,29297 | 4,735616 | 3,140697 | 5,092461 |
| 9 | 36,01389 | 30,3851 | 10,859 | 8,115594 | 6,980663 | 4,050842 | 8,990352 | 3,448721 | 3,788088 | 3,516604 | 4,16835 | 3,086868 | 5,606012 |
| 10 | 41,98066 | 30,3851 | 10,859 | 3,758177 | 6,258278 | 4,119564 | 4,666138 | 19,10712 | 4,867858 | 5,215647 | 4,291541 | 4,829063 | 19,81016 |



| c1 | c2 | c3 | c4 | c5 | c6 | c7 | c8 | c9 | c10 | c11 | c12 | c13 | c14 | c15 | c16 | c17 | c18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90,776573 | 34,169 | 32,729 | 28,478 | 27,840 | 30,603 | 26,472 | 35,212 | 136,269 | 28,73 | 55,362 | 43,36 | 32,129 | 24,9086 | 78,410 | 28,254 | 27,487 | 33,008 |
| 32,075834 | 39,142 | 44,470 | 25,101 | 29,807 | 34,902 | 32,223 | 18,768 | 28,4937 | 23,50 | 20,730 | 49,46 | 47,983 | 37,8277 | 15,779 | 32,998 | 18,937 | 17,929 |
| 27,547488 | 37,982 | 32,703 | 27,004 | 27,092 | 44,018 | 36,281 | 26,181 | 37,0651 | 55,11 | 46,663 | 35,32 | 34,108 | 38,7849 | 29,405 | 29,838 | 28,441 | 45,319 |

Figure 3.9. Random costs for each road segment in GIS environment

Accessibility is modeled for each of the MCS-based random costs by using service area function and model builder capabilities of GIS. The service area function connects points of equal travel time away from a service or services on a transportation network and creates polygons, which represent the catchment area boundaries. If a service location is defined as the reference point, polygons can be drawn connecting points in all directions that can be reached within a threshold time or distance. Locations inside the polygons are determined as accessible and outside the polygons are determined as inaccessible. The proposed stochastic model calculates the catchment area boundaries for each of the MCS-based random costs for a defined time threshold (five minutes in the case study) and convert each of the calculated boundary polygons to a binary raster map with a classification of 1 for accessible and 0 for inaccessible areas in ArcGIS model builder environment (Figure 3.10).

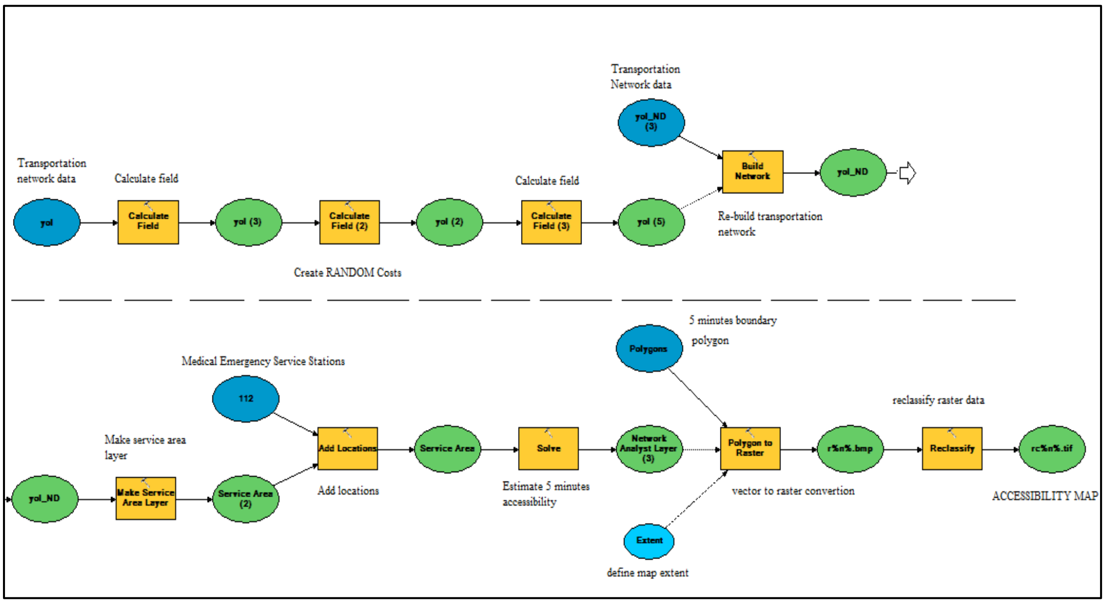


Figure 3.10. Calculation of catchment area boundaries for each of the MCS-based random costs in ArcGIS model builder environment

The sum of these binary raster maps are used to produce a final stochastic accessibility map, which have probability scores of accessibility in terms of all possible combination of catchment area boundaries. For example, if 1000 simulations are performed to model accessibility of emergency services for a defined threshold of five minutes, the pixel value of 0 mean there is 0% probability, 500 mean there is 50% probability and 1000 mean there is 100% probability that a particular cell have five minutes emergency service accessibility.

### 3.5. Model validation

The proposed stochastic model is validated by comparing estimated service area boundaries with the actual travel time data.

The model validation is generally composed of three main steps, which are;

- calculation of actual travel time boundaries for a defined time threshold
- estimation of service area boundaries for the same time threshold
- evaluating Root Mean Squared Error (RMSE) and probability scores based on actual and predicted travel times.

The Root Mean Squared Error (RMSE) is one of the most commonly used accuracy measures which basically show how close estimations are to actual practices. It is obtained by finding the differences between values predicted by a model or an estimator and the values actually observed.

The RMSE is calculated with the following equation;

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(e_i - o_i)^2} \tag{10}$$

where N is the number of test trips, e is the estimated time for a defined traveling time threshold and o is the actual traveling time for the same traveling time threshold. The smaller the Root Mean Squared Error, the closer the estimations to the actual practices (Lehmann and Casilla 1998).

# CHAPTER 4

# CASE STUDY: MEDICAL EMERGENCY SERVICE ACCESSIBILITY

## 4.1. Introduction

The proposed methodology is implemented with a case study on medical emergency service accessibility in Eskisehir city. Medical emergency service accessibility reflects the response level of medical emergency services by ambulances to reach to their catchment areas within critical time thresholds and help to identify the critical areas that are out of medical emergency service range.

Although the case study is implemented on medical emergency service accessibility, the primary focus of the study is not to evaluate a specific accessibility condition in a detailed manner but to provide a discussion and comparison between the deterministic and stochastic accessibility modeling in terms of accuracy and reliability of the catchment areas.

As five minutes is a critical time for saving lives from medical emergency point of view, and accepted as a worldwide-determined time threshold in modeling of medical emergency service accessibility (Blackwell et al. 2009), both of the proposed stochastic model and conventional deterministic models are implemented by considering a time threshold of five minutes.

### 4.1.1. Case study area

Eskisehir city is one of the biggest cities of Turkey with an urban population of nearly 630.000 according to the address based population registration system of Turkish Statistical Institute (TSI) for year 2010 (TSI web page, last visited on 01.07.2011).

It is in the northwestern part of the Central Anatolia, 792 meters above sea level, located on the banks of the Porsuk River and covers an area of nearly 9,700 hectars. The city is 233 kilometers to the west of Ankara capital city, 330 kilometers to the southeast of Istanbul city and 78 kilometers to the northeast of Kutahya city. Eskisehir city is governed by the Eskisehir metropolitan municipality, including 66 neighbourhoods and 2 main metropolitan districts, which are Tepebaşı and Odunpazarı (Figure 4.1).

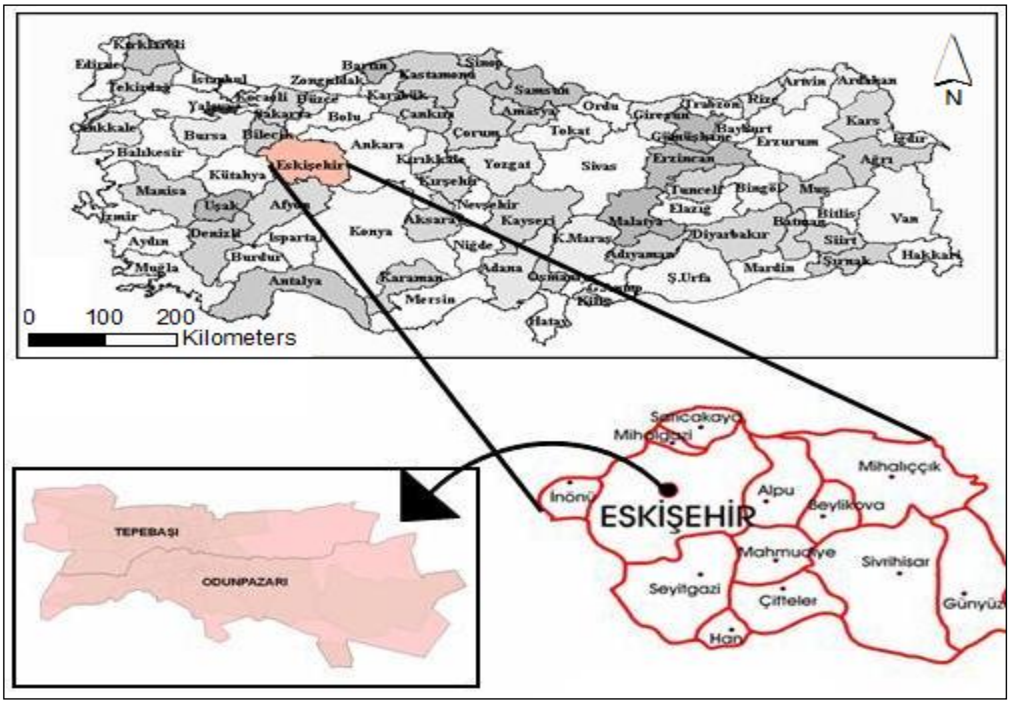


Figure 4.1. The case study area, Eskisehir city

Eskisehir city has nationwide importance due to having Turkey's many important administrative, commercial, health and educational facilities. The city is home to tens of public, private and university hospitals some of which are Osmangazi University Hospital, Anadolu University Hospital, Eskisehir Public Hospital, Yunus Emre Public Hospital, Onvak Private Hospital, and Verta Private Hospital. As the city is also home to Turkey's two of the biggest universities, which are; Anadolu University and Eskisehir Osmangazi University, it is widely known as "students' city" in Turkey. (Eskisehir Metropolitan Municipality web page, last visited on 05.07.2011).

There are four main reasons to select Eskisehir city as case study area in the research.

- The convenient scale of the city and the transportation network in terms of time and budget limitations of the research
- GIS_based data availability and GIS_based data support of Eskisehir Metropolitan Municipality such as transportation network, administrative boundaries, location of medical emergency services etc.
- Accommodation support of Eskisehir Odunpazarı Municipality during the case study trips to Eskisehir
- Legislative support of Health Directorate and Medical Emergency Command and Control Center Directorate of Eskisehir province during GPS data collection by ambulances

### 4.1.2. Definition of medical emergency

The emergency term is defined in the literature as "*…an unexpected event which places life and/or property in danger and requires an immediate response through the use of routine community resources and procedures…*" (Drabek 1996), "*…a sudden and usually unforeseen event that calls for immediate measures to minimize its adverse consequences…*" (United Nations Department of Humanitarian Affairs 1992) and *"…an unexpected occurrence or sudden situation that requires immediate action…It may involve communities (as a disaster does) or individuals (which a disaster does not)…*" (Porfiriev 1995). All the definitions points out a common direction; emergency is an unexpected and sudden event, involves loss of lives, injuries, structural or environmental damages or threads, and requires urgent action.

The emergency term involves a wide variety of emergencies such as security/police service related emergencies, fire/fire service related emergencies, medical health/medical emergency service related emergencies etc. However, the focus in the case study is limited to medical emergency service related emergencies, which necessitate urgent assistance by the medical emergency service stations, which are usually ambulances, located on the medical emergency service stations and operated by the medical emergency service command and control centers.

### 4.1.3. Actors of medical emergency

The 3359 numbered law of main health services, 10588 numbered instructions of health services and the 11.05.2000 dated and 24046 numbered instructions of emergency health services arrange the main structure of the medical emergency services in Turkey for providing equal, accessible, qualified, productive, effective and quick emergency health services. According to above mentioned laws and regulations "All the people whatever their social and economical background are, have right to have very fast and professional medical emergency services when they are in an emergency situation".

There are seven hierarchical actors who are responsible from the medical emergency services in Turkey;

- Ministry of Health
- General Directorate of Basic Health Services
- Health Directorate of the Province
- Directorate of Emergency Health Services
- Medical Emergency Service Command and Control Center
- Medical Emergency Service Stations
- Emergency Departments of Hospitals

For the national scale, Ministry of Health and General Directorate of Basic Health Services, for the province scale, Health Directorate of the Province and Directorate of Emergency Health Services are responsible from the management and organization of medical emergency services such as planning, coordination, training and inspection.

Medical Emergency Service Command and Control Centers are the departments where medical emergency calls are answered and organized accordingly. The medical emergency service command and control centers are managed by the head doctors of the control center and responsible from the organization, coordination and cooperation among patients, medical emergency service stations and emergency departments of hospitals.

The medical emergency service stations operate by the instructions of the medical emergency service command and control centers and have the emergency response teams including ambulances, drivers, doctors, health personnel and the related equipment (Ministry of Health web page last visited on 07.09.2007, Health directorate of the Eskisehir province web page last visited on 07.09.2007, İzmir 112 web page last visited on 12.09.2007).

### 4.1.4. The work flow of medical emergency services

When there is an emergency call because of an illness, injury or accident, a trained health staff or nurses from the Medical Emergency Service Command and Control Centers, who are called “call taker or call operator”, absolutely receives the call, decides whether it is a true call or not and quickly determines if medical help is needed by the ambulances.

If a medical response need by the ambulances is convinced by the call taker or call operator, the call is immediately transferred to the advisor doctor. While the advisor doctor inform and charge the closest medical emergency service station for an immediate response by using the telecommunication infrastructure (local phone, GSM or radiophone), vital medical instructions and advises are also provided on how to help to the victim until the medical emergency teams arrive to the incident location.

After the medical emergency service stations are charged by the medical emergency service command and control center for an immediate response, a fully equipped medical emergency service team, including ambulance, doctor, health personnel and driver, are dispatched from the medical emergency service station to the given address. During the response process, medical emergency service command and control center also guide the medical emergency service team about the incident area, victim conditions and the possible routes to reach to the incident area.

When the charged team arrives, they determine the victim’s condition and give first care by necessary supplies and equipment at the incident place, and transfer the victim to the closest emergency department of hospitals if needed (Health directorate of Eskisehir province web page last visited on 07.09.2007, American Red Cross 2005).

In Eskisehir case, there are four active medical emergency service stations which are north station (officially known as station 4), south station (officially known as station 1), east station (officially known as station 2), and west station (officially known as station 3) and one medical emergency service command and control center which is West station (officially known as station 3). Each of the medical emergency service stations is having 1 fully equipped medical emergency service team, including ambulance, doctor, health personnel and driver (Eskisehir Metropolitan Municipality web page, last visited on 05.07.2011, Medical Emergency Service Command and Control Center of Eskisehir).

## 4.2. Data collection

The following data was collected to implement the proposed stochastic model;

- Digital transportation network data of Eskisehir Metropolitan area and their hierarchies
- The location of medical emergency service stations in Eskisehir
- GPS-based floating car data of Eskisehir Metropolitan area

The digital transportation network data and their road type hierarchies (highways, boulevards, main streets, streets and dead-end streets) and the location of medical emergency service stations (there are four medical emergency service stations which are north, south, east and west) was obtained from Eskisehir Metropolitan Municipality and integrated into a GIS database to be used in GIS-based accessibility network analyses (Figure 4.2, Figure 4.3).

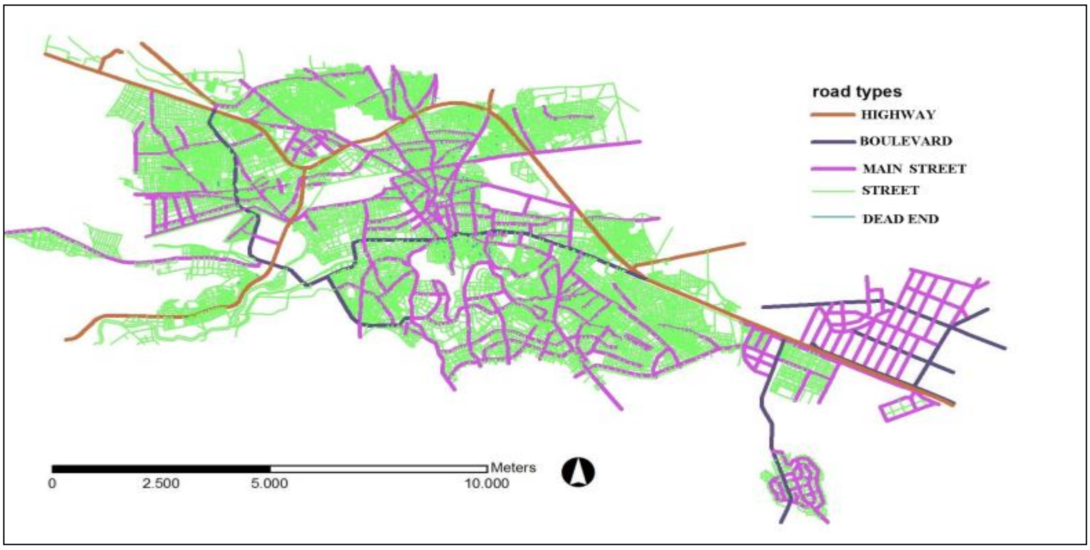


Figure 4.2. Digital transportation road network data with related hierarchies

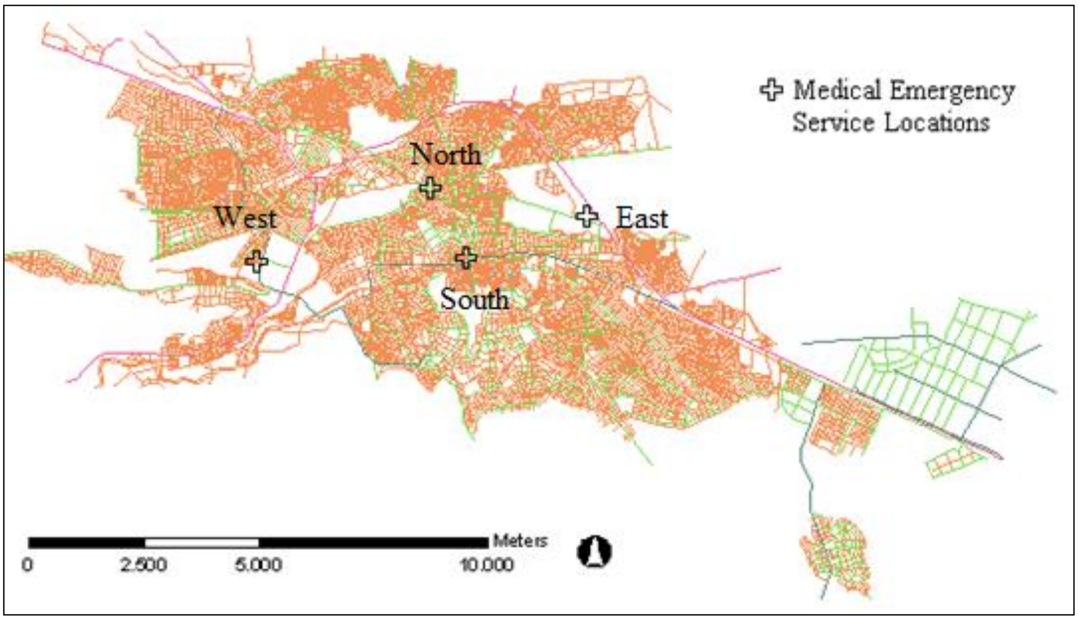


Figure 4.3. The location of medical emergency service stations on transportation road network

The GPS-based floating car data of Eskisehir Metropolitan area was not available in the transportation department of Eskisehir metropolitan municipality. Therefore, empirical GPS-based floating car data was collected in Eskisehir city by 2 weeks fieldworks on August 2007 and February 2008 with sample track intervals of 50 meters (Figure 4.4). A Magellan Explorist 600 type GPS receiver was mounted on a probe vehicle and the vehicle location, speed and time information was regularly recorded between 07:00 a.m. and 22:00 p.m. during fieldworks for both peak and normal time periods including weekdays (Monday, Tuesday, Wednesday Thursday, Friday) and weekends (Saturday and Sunday). Most of the main road segments, which are highways, boulevards and main streets) are covered in the GPS-based floating car data collection process (nearly 75% of the total). The inner streets and dead-end streets are partly covered (nearly 10% of the total) because of the time and budget limitations of the research. However, the inner streets and dead end streets do not have a considerable effect on the accessibility results when compared with the highways, boulevards and main streets.

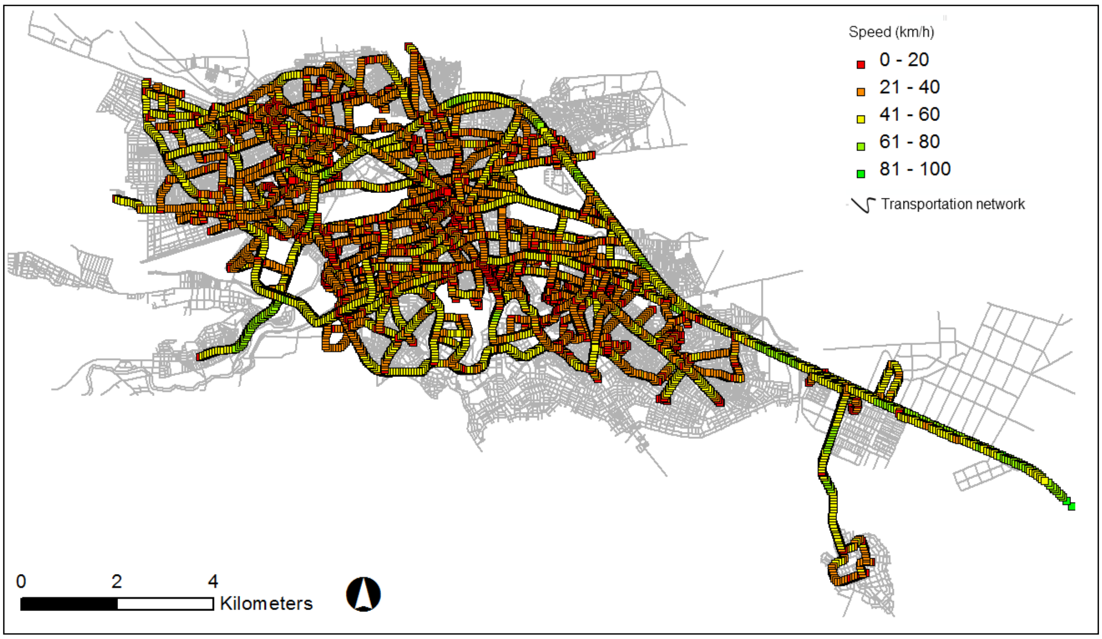


Figure 4.4. GPS-based floating car traffic-data collected by two-week fieldwork with 50-meter track intervals on August 2007 and February 2008

In order to calibrate GPS-based floating car data (probe vehicle based) in terms of medical emergency response vehicles (ambulances), an additional 1-week fieldwork was performed on May 2008. A Magellan Explorist 600 type GPS receiver was mounted on four different medical emergency service vehicles operating on four different stations by special permission from the Ministry of Health, Health Directorate of Eskisehir province and Medical Emergency Command and Control Center Directorate of Eskisehir province and the ambulance location, speed and time information was regularly recorded while the ambulances are operating for emergency calls (Figure 4.5).

