ESTIMATION OF TIME-DEPENDENT LINK COSTS USING GPS TRACK DATA

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

AHMET DÜNDAR ÜNSAL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
GEODETIC AND GEOGRAPHICAL INFORMATION TECHNOLOGIES

DECEMBER 2006

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Zuhal Akyürek
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Nurünnisa Usul
Supervisor

Examining Committee Members

Prof. Dr. Özdemir Akyılmaz (METU, CE)

Assoc. Prof. Dr. Nurünnisa Usul (METU, CE)

Assoc. Prof. Dr. Şebnem Düzgün (METU, MINE)

Assist. Prof. Dr. Zuhal Akyürek (METU, CE)

Dr. Hediye Tüydeş (METU, CE)

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name: Ahmet Dündar Ünsal

Signature :

ABSTRACT

ESTIMATION OF TIME-DEPENDENT LINK COSTS
USING GPS TRACK DATA

Ünsal, Ahmet Dündar

MS, Department of Geodetic and Geographical Information Technologies
Supervisor: Assoc. Prof. Dr. Nurünnisa Usul

December 2006, 76 Pages

Intelligent Transport Systems (ITS) are becoming a part of our daily lives in various forms of application. Their success depends highly on the accuracy of the digital data they use. In networks where characteristics change by time, time-based network analysis algorithms provide results that are more accurate. However, these analyses require time-based travel speed data to provide accurate results. Conventionally, traffic data are usually obtained using the data provided from loop-detectors. These detectors usually exist on main arteries, freeways and highways; they rarely exist on back roads, secondary roads and streets due to their deployment costs. Today, telematics systems offer fleet operators to track their fleet remotely from a central system. Those systems provide data about the behaviors of vehicles with time information. Therefore, a tracking system can be used as an alternative to detector-based systems on estimating travel speeds on networks.

This study aims to provide methods to estimate network characteristics using the data collected directly from fleets consisting of global positioning system (GPS) receiver equipped vehicles. GIS technology is used to process the collected GPS data spatially to match digital road maps. After matching, time-dependent characteristics of roads on which tracked vehicles traveled are estimated. This estimation provides data to perform a time-dependent network analysis.

The methods proposed in this study are tested on traffic network of Middle East Technical University campus. The results showed that the proposed methods are capable of measuring time-dependent link-travel times on the network. Peak hours through the network are clearly detected.

Keywords: time-varying network analysis, map-matching, link cost estimation, fleet tracking

ÖZ

GPS TAKİP VERİLERİ KULLANILARAK, ZAMANA BAĞLI YOL AĞI SEYİR MALİYETLERİNİN HESAPLANMASI

Ünsal, Ahmet Dündar

Yüksek Lisans, Jeodezi ve Coğrafi Bilgi Teknolojileri Bölümü
Tez Danışmanı: Doç. Dr. Nurünnisa Usul

Aralık 2006, 76 Sayfa

Akıllı Ulaşım Sistemleri (AUS) farklı uygulamalarla hayatımızın bir parçası haline geldi. AUS'un başarısını etkileyen en önemli unsur, sistemce kullanılan verilerin gerçeklik düzeyidir. Seyir karakteri zamana bağımlı değişkenlik gösteren yol ağlarında, daha doğru analiz sonuçları elde edebilmek için zamana bağlı değişiklikleri hesaba katan analiz metotları kullanılmalıdır. Ancak zamana bağlı analizler, zamana bağlı verinin varlığını gerektirir. Bugün, zamana bağlı trafik veri ölçümlerinde genelde yollara kurulumu yapılmış özel dedektörlerden elde edilen veriler kullanılmaktadır. Ancak yüksek maliyetlerinden dolayı bu üniteler sadece ana arterlere sınırlı sayıda kurulabilmektedir. Bu da zamana bağlı veri derinliğini azaltmaktadır. Telekomünikasyon ve mobil cihaz teknolojilerinde sağlanan ilerleme, firmaların araçlarına ait konum bilgilerini canlı olarak takip edebilmesini sağlamaktadır. Filo takibi adı verilen bu yöntemle araçların anlık konumlarına dair veriler toplanabilmektedir. Sahadan gelen bu verinin analizi ile zamana bağlı değişen trafik seyir karakteristiklerinin düşük maliyetlerle ölçülmesi mümkün olabilir.

