ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

AN OPEN SOURCE SPATIAL SOFTWARE FOR TRANSPORTATION INFRASTRUCTURE PERFORMANCE METRICS

M.Sc. THESIS

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Department of Geomatics Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ULAŞTIRMA ALTYAPI PERFORMANS ÖLÇÜTLERİ İÇİN MEKANSAL AÇIK KAYNAK KODLU YAZILIM

YÜKSEK LİSANS TEZİ

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Ömer AKIN, a M.Sc. student of ITU Graduate School of Science Engineering and Technology 501171639 successfully defended the thesis entitled “AN OPEN SOURCE SPATIAL SOFTWARE FOR TRANSPORTATION INFRASTRUCTURE PERFORMANCE METRICS”, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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ABBREVIATIONS

CLC	: Corine Land Cover
EEA	: European Environment Agency
GDP	: Gross Domestic Product
GIS	: Geographic Information Systems
GRASS	: Geographic Resources Analysis Support Systems
IEC	: International Electrotechnical Commission
IETT	: Istanbul Electricity, Tramway and Tunnel General Management
ISO	: International Organization for Standardization
MIT	: Massachusetts Institute of Technology
OD	: Origin Destination
OGC	: Open Geospatial Consortium
OSI	: Open Source Initiative
OSM	: OpenStreetMap
OSS	: Open Source Software
PCSS	: Proprietary Closed Source Software
QGIS	: Quantum Geographic Information Systems
SANET	: Spatial Analysis on a Network
SATRAP	: Spatial Analyst of Transportation Performance
STAM	: Space-Time Accessibility Measures
TUBITAK	: Scientific and Technological Research Council of Turkey
UNA	: Urban Network Analysis Toolbox
WGS	: World Geodetic System

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AN OPEN SOURCE SPATIAL SOFTWARE FOR TRANSPORTATION INFRASTRUCTURE PERFORMANCE METRICS

SUMMARY

Transportation is one of the most important components of a city's development. To detect and address the challenges coming from rapid urbanization of cities, performance of transportation infrastructure should be monitored and evaluated continuously. Monitoring/evaluating the performance of a transportation infrastructure quantitatively will assist policy makers to support their decision functions. In order to monitor/evaluate a transportation network's desired spatial aspects, several spatial performance metrics exist in the literature. From those, "connectivity" and "accessibility" metrics are the ones that enlighten the topological features of a transportation network and configuring its relation between land use/cover. Connectivity metrics provide the quantitative topological relationships of the network parts for performance monitoring of a desired transportation network. Accessibility metrics on the other hand, examine land use/cover attributes and comprehends its relation with transportation. Mentioned metrics necessitate a spatial analysis environment to obtain meaningful and illustrated results. Several Geographic Information Systems (GIS) based methodologies/tools/software were developed to answer the needs of spatial analysing environment, yet desired integrated model for analysing these metrics do not exist as a compact tool. Also existing tools are mostly working under commercial GIS software. At this point, open source thinking has very beneficial contributes in terms of being free, available and manipulatable. With the advantages of open source thinking, an integrated model that is not created before, can be produced and published for free. In order to analyse spatial data by calculating the mentioned metrics, an open-source software running under a commercial software was developed and tested to several decision makers and researchers in a project named "Geographic Information Systems Based Roadway Accessibility Analysis" that was supported by Scientific and Technological Research Council of Turkey (TUBITAK) Grant No: CAYDAG-115Y692. By the lights of the feedbacks given by decision makers and researchers for the developed tool, need of an open source software development has been understood in all aspects.

In this thesis, an integrated software named Spatial Analyst of Transportation Performance (SATRAP) that quantifies and illustrates connectivity and accessibility metrics was developed to evaluate the transportation networks in different spatial aspects with open source approach. The software is designed as an independent GIS software that can calculate transportation performance metrics with all-round open source approach. It has necessary functionalities with a user friendly interface for decision makers. In addition, the software expects minimum level of spatial data from user to perform the analyses. User can obtain, analyse and visualize open source data without handling any technical difficulties with SATRAP. To validate SATRAP,

seven different cities that are similar in terms of their metropolitan characteristics were selected as a case study to calculate performance metrics of them. Connectivity analyses for these cities were measured with degree, betweenness and closeness metrics. The results were visualized to identify critical points in the network. Accessibility analyses on the other hand, were computed with potential and daily accessibility metrics for cities. In this context, urban and destination classes of land use maps were used as origin and destination points for analyses. These points were then given to the software as input points to be used in the accessibility analysis and the results were visualized. All data used for applications and the method developed were open source.

Software successfully produced meaningful results and maps without an obligation to have road network data. Resulted connectivity maps clearly showed the topological distribution of cities. Distribution of network's spatial characteristics was observed similar as expected from majority of cities. As an exception, Istanbul showed a different pattern in closeness measure. It can be claimed that, unexpected spatial pattern of Istanbul mostly depends on its irregular urbanization process. Resulted accessibility values also indicated this irregularity. Conclusions based on the comparison helped to interpret the performance of transportation networks relatively. Then, performance of the developed software was tested by comparing it with a likewise tool using various quality aspects. Performance of SATRAP was found satisfactory and improvable. The biggest advantage of software that its independent implementation that provides various analyses for performance monitoring with a user friendly interface. Furthermore, another important advantage of the software is that the user can obtain a web map where the result of analysis can be interpreted instantly without the need for any GIS software. An open source approach to such analyses will allow the methods and results to become widespread and enable decision makers to build cities more liveable and sustainable accordingly.

ULAŞTIRMA ALTYAPI PERFORMANS ÖLÇÜTLERİ İÇİN MEKANSAL AÇIK KAYNAK KODLU YAZILIM

ÖZET

Ulaşım ağları, şehrin ekonomik, sosyo-kültürel yapısından ve nüfus dağılımından başlıca etkilenen ve şehrin yaşanılabilirliğini etkileyen başlıca unsurlarından biri olarak sayılmaktadır. Şehirlerin hızlı kentleşmesinden kaynaklanan problemleri tespit etmek için ulaşım altyapısının performansı sürekli izlenmeli ve nicel olarak değerlendirilmelidir. Bu değerlendirme, geleceğe yönelik yatırımlar konusunda karar mercilerine fayda sağlamakla kalmayıp, mevcut ulaşım sisteminin durumu ve ihtiyaçları hakkında da bilgi sağlar. Büyük şehirlerin ulaşım sorunları, şehir, şehir sakinleri, arazi ve ulaşım arasındaki mekansal bir korelasyon olarak ele alınabilir. Bu nedenle konum bilgisine dayalı çeşitli incelemeler, ulaşım ağlarını izlemek ve hesaplamak için gereklidir. Bir ulaşım ağınının performansını izlemek/hesaplamak adına literatürde hali hazırda tanımlanmış bazı farklı ölçütler mevcuttur. Bunlardan, "ağ bütünlüğü" ve "erişilebilirlik" ölçütleri, bir ulaştırma ağını topolojik açıdan değerlendirmek ve arazi kullanımı ile arasındaki ilişkiyi ortaya koymak için kullanılır. Ulaşım ağının performansı, kendisinin ve çevresinin topolojik özellikleri ile ilişkilendirilir. Bu özellikler ağ bütünlüğü ölçütünün odak noktalarıdır. Ağ bütünlüğü analizleri ulaşım ağının, ihtiyaçlara cevap verecek şekilde; sürdürülebilir ve gelişebilir olarak tasarlanması için karar vericilere mekansal bilgi sağlar. Öte yandan erişilebilirlik ölçütleri, ulaşım ağı ile arazi kullanımı arasındaki ilişkiye odaklanmaktadır. Ulaşım ile arazi kullanımı, bir şehrin sürekli etkileşim halinde olan iki temel öğesi olarak ele alındığında, bu ilişkinin sayısal değerler ile ortaya konulması karar vericiler için, büyük önem arz etmektedir. Coğrafi Bilgi Sistemleri (CBS), mekansal verinin elde edilmesi, işlenmesi ve görselleştirilmesi bakımından bahsedilen ölçütlerin hesaplanabilmesi adına işlevsel bir analiz ortamıdır. Ancak bahsedilen ölçütlerin hesaplanması adına çeşitli CBS tabanlı analiz yöntemleri/araçları geliştirilmiş olsa da, istenilen bütünleşik analiz ortamını sağlayan herhangi bir araç mevcut değildir. Ayrıca varolan araçlar, genellikle ticari yazılımlar altında çalışmaktadır. Bu noktada, açık kaynak felsefesi; bedava, ulaşılabilir ve değiştirilebilir olma açısından mekansal analizlerin yapılmasına katkı sağlayabilir. Açık kaynak kodu, bir yazılımın lisans alma mecburiyeti olmadan dağıtılmasını ve yazılımın kaynak kodlarınının herkes tarafından düzenlenebilmesini ifade eder. Açık kaynak kodlu bir yaklaşım ile, ihtiyaçlara yönelik ve bütünleşik bir analiz modeli üretilebilir, ve ücretsiz olarak yayınlanabilir. Bahsedilen ölçütleri hesaplayarak mekansal veriyi analiz etmek adına, ticari bir yazılım altında çalışan açık kaynak kodlu bir araç, Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (TÜBİTAK) tarafından desteklenen "Coğrafi Bilgi Sistemleri Tabanlı Karayolu Ulaşımı Erişilebilirlik Analizi" projesinde geliştirilmiş, karar vericiler ve araştırmacılar tarafından test edilmiştir. Karar vericilerden ve araştırmacılardan test sonucu alınan geri dönüşler ışığında, bağımsız ve kolay kullanılabilir bir açık kaynak kodlu yazılım geliştirmeye duyulan ihtiyaç tüm yönleriyle anlaşılmıştır.

Bu tez kapsamında, ağ bütünlüğü ve erişilebilirlik ölçütlerinin analizini yapan Spatial Analyst of Transportation Performance (SATRAP) isimli, açık kaynak kodlu bütünleşik bir yazılım geliştirilmiştir. Geliştirilen yazılımın, hiçbir ticari yazılıma bağlı olmadan çalışabilen ve karar vericiler için gerekli işlevsellikleri sağlayan, bütünleşik bir yazılım olması hedeflenmiştir. Bahsedilen analizlerin teknik zorlukları bakımından karar vericiler tarafından uygulanamama sorununa çözüm olarak yazılım, son kullanıcıya kolay kullanım sağlayacak bir arayüze sahiptir. Ayrıca yazılım, kullanıcıdan analizi yapabilmesi için minimum düzeyde veri beklemektedir. Kullanıcı, açık kaynak kodlu veriyi, geliştirilen yazılım ile, hiçbir teknik zorlukla karşılaşmadan elde edebilir, analiz edebilir ve sonuçları görselleştirebilir. Deneysel bir çalışma olarak, metropolitan olma özellikleri bakımından benzerlik gösteren, aralarında İstanbul'un da olduğu farklı kıtalarda bulunan yedi farklı şehir seçilmiştir. Seçilen şehirler, İstanbul, Paris, Rio de Janeiro, Londra, Madrid, Cape Town ve New York'dur. Seçilen şehirlerin kalabalık bölgeleri için, ağ bütünlüğü analizleri olan derece, arasındalık ve yakınlık ölçütleri, geliştirilen yazılım kullanılarak, herhangi bir mekansal veri kullanmadan hesaplanmıştır ve sonuçlar görselleştirilerek ağdaki kritik noktalar tespit edilmiştir. Erişilebilirlik analizi ise, potansiyel ve günlük erişilebilirlik ölçütleri ile ele alınmış ve arazi kullanımı ile ulaştırma ağı arasındaki ilişkiyi belirlemek için uygulanmıştır. Erişilebilirlik analizinde, arazi kullanımı haritalarından alınan kent sınıfı, analiz için başlangıç noktaları olarak, endüstriyel bölgeler sınıfı ise hedef noktaları olarak kullanılmıştır. Oluşturulan başlangıç/bitiş noktaları daha sonra yazılıma erişilebilirlik analizlerinde kullanılacak girdi noktalar olarak verilmiş ve analiz sonuçları görselleştirilmiştir. Uygulamalar için kullanılan tüm veriler ve geliştirilen yöntem, açık kaynaklıdır. Ağların performansları ve arazi kullanımı ile sahip oldukları ilişkiler SATRAP kullanılarak nicel olarak hesaplanmış ve sonuçlar görselleştirilip karşılaştırılmıştır.

Ağ bütünlüğü için hesaplanan ölçütler kullanılarak sonuç haritalar üretilmiş ve merkezlik değerleri yüksek/düşük bölgelerin tespiti sağlanabilmiştir. Aynı zamanda üretilen haritalar ile, ulaştırma ağının şehir içindeki dağılımı yorumlanmış ve darboğazlar veya önlem alınması gereken yerlerin tespit edilebileceği gözlemlenmiştir. Arasındalık ve derece merkezliği şehirler arasında benzer yönelim gösterirken, yakınlık ölçütü için İstanbul'da bir istisna söz konusudur. Şehrin bir bölgesinde yoğunlaşması beklenen yakınlık metriğinin İstanbul'da bu beklenen normal dağılıma sahip olmadığı gözlemlenmiş ve bu durum, şehrin düzensiz kentleşmesinin bir sonucu olarak yorumlanmıştır. Analizlerin sayısal sonuçları yorumlandığında şehirlerden Paris'in en düzenli ve gelişmiş ulaşım ağına sahip olduğu sonucuna varılmıştır. Erişilebilirlik analizinde ise, günlük bazda erişilebilirlik, şehirler arasında çok farklılık göstermemiştir. Potansiyel erişilebilirlikte İstanbul'un son sırada yer alması, ulaşım ağının diğer şehirlere kıyasla yetersiz olduğuna dair bir bulgudur. Ayrıca, bütün şehirlerde merkezlik ve erişilebilirlik ölçütleri arasında paralellik saptanmıştır. Bu bulgu, iki ölçüt arasında bir korelasyon olduğunun işaretidir. Karşılaştırmadan doğan sonuçlar, ulaştırma ağlarının performanslarını görece anlamaya yardımcı olmuştur. Geliştirilen yazılım ile minimum veri ve teknik detay ile son kullanıcının fayda sağlayabileceği bir tasarım hedeflenmiş ve yazılımın performansı, uluslararası standardlarca belirlenmiş kalite ölçütlerine göre değerlendirilmiştir. Bu değerlendirme için SATRAP, benzer fonksiyonlara sahip bir araç ile karşılaştırılmıştır. Değerlendirme sonucunda, yazılımın performansı yeterli ve geliştirilebilir olarak yorumlanmıştır. Programın en önemli özelliği, bütünleşik bir analiz aracı olarak tasarlanmasıdır.