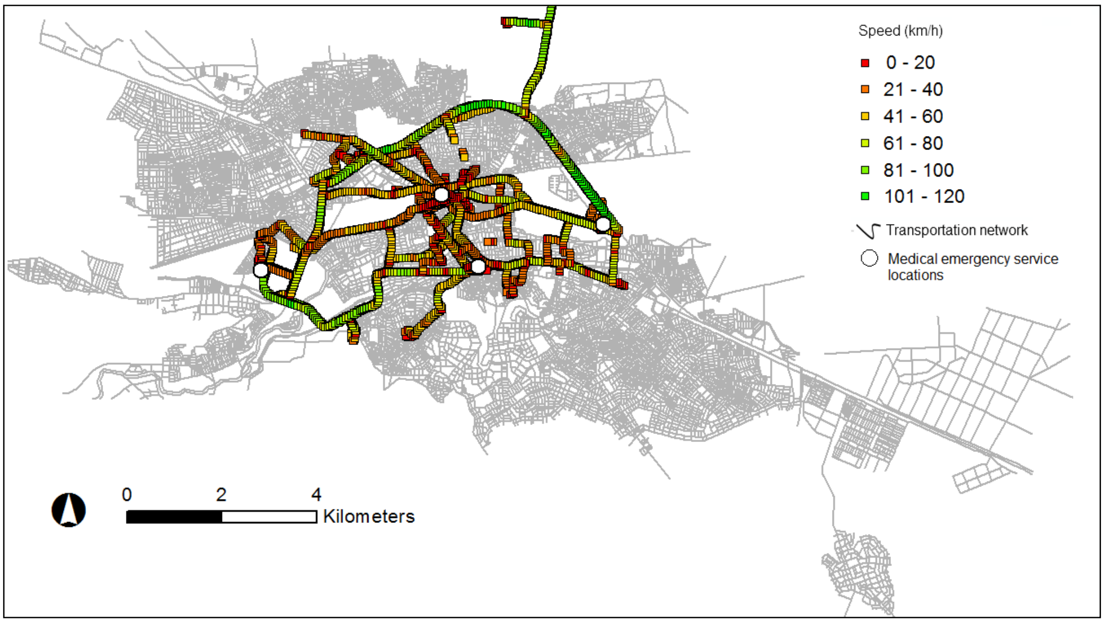


Figure 4.5. GPS-based floating car traffic-data collected by four medical emergency service vehicles with 50-meter track intervals in May 2008

The GPS data collected by ambulances is used for both calibrating GPS-based floating car data (probe vehicle data) in terms of medical emergency response vehicles (ambulances), and validating the accuracy and reliability of the proposed stochastic model.

Although GPS-based data is collected in a short term and used in the proposed model because of the time, budget and data availability limitations, it is always possible to implement the model with more detailed and complex traffic-data according to aim, budget and detail needs of the study.

## 4.3. Data preperation

### 4.3.1. Determination of road segments with and without data

The road segments with and without GPS-based floating car data are determined by overlay capabilities of GIS in ArcGIS model builder environment (Figure 4.6).

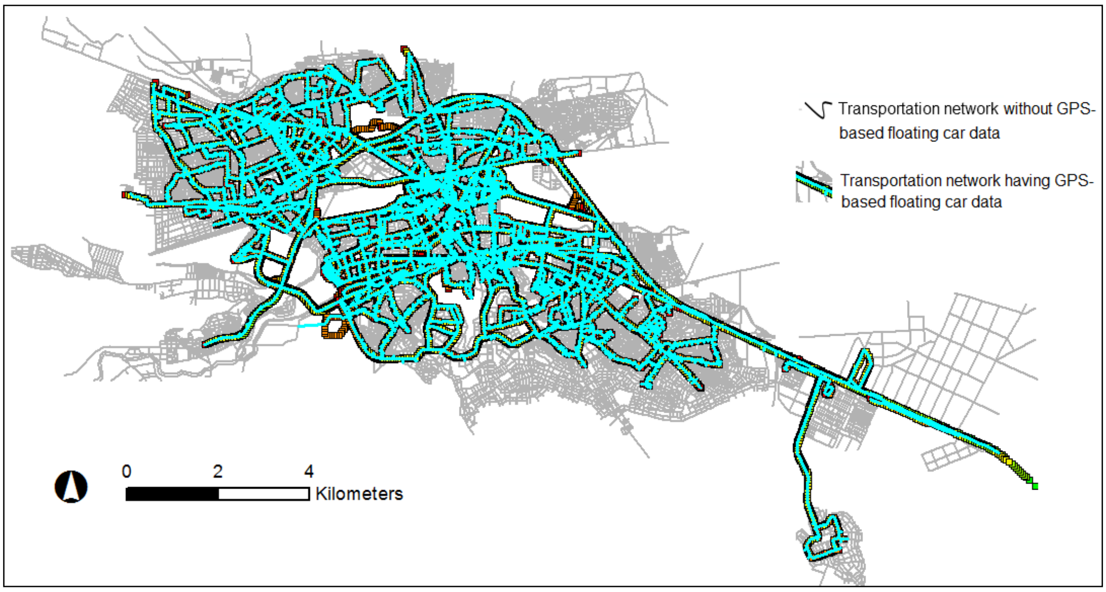
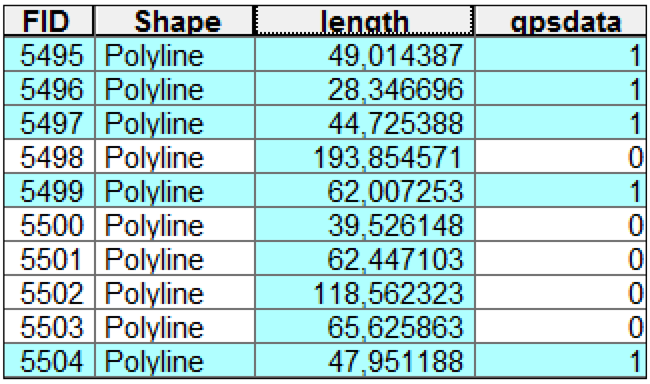


Figure 4.6. Road segments with and without GPS data

The GPS data information for the road segments are added into the attribute table of road data as Boolean information of 0 and 1. A GPS_data field is added to road attribute table and filled with 1 for the road segments that have GPS data and filled with 0 for the road segments that do not have GPS data (Figure 4.7).



| FID | Shape | length | gpsdata |
|---|---|---|---|
| 5495 | Polyline | 49,014387 | 1 |
| 5496 | Polyline | 28,346696 | 1 |
| 5497 | Polyline | 44,725388 | 1 |
| 5498 | Polyline | 193,854571 | 0 |
| 5499 | Polyline | 62,007253 | 1 |
| 5500 | Polyline | 39,526148 | 0 |
| 5501 | Polyline | 62,447103 | 0 |
| 5502 | Polyline | 118,562323 | 0 |
| 5503 | Polyline | 65,625863 | 0 |
| 5504 | Polyline | 47,951188 | 1 |

Figure 4.7. The GPS data information for the road segments in the attribute table of road data as Boolean information of 0 and 1

### 4.3.2. Extraction of speed statistics

The speed statistics are extracted from the GPS-based floating car data in order to integrate with the road attribute table. In this step, two alternative approaches are performed and compared, one of which is the extraction of speed statistics by interpolation from the GPS-based floating car data and the second is the direct extraction of speed statistics from the GPS-based floating car data.

Both extraction by interpolation (with pixel size of 1 meters) and direct extraction of speed statistics from the GPS-based floating car data took nearly 10 minutes time in Intel Core Quad CPU, 2.44 GHz, 4 Gigabyte Ram, 64 bit operating system desktop computer (There are nearly 22.000 point features in the GPS-based floating car data and 26.000 line features in the transportation network). However, the process time can be less or more depending on the number of features in the GPS-based floating car and transportation network data, the pixel size of the produced speed surface and accessibility map and the hardware configuration of the used computer.

In extraction by interpolation, the average mean and standard deviation are extracted from the interpolated speed surface (Figure 4.8). The extracted statistics for different road types are; 53.36 km/h mean speed for highways with 14.51 km/h standard deviation, 43.79 km/h mean speed for boulevards with 14.78 standard deviation, 34 km/h mean speed for main streets with 11.70 standard deviation, 30.96 km/h mean speed for streets with standard deviation of 11.79 and 28.96 km/h mean speed for dead-end streets with standard deviation of 11.87 (Figure 4.9).

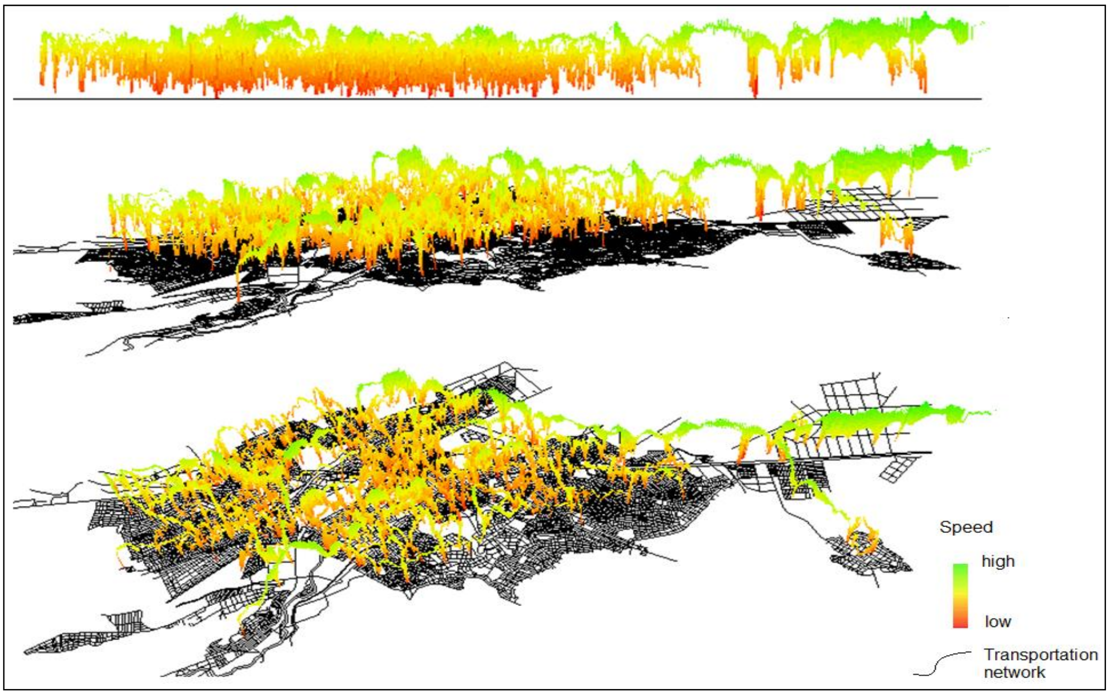


Figure 4.8. Raster speed surface produced from GPS-based floating car data by using IDW interpolation

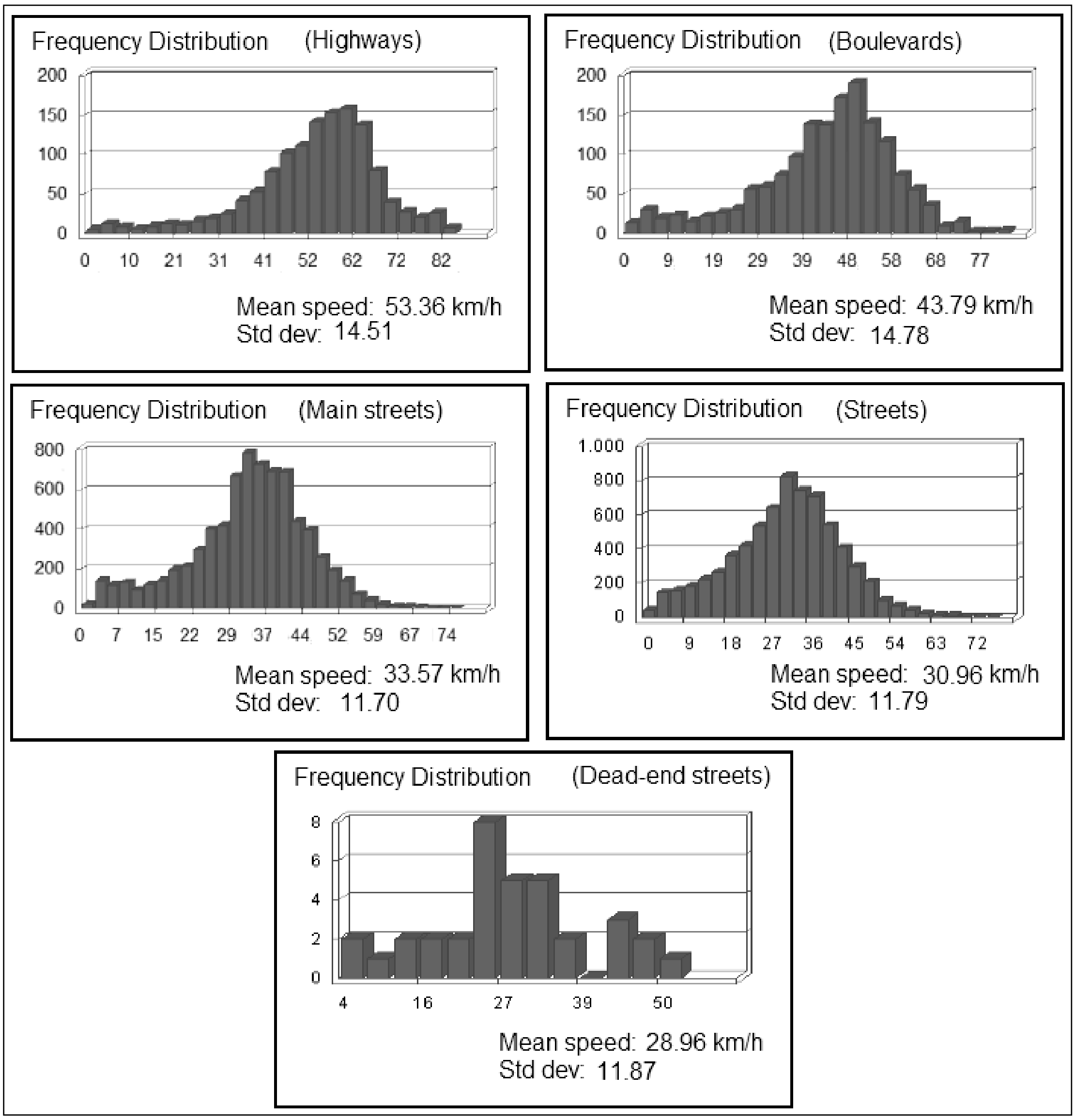
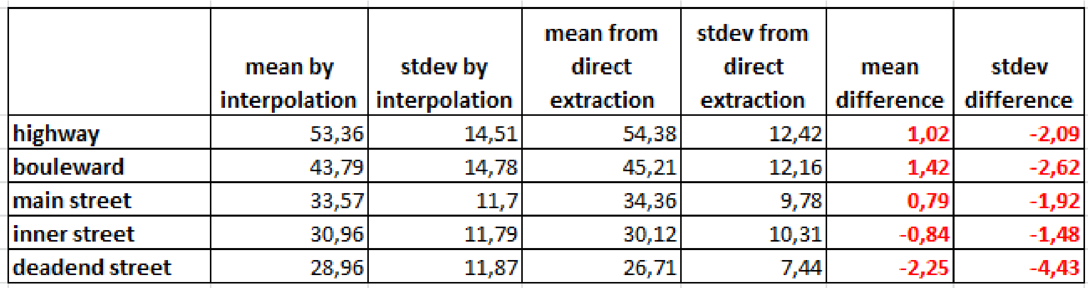


Figure 4.9. The observed mean and standard deviation statistics for different road types extracted from the interpolation-based approach

In direct extraction, the speed statistics are directly extracted from the GPS data without any interpolation. The process is performed in ArcGIS Model builder environment by using the selection, buffer, and overlay (spatial join and identity) capabilities of GIS. Speed statistics from direct extraction for different road types are; 54,38 km/h mean speed for highways with 12,42 km/h standard deviation, 45,21 km/h mean speed for boulevards with 12,16 standard deviation, 34,36 km/h mean speed for main streets with 9,78 standard deviation, 30,12 km/h mean speed for streets with standard deviation of 10,31 and 26,71 km/h mean speed for dead-end streets with standard deviation of 7,44.

The speed statistics by interpolation are insignificantly close to directly extracted speed statistics (Table 4.1). Although, both approaches can be used in the extraction of speed statistics part of the methodology, direct extraction can be considered as more accurate and reliable when compared with the interpolation-based extraction, as there is not any interpolation in the extraction process. However, extraction by interpolation can be preferred when there is limited spatial join and identity capabilities of the used GIS software.

Table 4.1. Comparison of cost statistics produced from direct extraction and interpolation-based extraction

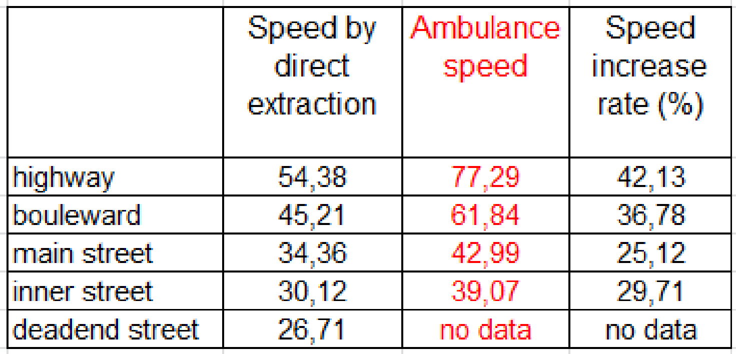


| | mean by interpolation | stdev by interpolation | mean from direct extraction | stdev from direct extraction | mean difference | stdev difference |
|---|---|---|---|---|---|---|
| **highway** | 53,36 | 14,51 | 54,38 | 12,42 | 1,02 | -2,09 |
| **boulevard** | 43,79 | 14,78 | 45,21 | 12,16 | 1,42 | -2,62 |
| **main street** | 33,57 | 11,7 | 34,36 | 9,78 | 0,79 | -1,92 |
| **inner street** | 30,96 | 11,79 | 30,12 | 10,31 | -0,84 | -1,48 |
| **deadend street** | 28,96 | 11,87 | 26,71 | 7,44 | -2,25 | -4,43 |

### 4.3.3. Cost calibration

As the case study is implemented on medical emergency service accessibility, speeds extracted from GPS-based floating car data by direct extraction is calibrated according to the speeds extracted from the ambulance data. The speed increase rates are detected as 42% for highways, 36,78% for boulevards, 25,12% for main streets and 29.71% for inner streets. As there is no ambulance data on deadend streets, deadend street speeds are also increased by 29,71% by considering that they are inner streets (Table 4.2).

Table 4.2. Calibration of probe vehicle speeds according to ambulance speeds.



| | Speed by direct extraction | Ambulance speed | Speed increase rate (%) |
|---|---|---|---|
| highway | 54,38 | 77,29 | 42,13 |
| bouleward | 45,21 | 61,84 | 36,78 |
| main street | 34,36 | 42,99 | 25,12 |
| inner street | 30,12 | 39,07 | 29,71 |
| deadend street | 26,71 | no data | no data |

Because of the time, data and budget limitations of the research, the proposed model is implemented by using short term collected and one-probe-vehicle-based GPS data without considering time-based variations such as rush hour, seasonal, weekend/weekday traffic conditions.

However, when long term collected and large quantity of probe-vehicle based GPS data is obtained, the proposed model can also be implemented considering time dependent variations like rush hour, seasonal, weekend/weekday traffic etc. The detail and complexity of the GPS data and the considered time dependent variations in the model (seasonal variations, rush hour variations, etc) are mostly based on the aim, the budget and the detail needs of the study.

For example, by using the time field in the GPS-based floating car data, the speed statistics of the transportation network can be determined according to different time intervals as shown in Figure 4.10.