Bu çalışma, küresel konumlandırma sisteminden elde edilen araç takip verilerinin analizi ile, yol ağlarındaki seyir karakteristiklerini ölçmeyi amaçlamaktadır. Bu analizlerde, gelen verilerin sayısal haritalarla ilişkilendirilmesi ve mekansal olarak sorgulanabilmesi için Coğrafi Bilgi Sistemleri (CBS) araçları kullanılır. CBS yardımıyla yollarla ilişkilendirilen araç takip verileri kullanılarak, yol ağı seyir karakteristikleri hesaplanır. Elde edilen zamana bağlı seyir karakteristik bilgileri seçilen zamana bağlı analizde kullanılır.

Bu çalışmada önerilen yöntemler Orta Doğu Teknik Üniversitesi kampüs yol ağında test edilmiştir. Testler sonucunda, yol ağı üzerindeki bağlantıların aşılma süreleri ölçülmüş ve bu ölçümler doğrultusunda kampüs yol ağında trafik yoğunluğu yaşanan aralıklar tespit edilmiştir.

Anahtar Kelimeler: zamana bağlı değişen yol ağı analizi, harita ilişkilendirmesi, yol ağı seyir karakteristikleri tahmini, araç takibi

To My Mother

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude to my supervisor Assoc. Prof. Dr. Nurünnisa Usul and Dr. Hediye Tüydeş for their guidance, advice, criticism, encouragements and insight throughout the study.

I would also like to thank Mr. Alim Küçükpehlivan, Mr. Tuncay Küçükpehlivan and Mr. Ahmet Dabanlı for their support for the software packages used in the study.

I would like to thank Inta Spaceturk for sharing the satellite imagery of the study area. The sincere efforts of staff, including Mr. Tuna Ünsal, Mr. Gökhan Eke and Mr. Bülent Öztürk, will be gratefully remembered.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

As mobile communications and information processing technologies advance, data collection from vehicles equipped with mobile Global Positioning System (GPS) receiver become a common method for tracking fleets. Data collected during travel can either be transferred directly to a central server real-time by utilizing a mobile communication infrastructure, or stored in a storage device located in the tracked vehicle and transferred to central server with offline techniques. These systems are commonly referred as vehicle telematics systems. Data collected through tracking methods provide vehicle position associated with tracking time information. Receivers may also provide a motion vector representing instantaneous change in vehicle position.

The data collected through a vehicle tracking system can be used to estimate time-dependent travel times on traffic networks. Today, analyzing the data derived from loop detectors is the most common way of estimating travel times or travel speeds. However, due to high costs of detector deployments, applications of these systems are usually limited to freeways, highways and main arterials. An accurate estimation of travel times require frequently installed detectors. GPS-based vehicle tracking systems can offer a low-cost solution to estimate travel times or travel speeds on a traffic network.

1.1. Problem Definition

This study aims to develop a set of methodologies to derive traffic network characteristics by employing the data obtained from GPS receiver equipped vehicles. A digital road map, modelling the traffic network of the study area, is developed using

GIS-tools. This road map not just simply model the network, also fulfill the needs of map-matching methods, such as geometric accuracy of map features. Successor steps, which are needed to estimate traffic network characteristics, require track-data to be matched with digital road network. In addition to basic point-to-curve matching systems, route-based matching methods to integrate topological control to matching process are proposed to refine the results. Continuity of point-to-curve matched track data is checked againts topology of network, detected mis-matches are post-processed for correction. Once the routes are created by route-based matching step, the data are analyzed to estimate charactericstics of the network by calculating the link travel times. Link travel times are calculated either by detecting, approximating or estimating vehicles' entry or exit-times to the links.

To find the time-dependent link costs, estimated link travel times, derived from the steps above are analyzed in various time windows to figure out the changes on the characteristics of the network over time. A time-dependent shortest path analysis is performed to present an example implementation utilizing calculated time-dependent network-characteristics data.

1.2. Structure of the Thesis

In Chapter 2, the literature for three main subjects are reviewed. Initially, the studies focusing on networks as general are reviewed. This section summarizes the basics of mathematical and computational methods, on which many techniques proposed in this study are based. Next, the GIS studies that specifically focus on the scope of this study are reviewed. The roles of GIS in the field of transportation and vehicle telematics are given. Major contributions to map-matching tecniques are summarized. Finally, the major studies on the shortest-path problems are reviewed.