Ayrıca kullanıcının, analiz sonuçlarını herhangi bir CBS yazılımına ihtiyaç duymadan yorumlayabileceği bir web harita elde edebiliyor olması, yazılımın önemli bir başka avantajıdır. Halihazır CBS yazılımlarında mevcut olmayan bu gibi analizlerin açık kaynak yaklaşımı ile ele alınması, yöntemlerin ve sonuçların yaygınlaşmasına ve karar vericilerin buna uygun şekilde daha yaşanılabilir ve sürdürülebilir şehirler inşa etmelerine olanak sağlayacaktır.

1. INTRODUCTION

Since great portion of population is categorized as resident in urban areas; urbanization process need to be ensured sustainable, reliable and manageable in a way that is suitable for modern city problems. These problems have undeniable effects on modern society, therefore, within the last decades preventing such problems is the main attention of planners and decision makers (Watson, 2009). Unplanned urbanization, rapidly growing population, the increase in vehicle ownership have revealed the problem of urban transportation in all major cities. Due to lack of coordination between urban policies, the mobility of people or goods are reduced and this causes social/economic damage to the cities. Since the need for mobility is expanding, transportation infrastructure must be monitored and designed in effective and sustainable ways. With better transportation planning/operation, the relationship between vehicles, road networks, and people will be enhanced and this will lead an efficient, convenient, safe and intelligent city (Xiong et al., 2012). As Gilbert and Tanguay (2000) states, a well-designed transportation network has three prominent features. First; providing a safe opportunity of accessing individuals, society or goods in a manner consisting with human and ecosystem health. Second; being affordable and operatable by offering choices among transportation modes with equity between people. Third; reusing and recycling its components and minimizing the land use. By the lights of this definition, interaction between land use and transportation, also performance of the transportation systems should be monitored for efficient and intelligent transportation investments. In mega cities, lack of ability to monitor/evaluate the performance of transportation leads an expensive and pollutant highway transportation to be developed rather than more efficient and sustainable transportation systems. In order to monitor/evaluate these components, several metrics are available in the literature. These metrics have spatial characteristics in terms of being topological and temporal in space, however, there is no existing integrated approach or a common methodology to implement these various metrics on a spatial information system. This problem leads to decision makers failing to monitor these performance criteria to improve their decisions. Geographic Information Science (GIS) have the ability and capacity to monitor/evaluate these metrics and visualize the results in a way associated with the space. Current commercial GIS software though, can not address the problem with an aggregate approach. Thus, end user has to deal with many technical complexities. Rapid development in information technologies could help to elevate this bottleneck. Open source thinking has the key role on that situation in terms of being free, independent and manageable in a manner of answering the necessities of policy makers. In spatial science, implementations of advanced spatial analytical methods have been an active area of study in last 20 years with the rise of open source software (Goodchild et al., 2000; Rey, 2009; Okabe, 2016).

1.1 Statement of the Problem

With the rapid urbanization of metropolitan cities, transportation infrastructure and activities should be benchmarked and continuously monitored. This procedure helps to understand the necessities coming from urbanization and provide better transportation policies and investments. There exist several performance indicators in the literature such as connectivity and accessibility where these metrics have spatial components and produce quantitative topological relationships. However, continuous monitoring process includes several technical and decision making complexities, where several interdisciplinary knowledge should be integrated for comprehensive decision making process. Since all aforementioned performance metrics have spatial structure, they should be examined in GIS environment to achieve best possible sustainable solutions for a city.

GIS have benefits as it provides rapid and cost-effective analysis environment in spatial context in order to measure performance metrics quantitatively and expose the interaction between city and transportation. Hence, there exists several applications/methodologies/tools that were developed in the scope of this problem. Several GIS tools/software such as Urban Network Analysis Toolbox that is developed by Massachusetts Institute of Technology (MIT) have the ability to measure several performance metrics such as connectivity (Sevtsuk and Mekonnen, 2012). However, current on-shelf GIS software are not providing adequate environment to calculate these metrics. The requested functionalities are not provided in terms of having adequate detail level, being independent on commercial software and avoiding technical complexities. This challenge was also observed in a recent study conducted under the project named "Geographic Information Systems (GIS) Based Roadway Accessibility Analysis" that was supported by Scientific and Technological Research Council of Turkey (TUBITAK) Grant No: CAYDAG-115Y692. Within that project, two separate open source network analysis tools that are embedded to commercial GIS software have been developed (Akın et al., 2019). The results were tested to decision makers from Istanbul Electricity, Tramway and Tunnel General Management (IETT) and researchers from Istanbul Technical University and Yildiz Technical University. According to feedbacks from decision makers and researchers, a tailor made, easy to use, independent open source software that can calculate these metrics is highly welcomed.

To overcome such issues briefly described above, the main opportunity is open source spatial thinking. With the benefits of open source, these technical complexities can be avoided while providing requested functionalities. These spatial analyse processes should be automated, where the policy makers necessitate more generic and easy to use tools to support their decision functions. Also, reachability to open source data and software make researchers or policy makers to use them efficiently to obtain decisive quantitative results on their field of study. Sharing information and generalising the results through an open source methodology/software are very decisive for the proper and sustainable management of the urbanization.

1.2 Thesis Objectives

In the scope of this study, the main objective is to create an open source software to calculate accessibility and connectivity metrics based upon spatial database. In order to test the designed open source software named Spatial Analyst of Transportation Performance (SATRAP), transportation performance metrics of selected districts of world-wide seven mega cities including Istanbul will be calculated and compared. This comparison will be performed with only using open source data as input. The developed software is aimed to be free, reliable and available for policy makers and researchers.

1.3 Thesis Outline

This thesis is organized as follows. First, the background of performance metrics and open source thinking are introduced in Chapter II. Then in Chapter III, used data and methodology to perform the analyses are introduced. In Chapter IV, functionalities of the developed software SATRAP are introduced. Then, illustrative transportation network analyses for several districts of seven mega cities including Istanbul are presented as a case study and performance of SATRAP is criticized. Finally, the subject is concluded in Chapter V.

2. LITERATURE REVIEW

Among all components of urban planning; transportation planning is a fundamental element of the city organization and citizens' daily life (Zhu and Liu, 2004). According to Chen et al. (2002), development of a city depends majorly upon an efficient, suitable, stable and reliable transportation system that provides safe, easy and efficient mobility of people and benefits. In other words; urban planning policy aims to compose a "compact city" that requires a nourishing transportation network (Kaufmann and Sager, 2006). For this reason, transportation planners are in search of evaluating the effectiveness of current transportation network and developing transportation projects (Bhat et al., 2000). Transportation planning consists of spatial components, thus it is a specified case that requires a spatial correlation with general planning (Hall and Tewdwr-Jones, 2010). This spatial correlation can be described quantitatively by spatial information analyse methods. Among these methods/metrics, connectivity and accessibility metrics focus on the performance of a transportation network and the relation between land use and transportation.

The term connectivity indicates a network's connectedness, robustness and distribution of these characteristics. The term is also used to identify how well network parts connect to each other. So, the parts that have weaker connections can be identified in order to build a more resilient transportation system by creating alternatives of those parts. Several studies have been conducted about connectivity by several different disciplines in order to monitor a network quantitatively (Freeman, 1978; Bonacich, 1987; Borgatti et al., 2006; Crucitti et al., 2006; Opsahl et al., 2010; Cheng et al., 2015). Studies has shown that these analyses can be useful evaluators for transportation phenomena. O'Kelly et al. (2006) states that each node has an impact on the resilience and vulnerability of the whole network. Demirel et al. (2015) states that better connectivity indicates a more sustainable and resilient transportation system. In their study, quantified connectivity metrics were calculated to monitor the status of the transportation network related to sea level rise. Also Sevtsuk (2010) used these metrics to explain the importance of nodes in terms of the flow of pedestrian traffic that passes through them.

Accessibility on the other hand is another metric to evaluate a transportation network in terms of finding out the relationship between the network and spatial structure of a city. Land cover/use and infrastructure policies are often evaluated with quantitative and easy to interpret accessibility metrics (Geurs and van Wee, 2004). Thus, it can be considered as a fundamental concept in urban and transportation management (Miller, 1999). From the different applications of the accessibility, four types of components can be identified as land use, transportation, temporal and individual components (Geurs and van Wee, 2004). Land use component shows the distribution of opportunities in space (Geurs and Ritsema van Eck, 2001) and its interaction between transportation have long been studied in the literature (Alonso, 1964; Boyce, 1980; Anas, 1982; Wegener and Fürst, 1999; Demirel, 2004; Lopez-Ruiz et al., 2013). This interaction can be described by accessibility metrics enabling to detect areas with low/high accessibility and also track changes in accessibility after a new transportation system is constructed in order to aid decision makers for consistent urban and transportation development. Besides, determining the needs in urban areas by these metrics will lead decision makers to develop unique solutions for different problems. With the advances of spatial information science, relation between the components of accessibility can be addressed with an integrated approach. In that context, land cover/use information and database generated by spatial observation methods can contribute to analyse transportation networks (Shoman and Demirel, 2018). These land cover/use observations can enlarge our understanding and increase our ability to examine complex patterns in transportation and by this way local decision makers can enhance their decisions with such tools and technologies (Fuller et al., 2002). To indicate the relationship, Han et al. (2009) used land use data resulted from remotely sensed images to investigate the relation between Shanghai's accessibility status with land use. Wang et al. (2016) also measured the accessibility and changes in its spatial characteristics in different land use areas of Beijing.

GIS based frameworks have become a necessity in terms of having spatial examination and evaluation (Bhat et al., 2000). GIS is described as the science and technology of measuring and representing geographic phenomena (Chrisman, 1999), thus it has the ability of measuring performance metrics and evaluating land use/cover relation with transportation within an integrated model. With the advances of spatial science, new, free and accessible tools are needed to make these analyses available to spatial analysts from different disciplines and decision makers (Sevtsuk and Mekonnen, 2012). However, aforementioned metrics can not be calculated by on-shelf GIS software. There exist several accessible GIS tools/methodologies providing various network analyses. Toolbox named Axwoman developed by Jiang et al. (1999); an open source software named Space-Time Accessibility Measures (STAM) developed by (Miller and Wu, 2000); a toolbox named Spatial Analysis on a Network (SANET) developed by Okabe et al. (2006) and several other custom built applications and methodologies (Miller and Wu, 2000; Jiang and Claramunt, 2002; Peponis et al., 2008; Okabe and Sugihara, 2012) have several network analyses functionalities. Sevtsuk and Mekonnen (2012) developed Urban Network Analysis Toolbox (UNA) that is an open-source toolbox built for ArcMap. The tool can compute five different types of centrality metrics of spatial networks. Researchers examined various subjects about networks and created tools that are qualified for analyses, however their methodologies never bring a compact, easy-to-use open source approach and their tools usually work dependent on a commercial software. Analysing performance measures that evaluate transportation network demands an integrated, easy-to-use model that allowing user to calculate these measures within a compact approach. For that, decision makers need such an open source application to support their decisions without handling any technical complexities.

2.1 Performance Metrics

Transportation network analyses fundamentally based on graph theory that first introduced by Euler in 1736 to solve his famous problem about Seven Bridges of Konigsberg (Biggs et al., 1986; Newman, 2003). Euler abstracted a spatial problem to a diagrammatic representation named graph that involves nodes and links as shown in Fig. 2.1

A graph is represented as a set of elements and the connections between them (Trudeau, 2013). The elements of the above definition are called nodes or vertices represented as A, B, C and D in Fig. 2.1 and the connections are called edges or links. From the

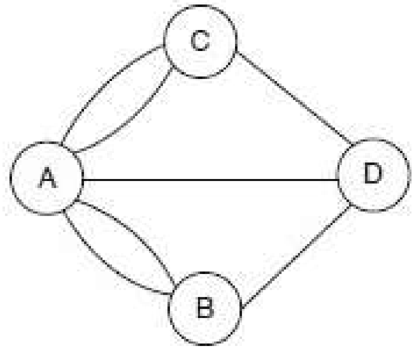

Figure 2.1 : A sample graph representation

view of transportation, representation of these elements are, intersections of streets for nodes and streets for links (Porta et al., 2006). Based on this theory, transportation networks can be characterized and described by spatial metrics and topological measures (Newman, 2010; Barthélemy, 2011). Connectivity and accessibility metrics have been quantified in the literature as being useful predictors for a number of spatial phenomena.

2.1.1 Connectivity

There are two topological type of connectivity measures that are node-based and link-based in the current literature in order to measure/monitor the performance of the parts belonging a transportation network. Centrality metrics that are node-based connectivity measures was first introduced by Bavelas (1948). The main idea behind the centrality is its usage for characterizing a node's importance. It is a fundamental element to define complex networks in terms of generating and sustaining ability to build a connection between two or more points (Reggiani et al., 2015). Several studies have been conducted in the literature to quantify how much a node is important (Bonacich, 1987; Borgatti et al., 2006; Crucitti et al., 2006; Opsahl et al., 2010; Cheng et al., 2015). Freeman (1978) observed the advantages of a node on a network from three different aspects that are its tie number between other nodes, controlling the flow between others and reachability to all other nodes. Based on these three aspects, he formalized these measures as degree, betweenness and closeness metrics respectively.