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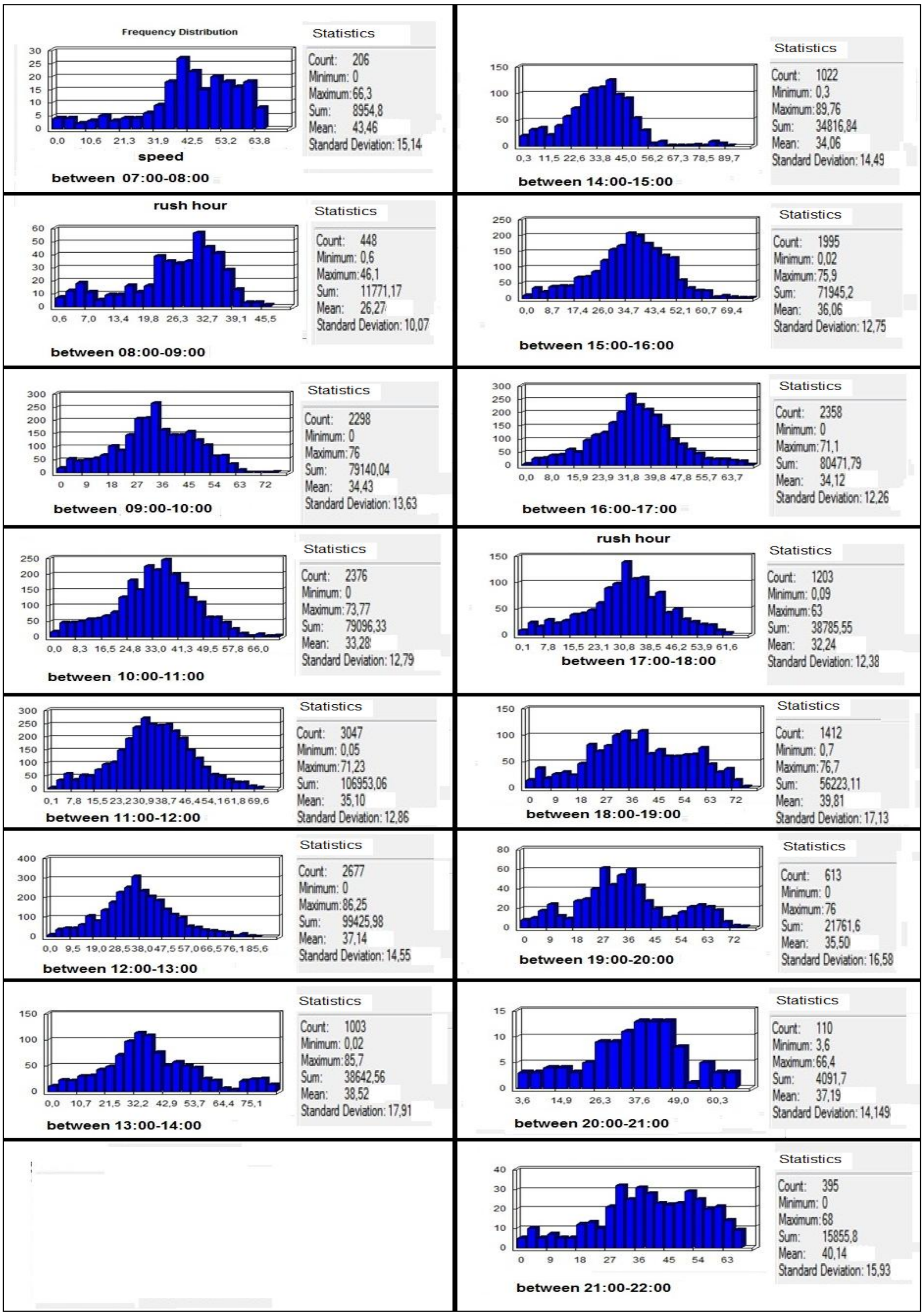


Statistics
Count: 206
Minimum: 0
Maximum: 66,3
Sum: 8954,8
Mean: 43,46
Standard Deviation: 15,14

Statistics
Count: 448
Minimum: 0,6
Maximum: 46,1
Sum: 11771,17
Mean: 26,27
Standard Deviation: 10,07

Statistics
Count: 2298
Minimum: 0
Maximum: 76
Sum: 79140,04
Mean: 34,43
Standard Deviation: 13,63

Statistics
Count: 2376
Minimum: 0
Maximum: 73,77
Sum: 79096,33
Mean: 33,28
Standard Deviation: 12,79

Statistics
Count: 3047
Minimum: 0,05
Maximum: 71,23
Sum: 106953,06
Mean: 35,10
Standard Deviation: 12,86

Statistics
Count: 2677
Minimum: 0
Maximum: 86,25
Sum: 99425,98
Mean: 37,14
Standard Deviation: 14,55

Statistics
Count: 1003
Minimum: 0,02
Maximum: 85,7
Sum: 38642,56
Mean: 38,52
Standard Deviation: 17,91

Statistics
Count: 1022
Minimum: 0,3
Maximum: 89,76
Sum: 34816,84
Mean: 34,06
Standard Deviation: 14,49

Statistics
Count: 1995
Minimum: 0,02
Maximum: 75,9
Sum: 71945,2
Mean: 36,06
Standard Deviation: 12,75

Statistics
Count: 2358
Minimum: 0
Maximum: 71,1
Sum: 80471,79
Mean: 34,12
Standard Deviation: 12,26

Statistics
Count: 1203
Minimum: 0,09
Maximum: 63
Sum: 38785,55
Mean: 32,24
Standard Deviation: 12,38

Statistics
Count: 1412
Minimum: 0,7
Maximum: 76,7
Sum: 56223,11
Mean: 39,81
Standard Deviation: 17,13

Statistics
Count: 613
Minimum: 0
Maximum: 76
Sum: 21761,6
Mean: 35,50
Standard Deviation: 16,58

Statistics
Count: 110
Minimum: 3,6
Maximum: 66,4
Sum: 4091,7
Mean: 37,19
Standard Deviation: 14,149

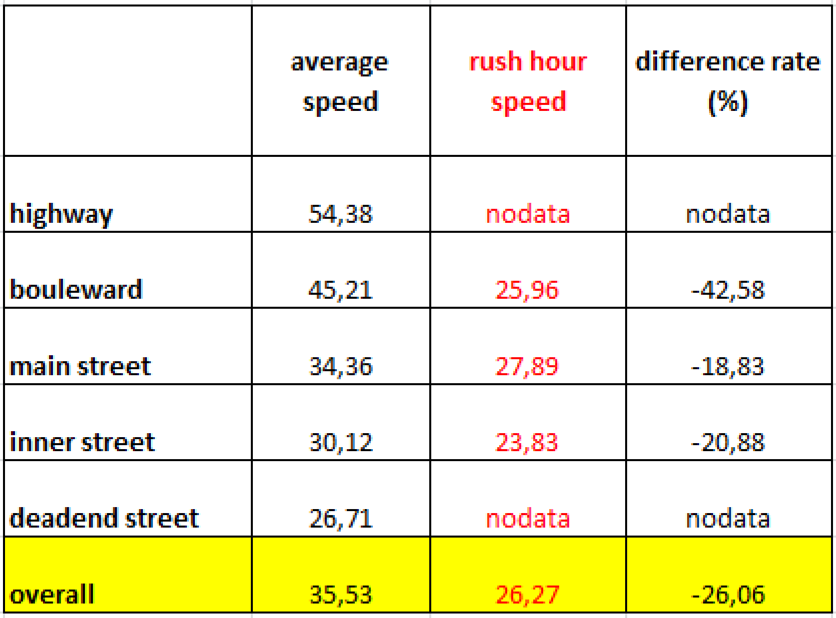
Statistics
Count: 395
Minimum: 0
Maximum: 68
Sum: 15855,8
Mean: 40,14
Standard Deviation: 15,93

Figure 4.10. Speed statistics of GPS-based floating car data according to different time intervals

According to Figure 4.10, 08:00 am-09:00 am and 17:00-18:00 time intervals can be determined as rush hour in the transportation network. When whole time average speed in the transportation network is considered, there is a 26.06% decrease in average speed between 08:00 am and 09:00 am interval and 9.25% decrease in average speed between 17:00 and 18:00 interval.

For example, when the 08:00 am and 09:00 am rush hour time interval is focused, it can be observed that there is a 42,58% speed decrease in boulewards, 18,83% speeed decrease in main streets and 23,83% speed decrease in inner streets (Table 4.3).

Table 4.3. Rush hour speed change according to transportation network hierarchies



| | average speed | rush hour speed | difference rate (%) |
|---|---|---|---|
| highway | 54,38 | nodata | nodata |
| bouleward | 45,21 | 25,96 | -42,58 |
| main street | 34,36 | 27,89 | -18,83 |
| inner street | 30,12 | 23,83 | -20,88 |
| deadend street | 26,71 | nodata | nodata |
| overall | 35,53 | 26,27 | -26,06 |

In the deterministic model, three different cost alternatives are determined. In the first alternative, average of the collected GPS-based speed data according to the transportation network hierarchies are used as cost values which are 77,29 km/h for highways, 61,84 km/h for boulevards, 42,99 km/h for main streets, 39,07 km/h for streets and dead-end streets.

In the second alternative, the speed limits are increased by 20 km/h for ambulances without considering any detailed traffic data information and used as ambulance-based cost values, which are 110 km/h for highways, 90 km/h for boulevards, 70 km/h for main streets, 50 km/h for streets and 30 km/h for dead-end streets. This simple approach is generally prefered when there is no or limited traffic data information and widely used by many accessibility modeling research because of their simplicity (e.g. Emelinda et al. 1995, Juliao 1999, Ritsema van Eck and de Jong 1999, O'Sullivan et al. 2000, Fortney et al. 2000, Brabyn 2002, Makri 2002, Luo and Wang 2003, Luo 2004, Bixby 2004, Messina et al. 2006, Scott et al. 2006, Nadine et al. 2006, Sylvie 2007, Goulias 2007, Charreirea and Combierb 2008, Mitchel et al. 2008, McGrail and Humphreys 2009, Lotfi and Koohsari 2009, Vahidnia et al. 2009).

In the third alternative, the Eucledian distance based bird-flight distance is used as a cost value without considering the transportation network. The equivalant of five minutes accessibility cost threshold, a 5.8 km length buffer, is used starting from the emergency service locations by considering 70 km/h as an average birdflight speed in all directions. This approach is also widely used in GIS-based accessibility modeling literature because of its simplicity. However, it is not realistic, especially when considered highly variable speeds in the transportation network.

### 4.3.4. Integration of speed statistics with the road segments

The integration step in the model covers the integration of extracted and calibrated speed statistics with the attribute table of the road segments. For each of the road segments that have GPS-based floating car data, the local speed statistics for each of the road segments are integrated with the transportation network data (Figure 4.11). For each of the road segments that do not have GPS data, speed statistics for each of the road types (highway, boulevard, street etc.) are integrated with the transportation network data.

Figure 4.11. The local mean and standard deviation of speed integrated with the transportation network data

According to the local speed statistics, higher standard deviation can be observed in the highway and boulevard segments of the transportation network. However, a specific standard deviation pattern could not be observed in the main streets, streets and deadend streets. On the other hand, mean speed is observed decreasing regularly from highway and bouleward segments to main street, street and dead end street segments as expected.

In order to perform MCS, there is a need to determine the best fitting probability density function for the speed data. Therefore, GPS-based floating car data is statistically analyzed by using Easy Fit distribution fitting software. As the results are significantly close to the normal distribution, the normal distribution is used as input distribution function to produce random costs in MCS.

## 4.4. Monte Carlo simulations

The best fitting distribution function, the extracted speed statistics of mean and standard deviation and the length of the road segments are used as input variables in ArcGIS Model builder programming environment and random time costs for each road segment is produced as an output.

In Monte Carlo Simulations (MCS), random transportation costs are produced from directly extracted and calibrated mean and standard deviation statistics. During the stochastic modeling process, for the road segments that have GPS data, the local mean and standard deviation values are used for generation of random transportation costs. For the road segments that do not have GPS data, the average mean and standard deviation values are used for generation of random transportation costs.

In the stochastic model, a total number of 1000 Monte Carlo simulations are performed within nearly 13,5 hours time in Intel Core Quad CPU, 2.44 GHz, 4 Gigabyte Ram, 64 bit operating system desktop computer and the simulations are cut off after 1000 simulations as considerable change is not observed in the results (Figure 4.12). The process time can be less or more depending on the number of features in the transportation network and service locations data, the pixel size of the produced binary raster accessibility map and the hardware configuration of the used computer.

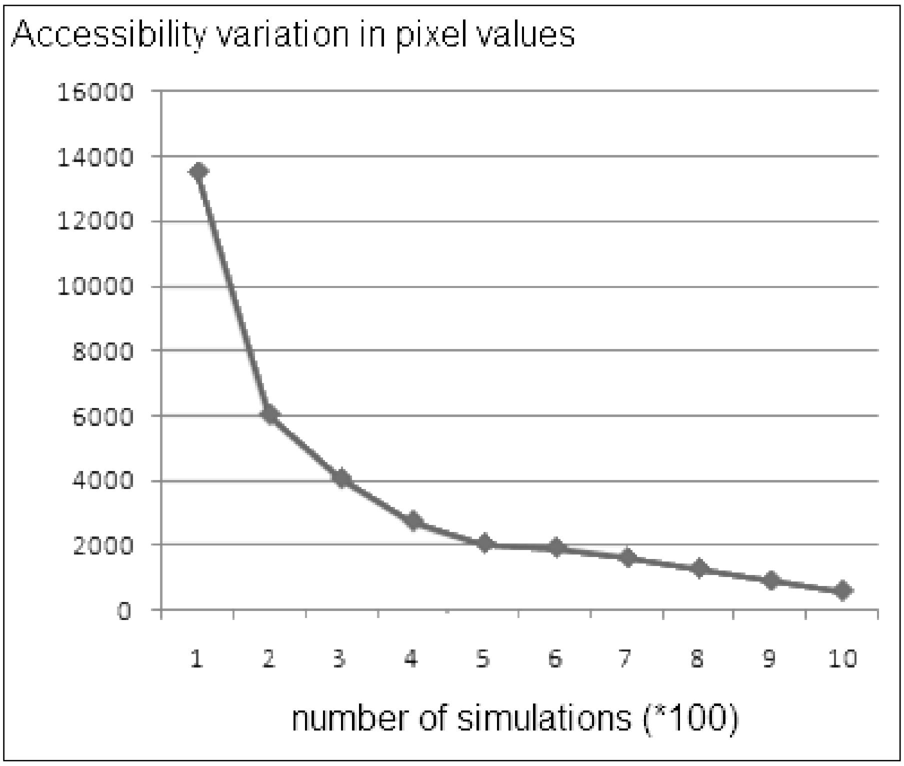


Figure 4.12. Variation in pixel values with number of simulations

## 4.5. Comparison of deterministic and stochastic models

The five minutes medical emergency service accessibility is modeled both by the deterministic model in three different cost alternatives (buffer-based costs, without GPS-based costs, GPS-based costs) (Figure 4.13) and by the proposed stochastic model as described in section 4.3 (Figure 4.14) and the results are compared.

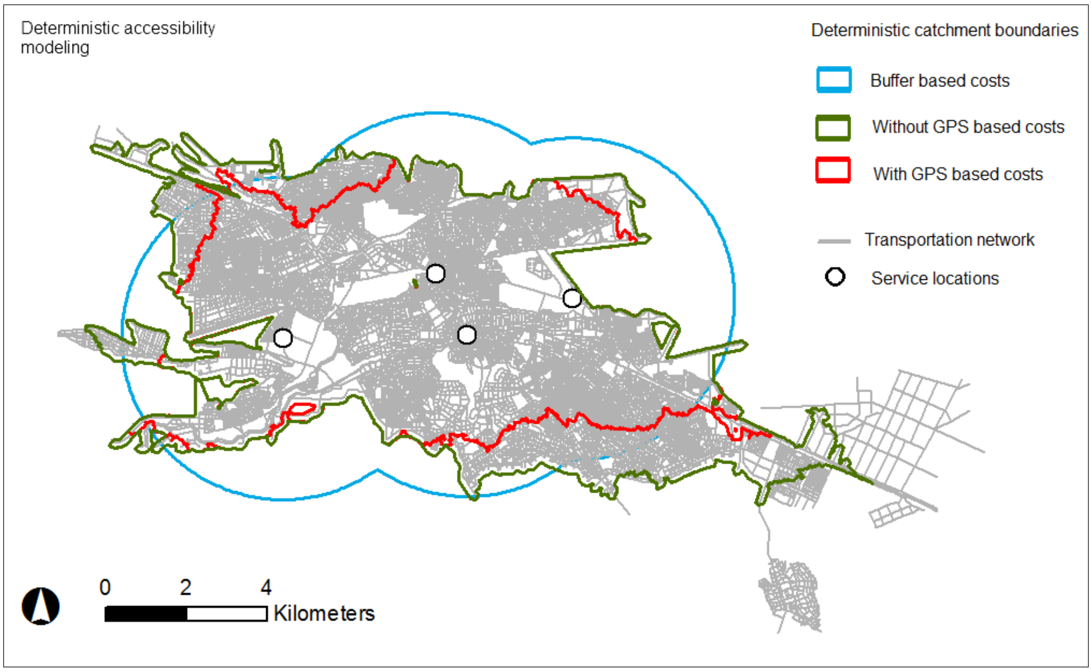


Figure 4.13. Deterministic modeling of accessibility for medical emergency services in Eskisehir

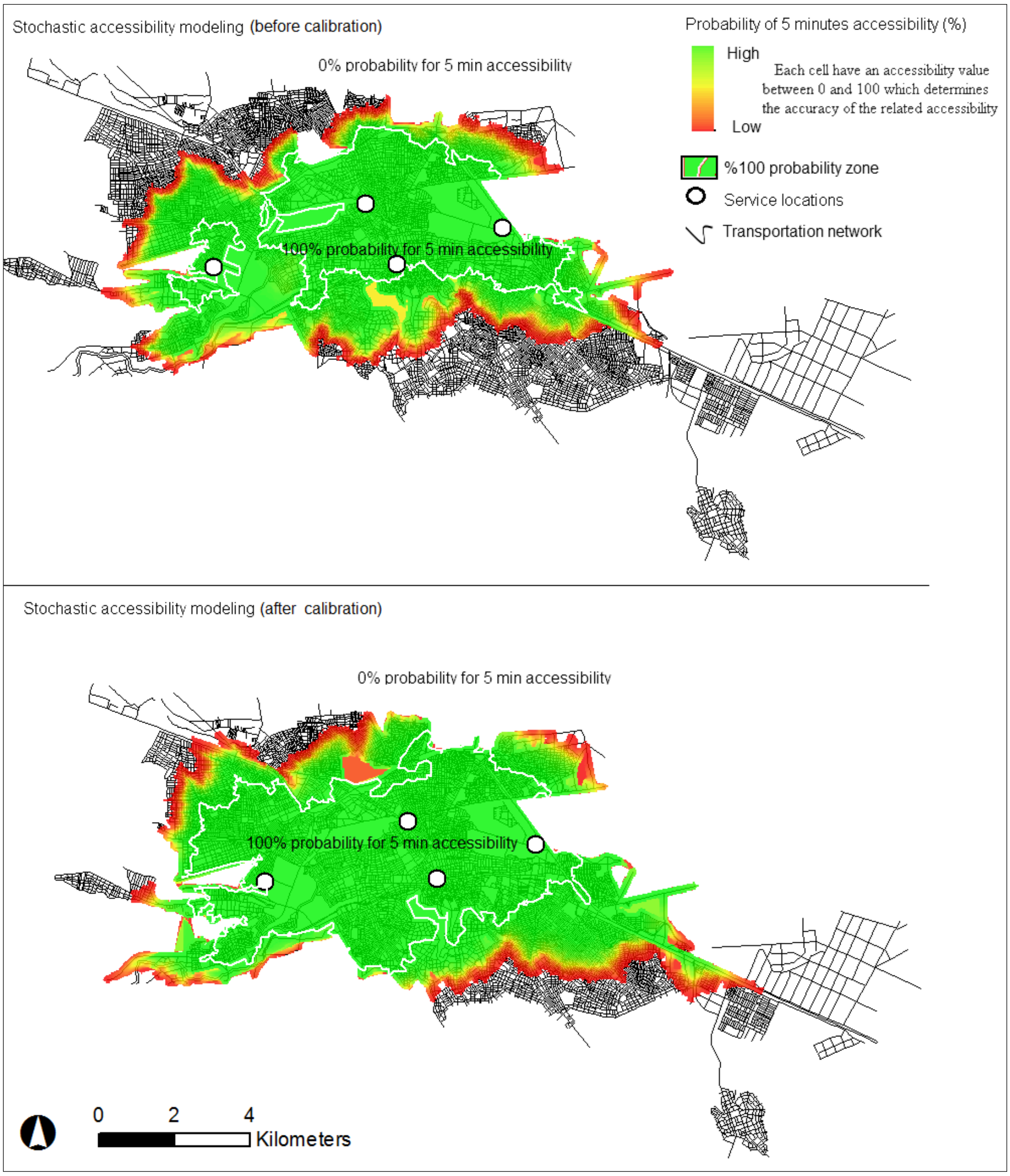


Figure 4.14. Stochastic modeling of accessibility for medical emergency services in Eskisehir

When the deterministic and the stochastic models are compared, it can be said that; five minutes catchment area boundary estimations are significantly different from each other. The estimated catchment area boundary differences can reach up to 4-5 km in length and 29-30 km$^2$ in area, which can be considered as an important difference from accuracy and reliability point of view and can directly affect/mislead accessibility, location/allocation and service/catchment area related strategy development and decision making process. Especially buffer-based boundary estimations have great potential to overestimate or underestimate the actual accessibility pattern, as they do not consider transportation network traveling costs. Moreover, many areas where there is no transportation network, is in the accessible zone in buffer-based approach.

The GPS-based and without GPS-based estimations can be considered as more realistic when compared to the buffer-based approach as they use transportation network based costs in the estimation process. However, the estimated catchment area boundary differences can still reach up to 2-3 km in length and 7-8 km² in area and the decision maker have no idea about the accuracy and reliability of the boundaries as deterministic models could not handle variations in traveling costs. Additionally, it must also be pointed out that, when compared with the without GPS-based estimation, the GPS-based estimation is more accurate and reliable as the costs are directly determined by considering GPS-based real traffic conditions.

When the deterministic catchment area boundaries are overlaid with the probabilistic catchment area boundaries in GIS environment, the catchment area boundary differences between the models can be observed (Figure 4.15).

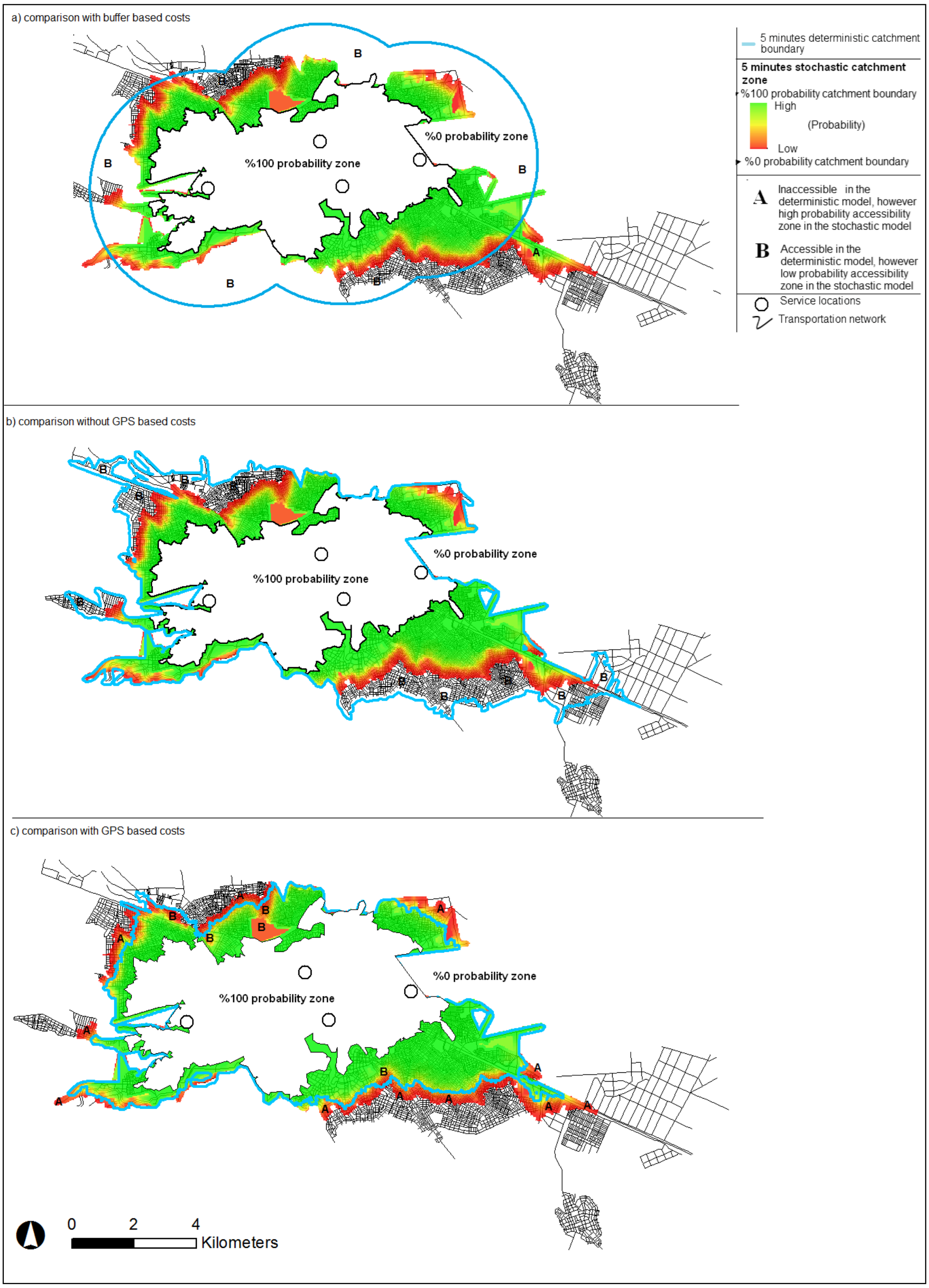


Figure 4.15. The overlay of stochastic and deterministic modeling of accessibility in GIS environment

The five minutes probabilistic catchment area boundaries are significantly different from the crisp catchment area boundaries of the deterministic model, especially when compared to the buffer-based and without GPS-based deterministic models. Although the GPS-based deterministic estimation is the most similar estimation to the stochastic model, there is still significant difference in terms of catchment area boundaries.