Chapter 3 describes the chosen tecniques and proposed methods. Steps required to develop a digital network using GIS application programming interface are presented. Detailed steps of the network development process are given. Next, the proposed map-matching algorithm is studied step-by-step which is followed by the description of the proposed algoritmic steps which are required to estimate the network characteristics.

In Chapter 4, results of the proposed methodology are presented. First, a brief introduction of selected study environment, the campus network of Middle East Technical University is presented including the characteristics of the network. The specifications and attributes of the GPS track data for the study area are given. The results of map-matching process are discussed prior to presentation of the results derived from link-travel time estimation step. In addition, the results of least-cost path analyses, performed between a selected set of origins and destinations in order to find temporal changes on the calculated paths are presented.

Chapter 5 presents the conclusions derived from the implementation of the proposed methodology. Possible practices based on the contributions of the study are discussed. The improvements that can be built up on this study are summarized.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the literature for main subjects involved in this study are reviewed. Section 2.1 reviews the studies on defining a network mathematically and the studies of computational science that proposed data structures to handle those mathematical models. This section summaries the basic mathematical and computational concepts about techniques which are used in this study. Section 2.2 reviews the GIS studies that specifically focus on transportation and map-matching techniques, in addition to role of GIS in transportation and vehicle telematics. Section 2.3 reviews the studies on general shortest-path problems. Followed by a review of the time-varying shortest path algorithms, on which our test scenarios are based to test network with estimated characteristics.

2.1. Mathematical Models for Representing Networks

A network is represented as a *graph* in mathematics and computer science. A graph is a set of objects called *points* or *vertices* connected by links called *edges*. Edges can either have directions or not. An undirected edge from point A to point B is considered to be the same thing as a link from point B to point A. Figure 2.1 is a graphical representation of a *graph* which is denoted as G= (V,E) where V is the set of vertices and E is set the of edges; V={A,B,C,D,E,F} and E={e_1,e_2,e_3,e_4,e_5,e_6,e_7}.

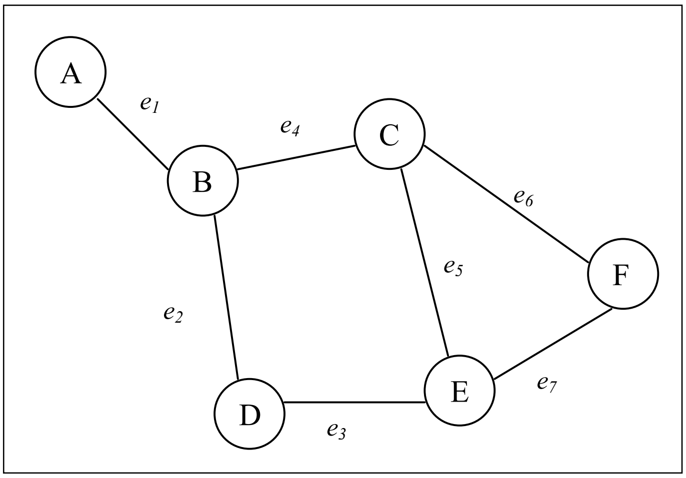


Figure 2.1 A labeled graph with six vertices and seven edges

A graph with directed edges is called *directed graph*, shortly *digraph*. In a digraph, a single edge can connect two vertices through a single direction. Two vertices that are connected in two directions (A to B and B to A) are represented by two distinct edges as shown in Figure 2.2. Diestel (1997) described a graph as a pair G=(V,E) of sets such that $E \subseteq [V]^2$; thus the elements of E are 2-element subsets of V.

Two edges sharing a common vertex are called *adjacent edges*, and similarly two vertices sharing a common edge are called *adjacent vertices*. At an edge that connects two vertices, any of the vertices is *incident* to that edge. A *path* in a graph is a subset graph which consists of sequential vertices, from each of whose vertices there is an edge to the next vertex in the sequence. The initial vertex is called *start vertex,* and the last vertex in the sequence is called *end vertex*. A path with a start vertex which is same with its end vertex is called a *cycle*. A *loop* is an edge that connects a vertex to itself.

A graph can also include weight data on its edges or vertices. Weight data determine the cost of traversing through the edges or vertices. A graph with weights is called a *weighted graph.* A graph having labels on its vertices is called a *vertex-labelled graph*. Same way *edge-labelled graphs* refer to the ones with labeled edges.