Among these metrics, degree centrality is the first and conceptually the simplest centrality definition. Introduced by Shaw (1954) on the idea that important nodes have the largest number of ties to other nodes. In a graph, degree of a node is the number of edges incident with the node (Freeman, 1978; Porta et al., 2006). The advantage of degree centrality is its simplicity due to only neighbours of a node must be known in order to be calculated (McPherson et al., 2001). Several studies have been conducted by using degree centrality to find crucial parts of different modes of transport such as air transport, public transport, maritime transport (Scheurer and Porta, 2006; Laxe et al., 2012; Wang et al., 2011)

Another metric betweenness, basically is the number of shortest paths that pass through a node (Borgatti, 2005). The idea behind it, if there is a message travelling from node A to D in a graph where the edges have same length as shown in Fig. 2.2, it is expected from message to pass through node B or C with the same probability of 50% (Freeman, 1978). So, points B and C have the same betweenness value. In complex graphs though, this condition is not held as the weights of the edges (can be thought as distances in transportation networks) or nodes are different. In that case, finding the betweenness value of a node gives a chance to understand the network by monitoring a node's volume of traffic that pass through it. (Borgatti, 1995). There exist several studies in the literature about using betweenness metric to monitor traffic in transportation networks (Puzis et al., 2013; Gao et al., 2013). Also, Barthelemy et al. (2013) used betweenness to identify the evolution of Paris's urban fabric in terms of the transportation.

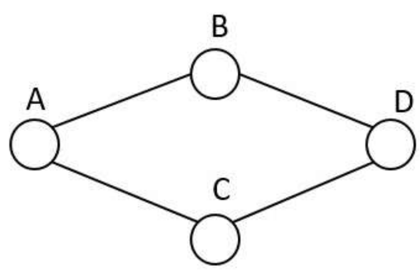

Figure 2.2 : Theory of betweenness

Whereas betweenness calculations are performed to find the traffic volumes passing by each node in a graph, closeness calculations are performed to indicate how close a node is to all surrounding nodes (Sevtsuk and Mekonnen, 2012). In a graph, closeness centrality of a node is calculated as the sum of the length of the shortest paths between the node and all other nodes in the graph (Freeman, 1979). Thus the more central a node is, the closer it is to all other nodes. The idea behind closeness is a node originating in the most geographically central position in a network can spread throughout the network in the shortest time (Bavelas, 1948). A more central point has the shortest distance with all other paths connected, means shorter times and lower costs from/to this point (Freeman, 1978). In view of transportation, higher closeness can be an indicator of economic value of the land, since land value of a location is commonly related with the savings in transportation cost (DiPasquale and Wheaton, 1996).

Measuring the connectivity of a transportation network indicates the topological aspects of individual parts by determining their characteristics as degree, betweenness and closeness. Those metrics were widely used in the literature to describe the connectivity of a network. Results show that, performance of a transportation network can be described with the information provided by these metrics. For that, this research focused on mentioned centrality metrics degree, betweenness and closeness.

2.1.2 Accessibility

Accessibility term is first appeared on Hansen (1959)'s study as ease of reaching desired destinations. The definition of accessibility has changed over time with new approaches such as selecting different transportation modes, interactions with land use and with different spatial constraints. In a more recent and detailed definition, accessibility is the ability to reach a desired destination easily from a specific location through a certain transportation mode (Morris et al., 1979; Geurs and van Wee, 2004; Tenkanen et al., 2016). In order to evaluate the components of accessibility, there are more than forty metrics divided into five main groups that are spatial separation, cumulative opportunity, gravity, utility and time-space measures (Chen et al., 2007). Among these measures, to emphasize the interaction between land use and transport components of accessibility, gravity measure has been used in the literature. The gravity metric includes zonal attractiveness as an attraction or opportunity factor and impedance between zones as a separation factor (Chen et al., 2007). Two indicators within the gravity measure, namely potential and daily accessibility metrics exist, in order to represent mentioned relationship quantitatively.

Stewart (1947) and Harris (1954) have developed and used the potential concept in location analysis to find distribution of population and market potentials respectively. Hansen (1959) was the first author who described the accessibility by using potential concept and defined accessibility as "the potential of opportunities for interaction". This metric can evaluate the land use and transport elements together, thus it can be thought as a social indicator for analysing the accessibility level for different socio-economic groups (Geurs and van Wee, 2004). Several studies in order to emphasize this interaction between land use and transport have been conducted (Gutiérrez, 2001; Krizek, 2010; Cao et al., 2013; Karou and Hull, 2014; Demirel et al., 2017).

Daily accessibility metric on the other hand is similar to potential accessibility but applies a different level of detail by putting an impedance value for calculations. With this metric only the interactions within a zone or a zone's neighboring areas are measured and monitored (Lutter et al., 1992). It can be thought as analysing the opportunities that an individual or property can reach within a day (Geurs, 2006). According to Iacono et al. (2008), 3 km walking is accepted for daily accessibility calculations as it is the maximum distance for people to walk to their destinations of work or shopping in a day.

Evaluating the accessibility metrics can reveal the spatial correlation between land use and transportation quantitatively. In order to capture this relation, gravity measures were widely implemented by researchers successfully. Potential and daily accessibility metrics within gravity measure were calculated in this research for evaluating the qualification of transportation against urban demands.

2.2 Open Source Spatial Software

The term software is divided into two groups that are proprietary closed source software (PCSS) and open source software (OSS) also known as commercial software and free software respectively. The main difference between the two categories that are ease of reaching to software's source codes and usage licenses (Friedrich, 2014). OSI (2019) defines the open source software as "software that can be freely used, changed and shared by anyone". The main advantage of OSS is that, its development process benefits from the expertise of worldwide researchers and/or developers compared to limited group of PCSS developers working for a single company (Kavanagh, 2004). Weber (2004) described three main aspects of an open source software as; free re-distribution of software without license and copyright, distribution of the source code with the software without any distribution cost and enabling the software to be changed by anyone. Open source approach is one of the effective ways to enhance the capacity of producing new solutions where existing approaches are limited or inadequate in the field of subject.

From a view of spatial thinking, open source software has first appeared in GIS applications in 1980s. In early 1990s, a society named Open Geospatial Consortium (OGC) had an important role on open source thinking to be a key element in spatial process and analyses (OGC, 2019). With the benefits of open source, GIS science had the chance to reveal its methods. An open source GIS software can provide freedom in the spatial analyses, automate complex processes and allow working without being dependent on any software. In spatial science, implementations of advanced spatial analytical methods have been an active area of study within last 20 years (Goodchild et al., 2000; Rey, 2009; Okabe, 2016). The computational parts of mentioned analyses can be implemented in software environment in principle, yet the implementation demands time, cost and advanced skills of computer programming. With the help of open source GIS tools and software, user-friendly tools can be developed for efficiently analysing spatial data (Okabe and Sugihara, 2012). Developed tools proved their quality so far in spatial sciences by the lights of empirical researches (Stefanakis and Prastacos, 2008; Steiniger and Bocher, 2009).

One of the early implementers of network analyses, Jiang et al. (1999), developed an extension named Axwoman that calculates geometric accessibility within desktop GIS software ArcView. Miller and Wu (2000) proposed a GIS software STAM that implements space-time accessibility measures. Jiang and Claramunt (2002) exhibited an application of space syntax principles based on the connectivity of the nodes. SANET is another software package that plugged in ArcMap provides thirteen different tools for network analysis (Okabe et al., 2006). Urban Network Analysis Toolbox is another tool that can perform several centrality measures including betweenness, closeness and straightness developed by Sevtsuk and Mekonnen (2012). Also, open source software Quantum GIS (QGIS) provides limited network analyses through its built-in functions, yet several tools named plug-ins can be developed by analysts and developers in QGIS environment. A plug-in named "pgRouting" allows user to perform centrality analyses within QGIS (Obe et al., 2017). Furthermore, Geographic Resources Analysis Support System (GRASS) is another open source GIS software having several functionalities about the subject of interest, but its functionalities are considerably difficult to implement in terms of having technical complexities (Neteler and Mitasova, 2013). Table 2.1 summarizes existing tools and software that focus on transportation performance by their dependencies and functionalities.

Table 2.1 : Existing tools and software

Tools	Dependencies	Functionalities
Axwoman (Jiang et al., 1999)	Works under ArcView	Geometric Accessibility
STAM (Miller and Wu, 2000)	Open Source	Space-Time Accessibility
SANET (Okabe et al., 2006)	Works under ArcMap	Network Analysis Tools
UNA (MIT, 2012)	Works under ArcMap	Several Connectivity Metrics
pgRouting (Obe et al., 2017)	QGIS plugin	Several Connectivity Metrics
GRASS (Neteler and Mitasova, 2013)	Open Source	Network Analysis Tools

Tools focus different aspects of a transportation network by using various spatial metrics. Despite the fact that developed tools have many benefits, an integrated model is not achieved within a compact and open source approach. This study mainly focused on developing such a software that implements three different connectivity and two different accessibility metrics with an easy-to-use interface.

In the scope of project named "Geographic Information Systems (GIS) Based Roadway Accessibility Analysis" that was supported by Scientific and Technological Research Council of Turkey (TUBITAK) Grant No: CAYDAG-115Y692, similar analyses were proposed and successfully accomplished with the developed open source tools (Akın et al., 2019). These tools were developed to work under a commercial software. Within the scope of the project, tools were individually tested to nine decision makers from Istanbul Electricity, Tramway and Tunnel General Management (IETT) and researchers from Istanbul Technical University and Yildiz Technical University. According to the conducted surveys after the tests, the development of an independent open source software that could calculate and visualize the transportation performance metrics is highly welcomed.

3. DATA AND METHODOLOGY

3.1 Study Area

In order to measure/compare the transportation performance metrics, developed methodology is applied on a case study where the subject of interests are mega cities. The cities are chosen among different continents according to their metropolitan characteristics. Istanbul, Paris, Rio de Janeiro, Madrid, London, Cape Town and New York were chosen as study areas in accordance with these criteria. Selected cities are shown in Fig. 3.1.

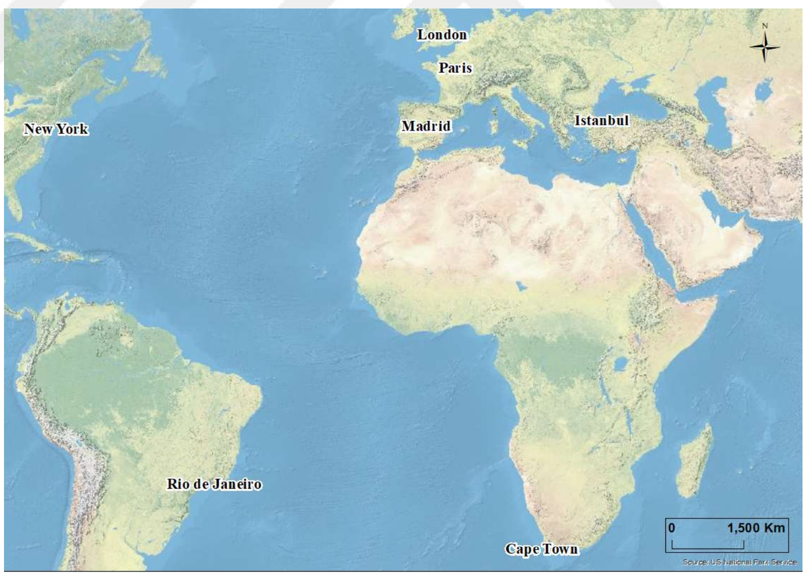

Figure 3.1 : Selected cities

From the selected cities, only the districts with high population density were selected in order to measure/monitor the complex structure of the networks (See Appendix A). Empty spaces within the district borders can be considered as airports, military zones, ports or forests. And as an exception, the whole city area of Cape Town was used in the analyses because of the population density information of districts were not available. The cities' selected districts' area and total road lengths are given in Table. 3.1.

Table 3.1 : Information of cities

Cities with Selected Districts	Area (km^2)	Total Road Length (km)
Istanbul	171.56	3.59
Paris	66.32	1.11
Rio de Janeiro	183.12	2.63
Madrid	109.30	1.91
London	189.25	2.84
Cape Town	2412.17	9.38
New York	531.88	8.11

3.2 Data

Qualified and available road network data is first needed to analyse transportation networks. Open-source network data in this phase is an advantage to take in terms of being free and available. Reaching open source data though can have some technical complexities depend on desired format and detail. In a qualified network data to perform analyses, topological connectivity should be built. In this thesis, expected topological structure and quality are provided by the underlying data source OpenStreetMap (OSM). OSM is a collaborative mapping project that provides free and editable map of the world (Corcoran et al., 2013). It is one of the greatest resources for acquiring spatial data and its data quality is generally quite high (Haklay, 2010).

In this study, two different transportation analyse metrics, connectivity and accessibility, were used. First analyse method connectivity, focus only on transportation performance, thus to utilize it only road network data is required. Instead of static network data, contemporary OSM network database is used for the calculations. This allows performing a more up-to-date analyses depending on the current road network data of interested regions in open source database. For the case studies, to access the road network data within the relevant district boundaries, vector type boundary data of interested districts should be obtained first. Vector type boundary data and the network data corresponding the study areas were derived from OSM database with using developed software's functionality.