The comparison between five minutes buffer-based deterministic and probabilistic catchment area boundaries indicates that; although most of the surrounding areas in the north, south, east and west parts of the case study area are observed in the accessible zone in the deterministic model, they are in the very low or no probability accessibility zone (in the 0% - 30% probability accessibility zone) in the stochastic model (B zones in Figure 4.15). The catchment area boundary differences can reach up to 4-5 km in length and 29-30 km$^2$ in area. Similarly, the south-east parts of the case study area are observed in the inaccessible zone according to deterministic model, however they are in the high probability accessibility zone (in the 75% - 90% probability accessibility zone) in the stochastic model (A zones in Figure 4.15). The catchment area boundary differences can reach up to 2-3 km in length and 1-2 km$^2$ in area. Many urban areas where there is no transportation network are also estimated in the accessible zone in buffer-based approach.

The comparison between five minutes without GPS-based deterministic and probabilistic catchment area boundaries indicates that; although some of the urban areas in the north-west and south-east parts of the case study area are in the accessible zone in the deterministic model, they are in the low probability accessibility zone (in the 0% - 30% probability accessibility zone) according to the stochastic model (B zones in Figure 4.15). The catchment area boundary differences can reach up to 2-3 km length and 7-8 km$^2$ in area.

The comparison between five minutes GPS-based deterministic and probabilistic catchment area boundaries indicates that; although some of the urban areas in the north and south parts of the case study area are observed in the inaccessible zone in the deterministic model, they are in the moderate and low probability accessibility zone (in the 1%-76% probability accessibility zone) according to the stochastic model (A zones in Figure 4.15). The catchment area boundary differences can reach up to 0,5-1 km in length and 3-4 $km^2$ in area. Similarly, the north and south parts of the case study area are observed in the accessible zone in the deterministic model, however they are in the low and moderate probability accessibility zone (in the 1%-75% probability accessibility zone) in the stochastic model (B zones in Figure 4.15). The catchment area boundary differences can reach up to 0,5-1 km length and 1-2 $km^2$ in area.

The overall comparison demonstrated that catchment area boundary differences within deterministic models could be significantly different from accuracy and reliability point of view and can directly affect/mislead accessibility, location/allocation and service/catchment area related strategy development and decision making process.

The main benefit of the proposed stochastic methodology is that; it could provide additional information related with the accuracy and the reliability of the catchment area boundaries in accessibility modeling, which means better decision support for the decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues. The proposed stochastic model allows systematic treatment of uncertainties related with the catchment area boundaries and the crisp catchment area boundaries in the deterministic model turns into probabilistic catchment area boundaries providing decision makers to operate different levels of uncertainty in modeling of accessibility.

By this way, it is possible to differentiate regions that have low / moderate / high probability of having five minutes of emergency service accessibility. There is only a 75% probability that the place x have five minutes emergency service accessibility can only be predicted by the stochastic model which is not possible to obtain in the deterministic model (Figure 4.16).

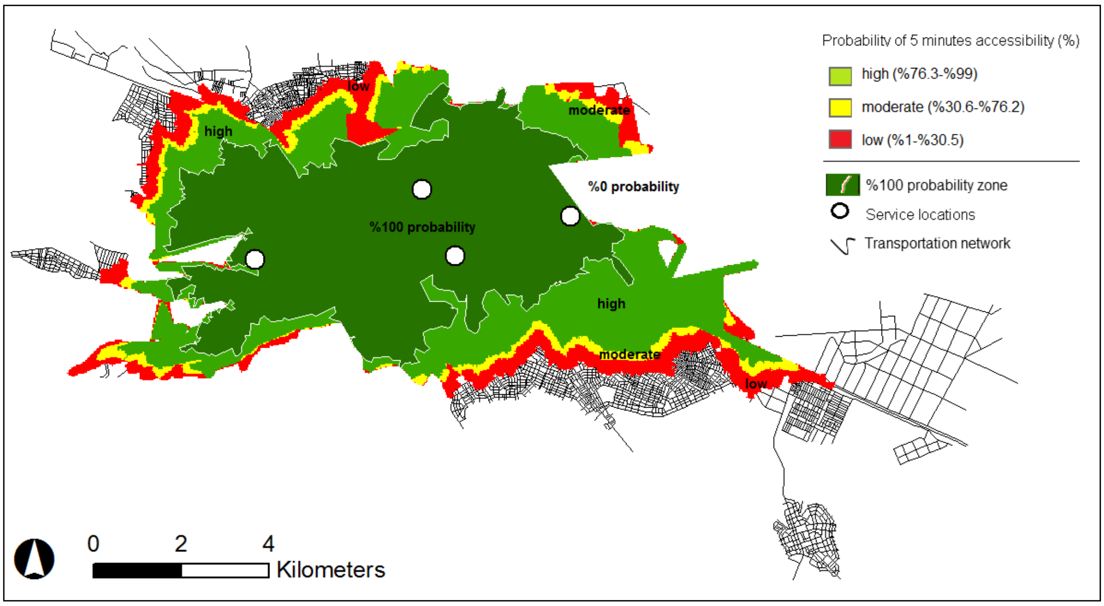


Figure 4.16. Low, moderate and high probability regions of having five minutes of medical emergency service accessibility

For example, by using Figure 4.16, and Figure 4.28, it is possible to differentiate neighbourhoods of Eskişehir according to their mean probability of having five minutes of medical emergency service accessibility which could directly improve strategy development and decision making capabilities of accessibility related decision makers (see Figure 4.17 and Table 4.4).

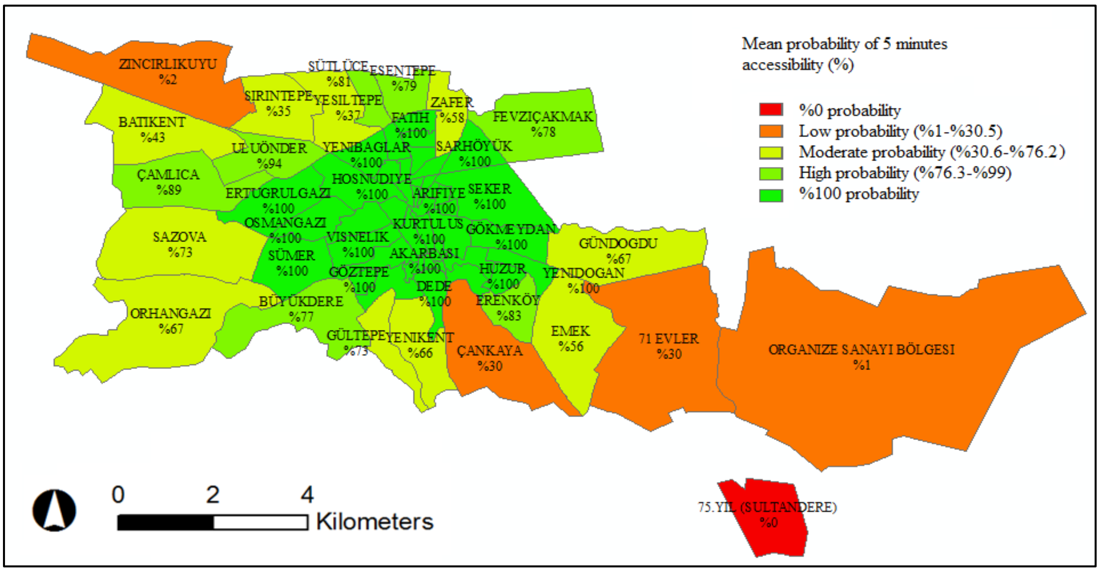


Figure 4.17. Neighbourhoods of Eskişehir according to mean probability of having five minutes of medical emergency service accessibility

Table 4.4. Neighbourhoods of Eskişehir according to mean probability of having five minutes of medical emergency service accessibility

| **Neighbourhoods of Eskişehir** | **Mean probability of having five minutes medical emergency service accessibility** |
|---|---|
| 75. Yıl (Sultandere) | **0% probability** |
| Çankaya, Organize Sanayi Bölgesi, 71 Evler and Zincirlikuyu | **Low probability**<br>(1%- 30.5%) |
| Batıkent, Emek, Gültepe, Gündoğdu, Orhan Gazi, Sazova, Şirintepe, Yenikent, Yeşiltepe and Zafer | **Moderate probability**<br>(30.6%- 76.2%) |
| Büyükdere, Çamlıca, Erenköy, Esentepe, Fevzi Çakmak, Sütlüce and Ulu Önder | **High probability**<br>(76.3%-99%) |
| Akarbaşı, Akcami, Akçağlan, Alanönü, Arifiye, Bahçelievler, Cumhuriye, Cunudiye, Dede, Deliklitaş, Ertuğrulgazi, Eskibağlar, Fatih, Gökmeydan, Göztepe, Güllük, Hacı Ali Bey, Hacı Seyit, Hayriye, Hoşnudiye, Huzur, İhsaniye, Işıklar, İstiklal, Karapınar, Kırmızı Toprak, Kumlubel, Kurtuluş, Mamure, Mustafa Kemal Paşa, Orta, Osmangazi, Ömerağa, Paşa, Sarhöyük, Şarkiye, Şeker, Sümer, Tunalı, Vişnelik, Yeni, Yenibağlar, Yenidoğan and Yıldıztepe | **100% probability** |

According to Figures 4.16 and 4.17,

- 75. Yıl (Sultandere) is the most critical neighbourhood with 0% probability of five minutes medical emergency service accessibility. Çankaya, Organize Sanayi Bölgesi, 71 Evler and Zincirlikuyu are the second-degree most critical neighbourhoods with low probability (1%-30.5%) of five minutes medical emergency service accessibility. Batıkent, Emek, Gültepe, Gündoğdu, Orhan Gazi, Sazova, Şirintepe, Yenikent, Yeşiltepe and Zafer neighbourhoods are the third-degree critical neighbourhoods with moderate probability (30.6%-76.2%) of five minutes medical emergency service accessibility. Operating different levels of uncertainity in accessibility modeling could directly help better determination of the strategical priorities, improve strategy development, and decision making capabilities of the decision makers.

- Two new or re-located medical emergency service stations are seem to be needed in Eskişehir city, one of which is in the northwest part of Eskişehir (near Zincirlikuyu, Batıkent, Şirintepe and Ulu Önder neighbourhoods) and the other is in the southeast part of Eskişehir (75. Yıl (Sultandere), Organize Sanayi Bölgesi and 71 Evler neighbourhoods). However, by considering only critical neighbourhood information, taking a location/allocation decision about medical emergency service stations can be misleading for the decision makers. In order to able to make a reliable decision about the location/allocation of medical emergency service stations, some additional information must also be considered by the decision makers such as;
    - a) excessive service regions (the urban regions that are accessible by more than one medical emergency service stations)
    - b) the amount of supply and demand (e.g. according to the 24046 numbered instructions of emergency health services, the

    served population must be at least 50.000 people for establishment of a new medical emergency service station etc.)
    - c) the balance of cost and benefit (e.g. the establishment of an additional medical emergency service station could be infeasible for the government or municipality)
    - d) the amount and distribution pattern of the medical emergency related incidents etc.

- The medical emergency service accessibility in Eskişehir city seems to be highly affected from the linear development of the transportation network. As most of the major transportation network (highways and boulewards) are in the east-west direction, the medical emergency service accessibility is observed higher in the east-west direction and lower in the north-south direction. However, as an alternative to location/allocation of medical emergency service stations, medical emergency service accessibility can also be improved by special traffic arrangements and transportation network enhancements especially considering frequently used routes from medical emergency service stations to inaccessible areas. For example, organizing emergency bands on roads to speed up response could significantly improve the medical emergency service accessibility to the critical neighbourhoods.

Because of the time, data and budget limitations of the research, the GPS-based floating car dataset could not be collected large enough to handle time-based variations and the proposed model is implemented by using data collected for short term and one probe-vehicle-based GPS data without considering time-based variations such as rush hour, seasonal, weekend/weekday traffic conditions.

However, when data collected for long term and large quantity of probe-vehicle based-GPS data is obtained, the proposed model can also be implemented considering time-based variations like rush hour, seasonal, weekend/weekday traffic etc. For instance, when traveling costs are calibrated according to rush hour traffic conditions as given in Figure 4.10 and Table 4.3, the change of five minutes accessibility in rush hour time interval can also be observed (Figure 4.18).

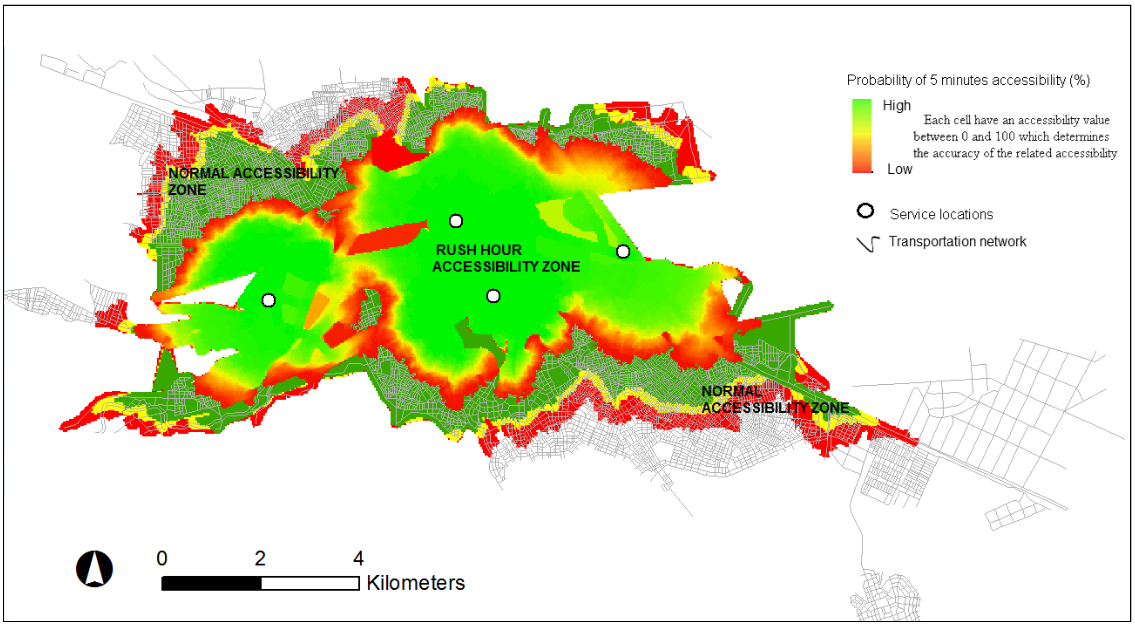


Figure 4.18. The five minutes accessibility in rush hour traffic conditions

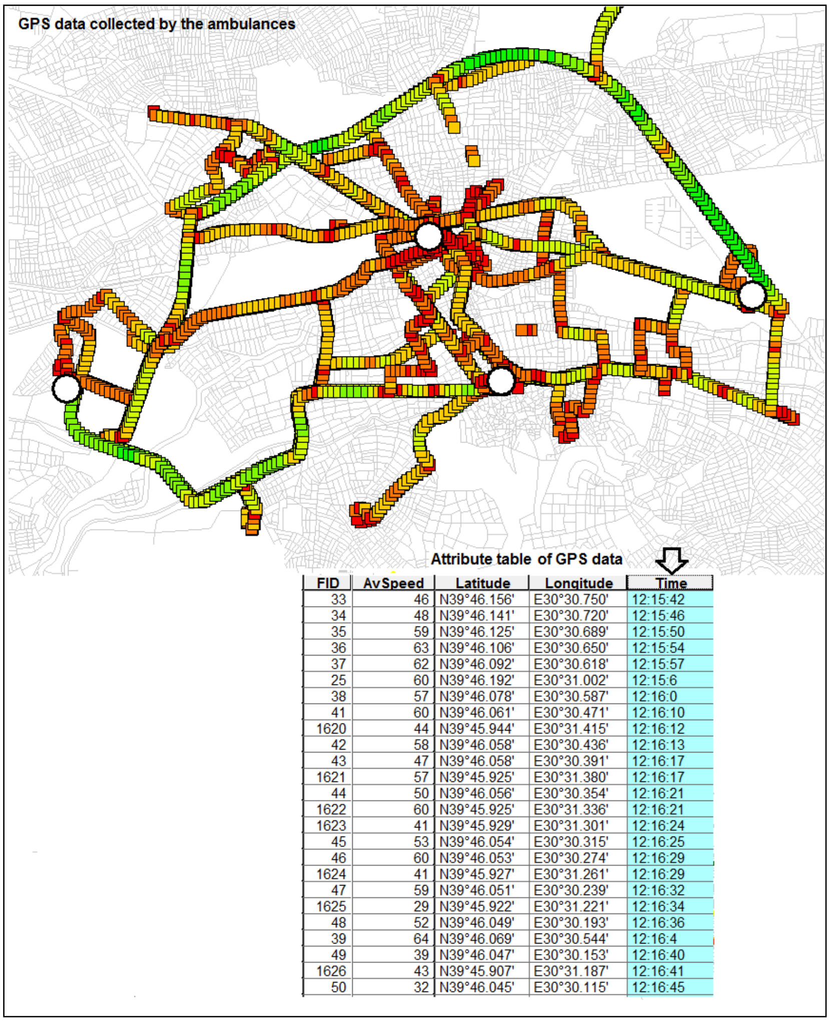
According to Figure 4.18, catchment area boundaries in rush hour traffic conditions is significantly different than the normal hour traffic conditions. Although the urban areas, especially in the north-west and south-east parts of the case study area, are inaccessible in rush hour traffic conditions, they are accessible in normal hour traffic conditions. The catchment area differences between normal time and rush hour traffic conditions can reach up to 3-4 km length and 14-15 $km^2$ in area.

When data collected for long term and large quantity of probe-vehicle based-GPS data is obtained, differentiating the obtained/collected traffic data in terms time-based variations (such as rush hour, seasonal, day/night, weekend/weekday etc.) and considering each of the condition separately in a stochastic manner could directly improve the accuracy and reliability of the proposed stochastic model and can be more convincing and informative for the decision makers who use the model.

## 4.6. Model validation

The accuracy and reliability of the GPS-based stochastic accessibility model is tested by Magellan Explorist 600 type GPS receivers mounted on four different medical emergency service vehicles operating on four different medical emergency service stations (north, south, east and west) on May 2008.

The time field in the attribute table of the GPS data collected by ambulances is used to determine actual traveling time information in model validation (Figure 4.19). The other fields in the GPS data collected by ambulances are FID (the unique id of the collected GPS data), Avspeed (the measured speed at that location), Latitude (the geographical coordinate of the ambulance in term of Latitude) and Longitude (the geographical coordinate of the ambulance in term of Longitude).



| FID | AvSpeed | Latitude | Longitude | Time |
|---|---|---|---|---|
| 33 | 46 | N39°46.156' | E30°30.750' | 12:15:42 |
| 34 | 48 | N39°46.141' | E30°30.720' | 12:15:46 |
| 35 | 59 | N39°46.125' | E30°30.689' | 12:15:50 |
| 36 | 63 | N39°46.106' | E30°30.650' | 12:15:54 |
| 37 | 62 | N39°46.092' | E30°30.618' | 12:15:57 |
| 25 | 60 | N39°46.192' | E30°31.002' | 12:15:6 |
| 38 | 57 | N39°46.078' | E30°30.587' | 12:16:0 |
| 41 | 60 | N39°46.061' | E30°30.471' | 12:16:10 |
| 1620 | 44 | N39°45.944' | E30°31.415' | 12:16:12 |
| 42 | 58 | N39°46.058' | E30°30.436' | 12:16:13 |
| 43 | 47 | N39°46.058' | E30°30.391' | 12:16:17 |
| 1621 | 57 | N39°45.925' | E30°31.380' | 12:16:17 |
| 44 | 50 | N39°46.056' | E30°30.354' | 12:16:21 |
| 1622 | 60 | N39°45.925' | E30°31.336' | 12:16:21 |
| 1623 | 41 | N39°45.929' | E30°31.301' | 12:16:24 |
| 45 | 53 | N39°46.054' | E30°30.315' | 12:16:25 |
| 46 | 60 | N39°46.053' | E30°30.274' | 12:16:29 |
| 1624 | 41 | N39°45.927' | E30°31.261' | 12:16:29 |
| 47 | 59 | N39°46.051' | E30°30.239' | 12:16:32 |
| 1625 | 29 | N39°45.922' | E30°31.221' | 12:16:34 |
| 48 | 52 | N39°46.049' | E30°30.193' | 12:16:36 |
| 39 | 64 | N39°46.069' | E30°30.544' | 12:16:4 |
| 49 | 39 | N39°46.047' | E30°30.153' | 12:16:40 |
| 1626 | 43 | N39°45.907' | E30°31.187' | 12:16:41 |
| 50 | 32 | N39°46.045' | E30°30.115' | 12:16:45 |

Figure 4.19. Actual traveling time information in the GPS-based floating car data

The validation of the model is composed of three main steps. The first step is calculation of actual traveling time boundaries for each of the medical emergency service stations (north, south, east and west) for five minutes time threshold. The second step is estimation of five minutes service area boundaries for each of the medical emergency service stations (north, south, east and west) by using the determininistic and the proposed stochastic model. The third step is comparison of traveling time differences between actual and estimation in terms of Root Mean Squared Error (RMSE) for the deterministic models and in terms of probability scores for the stochastic models. Finally, an error matrix is created.