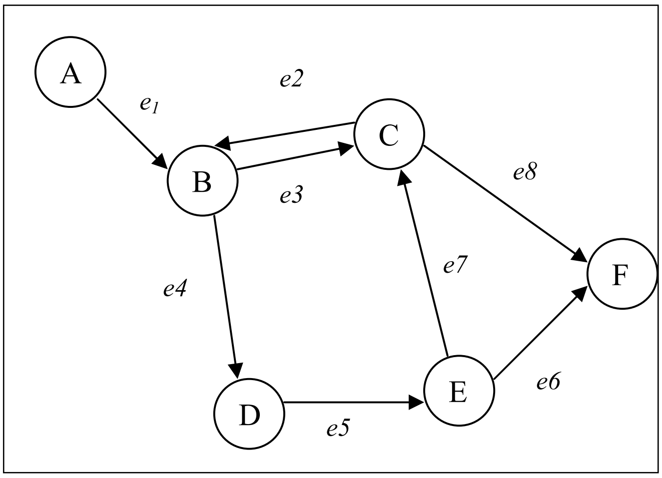


Figure 2.2 A labeled digraph with six vertices and eight edges

A *weighted graph* is called a network. Networks are practical applications of graph theory. They have a wide area of usage in both social and natural applied sciences. Social relations, roads, internet infrastucture, etc. can be modelled using networks. In this study, weighted-digraph structure is used to represent a road network mathematically. The attributes of the roads such as speeds, traffic intensity and elevation change, give the weights of edges.

2.1.1 Graph Data Structures

In computer science, graphs are represented as an abstract data type, holding nodes and edges of graphs including their connectivity information. Several studies proposed solutions for representing digraphs, depending on the algorithm proposed for implementation.

Christofides (1975) proposes the use of matrices as the most suitable way to represent graphs algebraically. One proposed way of representation is Adjacency Matrix. In mathematics and computer science, the adjacency matrix for a finite graph G with n vertices is an n × n matrix, where the non-diagonal entry a_{ij} is the number of edges joining vertex i and j, and the diagonal entry a_{ii} is either twice the number of loops at vertex i or just the number of loops, as shown in Table 2.1.

In graphs, the incidence matrix of a directed graph G is an n (V) × n (E) matrix of b_{ij}, such that b_{ij} is equal to − 1, if the edge x_j exits vertex V_i, 1 if it enters vertex V_i and 0 otherwise. An oriented incidence matrix of an undirected graph G is the incidence matrix, in the sense of directed graphs, of any orientation of G. That is, in the column of edge e, there is (a + 1) in the row corresponding to one vertex of e, and (a - 1) in the row corresponding to the other vertex of e, and all other rows have 0 (Table 2.2).

Table 2.1 Adjacency matrix representation of graph given in Figure 2.2

	A	B	C	D	E	F
A	0	1	0	0	0	0
B	0	0	1	1	0	0
C	0	1	0	0	0	1
D	0	0	0	0	1	0
E	0	0	1	0	0	1
F	0	0	0	0	0	0

Table 2.2 Incidence matrix representation of graph given in Figure 2.2

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8
A	1	0	0	0	0	0	0	0
B	-1	0	0	1	0	0	0	0
C	0	1	-1	0	0	0	-1	1
D	0	-1	1	-1	1	0	0	0
E	0	0	0	0	-1	1	1	0
F	0	0	0	0	0	-1	0	-1

In large networks, matrix data structures fail due to the large amount of memory they require. An adjacency matrix structure representing a graph with 100.000 nodes, which consume one-bit per connectivity information (per matrix cell) requires over one gigabyte of memory, which is not quite practical for today's computers. In large graphs, list structures are preferred for both incidence and adjacency structure.

Incidence list structure is an array that represents edges with associated vertex pairs. Each ordered vertex pair defines the connecting edge and optionally weights associated with the edge. In adjacency list structure, each vertex has a list of vertices that it is connected to. This structure may result in data redundancy in graphs with undirected edges. List data structures require less memory than matrix structures, while performing worse in computation time. Optimal structure to be used mostly depends on the size of the graph.