On the other hand, accessibility analyses demand origin and destination points as well as road network data to utilize Origin-Destination matrices that store the impedance value between them. To expose the relationship between land use and transportation, origin and destination points were derived from the land information that is obtained from European Urban Atlas's open source Corine Land Cover (CLC) database for year 2018. CLC is a European programme, coordinated by the European Environment Agency (EEA), providing consistent information on land cover and land cover changes across Europe. The spatial resolution of land use data was 100 * 100 (Copernicus, 2019). Since, freely available land use data in the same standards as other cities were not found for Cape Town, Rio de Janeiro and New York, accessibility analyses could not be performed for these cities.

3.3 Methodology

To calculate connectivity and accessibility, algorithms of three centrality metrics named degree, closeness and betweenness; and two accessibility metrics named potential and daily accessibility were implemented to developed software named SATRAP. Followed workflow in this study is presented in the Fig. 3.2 and explained in detail in further subsections.

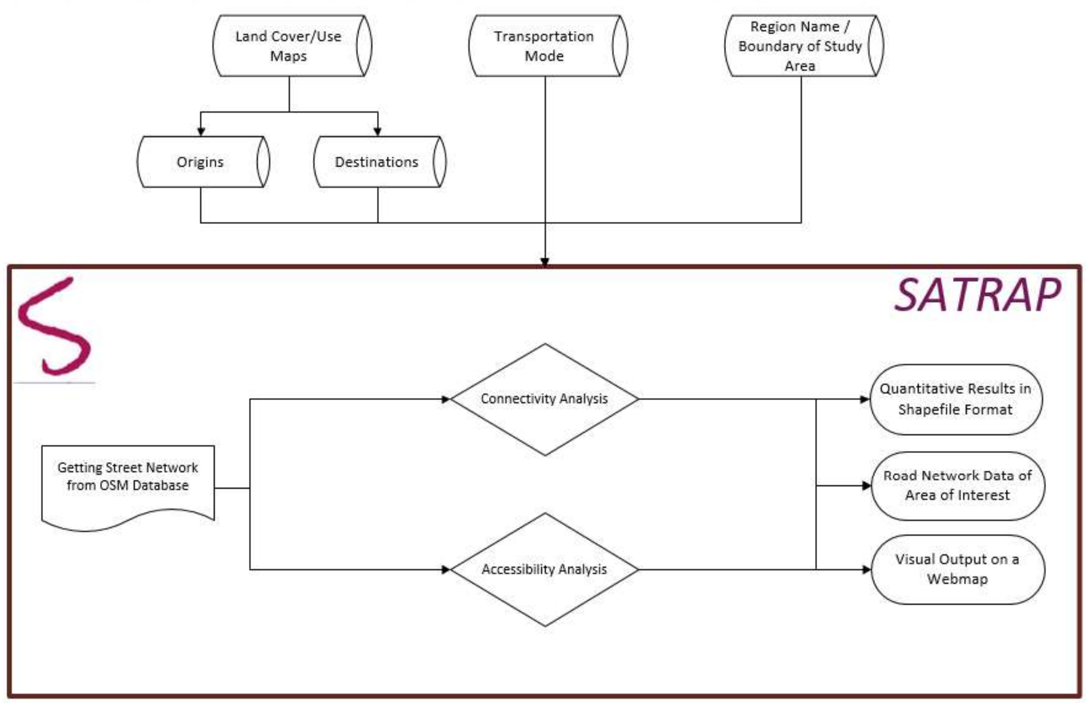

Figure 3.2 : Workflow of followed methodology

3.3.1 Performance metrics

Three metrics as connectivity measures were calculated namely; degree, closeness and betweenness. In a graph, Nieminen (1974) formalized degree centrality (C^D) of a node i as;

$$C_i^D = \frac{k_i}{n-1} \tag{3.1}$$

where the degree k_i of node i is defined in terms of the adjacency matrix as $k_i = \sum_{j \in N} a_{ij}$ in Eq. 3.1.

Analysis can be made in smaller scale to find critical components of transportation where actions have to be made. High degree values indicate how much connections the node have. In transportation, finding a degree of a node leads to find the bottleneck points to moderate the network.

Second metric used was betweenness. Betweenness centrality of a node i can be described as the sum of the fraction of all pairs of the shortest paths that pass through i and formulated as in Eq. 3.2;

$$C_B(i) = \sum_{s,t \in V} \frac{\sigma_{s,t}(v)}{\sigma_{s,t}} \tag{3.2}$$

where V is the set of nodes, $\sigma_{s,t}$ is the number of shortest (s,t) paths, and $\sigma_{s,t}(v)$ is the number of those paths passing through some node v other than s,t.

In betweenness calculations, traffic between nodes travels along only shortest paths. By taking all of the nodes in a network, the measure takes into account traffic moving from all origins to all targets. So this measure, for a transportation network, shows the critical points where traffic volume is considerably high. It is important to detect critical parts in order to reduce stress in this parts and produce alternatives to them.

Last, closeness metric was calculated. In Eq. 3.3, closeness centrality of a node i is described as;

$$C(i) = \frac{n-1}{\sum_{v=1}^{n-1} d(i,v)} \tag{3.3}$$

where $d(i,v)$ is the shortest path distance between node i and v, and n is the number of nodes that can reach i. Geometric bias towards the centroid of network is major finding of closeness (Sevtsuk, 2010). Thus, finding the spatial center allows decision makers to determine where the expectation of problems at its maximum.

The second performance metric, accessibility was calculated to indicate the relation between land use and transportation. Two metrics namely potential and daily accessibility, within accessibility context were chosen as they emphasize the aforementioned conditions about land use/transportation. The first metric used was potential accessibility. Equation of the potential accessibility could be described as;

$$A_p = \sum_j \frac{w_j}{c_{ij}} \tag{3.4}$$

In Eq. 3.4, W_j stands for economic or attraction potential such as GDP or population of destination zone, j, $c_i j$ indicates travel cost (distance/time) between origin zone i and destination zone j. For potential accessibility calculations, all of the destinations were considered equally attractive, so the attraction potential W_j was taken as 1.

Second metric used daily accessibility is based on the same structure with potential accessibility but applies a threshold value in the calculations. So, the equation only works under the certain circumstances. In Eq. 3.5, daily accessibility is formulated as;

$$A_d = \sum_j \frac{\delta_{ij} w_j}{\left(c_{ij}\right)^{\beta}} \tag{3.5}$$

where, β is the distance decay parameter, while δ_{ij} is a binary variable of daily accessibility, which equals 1 if $c_{ij} \leq c_{max}$ and 0 if other. Finally, c_{max} is the daily accessibility threshold limiting the neighboring area. In this thesis, Iacono et al. (2008)'s approach of maximum walking distance was used, thus the daily accessibility threshold was taken as 3 km and distance decay parameter was set equal to 1 by using a heuristic approach. Also for daily accessibility calculations, attraction potential was taken as 1 likewise in potential accessibility calculations.

Accessibility metrics utilize Origin-Destination (OD) matrices and these OD matrices store the travel impedance values between each origin and destination (Liu and Zhu, 2004). So, vector type origin and destination points that are derived from land use information and road network were used as inputs. "Continuous Urban" class of land cover/use data stands for origins, since it represents the places where people live and "Industrial and commercial units" class stands for destinations, since it represents where people usually go for their work or social habits. For further spatial analyses, raster land use/cover data should be transformed into vector data, where this is generally denoted by centroids of the achieved features. The resulted polygons differ in area and shape, thus, assigning a point to the geometric center of polygons for representing origins causes misleading results. The process of converting clustered polygons to representative points with same weights is significantly important. The methodology implemented in the Shoman and Demirel (2018) was followed in order to achieve high-resolution representative point creation from land use maps. Square meshes of 250 * 250 m cell area were used to grid the resulted polygons into regular squares. The class attribute of the dominant/major area was assigned to each cell, then each square was represented by a point in its centroid. The point creating process is shown in Fig. 3.3.

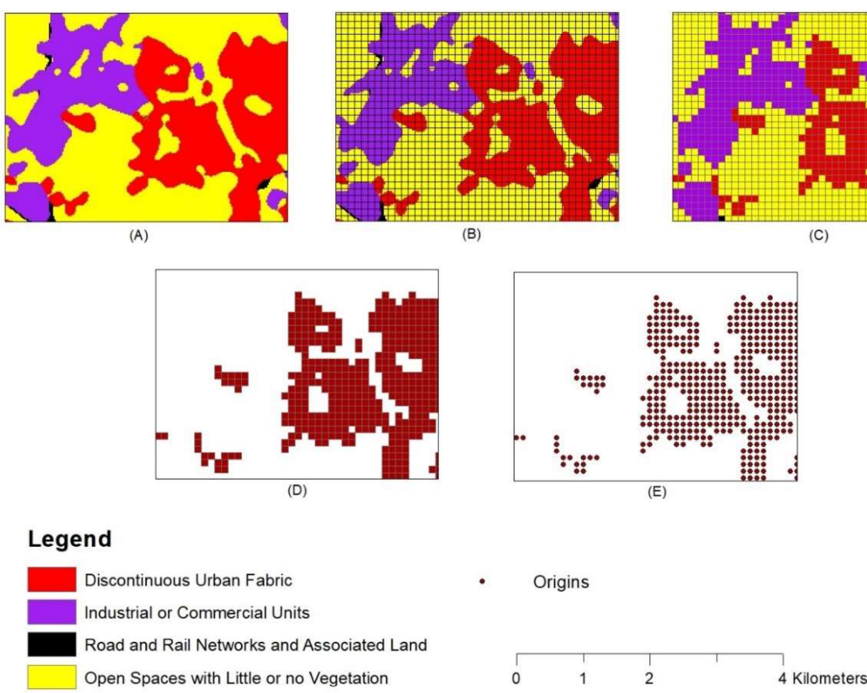

Figure 3.3 : Point data obtaining process

By using this methodology, changes in accessibility related to differences/changes in land use resulted from urban development and new transportation infrastructures can be determined.

3.3.2 Developed open source spatial software

To implement the methodology, an open source, stand-alone spatial analyse software named Spatial Analyst of Transportation Performance (SATRAP) have been developed and tested. SATRAP is designed to provide a user friendly interface that allows to automatize mentioned calculations without any complexities. All code parts are written in open source programming language Python version 3.6. First step of developing is compiling the algorithms needed for calculating the metrics and second step is designing an understandable, easy-to-use interface for convenience of end user. There is a wide range of different libraries for different spatial analysis purposes in Python and several ones that perform geospatial operations and calculations were used for implementing the algorithms. Used libraries and their roles were given in Table 3.2.

Table 3.2 : Used python libraries and their usage

Python Libraries	Usage
geopandas	Manipulating geospatial data and basic geoprocessing
osmnx	Obtaining OSM data
networkx	Establishing network topology
folium	Creating web map
pandas	Data manipulating
shapely	Basic geographic representations
tkinter	Creating interface

Developed software SATRAP's performance is also criticized. To test the performance of SATRAP, several quality attributes defined by International Organization for Standardization's norm ISO/IEC 9126 that are shown in Table 3.3 were used.

Table 3.3 : Quality attributes

Quality Attributes	Indicators
Usability	Understandability, Learnability, Operability
Maintainabiliy	Analysability, Stability, Testability
Portability	Adaptability, Installability
Efficiency	Time, Resources

Usability and maintainability could not be tested due to lack of enough users to test the software and conduct surveys. Hence, within the scope of this study only portability and efficiency were tested. To test the mentioned attributes, Urban Network

Analysis Toolbox that is created by MIT to analyse similar performance metrics was used to compare the software's functionalities (Sevtsuk and Mekonnen, 2012). For all functionalities, performance of SATRAP is tried to be understood in terms of sub-indicators adaptability and installability; also time and resources.

4. RESULTS AND DISCUSSIONS

4.1 Spatial Analyst of Transportation Performance (SATRAP)

To achieve mentioned compact and open source software, SATRAP is developed with its functionalities. As a case study, connectivity and accessibility metrics were calculated as performance evaluators of transportation infrastructure for seven cities' selected districts. All of the calculations were performed with user friendly interface. All of the functionalities and interfaces are described in further subsections in detail.

4.1.1 Main interface

Main interface shown in Fig. 4.1 consists two main sections that are Centrality Analysis and Accessibility Analysis and one extra section named Get Study Area including Help sections within all the sections. User can find specific instructions for every step from Help section.

Figure 4.1 : Main interface of SATRAP

Get study area aims to address the challenges in GIS where the major problem is lack of qualified, easy to reach data. From this section of SATRAP, needed boundary data of study area in shapefile format can be obtained and stored just by writing area's name as an input to "Region Name" entry box. The data will be downloaded and stored if it is available on OSM's database. Although OSM data is available for anyone, reaching this data in the desired level of detail can be challenging for the end user. By this way, end user will be avoided from constraints of acquiring necessary data. User also can use the output of this feature as the input of centrality analysis. The interface of this section is presented in Fig. 4.2.

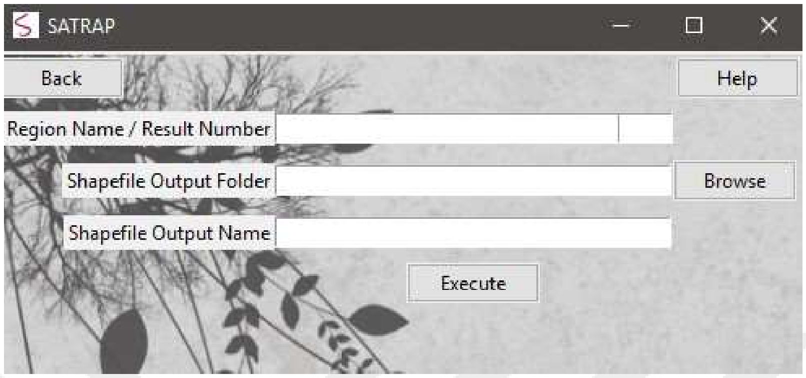

Figure 4.2 : Get study area functionality

One important consideration that should be taken into account is availability of the data in OpenStreetMap database and its result number if it is available. In order to ensure the data's availability, user should search the place's name on the search engine of OSM first on https://nominatim.openstreetmap.org/ website. Search results' data type can be vary depending on the search itself. From this varied results, polygon data must be exported. For this reason, an entry box named "Result Number" is designed to indicate the needed result's ordering number. If the first result is a polygon type data, the "Result Number" entry is not required still software will run when the result number is entered as "1". If polygon data is not the first result, user should fill the ordering number of the polygon result into "Result Number" entry box. From the remaining entry box, "Shapefile Output Folder" is the folder that the downloaded data is stored. User should define the output path via "Browse" button and the name of the file via "Shapefile Output Name" entry box.