In the first step, all ambulance trips starting from north, south, east and west medical emergency service stations are extracted from ambulance-based GPS data and used in determination of actual five minutes traveling time boundaries (Figure 4.20).

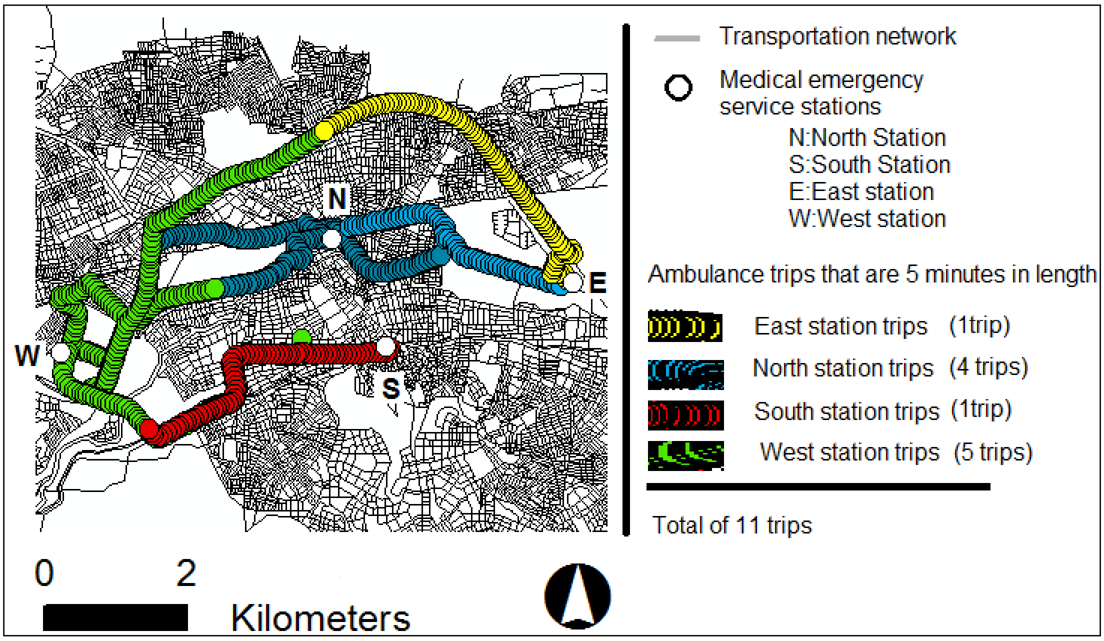


Figure 4.20. Ambulance trips starting from medical emergency service stations and five minutes in length

In the second step, for each of the medical emergency service stations (north, south, east and west), five minutes traveling time boundaries are estimated by using the three deterministic models and the proposed stochastic model.

In GPS-based deterministic model, average of the collected GPS-based floating car speed data according to the transportation network hierarchies are used as cost values, which are 77,29 km/h for highways, 61,84 km/h for boulevards, 42,99 km/h for main streets, 39,07 km/h for streets and dead-end streets.

In without GPS-based deterministic model, normal speed limits are increased by 20 km/h for ambulances without considering any detailed traffic data information and used as ambulance-based cost values, which are 110 km/h for highways, 90 km/h for boulevards, 70 km/h for main streets, 50 km/h for streets and 30 km/h for dead-end streets.

In buffer-based deterministic model, the Eucledian distance based bird-fligh distances are used as cost values without considering the transportation network. As an equivalance of five minutes threshold, a 5.8 km buffer operation is performed starting from each of the emergency service locations seperately by considering 70 km/h as an average birdflight speed (Figure 4.21).

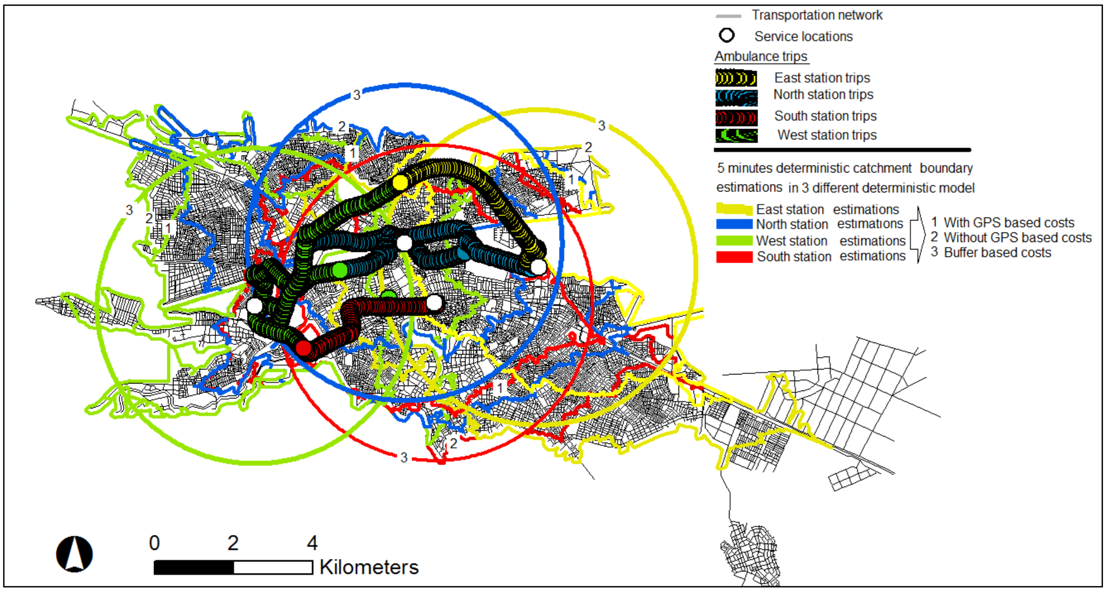


Figure 4.21. Five minutes catchment area boundary estimation in deterministic models

In stochastic model, five minutes probabilistic catchment area boundaries are calculated by using MCS-based random traveling costs for each of the medical emergency service stations (Figure 4.22-Figure 4.25). During stochastic modeling process, for each of the road segments that have GPS data, the mean and standard deviation statistics for each of the road segments are used for generation of random transportation costs. For each of the road segments that do not have GPS data, the mean and standard deviation statistics for each of the road types are used for generation of random transportation costs. The results are also compared with the three deterministic models and the ambulance-based GPS data.

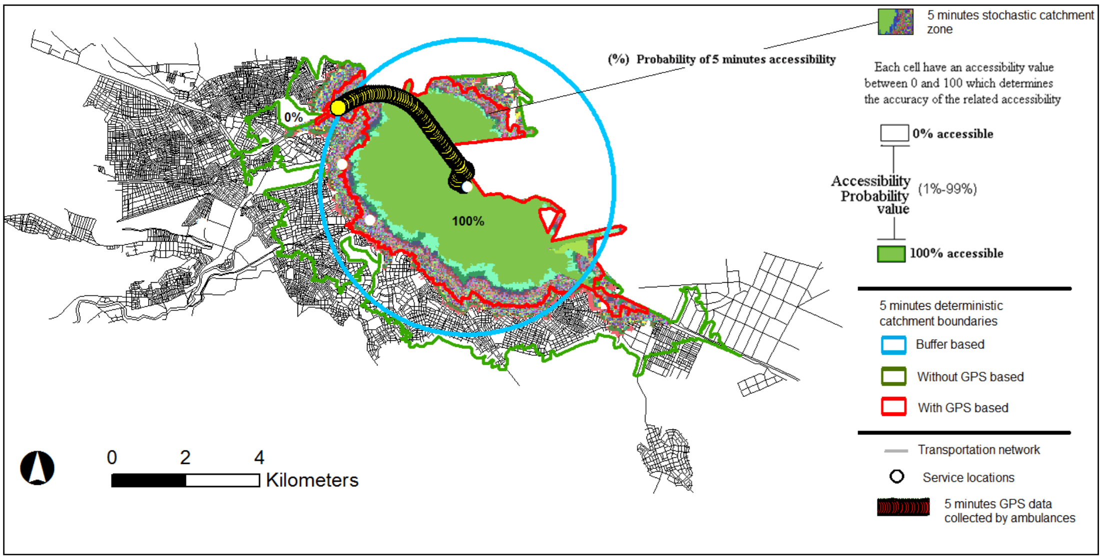


Figure 4.22. Five minutes probabilistic catchment area estimation in stochastic model (east station)

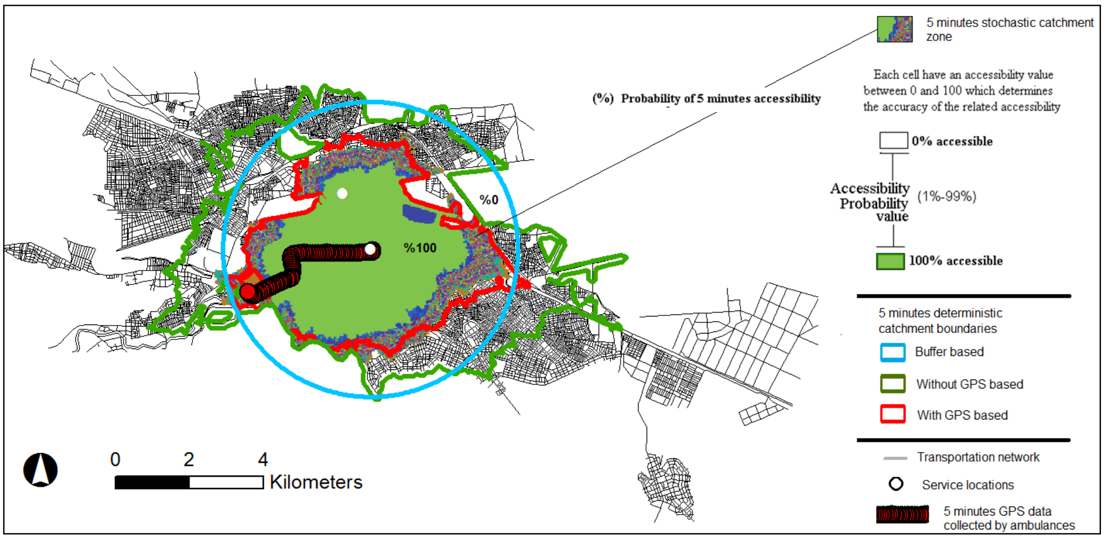


Figure 4.23. Five minutes probabilistic catchment area estimation in stochastic model (south station)

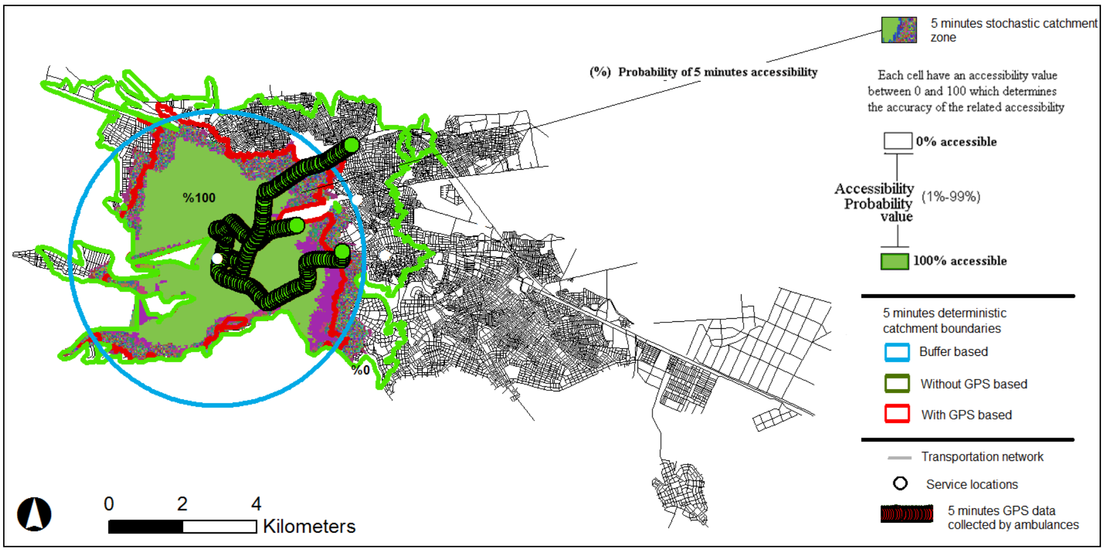


Figure 4.24. Five minutes probabilistic catchment area estimation in stochastic model (west station)

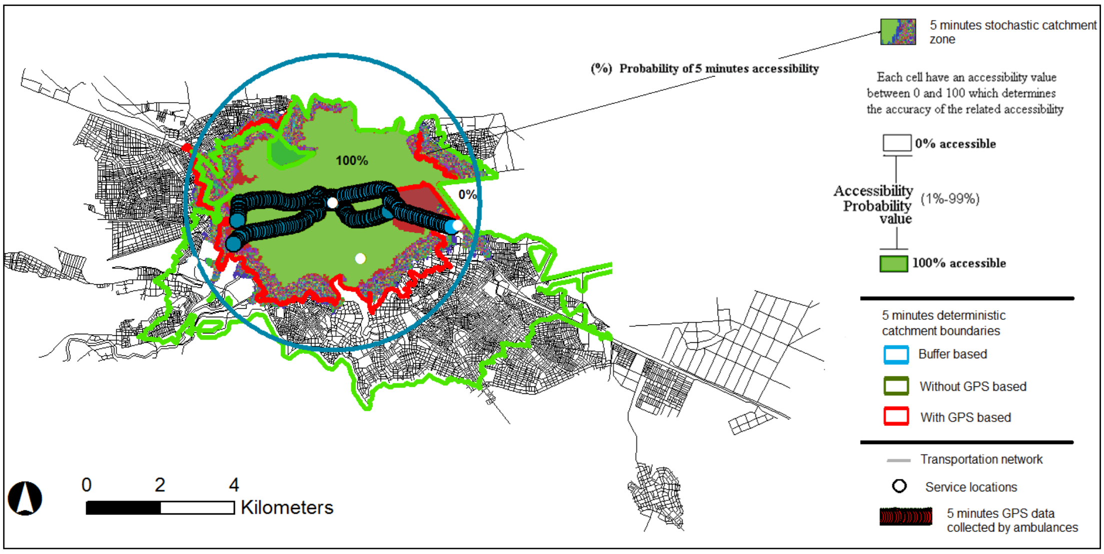
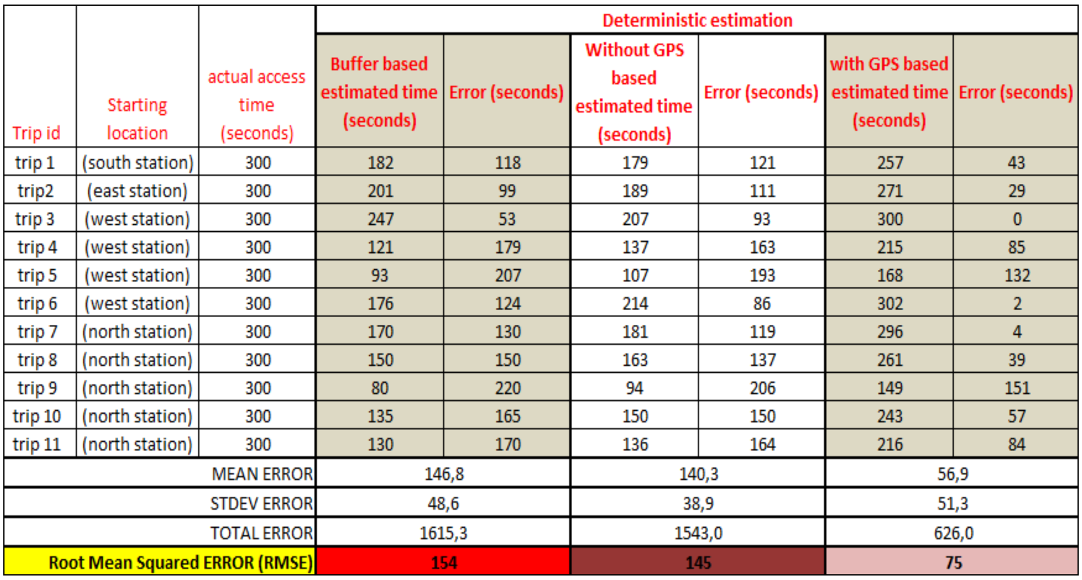


Figure 4.25. Five minutes probabilistic catchment area estimation in stochastic model (north station)

In the final step, the actual and estimated traveling time boundaries are compared and model errors are determined in terms of RMSE for the deterministic model (Table 4.5, Figure 4.26) and in terms of probability scores for the stochastic model (Table 4.6).

Table 4.5. Deterministic model errors in terms of RMSE



| Trip id | Starting location | actual access time (seconds) | Deterministic estimation | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Buffer based estimated time (seconds) | Error (seconds) | Without GPS based estimated time (seconds) | Error (seconds) | with GPS based estimated time (seconds) | Error (seconds) |
| trip 1 | (south station) | 300 | 182 | 118 | 179 | 121 | 257 | 43 |
| trip2 | (east station) | 300 | 201 | 99 | 189 | 111 | 271 | 29 |
| trip 3 | (west station) | 300 | 247 | 53 | 207 | 93 | 300 | 0 |
| trip 4 | (west station) | 300 | 121 | 179 | 137 | 163 | 215 | 85 |
| trip 5 | (west station) | 300 | 93 | 207 | 107 | 193 | 168 | 132 |
| trip 6 | (west station) | 300 | 176 | 124 | 214 | 86 | 302 | 2 |
| trip 7 | (north station) | 300 | 170 | 130 | 181 | 119 | 296 | 4 |
| trip 8 | (north station) | 300 | 150 | 150 | 163 | 137 | 261 | 39 |
| trip 9 | (north station) | 300 | 80 | 220 | 94 | 206 | 149 | 151 |
| trip 10 | (north station) | 300 | 135 | 165 | 150 | 150 | 243 | 57 |
| trip 11 | (north station) | 300 | 130 | 170 | 136 | 164 | 216 | 84 |
| MEAN ERROR | | | 146,8 | | 140,3 | | 56,9 | |
| STDEV ERROR | | | 48,6 | | 38,9 | | 51,3 | |
| TOTAL ERROR | | | 1615,3 | | 1543,0 | | 626,0 | |
| Root Mean Squared ERROR (RMSE) | | | 154 | | 145 | | 75 | |

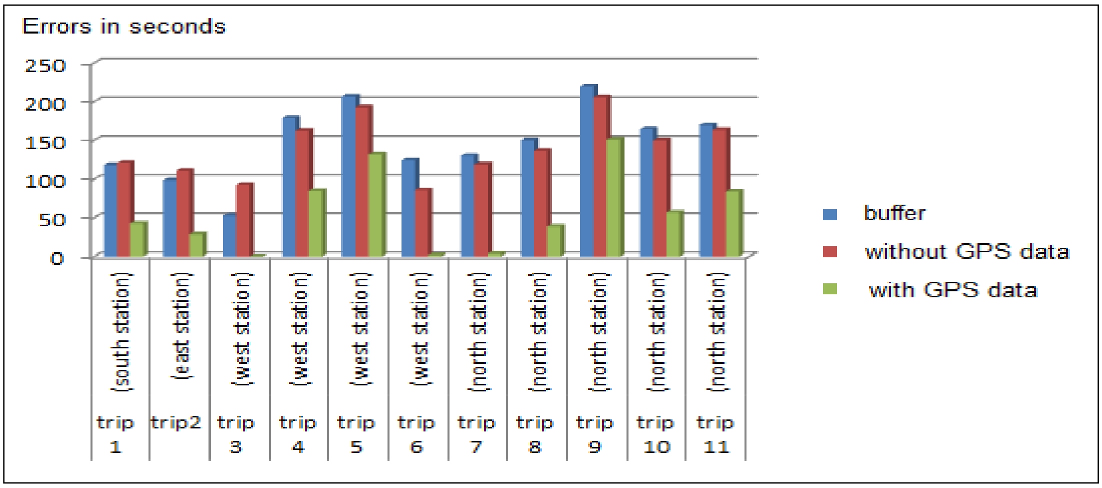
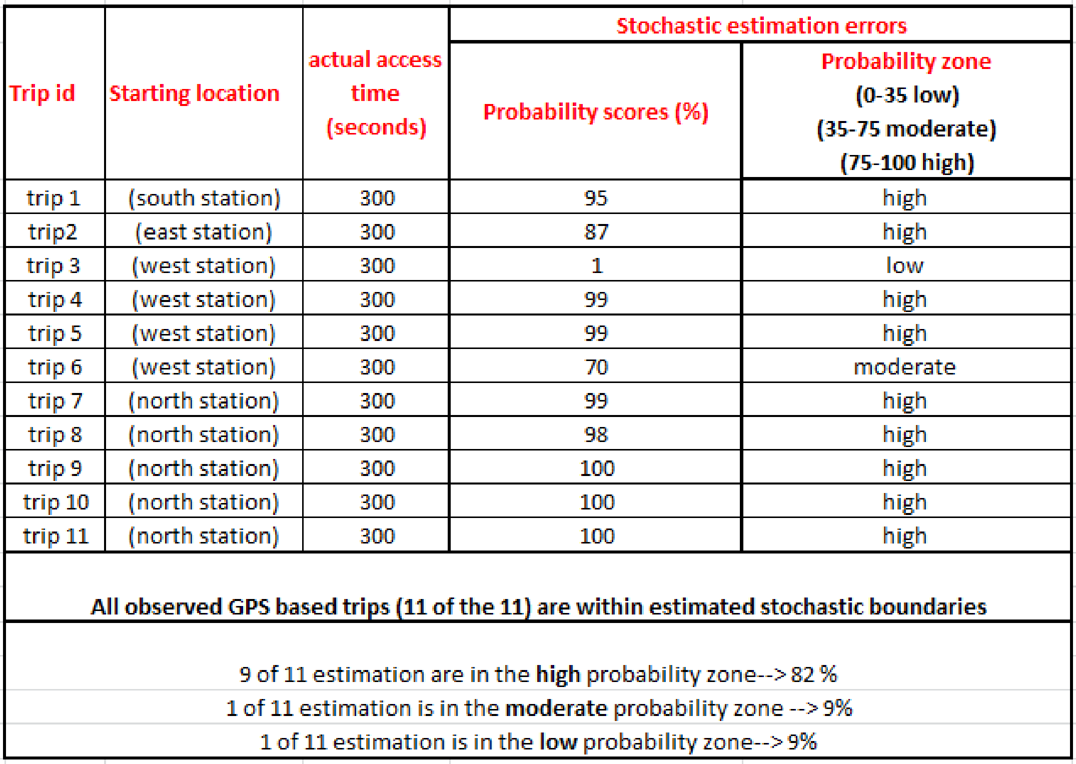