4.1.2 Centrality analysis

Centrality Analysis section was developed to measure centrality of the transportation network of the area user desire. Workflow of this functionality is illustrated in Fig. 4.3 and the interface of this section is shown in Fig. 4.4. Degree, closeness and betweenness metrics can be selected and calculated from the select box "Analysis Method".

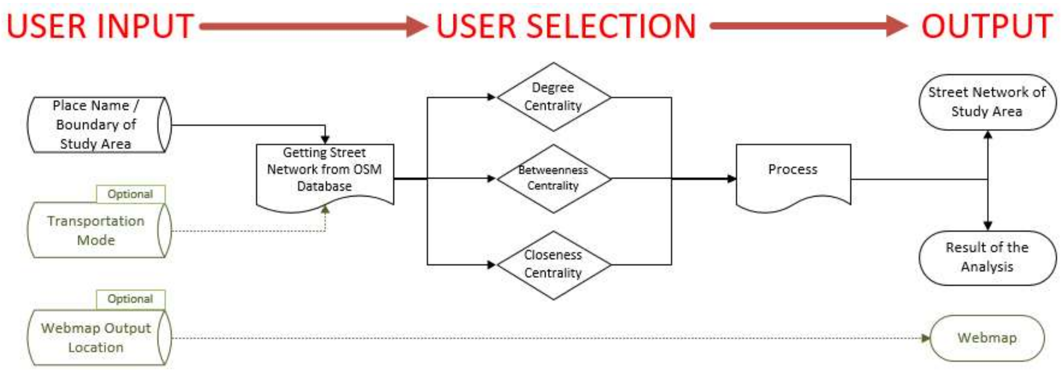

Figure 4.3 : Workflow of centrality analysis

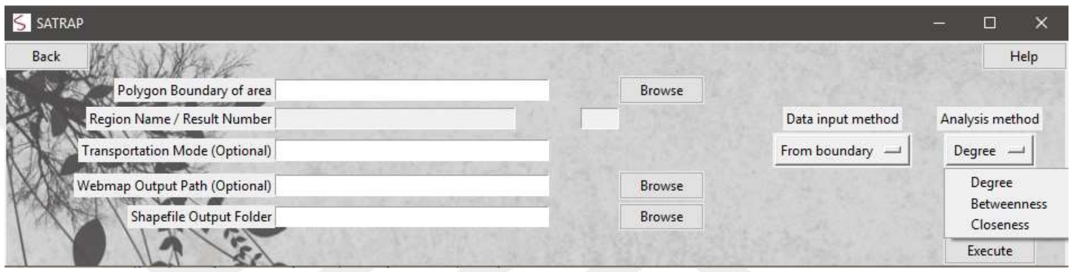

Figure 4.4 : Interface of centrality section

As input, the name of the study area or boundary of the study area in shapefile format is required from user. "Data input method" selection menu is particularly designed to allow user to choose desired method that is "From Boundary" or "From Region Name". If the region's name is given as input, first the availability of data on OSM database should be checked as in the Get Study Area functionality. Software will find the polygon area corresponding the region name given by user in order to get road network data of the area. In this way, user can perform the analyses by simply giving the name of the area that is aimed to be analysed. This feature is very useful for the provincial, district or neighborhood-based analyses for decision makers.

Also the boundary of the polygon area aimed to be analysed can be given to the software directly as an input in shapefile format. Software again will find the road network of given area and perform the analyses. As described, software uses OSM database in order to get corresponding road network. OSM uses WGS84 geographic reference system as standard. Thus, to get the correct road network data, input data should be in this reference system. However, this transformation/conversion process is done within the software. For that, coordinate system defined in input will not make any difference. Then software re-project the road network into the corresponding UTM zone where the calculation was made in a metric projected coordinate system.

This feature allows user to avoid any problem that occurs from the conflicts between coordinate systems. After getting the road network with node-edge topology, analyses are carried out and point type nodes with corresponding centrality values and road network data itself will be stored together on selected output path. "Shapefile Output Folder" entry box is for selecting the folder that the result of the analysis is stored. User should define the output path via "Browse" button. Analysis' result is stored with selected analysis' name. This input and output sections are compulsory for software to run, however there are optional parameters for a more detailed analysis and presentation as described below.

Software has the ability to evaluate transportation in various level of details. To assure this condition, an optional input "Transportation Mode" entry box is designed. In OSM network database, different transportation modes as network types are available in order to analyse the transportation in desired level of detail as shown in Table 4.1. With this functionality user can find, for instance, the critical components of pedestrian roads, bicycle roads or drivable roads separately. Every level of detail has a critical role while planning transportation networks in terms of being sustainable, comfortable and useful for every type of transportation mode. The default value for "Transportation Mode" feature is "all_private" in the software. User simply can write the keyword corresponding his/her subject of interest.

Table 4.1 : Transportation modes available on OSM database

Keyword	**Description**
drive	Drivable public streets (but not service roads)
drive_service	Drivable public streets, including service roads
walk	All streets and paths that pedestrians can use
bike	All streets and paths that cyclists can use
all	All (non-private) OSM streets and paths
all_private	All OSM streets and paths, including private-access ones

Also, developed software can produce a web map for visualizing the output of the calculations. After centrality analyses are performed, the resulted information is shown in five classes on a web map using the node's relevant metric values. For demonstration, closeness metric was calculated for London and resulted map is shown in Fig. 4.5. Obtaining a web map is a unique advantage compared to other mentioned tools/software.

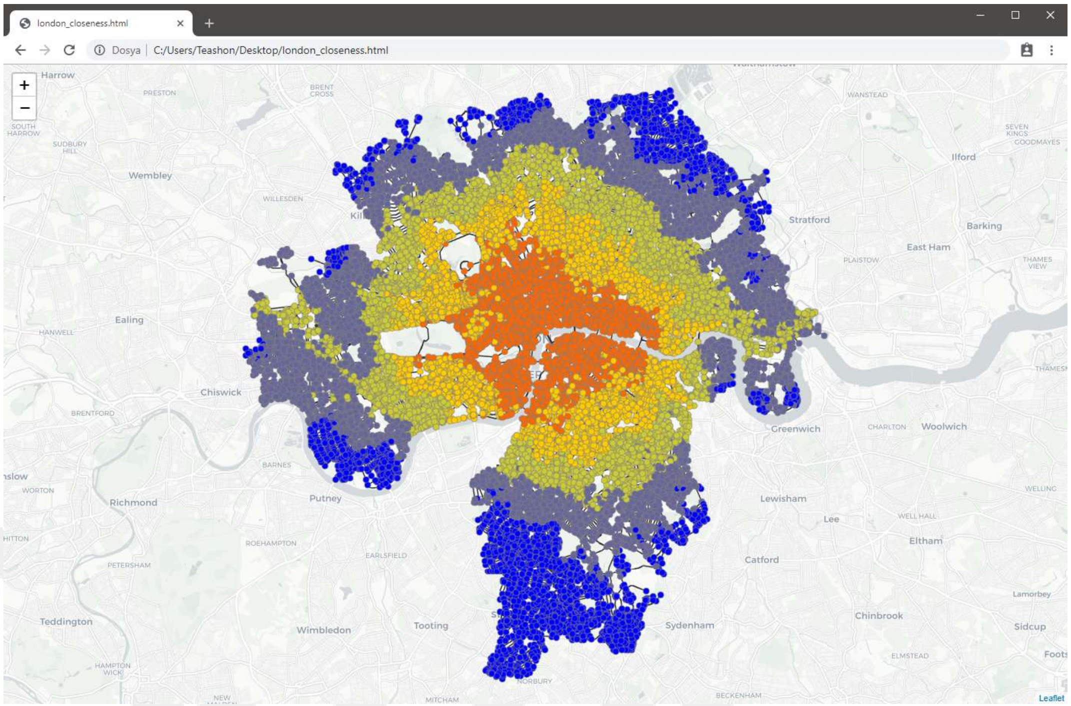

Figure 4.5 : Sample web map output

4.1.3 Accessibility analysis

Accessibility Analysis section was developed to measure accessibility between desired locations of user. Section Accessibility Analysis consists two types of accessibility analyses that are potential and daily accessibility. Implemented methodology is described with a simple chart in Fig. 4.6. In the interface shown in Fig. 4.7, type of analysis should be chosen from the select box "Analysis Method".

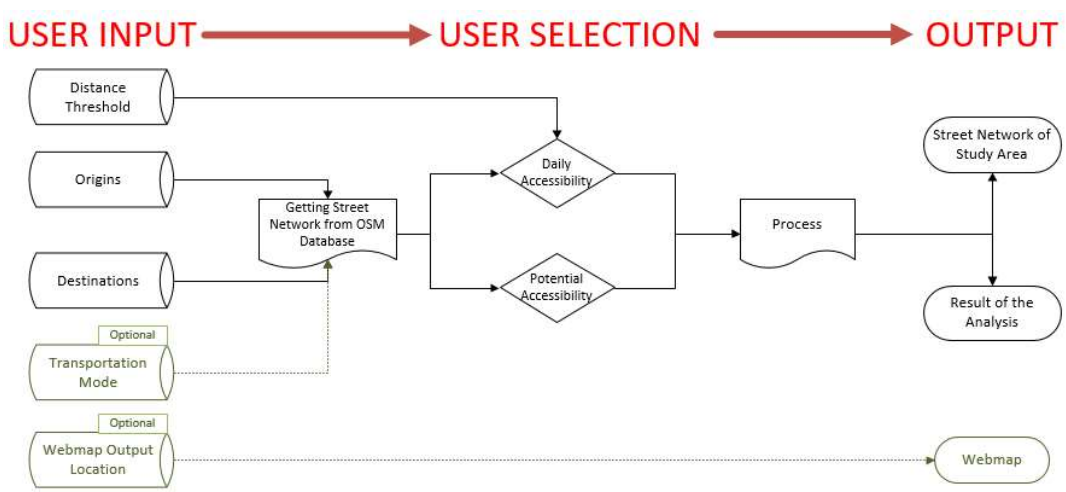

Figure 4.6 : Workflow of accessibility analysis

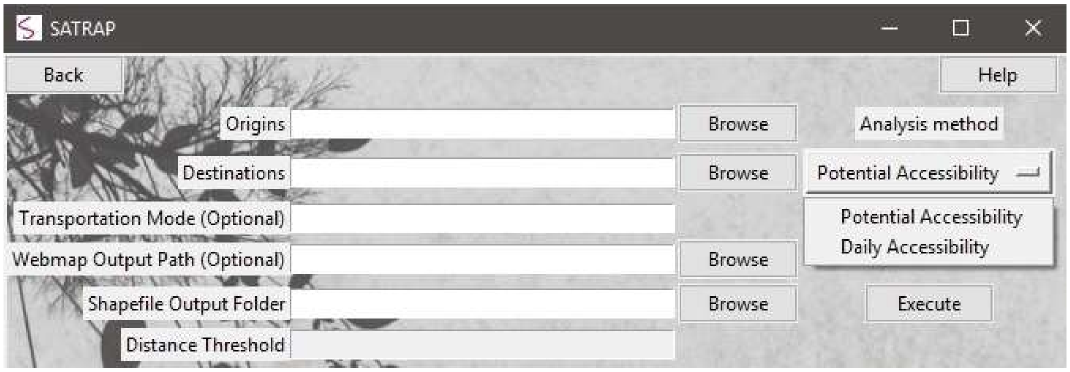

Figure 4.7 : Interface of accessibility section

Accessibility metrics utilize Origin-Destination (OD) matrices as previously mentioned that store travel impedance values between each origin and each destination. In the software, network distance between origins and destinations was used as default travel impedance to calculate an origin's or destination's accessibility. Also, other parameters consisted in Eq. 3.4 and 3.5 that are economic or attraction potential of origins/destinations were considered equal, and distance decay parameter was considered as "1". After selecting the type of analysis, origins and destinations should be entered in point type shapefile format by the user. Then the software will generate a closed area using the boundary points of given data and get the road network data within this closed area for calculations. Generating closed area by just using border points causes data loss on nearly located road network of these points. In order to prevent this loss, 1 km buffer was applied to the polygon created from border points' closed area to generate a bigger polygon. Then software calculates accessibility for each origin and destination and stores the origins and destinations with accessibility values in the desired output path. "Transportation Mode", "Webmap Output Path" and "Shapefile Output Folder" box work same as Centrality Analysis section. "Distance Threshold" box will be available on "Daily Accessibility" selection to implement user input threshold value on calculations.

To discuss, it is strongly recommended to improve the software to utilize an additional user input of road network rather than using OSM database automatically. By this way, temporal analysis would be an additional functionality that will provide temporal information of the network to decision makers. From several existing performance metrics, SATRAP is capable to use two of them successfully, and adequate to be improved by additional performance metrics. According to the needs of decision makers, SATRAP can be improved to utilize more metrics. Also, in further versions of software, created web map can be displayed dynamically on a website.

4.2 Case Study Results

First examined performance metrics, centrality metrics within connectivity measures, were computed for selected districts of all cities using SATRAP, where results are presented in Table 4.2.