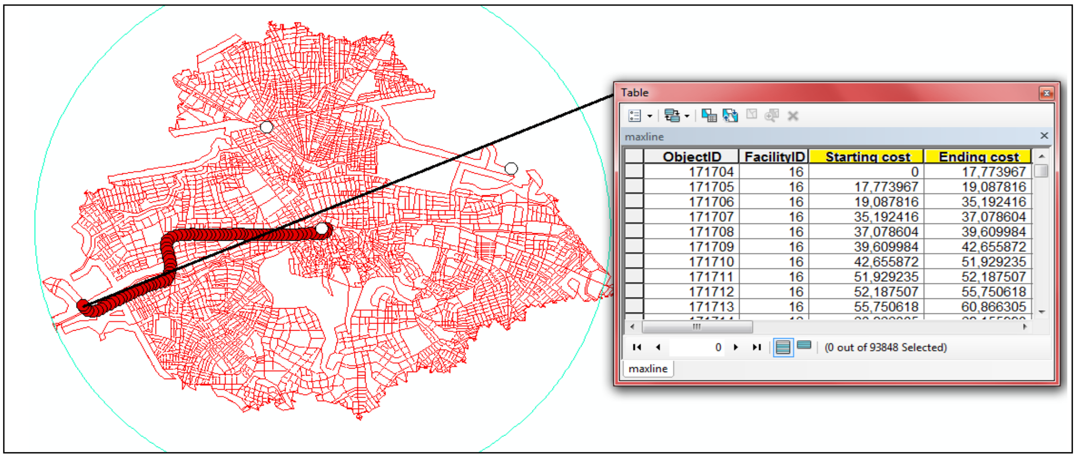
Figure 4.26. Deterministic model comparisons in seconds

Table 4.6. Stochastic model errors in terms of probability scores



| Trip id | Starting location | actual access time (seconds) | Stochastic estimation errors | |
|---|---|---|---|---|
| | | | Probability scores (%) | Probability zone<br>(0-35 low)<br>(35-75 moderate)<br>(75-100 high) |
| trip 1 | (south station) | 300 | 95 | high |
| trip2 | (east station) | 300 | 87 | high |
| trip 3 | (west station) | 300 | 1 | low |
| trip 4 | (west station) | 300 | 99 | high |
| trip 5 | (west station) | 300 | 99 | high |
| trip 6 | (west station) | 300 | 70 | moderate |
| trip 7 | (north station) | 300 | 99 | high |
| trip 8 | (north station) | 300 | 98 | high |
| trip 9 | (north station) | 300 | 100 | high |
| trip 10 | (north station) | 300 | 100 | high |
| trip 11 | (north station) | 300 | 100 | high |
| **All observed GPS based trips (11 of the 11) are within estimated stochastic boundaries** | | | | |
| 9 of 11 estimation are in the **high** probability zone--> 82 % | | | | |
| 1 of 11 estimation is in the **moderate** probability zone --> 9% | | | | |
| 1 of 11 estimation is in the **low** probability zone--> 9% | | | | |

In calculation of errors, the starting-ending cost calculation and overlay capabilities of ArcGIS network analyst software is used (Figure 4.27).



| ObjectID | FacilityID | Starting cost | Ending cost |
|---|---|---|---|
| 171704 | 16 | 0 | 17,773967 |
| 171705 | 16 | 17,773967 | 19,087816 |
| 171706 | 16 | 19,087816 | 35,192416 |
| 171707 | 16 | 35,192416 | 37,078604 |
| 171708 | 16 | 37,078604 | 39,609984 |
| 171709 | 16 | 39,609984 | 42,655872 |
| 171710 | 16 | 42,655872 | 51,929235 |
| 171711 | 16 | 51,929235 | 52,187507 |
| 171712 | 16 | 52,187507 | 55,750618 |
| 171713 | 16 | 55,750618 | 60,866305 |

Figure 4.27. The starting-ending cost calculation capabilities of ArcGIS network analyst

According to Table 4.4, GPS-based deterministic model, which is the most similar to the stochastic model, has the lowest error with 626 seconds total error and 75 RMSE. Without GPS-based model has the second degree with 1543 seconds total error and 145 RMSE. Buffer-based model has the third degree with 1615 seconds total error and 154 RMSE.

The results demonstrate that; although deterministic models based on Euclidian distance (buffer) or constant (fixed) average traveling speed are widely used in GIS-based accessibility modeling, they have great potential to over or underestimate actual catchment area boundaries because of their crisp catchment area boundary structure. Although, the five minutes traveling time boundary differences between the deterministic models and actual traveling conditions could reach up to 3-4 minutes in time, based on Table 4.5, it can be said that; integrating GPS-based floating car data into deterministic accessibility modeling process could directly help decreasing errors and increase accuracy and reliability.

According to Table 4.6, all of the actual ambulance trips (11 of the 11) are within the estimated stochastic boundaries. The 9 of the 11 ambulance trips (82%) are estimated in the high probability zone. 1 of the 11 ambulance trip (9%) is estimated in the moderate probability zone and 1 of the 11 ambulance trip (9%) is estimated in the low probability zone.

The comparison also demonstrates that, as the stochastic modeling allows handling all possible catchment area boundaries, instead of one average or maximum fixed catchment area boundary, the crisp catchment area boundaries in the deterministic model turn into more accurate and reliable probability based catchment area boundaries and provide better decision support for the decision makers by operating different levels of uncertainty in accessibility modeling.

## 4.7. The effect of catchment area boundaries on accessibility measures

It is known that, all kinds of accessibility measures, whether simple or sophisticated, are based on the total amount or ratio of demand and supply inside the catchment area boundaries. As deterministic catchment area boundaries based on fixed traveling costs can be significantly different from each other, and the decision makers have no idea about the accuracy and reliability of the deterministic catchment area boundaries, using deterministic models in accessibility modeling could create a vital shortage in terms of accuracy and reliability and can directly affect/mislead accessibility, location/allocation and service/catchment area related strategy development and decision making process.

At this point, the proposed stochastic methodology could create a significant improvement for the accessibility measures as they could consider all possible catchment area boundaries instead of one average fixed catchment area boundary, provide additional accuracy and reliability information, and handle different levels of uncertainty.

In order to exhibit the effect of catchment/service boundaries on accessibility measures, and demonstrate how accessibility measures are subject to change with different service/catchment area boundaries, the 2000-year polygon-based neighbourhood population of Eskisehir is obtained as an example dataset and used to represent the distribution of cumulative opportunities in the case study area (Figure 4.28).

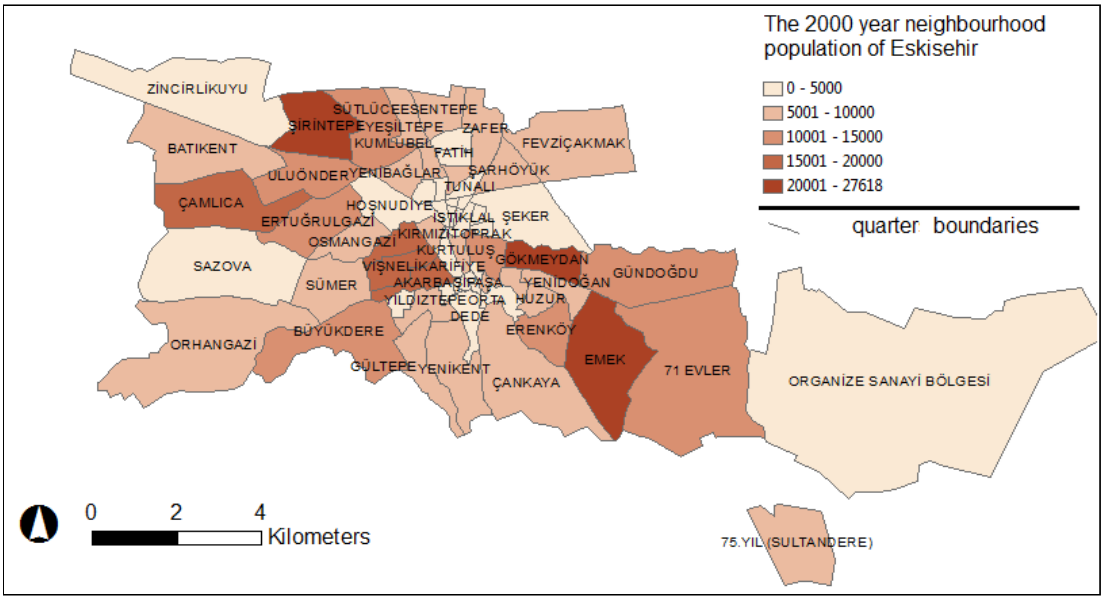


Figure 4.28. The 2000-year neighbourhood population of Eskisehir

As a point data set is required for performing an overlay analysis in GIS environment, the neighbourhood population data in polygon format is converted into a neighbourhood centroids data in point format as in Figure 4.29.

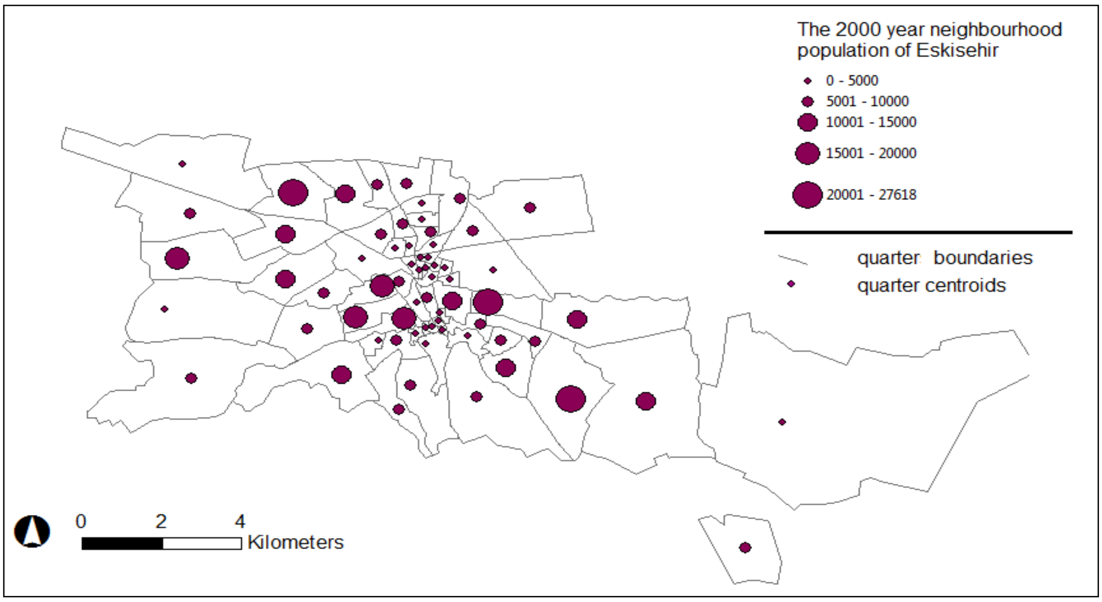


Figure 4.29. Convertion of polygon-based population data into point-based centroids

After polygon to centroid convertion process, the cumulative populations within five minutes medical emergency service/catchment area boundaries are calculated as a cumulative opportunity measure for three different deterministic and the proposed stochastic model (Figure 4.30). The result of the comparison is presented in Table 4.7.

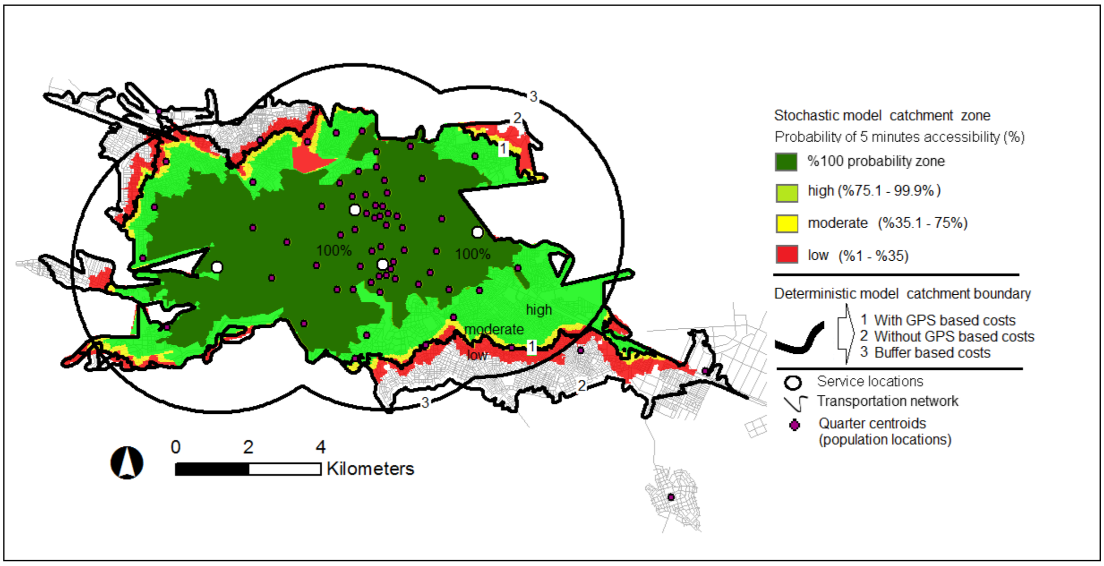
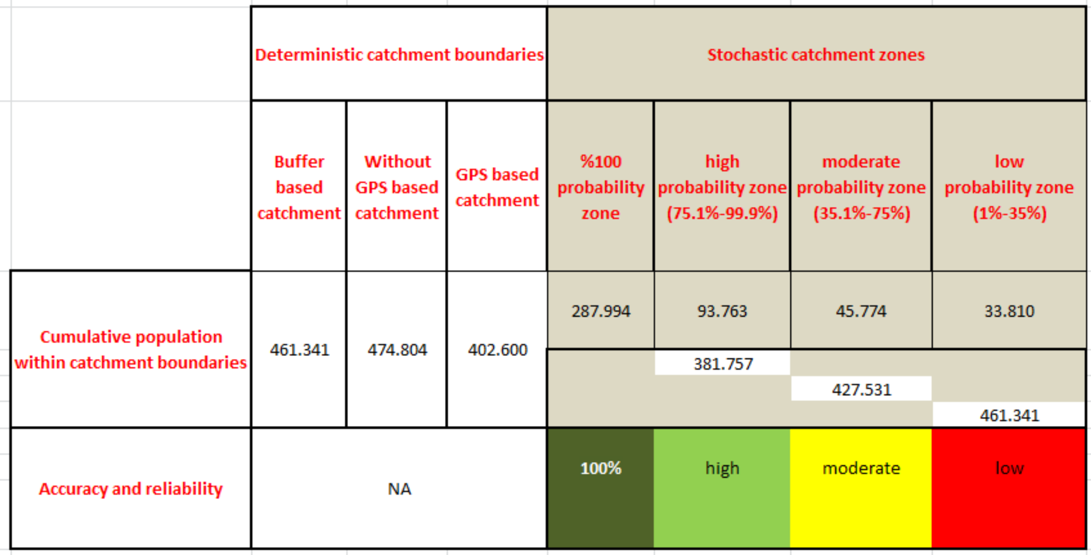


Figure 4.30. The cumulative populations within five minutes medical emergency service/catchment area boundaries

Table 4.7. The results of the comparison



|  | Deterministic catchment boundaries |  |  | Stochastic catchment zones |  |  |  |
|---|---|---|---|---|---|---|---|
|  | Buffer based catchment | Without GPS based catchment | GPS based catchment | %100 probability zone | high probability zone (75.1%-99.9%) | moderate probability zone (35.1%-75%) | low probability zone (1%-35%) |
| Cumulative population within catchment boundaries | 461.341 | 474.804 | 402.600 | 287.994 | 93.763 | 45.774 | 33.810 |
|  |  |  |  |  | 381.757 | 427.531 | 461.341 |
| Accuracy and reliability | NA |  |  | 100% | high | moderate | low |

According to Table 4.7, the cumulative population inside catchment area boundaries, based on deterministic and stochastic model, can be significantly different from each other.

For instance, when buffer-based catchment area boundary is considered, the cumulative population inside the catchment area boundary is 461,000 people and 62 of the 66 neighbourhoods are inside the five minutes buffer-based catchment area boundary except 71 Evler, 75.yıl / Sultandere, Organize Sanayi Bölgesi and Zincirlikuyu neighbourhoods.

When without GPS-based catchment area boundary is considered, the cumulative population inside the catchment area boundary is 474.804 people, which are nearly 14.000 people higher than the buffer-based model, and 65 of the 66 neighbourhoods are within the five minutes catchment area boundary except 75.yıl / Sultandere neighbourhoods.

When GPS-based catchment area boundary is considered, the cumulative population inside the catchment area boundary is 402.600 people, which is nearly 61.000 people higher than the buffer-based model and 74.000 people higher than the without GPS-based model, and 59 of the 66 of the neighbourhoods are inside the five minutes catchment area boundary except 71 Evler, Emek, Zincirlikuyu, 75.yıl / Sultandere, Şirintepe, Çankaya and Organize Sanayi Bölgesi neighbourhoods.

The comparison of cumulative opportunity measures based on deterministic catchment area boundaries clearly demonstrates that accessibility measures based on deterministic methodologies can be significantly different from each other. Moreover, decision makers do not have any idea about the accuracy and reliability of the results.

However, when stochastic catchment zones are considered, the cumulative populations inside catchment area boundaries are possible to evaluate according to the probability scores of accessibility. For instance, when the cumulative population inside high probability zone of five minutes accessibility is considered, in which probability values are between 75.1% and 99.9%, the cumulative population is 381.757 people, which is nearly 80,000 people higher than the buffer-based deterministic model, 93,000 people higher than without GPS-based deterministic model and 21.000 people higher than GPS-based deterministic model.

When the cumulative population inside moderate probability zone of five minutes accessibility is considered, in which the probability values are between 35.1% and 75%, the cumulative population is 427,531 people, which is nearly 34,000 people higher than buffer-based deterministic model, 47,000 people higher than without GPS-based deterministic model and 25000 people lower than GPS-based deterministic model.

When the cumulative population inside low probability zone of five minutes accessibility is considered, in which the probability values are between 0,1% and 35%, the cumulative population is 461,000, which is 13,000 people higher than without GPS-based deterministic model and 59,000 people lower than GPS-based deterministic model.

The stochastic catchment zones provide operating different levels of uncertainty in accessibility modeling such as high, moderate and low probability regions (green, yellow and red zones in Table 4.6). Large amounts of population, which are thought to be accessible according to deterministic models, are actually not accessible according to the high and moderate probability levels of the stochastic model. This multilevel approach improves accuracy and reliability in accessibility modeling and provides better decision support for the decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues.

# CHAPTER 5

# CONCLUSION

## 5.1. Conclusion

The main objective of the research, which is to develop a new stochastic methodology for GIS-based accessibility modeling process that could handle variations in traveling costs, consider all possible catchment area boundaries and improve accuracy and reliability in accessibility modeling, is successfully achieved.

Although deterministic models, which are generally based on Euclidian distance costs and fixed transportation network costs, are widely used in GIS-based accessibility modeling literature, the results of the research demonstrated that; deterministic approaches are not realistic in terms of calculation of traveling costs, especially when considered highly variable speeds in road segments and have uncertainty about the accuracy and reliability of the accessibility measures.

Deterministic models have great potential to over or underestimate actual catchment area boundaries because of their crisp structure. Accessibility measures calculated from deterministic models can be significantly different from each other and easily subject to change with different traveling cost considerations. For example urban areas, which are thought to be accessible according to deterministic models, can actually be not accessible or vice versa according to the stochastic model. In Eskişehir case, the estimated catchment area boundary differences can reach up to 4-5 km in length and 29-30 $km^2$ in area. Moreover, the decision maker have no idea about the accuracy and reliability of the boundaries in deterministic approaches as deterministic models could not handle variations in traveling costs.

Deterministic models could not provide information about the accuracy and reliability of the results, which is a vital shortage for the decision maker and could directly affect/mislead accessibility, location/allocation and service/catchment area related strategy development, and decision-making process.

The comparison of deterministic models demonstrated that, GPS-based and without GPS-based estimations can be considered as more realistic when compared to buffer-based estimations as they use transportation network based costs in the estimation process. Additionally, among the deterministic models, GPS-based estimation is the most accurate and reliable as the costs are directly determined by considering GPS-based real traffic conditions.

Compared to conventional deterministic models, the proposed stochastic methodology provides systematic treatment of uncertainties in the transportation costs and catchment area boundaries, significantly improve the accuracy and reliability of the accessibility measures and provide better decision support for the decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues.

By the help of the proposed methodology, the crisp catchment area boundaries in the deterministic model turns into probabilistic catchment area boundaries providing decision makers to operate different levels of uncertainty in modeling of accessibility. By this way, it is possible to differentiate regions that have low / moderate / high probability of having five minutes of emergency service accessibility. There is only a 75% probability that the place x have five minutes emergency service accessibility can only be predicted by the stochastic model which is not possible to obtain in the deterministic model.

Operating different levels of uncertainty in stochastic accessibility modeling, such as high, moderate and low probability regions, could directly improve determination of the priorities, strategy development and decision making capabilities of the decision makers.

When the results specific to case study area are considered, the main findings of the research can be gathered as follows;

- 75. Yıl (Sultandere) is the most critical neighbourhood with 0% probability of five minutes medical emergency service accessibility. Çankaya, Organize Sanayi Bölgesi, 71 Evler and Zincirlikuyu are the second-degree most critical neighbourhoods with low probability (1%-30.5%) of five minutes medical emergency service accessibility.

Batıkent, Emek, Gültepe, Gündoğdu, Orhan Gazi, Sazova, Şirintepe, Yenikent, Yeşiltepe and Zafer neighbourhoods are the third-degree critical neighbourhoods with moderate probability (30.6%-76.2%) of five minutes medical emergency service accessibility.

- Two new or re-located medical emergency service stations are seem to be needed in Eskişehir city, one of which is in the northwest part of Eskişehir (near Zincirlikuyu, Batıkent, Şirintepe and Ulu Önder neighbourhoods) and the other is in the southeast part of Eskişehir (75. Yıl (Sultandere), Organize Sanayi Bölgesi and 71 Evler neighbourhoods). However, taking a location/allocation decision about medical emergency service stations can be misleading for the decision makers by only considering critical neighbourhood information. In order to able to make a reliable decision about the location/allocation of medical emergency service stations, some additional information must also be considered by the decision makers such as;
    - excessive service regions (the urban regions that are accessible by more than one medical emergency service stations)
    - the amount of supply and demand (e.g. according to the 24046 numbered instructions of emergency health services, the served population must be at least 50.000 people for establishment of a new medical emergency service station etc.)
    - the balance of cost and benefit (e.g. the establishment of an additional medical emergency service station could be infeasible for the government or municipality)
    - the amount and distribution pattern of the medical emergency related incidents etc.
- The medical emergency service accessibility in Eskişehir city seems to be highly affected from the linear development of the transportation network. As most of the major transportation network (highways and boulewards) are in the east-west direction, the medical emergency service accessibility is observed higher in the east-west direction and lower in the north-south direction. Organizing emergency bands on

highways and boulevards, to speed up response could significantly improve the medical emergency service accessibility to the critical neighbourhoods in Eskişehir city.