Table 4.2 : Centrality metrics of cities

Cities with Selected Districts	Degree	Betweenness	Closeness
Istanbul	0.94	1.57	1.95
Paris	7.44	7.71	3.10
Rio de Janeiro	1.83	3.18	2.01
Madrid	3.61	3.82	2.99
London	1.80	3.08	1.26
Cape Town	0.41	0.78	1.88
New York	0.77	1.33	1.71

In table, average centrality values of nodes were given. Since these values are comparative, they are not meaningful alone. When degree centrality values were interpreted, it is at its maximum for Paris with 7.44 and minimum for Cape Town with 0.41. A transportation network that has higher degree value consists more connections/alternative roads between nodes. When examining the betweenness, a strong coherence is seemed with degree centrality. Higher betweenness value indicates higher capacity of bearing the flow volume pass through the nodes. Compared to Istanbul, nodes in Paris have intersection with the shortest paths nearly seven times more. That can be interpreted as; transportation volume is more uniformly distributed in Paris compared to others. Closeness centrality has reached its maximum in Paris with 3.10 and its minimum in London with 1.26. Istanbul is taking its place at fifth with 1.95. Closeness value of a node indicates its geographic centrality in terms of being more close to other nodes. It also captures city scale accessibility within the network itself. Then it can be said that, most geographically well-designed transportation network has the bigger closeness value. Results showed that, Paris and Madrid seem to be highly well-developed. By looking the average values on table, it is obviously understood that, Paris have the most well-developed network in terms of connectivity.

These values are not easy to interpret without illustrative resulted maps since the topological distribution is the main concern.

In degree centrality, no common spatial pattern was observed between cities. However, New York and Madrid showed similar pattern towards the center of the city as shown in Fig. 4.8. Although, there is no quantified correlation between them, spatial correlation was observed. As understood from maps, nodes with same degree values help to spread the traffic volume uniformly. That means, either the transportation system or the city is well planned.

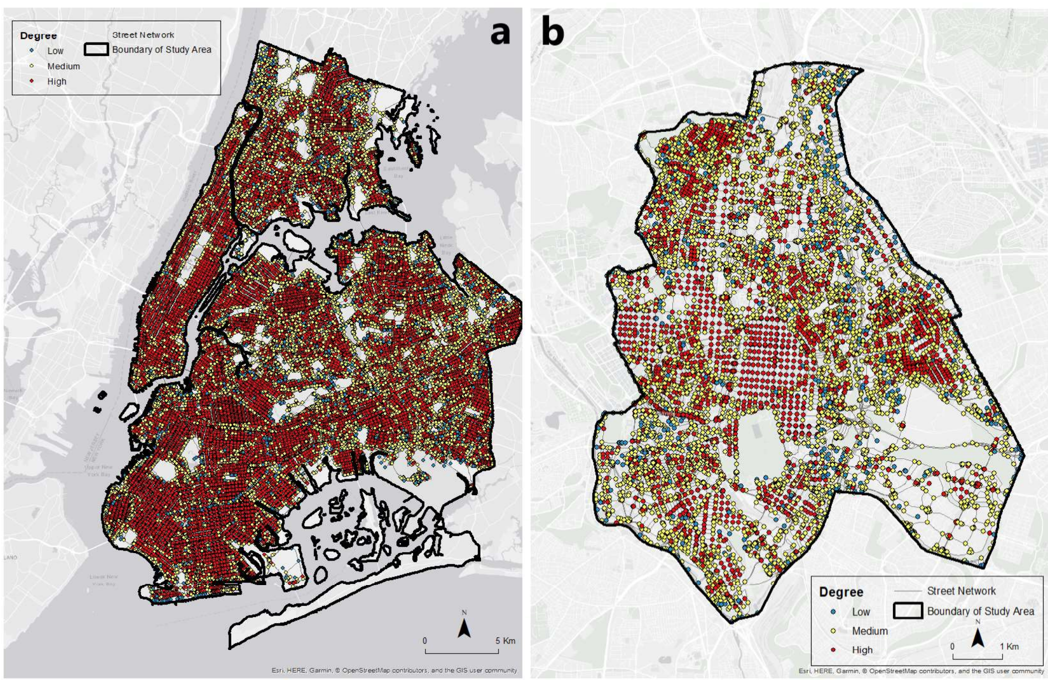

Figure 4.8 : Degree distribution of cities' selected districts. **a)** New York, **b)** Madrid

Betweenness pattern of cities, as understood from Fig. 4.9, represents main arteries of transportation network. Maps clearly enlightened the patterns that shows the parts with high traffic volume and these patterns help to interpret whether traffic bearer arteries spread homogeneously over the city. When looked at Istanbul, main arteries show a narrow distribution over the city center. When considering the scale and population of city, the distribution should be more uniform with more arteries.

In Fig. 4.10, closeness distribution of cities was shown. In a well-planned city, it is expected that nodes with high closeness value will be clustered in one place. In Paris and Rio de Janeiro, distribution is observed homogeneously at north whereas at center in other cities. As shown, nearly every city has uniform distribution except Istanbul.

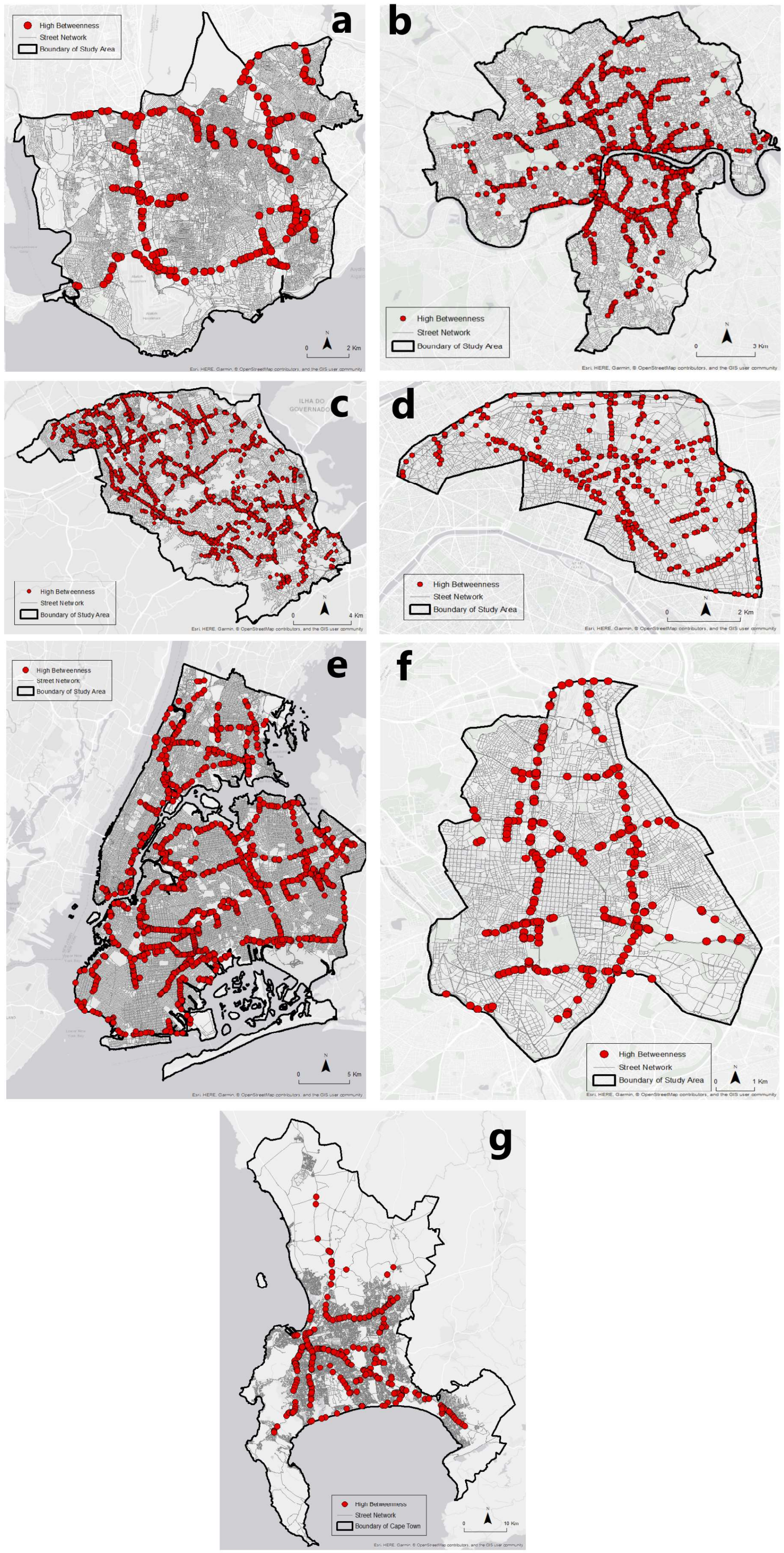

Figure 4.9 : Betweenness distribution of cities' selected districts. **a)** Istanbul, **b)** London, **c)** Rio de Janeiro, **d)** Paris, **e)** New York, **f)** Madrid, **g)** Cape Town

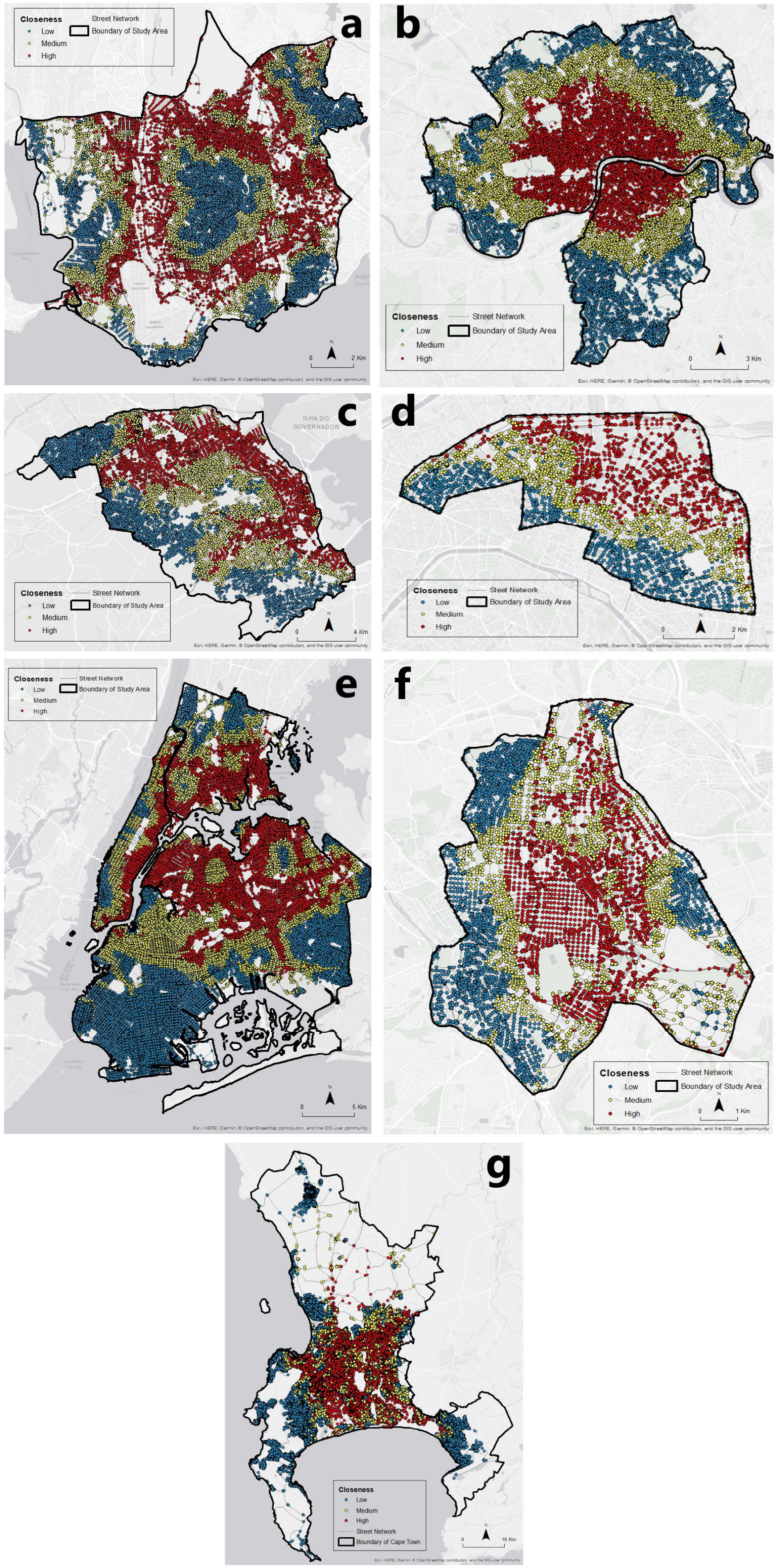

Figure 4.10 : Closeness distribution of cities' selected districts. **a)** Istanbul, **b)** London, **c)** Rio de Janeiro, **d)** Paris, **e)** New York, **f)** Madrid, **g)** Cape Town

As an exception, closeness is shown lowest at the city center and highest at the high betweenness areas as shown in Fig. 4.11. This could be a result of urbanization occurring near the transportation system and leading a complex and crowded city pattern.