## 5.2. Sustainability of the proposed methodology

As accessibility measures are concerned with equity and a better distribution of services in a region at national, regional, and local scales and widely accepted as key variables for many accessibility, related decision makers to test their supply/demand, location/allocation and service/catchment area related planning policies and strategies, the proposed stochastic accessibility modeling methodology can be used by many accessibility related establishments including local and metropolitan municipalities, ministries (e.g. health, education, agriculture, culture and tourism, energy and natural resources, environment and forest, transport and communication, industry and commerce, etc.), and public and private sector (e.g. real estate, industry, trade companies, shopping center administrations, etc.)

There are three basic data needed in the proposed stochastic accessibility modeling methodology, which are GIS-based transportation network, GIS-based service locations and GPS-based floating car data. GIS-based digital transportation network and GIS-based service locations can easily be obtained from transportation/planning department of municipalities. However, long term collected and large quantity of GPS-based floating car data can be considered as a critical concern from the sustainability of the proposed model point of view.

Collection of long term and large quantity of GPS-based floating car data is not currently a common task for many transportation departments of municipalities or ministries in Turkey. However, in a very close future, based on the general trend in the world, it can be expected that; GPS-based floating car data could easily be obtained from the transportation department of municipalities/ministries by the help of the GIS, GPS and GSM/GPRS based data communication technologies.

Once the GPS is integrated into the taxicabs, public transportation vehicles and/or volunteer private vehicles and started to communicate with the GIS-integrated data servers, located on the transportation department of municipalities, by the help of the GSM/GPRS based data communication technologies, it could be possible to obtain GPS data with any detail and complexity (including seasonal variations, rush hour variations, etc.) according to the aim, budget and specific detail needs of the study.

After GPS-based floating car data is obtained, an effective, accurate and reliable decision support is always possible for many accessibility related research by the help of the proposed stochastic model developed in ArcGIS model builder environment in order to support the accessibility modeling process.

## 5.3. Broader impacts

Although the proposed stochastic model is performed by using GPS-based floating car data because of its fast and accurate data obtaining and integrating possibilities with GIS, the other traffic data collection methods such as induction loops, optical systems etc. can also be integrated into the stochastic model and provide complementary traffic profile information, where it is not possible or partly possible to obtain satisfactory GPS-based floating car data. After the traffic speed data mean and standard deviation are integrated into a GIS-based digital transportation network, an effective decision support is possible for many accessibility, location/allocation and service/catchment area related studies.

As all kinds of accessibility measures, whether simple or sophisticated, are based on the total amount or ratio of demand and supply inside the catchment area boundaries, the proposed stochastic methodology could be implemented on modeling of any kind of accessibility measure, ranging from simple travel time measures to more sophisticated cumulative opportunity, gravity, two-step floating catchment area measures, etc and increase accuracy and reliability in accessibility modeling.

The proposed stochastic methodology can also easily be adapted to other kinds of accessibility related research such as central business district accessibility, job accessibility, recreational accessibility, trade center accessibility or educational accessibility etc. by considering other several transportation modes such as pedestrian, bicycle, car or public transport etc.

The detail and complexity of the obtained/collected traffic data and the considered traffic conditions in the model can also easily be arranged according to the aim, time, budget, data availability and specific detail needs of the study.

## 5.4. Limitations and future research

As there is time, data and budget limitations of the research, the proposed stochastic model is implemented by using short term collected and one-probe-vehicle-based GPS data without considering time-based variations such as rush hour, seasonal, weekend/weekday traffic conditions etc.

It is important to stress that; traffic can involve systematic time dependent patterns/variations (such as rush hour, seasonal, day/night, weekend/weekday etc). For instance, the rush-hour traffic condition can be very different from that at other times. Generalizing whole traffic data in a random process and hiding the potential systematic time dependent patterns/variations can be less convincing and informative for the decision makers who are supposed to deal with accessibility, location/allocation and service/catchment area related issues.

Differentiating the obtained/collected traffic data in terms of potential systematic time dependent patterns/variations (such as rush hour, seasonal, day/night, weekend/weekday etc.) and considering each of the condition separately in a stochastic manner could directly improve the accuracy and reliability of the proposed stochastic model and can be more convincing and informative for the decision makers who use the model. When long term collected and large quantity of probe-vehicle based GPS data is available, the proposed model is better to be implemented considering time dependent patterns/variations.

Another important issue is that; standard GIS softwares are general-purpose systems and could not always provide detailed support to the decision makers in accessibility measurement and evaluation. For example, modeling of accessibility in a GIS environment by using different accessibility modeling techniques (such as; isochrone, raster and zone-based techniques) and/or by using different types of accessibility measures (such as; cumulative opportunity, gravity, two-step floating catchment area measures etc.) are not directly applicable and requires huge effort, experience and time and necessitates many other types of softwares.

Consequently, the challenge about accessibility modeling process is a broader framework such as a GIS-based decision support system that could incorporate decision maker’s expert knowledge with specialized accessibility modeling capabilities and a user-friendly graphical interface. Development of such a system could provide more effective decision support for the decision makers in accessibility measurement and evaluation.

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# APPENDIX A

# PUBLICATIONS

The fundamental steps of the proposed methodology are published in Taylor & Francis, International Journal of Geographical Information Science, Volume 25, Issue 9, 2011, with DOI: 10.1080/13658816.2010.528419.

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# GIS-based stochastic modeling of physical accessibility using GPS-based floating car data and Monte Carlo simulation

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The term physical accessibility has long been used by geographers, economists, and urban planners and reflects the relative ease of access to/from several urban/rural services by considering the traveling costs. Numerous accessibility measures, ranging from simple to sophisticated, can be observed in the geographical information systems (GIS)-based accessibility modeling literature. However, these measures are generally calculated from a constant catchment boundary (a most likely or average catchment boundary) based on constant deterministic transportation costs. This is one of the fundamental shortcomings of the current GIS-based accessibility modeling and creates uncertainty about the accuracy and reliability of the accessibility measures, especially when highly variable speeds in road segments are considered. The development of a new stochastic approach by using global positioning system (GPS)-based floating car data and Monte Carlo simulation (MCS) technique could enable handling the variations in transportation costs in a probabilistic manner and help to consider all possible catchment boundaries, instead of one average catchment boundary, in accessibility modeling process. Therefore, this article proposes a stochastic methodology for GIS-based accessibility modeling by using GPS-based floating car data and MCS technique. The proposed methodology is illustrated with a case study on medical emergency service accessibility in Eskisehir, Turkey. Moreover, deterministic and stochastic accessibility models are compared to demonstrate the differences between the models. The proposed model could provide better decision support for the decision-makers who are supposed to deal with accessibility, location/allocation, and service/catchment area related issues.

**Keywords:** stochastic/probabilistic accessibility modeling; geographical information systems (GIS); global positioning systems (GPS); floating car data (probe vehicle data); Monte Carlo simulation

## 1. Introduction

The term physical accessibility has long been used by geographers, economists, and urban planners and basically reflects the relative ease of access to/from several urban/rural services by considering several traveling costs (Halden *et al.* 2000, Makri 2002, McGrail and Humphreys 2009). Physical accessibility measures are concerned with equity and a better distribution of people and activities in the territory and can be accepted as key variables for supporting supply/demand, location/allocation, and service/catchment area related planning

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policies and strategies at national, regional, and local levels (see Kuntay 1990, Juliao 1999, Halden *et al*. 2000, Radke and Mu 2000, Makri 2002).

As physical accessibility measures need organization of huge and complex spatial data sets, they often lend themselves to geographical information systems (GIS) for modeling. GIS have unique capabilities to handle spatially referenced information in a way which aids decision-making and provides a powerful interface for 'data storage, management, and manipulation capabilities for both spatial and attribute data,' 'core data analyses capabilities such as buffer, overlay, proximity, shortest path, raster cost-distance, etc.,' 'programming capabilities to handle current models or create new models,' and 'mapping and visualization capabilities to evaluate the results of the analyses' (Black *et al*. 2004).

Numerous accessibility measures, ranging from simple to sophisticated, can be found in the GIS-based accessibility modeling literature. The simple measures only consider proximity in terms of time and distance. The sophisticated ones consider both proximity and availability including the size of the supply and demand. Some of the most widely used accessibility measures in the literature are

- 'Travel time/distance measures, service/catchment areas' (travel time or distance to nearest supply/demand calculated from Euclidian/network-based costs),
- 'Cumulative opportunity measures' (consider the total amount of demand/supply inside the catchment areas),
- 'Population to provider ratio measures' (supply to demand ratios, calculated inside the catchment areas),
- 'Kernel density measures' (uses the Gaussian kernel approach to calculate the density value of each demand/supply),
- 'Gravity-based measures' (a combined indicator of accessibility and availability by considering the attractiveness of the supply/demand),
- 'Two-step floating catchment area (FCA) measures' (repeat the process of catchment area calculation twice for both supply and demand points), etc.

(For a detailed review, see Luo and Wang 2003, Guagliardo 2004, Bagheri *et al*. 2006, McGrail and Humphreys 2009.)

Whether simple or sophisticated, one of the fundamental shortcomings of the current GIS-based accessibility measures is that they are generally calculated from a constant catchment boundary (average or maximum catchment boundary) based on deterministic traveling costs such as 'Euclidian distance costs' or 'constant transportation network-based costs' (Figure 1). The Euclidian distance costs are simplified unconstrained costs and generally based on bird flight distances such as buffer polygons and Voronoi/Thiessen polygons. Constant transportation network-based costs are generally constrained by the road network and calculated from average or maximum speeds on classified road segments such as 120 km/h for highways, 50 km/h for main streets, and 30 km/h for local streets (see several examples, Ritsema van Eck and de Jong 1999, Makri 2002, Luo and Wang 2003, Bixby 2004, Lotfi and Koohsari 2009, McGrail and Humphreys 2009, Vahidnia *et al.* 2009).

Although the Euclidian distance costs and constant (fixed) average travel speed costs are widely used in GIS-based accessibility modeling literature, such deterministic costs are not realistic, especially when considering the highly variable speeds in road segments and having uncertainty about the accuracy and reliability of the accessibility measures in terms of deterministic catchment boundaries. Therefore, *the aim of this article* is to develop a stochastic methodology for GIS-based accessibility modeling process that could handle

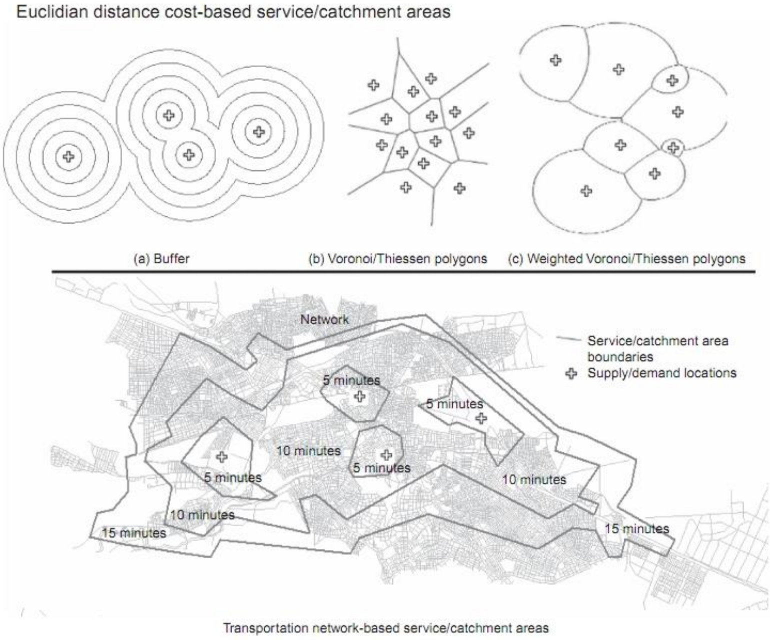

Figure 1. Constant catchment boundaries based on deterministic traveling costs.

variations in traveling costs and consider all possible catchment boundaries, instead of one average or maximum catchment boundary.

The main *benefit of the proposed stochastic methodology* is that the proposed stochastic model could provide additional information related to the accuracy and the reliability of the catchment boundaries in accessibility modeling, which means better decision support for the decision-makers who are supposed to deal with accessibility, location/allocation, and service/catchment area related issues. The proposed stochastic model allows systematic treatment of uncertainties related to the catchment boundaries and the crisp catchment boundaries in the deterministic model turn into probabilistic catchment boundaries providing decision-makers to operate different levels of uncertainty in modeling of accessibility.

The proposed stochastic methodology is illustrated with a case study on medical emergency service accessibility, in Eskisehir, Turkey, and the results of the deterministic and stochastic accessibility models are compared. The main focus of the case study is not to evaluate a specific accessibility condition in a detailed manner but to provide a methodological discussion and comparison between the deterministic and stochastic accessibility modeling process.

## 2. Proposed stochastic methodology

The proposed stochastic accessibility model consists of four major steps: (1) data collection, (2) generation of speed surface, (3) extraction of speed statistics, and (4) Monte Carlo simulation (MCS) (Figure 2).

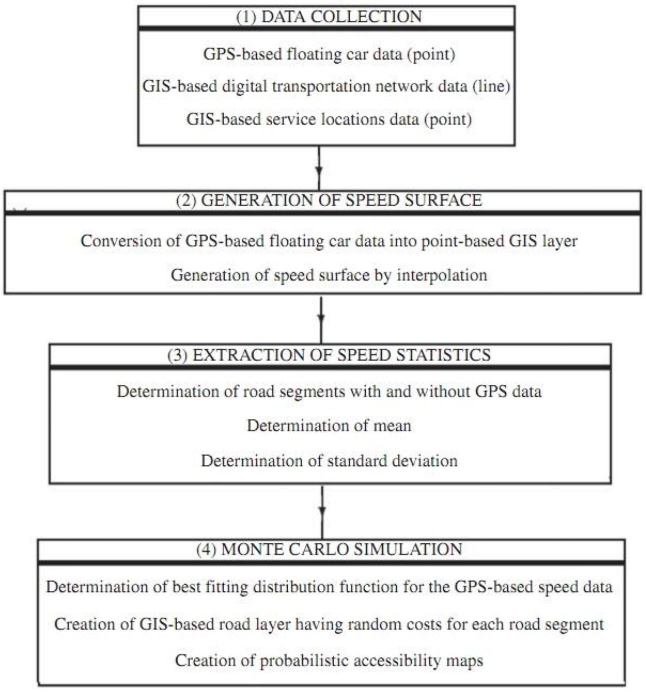

Figure 2. The flowchart of the methodology.

### *2.1. Data collection*

There are three basic data used in the model:

- Global positioning system (GPS)-based floating car data, which are in the form of point objects (includes location, speed, and time information with a predefined time or distance interval),
- GIS-based digital transportation network data, which are in the form of line objects (includes the road lengths/widths and location of road segments/junctions and basic classification of roads according to their types such as highways, boulevards, and main street),
- GIS-based service locations data, which are in the form of point objects (includes the location of the service locations).

The GPS-based floating car data are used in the model to understand the speed variations on road segments in terms of mean and standard deviation. Although there are several traffic data collection methods such as stationary traffic sensors (induction loops, optical systems), space and airborne techniques (observation from planes, satellites), and GPS-based floating car data (GPS probe vehicle data), the GPS-based floating car data method is one of the most suitable traffic data collection methods. The GPS-based floating car data method is based on recording position and speed from vehicle(s) moving in the traffic. The GPS-based floating car data, when integrated with GIS, can provide variations in transportation costs. Compared with conventional traffic data collection techniques, the GPS technique is able to provide speed information in a continuous manner with several detail and complexity depending on the track intervals (e.g., every 10 seconds or every 50 meters), day and time preferences (e.g., annual, seasonal, time-based variations: rush hours, normal hours, weekdays, or weekends, etc.), methodology (e.g., data collection from whole transportation network or only the main road segments), and accuracy (e.g., ranging from meters to centimeters based on the used GPS instrument). Moreover, such data collection is relatively fast and cheap as well as providing accurate position and speed with availability to be integrated in GIS (see several examples and detailed explanation in Zito *et al.* 1995, D'Este *et al.* 1999, Quiroga 2000, Taylor *et al.* 2000, Derekenaris *et al.* 2001, Mintsis *et al.* 2004, Daoqin *et al.* 2009).

The GPS-based floating car data can generally be obtained from the transportation department of municipalities. The detail and complexity of the GPS data and the considered traffic conditions in the model (seasonal variations, rush hour variations, etc.) are mostly based on the aim, the budget, and the detail needs of the study. For example, a research which requires accurate determination of catchment boundaries in rush hour time could need GPS data collected in long term (1 year or more) from the entire road segments for rush hour time with frequent track intervals or could support the GPS data with the data from other traffic data collection methods. However, GPS data collected only from the main street segments with large track intervals without considering a specific time or seasonal period could be enough for another research which does not require high accuracy and reliability in determination of catchment boundaries.

Although the proposed stochastic model is performed by using GPS-based floating car data, data from the other traffic data collection methods such as induction loops and optical systems can also be integrated into the stochastic model and provide complementary traffic profile information, where it is not possible or partly possible to obtain GPS-based floating car data.

The GIS-based digital transportation network and GIS-based service locations are the other basic data needed for modeling of accessibility and can be obtained from the related department of municipalities (e.g., department of transportation, planning).

### *2.2. Generation of speed surface*

Generation of a continuous speed surface is used in the model to extract the speed variation (mean and standard deviation statistics of each road segment) from the GPS-based floating car data and integrate with the transportation network. The GPS-based floating car data are generally obtained in log file format and need to be converted to a point data having attributes of $x$ and $y$ coordinates and speeds at that point. The continuous speed surface is created from the GPS-based floating car data by using the spatial interpolation and the buffer capabilities of GIS (Figure 3).

The inverse distance weighted (IDW) interpolation technique is used in the generation of speed surface. The aim of the interpolation is to fill the speed gaps between the known GPS points and create a continuous speed surface for the road segments that have GPS data. The IDW technique is mainly based on the assumption that the unknown cells are more alike to closer cells than those are farther. During the interpolation process, the road segments in the transportation network that have GPS data are buffered as their road widths and used as a boundary/mask object in the interpolation process. Using a boundary/mask object for the road segments that have no GPS data is a vital step in the interpolation process, as the speed surface is created for only the street segments that have GPS-based floating car data.

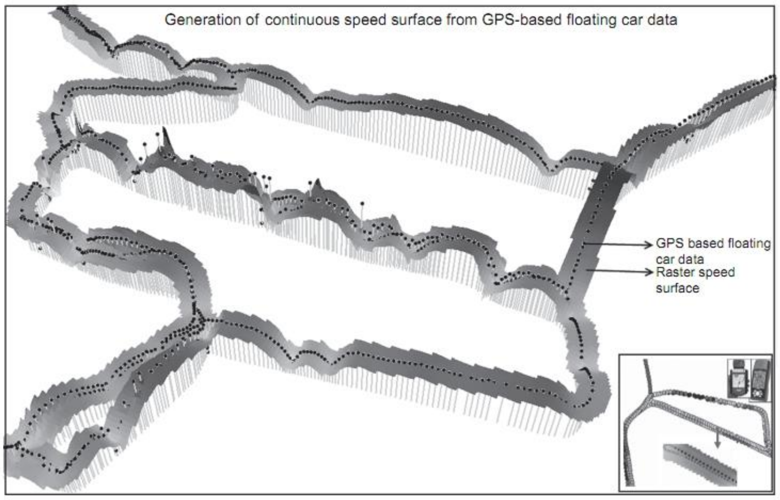

Figure 3. Production of raster speed surface from GPS data by using interpolation.

### 2.3. *Extraction of speed statistics*

Extraction of speed statistics step covers calculation of the mean and standard deviation statistics of speed data from the continuous speed surface for each of the road segments in the transportation network by using 'buffer,' 'join,' and 'zonal statistics' capabilities of GIS. For each of the road segments that have GPS data, the mean and standard deviation statistics of the speed are extracted from the speed surface. For each of the road segments that do not have GPS data, the average statistics of the GPS data according to their road types (highway, boulevard, street, etc.) are assigned.

### 2.4. *Monte Carlo simulation*

Stochastic transportation cost calculation approaches can be incorporated into the accessibility analyses by using simulation. The word 'simulation' refers to analysis of the effect of varying inputs on outputs of the modeled system. A simulation involves hundreds or thousands of evaluations of the model for all possible inputs and gives a probabilistic measure of the outputs. Monte Carlo simulation (MCS) method is a well-known method to create the random realizations of a deterministic model (Metropolis and Ulam 1949, Hoffman 1998). By integrating MCS method into GIS-based accessibility modeling process, possible random transportation cost values can be used instead of constant deterministic costs. Hence, the probability of an accessibility outcome can be obtained in terms of all possible catchment boundaries. By this way, accessibility can be expressed in terms of probability of having a certain accessibility measure instead of stating a deterministic accessibility measure. The probabilistic accessibility measures can take the uncertainties of transportation costs into account and enhance decision-making processes due to consideration of variability involved in the transportation cost parameters.

The aim of the MCS in the stochastic model is to produce random costs for the accessibility model. To perform MCS, there is a need to determine the best fitting probability density function for the speed data. Therefore, GPS-based floating car data are statistically analyzed by using Easy Fit distribution fitting software. Several probability density functions are tested and ranked by using the goodness of fit tests of Kolmogorov–Smirnov, Anderson–Darling, and chi-squared. The results showed that the best fitting probability density functions for the speed data are generalized extreme value, normal, Weitbull, Johnson, beta, log-logistic, and log-normal probability density functions. As the results are significantly close to the normal distribution, the normal distribution is used as input distribution function to produce random costs in MCS.

'The best fitting distribution function,' 'the extracted speed statistics of mean and standard deviation,' and 'the length of the road segments' are used as input variables in MATLAB programming environment and 'random time costs for each road segment' is produced as an output (Table 1).

As a final step, accessibility is modeled for each of the MCS-based random costs by using 'service area function' and 'model builder' capabilities of GIS. The service area function connects points of equal travel time away from a service or services on a transportation network and creates polygons which represent the catchment area boundaries. If a service is defined as the reference point, polygons can be drawn connecting points in all directions that can be reached within a threshold time or distance. Locations inside the polygons are determined as accessible and outside the polygons are determined as inaccessible. The proposed stochastic model calculates these catchment area boundaries for each of the MCS-based random costs for a defined time threshold (5 minutes in the case study) and converts each of the calculated boundary polygons to a binary raster map with a classification of '1' for accessible and '0' for inaccessible areas in model builder environment.