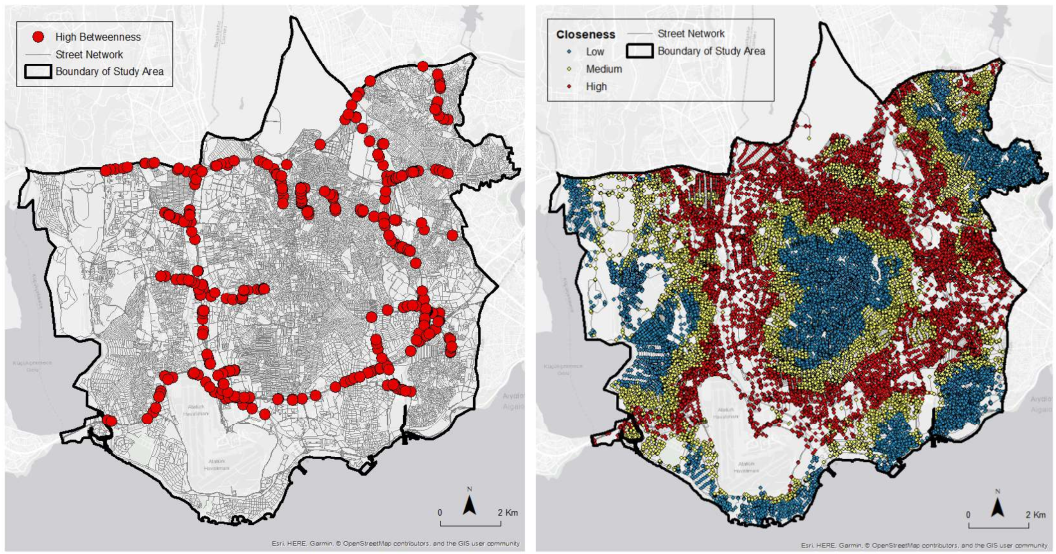

Figure 4.11 : Closeness and betweenness Istanbul's selected districts

On the other hand, accessibility measures were only computed for Istanbul, Paris, Madrid and London due to land use data unavailability. Results are presented in Table 4.3.

Table 4.3 : Accessibility values of cities

Cities with Selected Districts	Potential Accessibility	Daily Accessibility
Istanbul	0.17	0.55
Paris	0.30	0.58
Madrid	0.29	0.60
London	0.19	0.57

Results indicate that daily accessibility do not vary for studied cities. This result can be interpreted as cities' local transportation establishment have similarities. People or goods have equity in local accessibility in all examinations. However, cities have distinguishable potential accessibility values. That indicates the transportation networks of the cities have different characteristics in a bigger scale. While observing the results it is shown that, Istanbul takes the attention by being insufficiently accessible. This situation points out; the transportation network of Istanbul has non-satisfactory relation with the land use pattern of city. Irregular urbanization unfortunately resulted with low accessibility. This irregularity is also observed in closeness distribution. For that, it will not be a mistake to claim such a correlation between closeness and potential accessibility. In all cities, this correlation is seen, as both potential accessibility and closeness are sorted in the same way. It is seen that Paris is in the first place for both potential accessibility and centrality metrics. That indicates the transportation infrastructure of the city is well-developed and can inspire policy makers to plan satisfactory transportation networks. It is understood that accessibility in this context is a decisive metric to criticize transportation networks by their geographic structure.

All the analyse process of SATRAP is also tested with several quality attributes by comparing it with a likewise tool. To test the performance of SATRAP, portability and efficiency attributes from International Organization for Standardization's norm ISO/IEC 9126 were chosen. For comparison, Sevtsuk and Mekonnen (2012)'s Urban Network Analysis Toolbox was selected as it has similar functionalities with SATRAP. Result of comparison is presented in Table 4.4.

Table 4.4 : Comparison of performance indicators

Performance Indicators	SATRAP	Urban Network Analysis Toolbox
Adaptability	Works under Windows OS	Works under Windows OS
Installability	Open Source	Works under ArcMap
Time	Avg 34 min.	Avg 22 min.
Resources	Provides OS data	-

Urban Network Analysis Toolbox had a better performance according to time criterion. However, software can be improved with better memory management in further updated versions. To conclude, SATRAP is found efficient and satisfactory to examine a network spatially. With improvements of time efficiency, software will be more advantageous for spatial science applications.

Obtained results proved that, topological and spatial distributions can be detected quantitatively. Results can be used to enhance the understanding of network pattern according to city aspects. For instance, irregular distribution observed on Istanbul clearly demonstrates the urbanization have not progressed through city's geometric mean center as the other selected cities London, New York, Madrid and Cape Town. Relations revealed by closeness map of Istanbul is very informative for decision makers. By this quantitative and illustrative results, infrastructure planning indeed, could be supported. Comparisons alike in this study will allow the numerical determination of the topological characteristics of an advanced transportation network and will shed light on decision makers from several countries.

5. CONCLUSIONS

Several problems come from rapid urbanization process of cities and one majority among them is transportation. Transportation networks are one of the fundamental components of city to provide sustainable mobility between people and opportunities. Thus, performance of a network should be continuously monitored to bring useful perceptive for sustainable development with spatial performance measures. Among them, connectivity and accessibility metrics address the network integrity and ability to reach opportunities/demands over a network. These metrics can be calculated in GIS by various developed methodologies. These methodologies so far, have been developed diversely for such measures to be examined. Although there some accessibility and/or connectivity analyse tool existed separately, integrated and open source tool needs are not satisfied yet. For that, a performance analyst of transportation network is becoming a collective necessity for whom have concerns about subject. Here, open source thinking is providing an alternative where desired methodologies/tools/software can be developed and distributed freely and independently.

This study mainly focused on developing an independent GIS software that can evaluate the transportation performance metrics with all-round open source approach. All results constitute that; an integrated model using GIS methods contributes greatly to transportation performance monitoring in many aspects. With the implemented methodology, no spatial data is expected from analyst. That is a great advantage if data deficiency situations are considered. Another usefulness of the software is; no other GIS software is required for spatial analyses. Furthermore, the illustration of the results is also provided with web maps instantaneously. To continue, software produces a variety of results obtained from two different spatial analyses assembled in one tool, that is not developed by a likewise approach before. With the help of software, complex methodologies were facilitated considering the comfort of end user to utilize analyses without handling technical complexities. Relative to similar other tools/software, this function is a distinctive feature.

The designed software is considered as an "all-in-one tool" that is tailored for policy makers. Case study demonstrated that, software showed a satisfactory performance. Meaningful results obtained from created model clearly proved that, such integrated methodologies are applicable in a cost effective, easy and independent way. Since SATRAP had a successful performance, it is clearly demonstrated that; the software is improvable with more functionality and metrics according to the needs and requirements of policy makers who are the target group of this study. As all of the proposals were successfully achieved with the approach of open source development, open source philosophy need to become widespread.