The sum of these binary raster maps are used to produce a final stochastic accessibility map, which has probability scores of accessibility in terms of all possible combination of catchment boundaries. For example, if 1000 simulations are performed to model accessibility of emergency services for a defined threshold of 5 minutes, the pixel value of '0' means there is 0% probability, 500 means there is 50% probability, and 1000 means there is 100% probability that a particular cell have 5 minutes emergency service accessibility.

## 3. Case study

The proposed methodology is implemented in a case study on medical emergency service accessibility in Eskisehir, which is one of the biggest cities of Turkey with an urban population of nearly 620,000 according to official population census of 2009 (Figure 4).

Medical emergency service accessibility reflects the level of medical emergency services to reach their catchment areas within critical time thresholds and helps to identify the critical areas that are out of service range. The '5 minutes' is determined as threshold cost in modeling of medical emergency service accessibility as it is a critical time for saving lives from medical emergency response point of view (Blackwell *et al.* 2009).

Although the case study is implemented on medical emergency service accessibility, the primary focus of the study is not to evaluate a specific accessibility condition in a detailed manner but to provide a discussion and comparison between the deterministic and stochastic accessibility modeling in terms of accuracy and reliability of the catchment areas.

Table 1. Random costs of time in 'seconds' for each road segment.

| Road segment_ID | Length | Speed_mean | Speed_standard deviation | Random cost 1 | Random cost 2 | Random cost 3 | Random cost 4 | Random cost 5 | Random cost 6 | Random cost 7 | Random cost 8 | Random cost 9 | Random cost 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 293.5085 | 30.3851 | 10.859 | 41.24893 | 86.15652 | 33.37727 | 31.6213 | 59.07801 | 24.46133 | 24.47207 | 35.34768 | 31.22049 | 32.82367 |
| 1 | 250.6248 | 30.3851 | 10.859 | 22.65811 | 22.34145 | 17.04076 | 27.0898 | 25.65112 | 44.74891 | 60.25391 | 32.63668 | 22.202 | 30.28908 |
| 2 | 548.5082 | 54.6999 | 12.4341 | 51.77828 | 42.6084 | 37.44436 | 34.26819 | 36.84247 | 25.94823 | 26.44899 | 31.68833 | 35.4606 | 44.34082 |
| 3 | 1066.366 | 30.3851 | 10.859 | 98.19699 | 121.924 | 64.11029 | 110.4679 | 237.7253 | 111.4147 | 107.5058 | 154.9892 | 116.8837 | 161.1202 |
| 4 | 770.5008 | 30.3851 | 10.859 | 86.12195 | 77.01633 | 114.1006 | 82.72607 | 162.9962 | 98.20128 | 102.6084 | 68.21524 | 113.1037 | 135.0271 |
| 5 | 501.0478 | 54.6999 | 12.4341 | 59.80753 | 37.75437 | 57.93948 | 33.90026 | 47.18519 | 39.03712 | 41.60176 | 34.27442 | 27.20955 | 24.4512 |
| 6 | 376.6355 | 30.3851 | 10.859 | 55.35959 | 37.42892 | 29.18221 | 53.44374 | 54.39972 | 31.04412 | 44.10367 | 35.3051 | 31.07877 | 40.35177 |
| 7 | 44.12451 | 54.6999 | 12.4341 | 4.043421 | 1.819565 | 3.665775 | 4.033911 | 2.724377 | 3.491626 | 3.935074 | 4.290394 | 3.364814 | 2.604899 |
| 8 | 76.21749 | 54.6999 | 12.4341 | 5.17032 | 5.032397 | 5.578908 | 5.263328 | 4.109721 | 4.546001 | 7.29297 | 4.735616 | 3.140697 | 5.092461 |
| 9 | 36.01389 | 30.3851 | 10.859 | 8.115594 | 6.980663 | 4.050842 | 8.990352 | 3.448721 | 3.788088 | 3.516604 | 4.16835 | 3.086868 | 5.606012 |
| 10 | 41.98066 | 30.3851 | 10.859 | 3.758177 | 6.258278 | 4.119564 | 4.666138 | 19.10712 | 4.867858 | 5.215647 | 4.291541 | 4.829063 | 19.81016 |

Figure 4. The case study area.

### 3.1. Data

The following data were collected to implement the proposed stochastic model:

- Digital transportation network data of Eskisehir Metropolitan area and their hierarchies
- The location of medical emergency service stations in Eskisehir
- GPS-based floating car data of Eskisehir Metropolitan area

The digital transportation network data and their road-type hierarchies (highways, boulevards, main streets, streets, and dead-end streets) and the location of medical emergency service stations were obtained from Eskisehir Metropolitan Municipality and integrated into a GIS database to use in GIS-based accessibility network analyses (Figure 5).

The GPS-based floating car data of Eskisehir Metropolitan area were not available in the transportation department of Eskisehir Metropolitan Municipality. Therefore, empirical GPS-based floating car data were collected in Eskisehir city by 1-week fieldwork on August 2007 with sample track intervals of 50 m (Figure 6). A Magellan Explorist 600

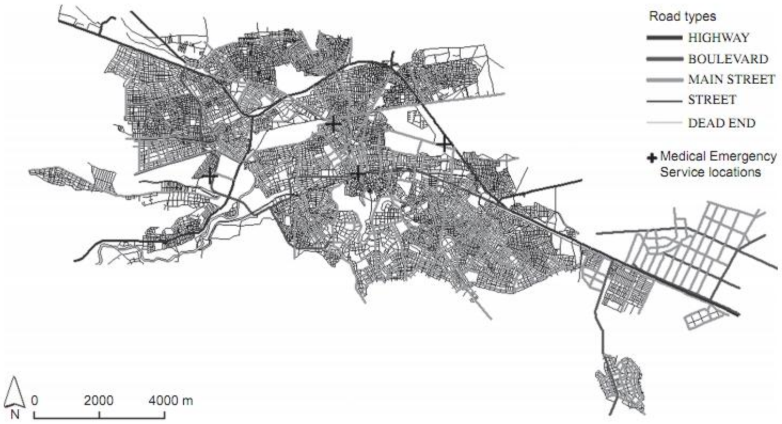

Figure 5. The data of digital transportation road network and the medical emergency service locations.

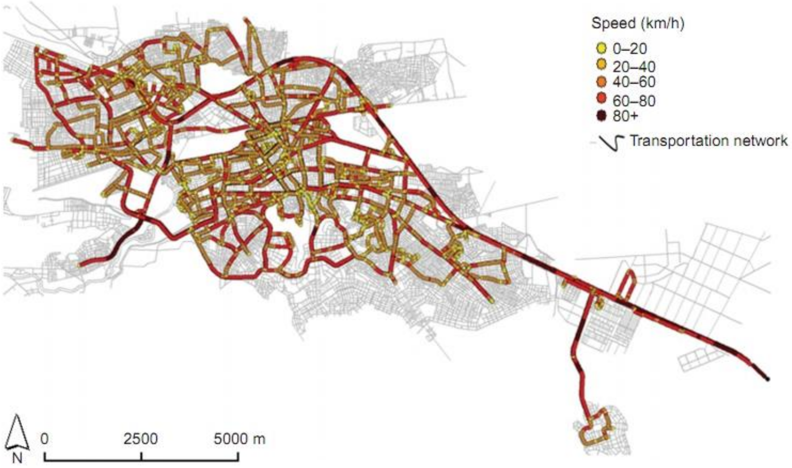

Figure 6. GPS-based floating car traffic data collected by 1 week field work in August 2007.

type GPS receiver was mounted on a probe vehicle and the vehicle location, speed, and time information was regularly recorded between 06:00 a.m. and 23:00 p.m. during 7 days for both peak and normal time periods including weekdays (Monday, Tuesday, Wednesday Thursday, Friday) and weekends (Saturday and Sunday). Most of the main road segments which are highways, boulevards, and main streets are covered in the GPS-based floating car data collection process (nearly 75% of the total). The inner streets and dead-end streets are partly covered (nearly 10% of the total) because of the time and budget limitations of the research. However, the inner streets and dead-end streets do not have a considerable effect on the accessibility results when compared with the highways, boulevards, and main streets. Although a short-term collected empirical GPS-based data are used in the proposed model because of the time, budget, and data availability limitations, it is always possible to implement the model with more detailed and complex traffic data according to aim, budget, and detail needs of the study.

### 3.2. *Implementation of the model*

Implementation of the model covers the generation of speed surface from GPS-based floating car data, extraction of speed statistics from the speed surface, and performing MCS. The whole process is implemented by using the ArcGIS Model Builder and MATLAB programming environments.

The average mean and standard deviation statistics extracted from the speed surface for different road types are 53.36 km/h mean speed for highways with 14.51 km/h standard deviation, 43.79 km/h mean speed for boulevards with 14.78 standard deviation, 34 km/h mean speed for main streets with 11.70 standard deviation, 30.96 km/h mean speed for streets with standard deviation 11.79, and 28.96 km/h mean speed for dead-end streets with standard deviation 11.87 (Figure 7).

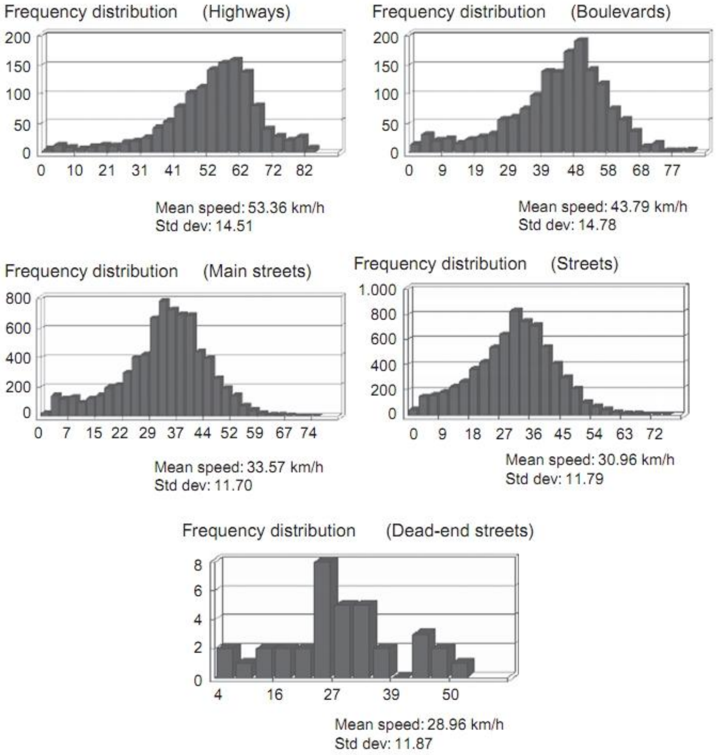

Figure 7. The observed mean and standard deviation statistics for different road types extracted from the GPS-based floating car data.

In the deterministic model, averages of the collected GPS speed data according to the transportation network hierarchies are used which are 53 km/h for highways, 44 km/h for boulevards, 34 km/h for main streets, 31 km/h for streets, and 29 km/h for dead-end streets.

In the stochastic model, random transportation costs produced from mean and standard deviation statistics by MCS are used. During the stochastic modeling process, for the road segments that have GPS data, the local mean and standard deviation statistics are used for generation of random transportation costs. For the road segments that do not have GPS data, the average mean and standard deviation statistics are used for generation of random transportation costs. As the main focus of the study is not to model a specific accessibility condition in a detailed manner, the traffic signal effect on accessibility is not taken into consideration in both of the deterministic and the stochastic model.

The generation of speed surface (with pixel size of 1 m) and extraction of speed statistics from the speed surface took nearly 10 minutes time in Pentium 3 GHz, 3.5 gigabyte RAM desktop computer (there are nearly 14,000 point features in the GPS-based floating car data and 26,000 line features in the transportation network). However, the process time can be less or more depending on the number of features in the GPS-based floating car and transportation network data, the pixel size of the produced speed surface, and accessibility map and the hardware configuration of the used computer.

### *3.3. Results*

The 5 minutes medical emergency service accessibility is modeled by both of the deterministic model (Figure 8) and the proposed stochastic model (Figure 9). In the stochastic model, a total number of 1000 MCS are performed within nearly 10 hours time and the simulations are cut off after 1000 simulations as a considerable change is not observed in the results (Figure 10).

When the results are overlaid in GIS environment, the differences between deterministic and stochastic models can be observed better. The 5 minutes catchment boundary in stochastic model is significantly different than the deterministic model. Although some of the urban areas in the northwest and south parts of the case study area are observed in the inaccessible zone in the deterministic model, actually they are found in the high-probability accessibility zone (in the 90–100% probability accessibility zone) according to the stochastic model (A zones in Figure 11). Similarly, the northeast and southwest parts of the case study area are observed in the accessible zone in the deterministic model, however they are in the very low probability accessibility zone (in the 20–30% probability accessibility zone) in the stochastic model (B zones in Figure 11). The observed catchment boundary differences can reach up to 2 km length, which can be considered as an important difference from accuracy and reliability point of view and can directly affect/mislead accessibility, location/allocation, and service/catchment area related strategy development and decision-making process.

Finally it can be said that the proposed stochastic model can be considered as more realistic when compared to deterministic model. The stochastic model could handle speed variations in road segments rather than using constant (fixed) deterministic speeds and consider all possible catchment boundaries by the help of the performed simulations. The benefit of the proposed stochastic model is that it could decrease uncertainty in accessibility modeling and increase accuracy and reliability by providing additional probability

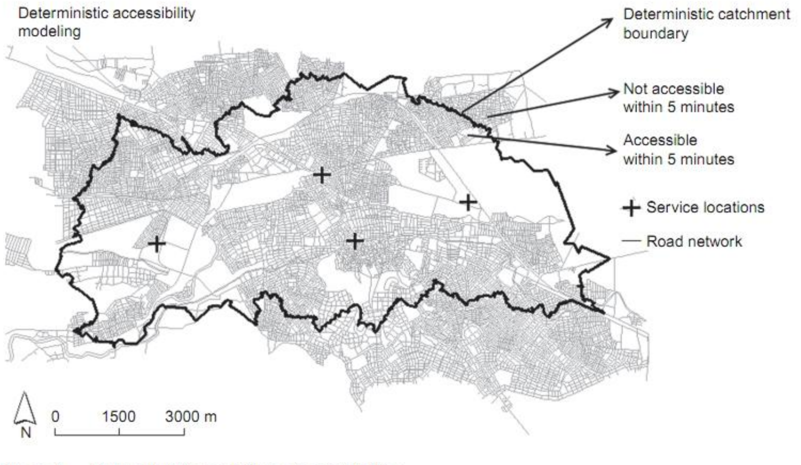

Figure 8. Deterministic modeling of accessibility.

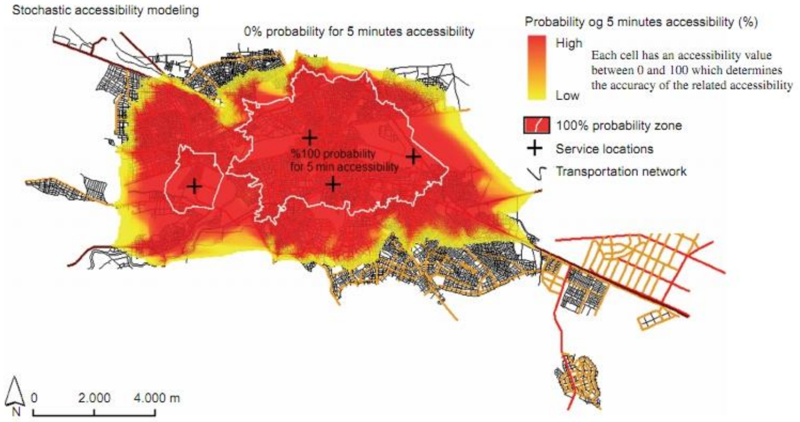

Figure 9. Stochastic modeling of accessibility.

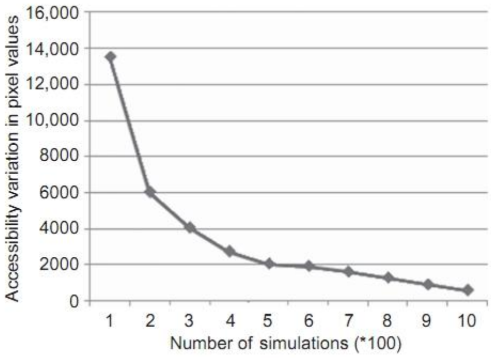

Figure 10. Variation in pixel values with number of simulations.

information related to the catchment boundaries. By this way, it is possible to differentiate regions that have low/moderate/high probability of having 5 minutes of emergency service accessibility or 'there is only a 75% certainty that the place '*x*' has 5 minutes emergency service accessibility' can be originally predicted, which is not possible to differentiate in the deterministic model.

## 4. Conclusions

Compared to previous deterministic methodologies which could only handle constant/fixed transportation costs (e.g., 50 km/h for all main streets) and constant/fixed catchment boundaries (a most likely or average catchment boundary), the proposed stochastic methodology could handle variations in transportation costs and could handle possible catchment

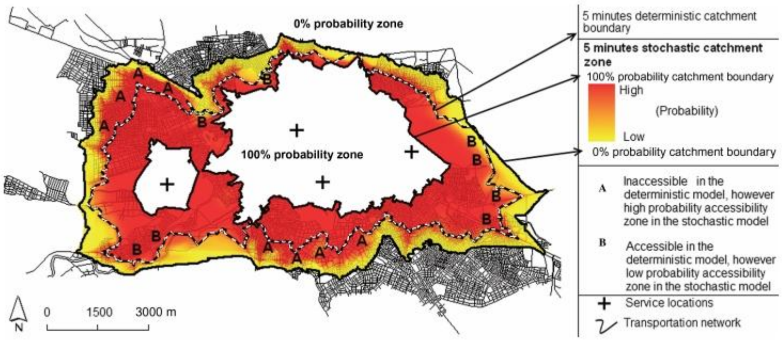

Figure 11. The overlay of stochastic and deterministic modeling of accessibility in GIS environment.

boundaries by the help of the MCS simulations. Hence, the proposed stochastic model provides systematic treatment of uncertainties in the transportation costs, creates a significant improvement on accuracy and reliability of accessibility measures in terms of catchment area boundaries, and provides better decision support for the decision-makers who are supposed to deal with accessibility, location/allocation, and service/catchment area related issues.

Although the proposed stochastic model is performed by using GPS-based floating car data because of its fast and accurate data obtaining and integrating possibilities with GIS, the other traffic data collection methods such as induction loops and optical systems can also be integrated into the stochastic model and provide complementary traffic profile information, where it is not possible or partly possible to obtain satisfactory GPS-based floating car data. After the traffic data, mean, and standard deviation statistics are integrated into a GIS-based digital transportation network, an effective decision support is possible for many accessibility, location/allocation, and service/catchment area related studies.

As the primary focus of this article is not to evaluate a specific accessibility condition in a detailed manner but to provide a methodological discussion and comparison between the deterministic and stochastic accessibility modeling process, the proposed model is implemented by using an empirical short-term collected GPS-based traffic data without considering potential systematic variations (such as rush hour, seasonal, weekend/weekday traffic condition). However, it is very important to stress that traffic can involve potential systematic patterns/variations (such as rush hour, seasonal, day/night, and weekend/weekday). For instance, the rush hour traffic condition can be very different from that at other times. Generalizing whole traffic data in a random process and hiding the potential systematic patterns can be less convincing and informative for the decision-makers who are supposed to deal with accessibility, location/allocation, and service/catchment area related issues. Differentiating the obtained/collected traffic data in terms of potential systematic patterns (such as rush hour, seasonal, day/night, and weekend/weekday) and considering each of the condition separately in a stochastic manner could directly improve the accuracy and reliability of the proposed stochastic model and can be more convincing and informative for the decision-makers who use the model. The detail and complexity of the obtained/collected traffic data and the considered traffic conditions (seasonal, rush hour variations, etc.) can also be rearranged by the decision-makers according to the aim, the budget, and the specific detail needs of their study.

The proposed stochastic methodology could be implemented on modeling of any kind of accessibility measure, ranging from simple travel time measures to more sophisticated cumulative opportunity, gravity, two-step FCA measures, etc. Moreover, the proposed stochastic methodology can easily be adapted to other kinds of accessibility-related studies such as central business district accessibility, job accessibility, recreational accessibility, trade center accessibility, or educational accessibility by considering other several transportation modes such as pedestrian, bicycle, car, or public transport, etc.

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## PROJECT EXPERIENCE

- "Afet Riskinin Kent Ölçeğinde Bütünleşik Bir Yaklaşımla Modellenmesi Ve Sürdürülebilir Kalkınma Politikalarına Entegrasyonu", OYP-YUUP, Acil Durum Kuruluşları Erişebilirliği Alt Bölümünün Oluşturulması,
  July 2004–June 2006, An Integrated Disaster Risk Assessment for Urban Areas for Sustainable Development: Earthquake Case (BAP-2005(R)08-11-02). *Director: Assoc. Prof. Dr. H. Sebnem Duzgun (Middle East Technical University)*
- "Güneydoğu Anadolu Projesinin Gelişimi Çerçevesinde Yerel Bölgesel Ulusal ve Uluslararası Etkileşimlerin Değerlendirilmesi" . ÖYP-YUUP, CBS Veritabanı Altlığının Oluşturulması
  July 2004–June 2006, Evaluation of local, regional, national and international interactions in the development of Southeast Anatolian Project (BAP-2005(R)08-11-02), *Director: Assoc. Dr. Sibel Kalaycıoğlu (Middle East Technical University)*
- "Fethiye-Göcek Özel Çevre Koruma Bölgesi Göcek Deniz Üstü Araçları Taşıma Kapasitesinin Belirlenmesi", CBS veritabanı altlığının oluşturulması, Çevre Ve Orman Bakanlığı, Özel Çevre Koruma Kurumu Projesi,
  April 2007–Dec. 2007, Determination of Carrying Capacity of Fethiye Göcek Special Environmental Protection Zone Marina (07-0303-2-0203)
  *Director: Assoc. Prof. Dr. Ahmet Cevdet Yalciner (Middle East Technical University)*
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  May 2010-May 2011, Lifelong Learning Strategy for Information Technologies (IT) in Çankırı and Sinop, *Director: Prof. Dr. H. Sebnem Duzgun (Middle East Technical University)*

## ACADEMICAL AWARDS

THIRD DEGREE, (2002), Revitalization Of Ineffective Using Of Urban Areas; Çeşme Dalyan case", Irkutsk Technical University, International Workshop Of International Baikal Winter University Of Urban Planning, Irkutsk, RUSSIA.

## OTHER EXPERIENCE

| **Year** | **Place** |
|---|---|
| July 2009 - May 2010 | University of California, BERKELEY, Institude of Urban and Regional Development, CA, USA, (Visiting Researcher) |