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APPENDICES

APPENDIX A.1 : Study Areas

APPENDIX A.1

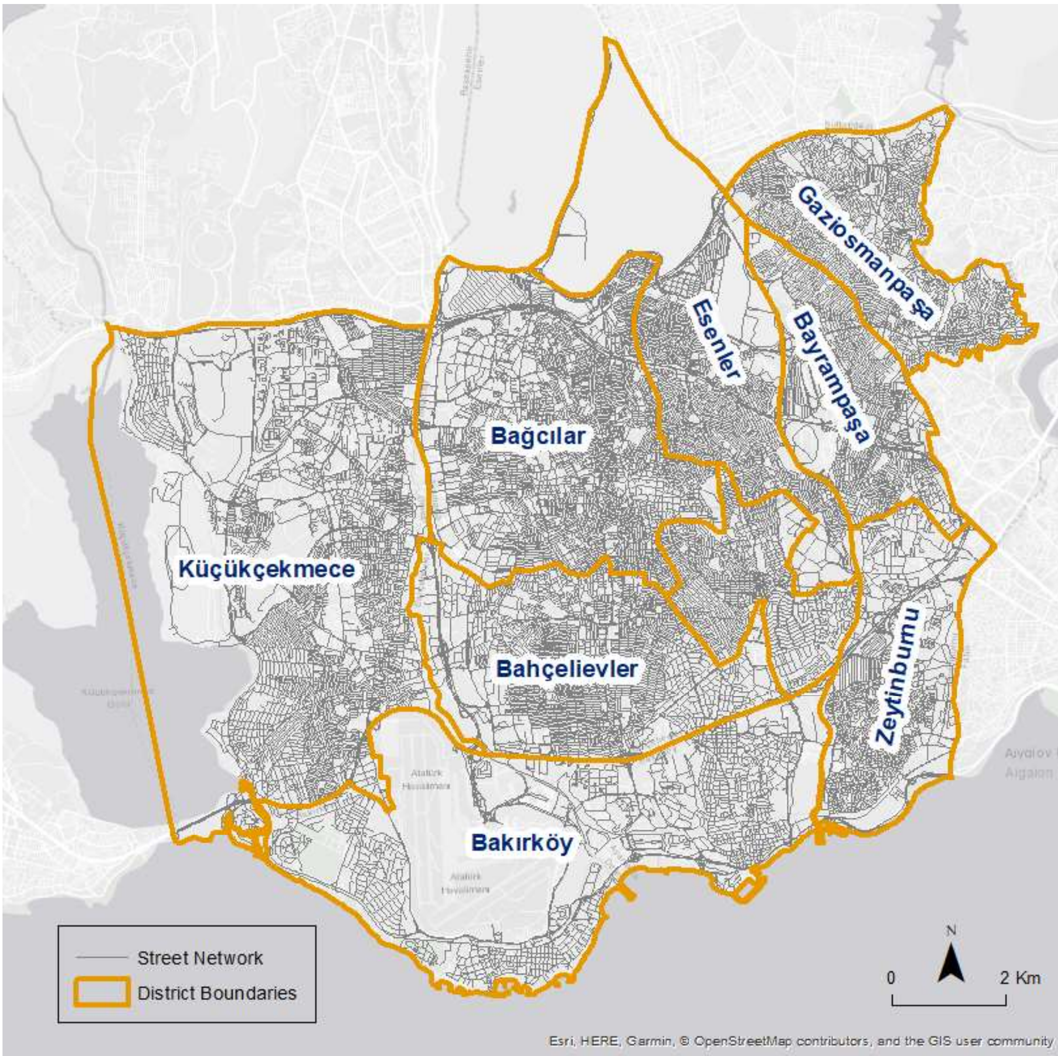

Figure A.1 : Study area of Istanbul

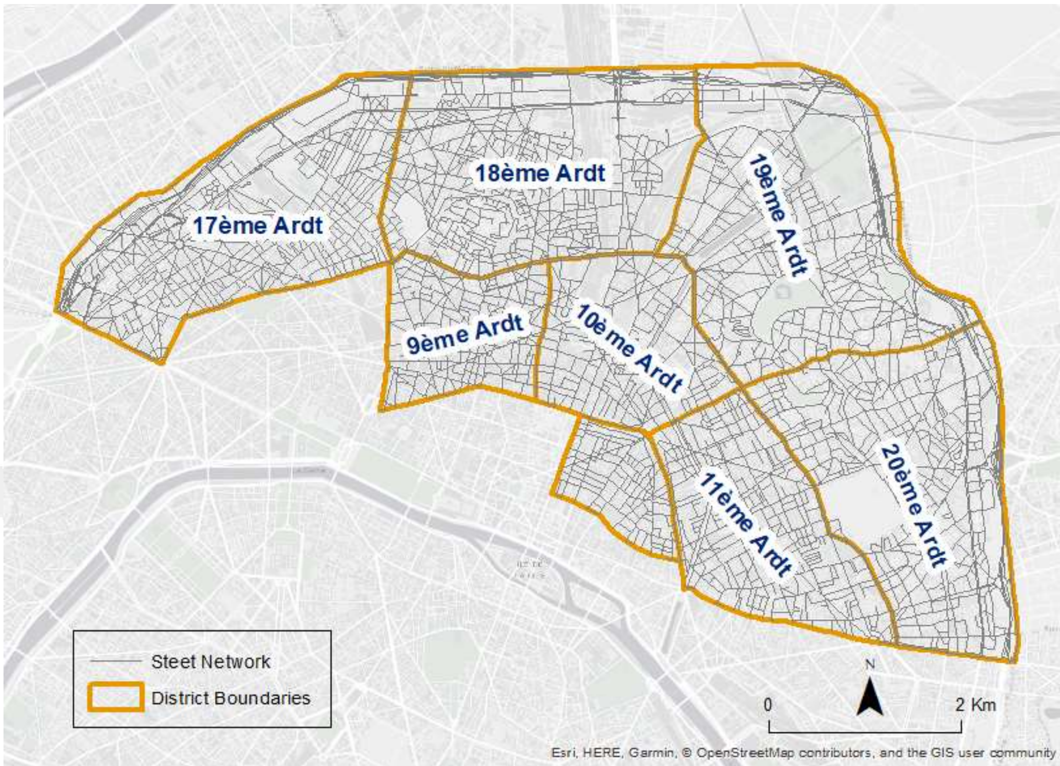

Figure A.2 : Study area of Paris

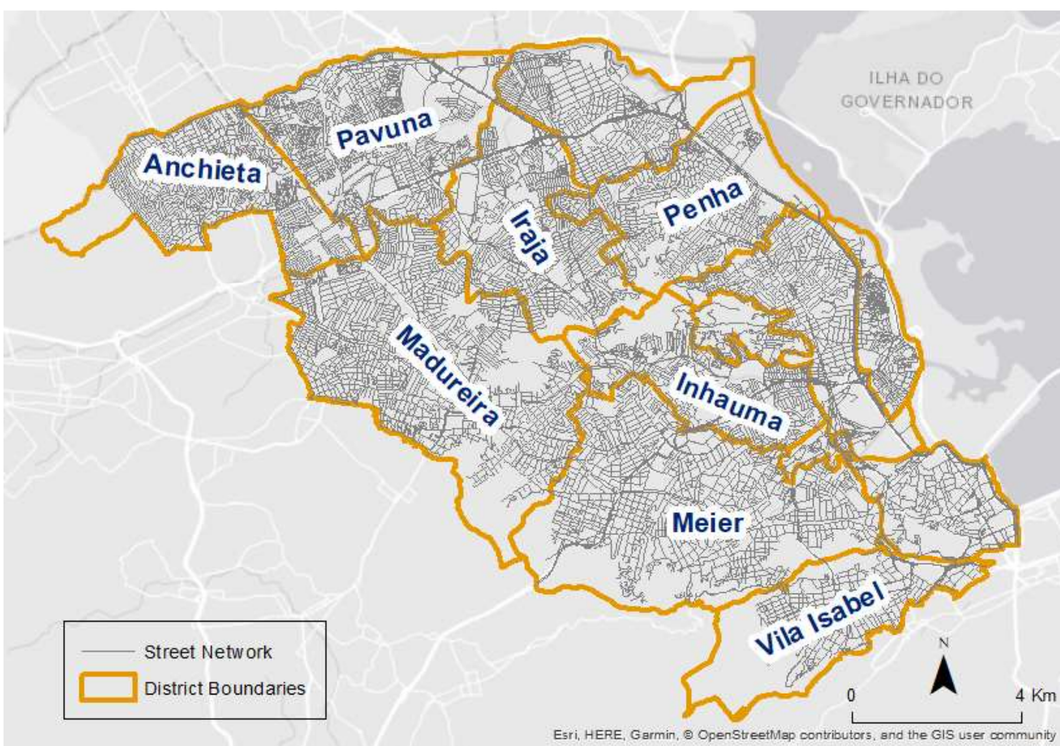

Figure A.3 : Study area of Rio de Janeiro

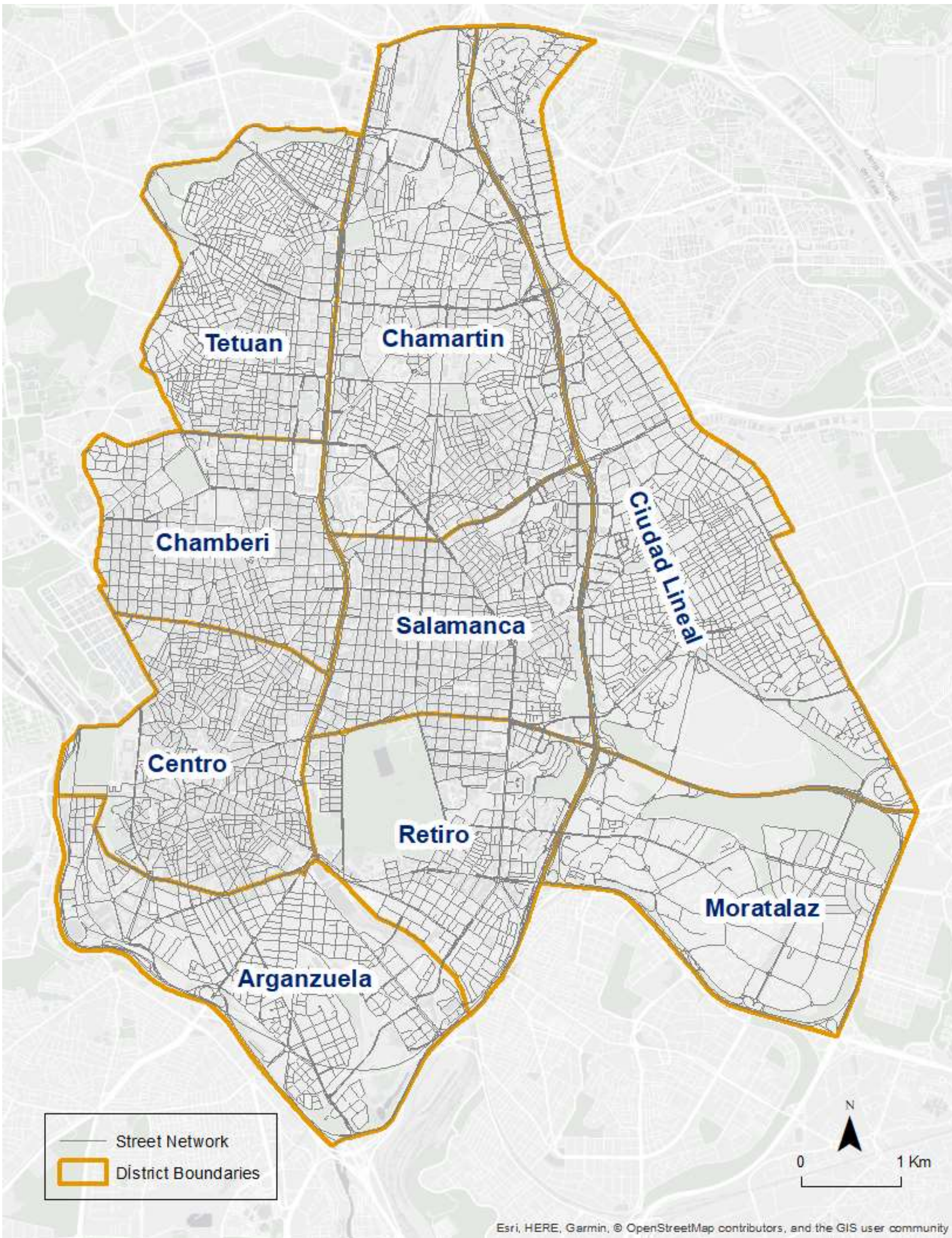

Figure A.4 : Study area of Madrid

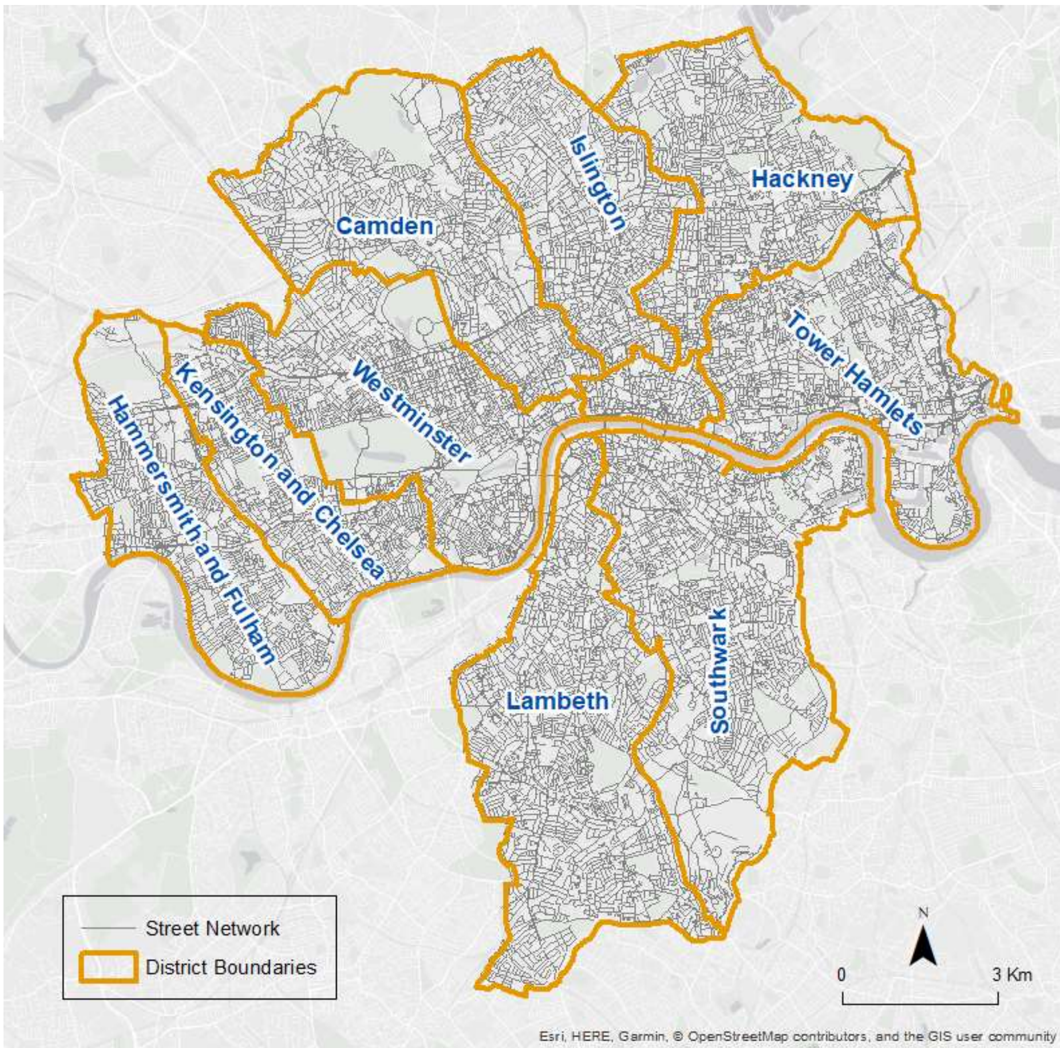

Figure A.5 : Study area of London

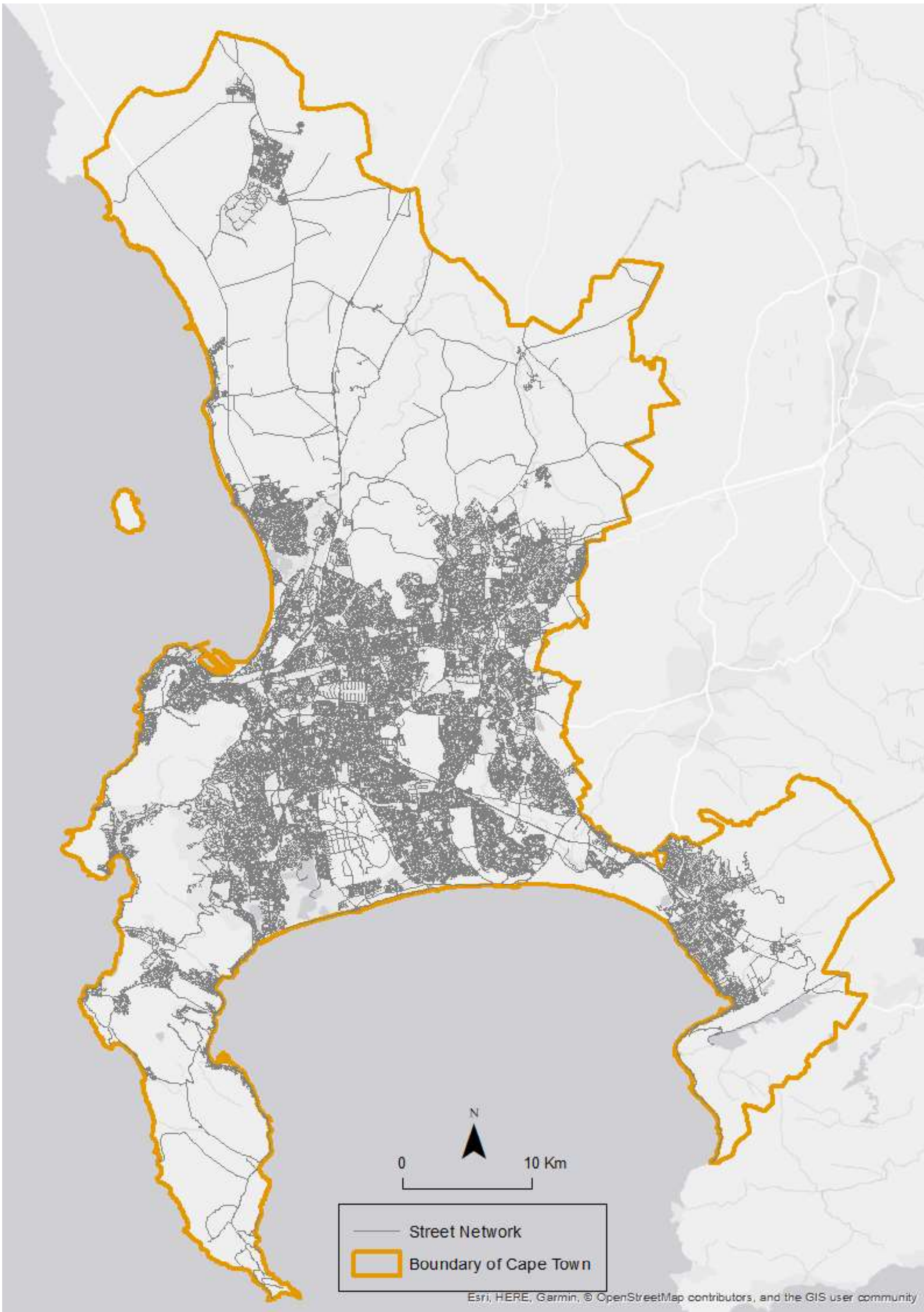

Figure A.6 : Study area of Cape Town

Figure A.7 : Study area of New York

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PROFESSIONAL EXPERIENCE AND REWARDS:

- 04/2018 - Now, Research Assistant, Istanbul Technical University, Civil Engineering Faculty, Geomatics Engineering Departmant.
- 08/2017 - 08/2018, Scholar, The Scientific and Technological Research Council of Turkey (TÜBITAK), Geographic Information Systems (GIS) Based Roadway Accessibility Analysis.
- 10/2017 - 04/2018, Freelancer Online Map Analyst, Lionbridge
- 01/2017 - 02/2017, Intern, Istanbul Grand Airport
- 01/2016 - 02/2016, Intern, Nokia Here Maps

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Akın, Ö.**, Eroğlu, A., Demirel, H. (2019). Açık Kaynak Kodlu Ağ Analiz Algoritmaları ve Arazi Örtüsü/Kullanımı Simülatörü *10. Türkiye Ulusal Fotogrametri ve Uzaktan Algılama Birliği Teknik Sempozyumu*, 26-29.
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