2.2. GIS for Transportation

This section summarizes the use of Geographic Information Systems technology in transportation science. Brief information about the capabilities of GIS on storing, querying and analyzing geographic information is presented, followed by a brief review of literature in GIS for transportation (GIS-T) field.

2.2.1 General Aspects of GIS

Briefly, GIS are a set of definitions and methods, which extend the information technologies to create, store, manage and analyze spatial (more specifically geographic) information and related problems. Therefore, GIS provide tools to a broad range of disciplines, whose problems may interact with space and geography, e.g. city planning, transportation, geology, etc.

There are efforts in GIS field focusing on the standardization of storing, managing and querying spatial data. Today, most of the database engines support spatial data types, most of which are defined and standardized by Open Geospatial Consortium, a body formed by the industry actors involved in GIS science and GIS technology (Goodchild, 1991). These actors include the commercial GIS-package providers, such as ESRI, MapInfo and Intergraph, which offer workstation packages ArcGIS, MapInfo Professional and Geomedia in their product range respectively.

In this study, GIS tools and methods provide the environment to create, store and analyze the vehicle tracking data, digital road maps and time-based traffic network characteristics data.

2.2.2 GIS for Transportation

The spatial analysis capabilities of GIS can provide an environment that fulfills the needs of transportation applications and analyses. “With the aid of GIS, a realistic simulation of a road-network can be produced in a link-node form with the establishment of topological relationships among the nodes and links” (Patterson, 1990). GIS studies for transportation are commonly referred as GIS for transportation (GIS-T) (Fletcher, 2000; Wiggins, et al., 2000). While most GIS packages have built-in or add-on solutions for transportation, they provide simple queries like shortest-path, traveling salesman, isochrones and dynamic segmentation on networks with fixed characteristics over time. (e.g. ArcGIS/ArcView with Network Analyst Extension, RouteWare for MapInfo and ArcGIS). Integration of full-featured transportation software packages to existing GIS packages, enable users to perform more advanced transportation operations within the rich spatial environment of GIS packages (e.g. TRANSPLAN linked with MapInfo or MGE) (Goodchild, 2000; Thong and Wong, 1997).

Traffic networks are represented by GIS-T data structures, dealing with movements or flow between spatial points. Nodes represent points at which flows originate or terminate. They may also be defined to represent changes in flow characteristics and changes in network topology. Links define the characteristics of flow between nodes. The direction of a link indicates the flow direction; the weight of a link is defined as a cost function that simulates the cost of traveling on the corresponding link (Miller and Shaw, 2001).

This study focuses on utilizing GIS abilities on map-matching techniques to analyze vehicle tracking data collected from field and creating a digital road network with time-dependent characteristics derived from analyzed data. Next sections will briefly present previous studies and concepts on traffic network representation using Geographical Databases and map-matching techniques to match geographical positions of tracked vehicles with digital maps.

2.3. Travel Time Estimation

The term Intelligent Transportation Systems (ITS) can be defined as the use of advanced technology in information gathering, processing, telecommunication and many other branches of engineering for providing efficient, safe, and less congested land transportation solutions with less impact on the environment" (Transport Canada, 2005). The practical benefits of ITS depend on the technical capabilities of software and hardware it utilizes. Basnayake (2004) listed the major services covered by ITS as Traveler Information Services (TIS), Traffic Management Services (TMS), Public Transportation Services, Electronic Payment Services, Commercial Vehicle Operations, Emergency Management Services, Vehicle Safety and Control Systems, and Information Warehousing Services. Fixed-sensors, which are deployed for TIS and TMS, initiated the studies that aim to find traffic characteristics of roads.

There have been various studies for estimating travel times or speeds using the data collected by vehicle detectors deployed on roads. Main purpose of these detectors is to measure traffic flow on a fixed point located on network. Several technologies are utilized for detection applications. Inductive loop vehicle detectors are one form of detection technology. "Data collection is typically done by inductive loop vehicle detectors embedded in (or lying on) roadways. A single detector loop provides information on traffic volumes (i.e. vehicle counts over an observational period) and occupancy (the proportion of an observational period during which the loop senses the presence of a vehicle" (Hazelton, 2004). Double inductive loop detectors also measure speeds of vehicles. There are also detection solutions based on image processing methods scanning infrared or visible range images. "Among all the applications, the predominant source of highway traffic information comes from single-loop loop detectors" (Petty, et al., 1998).

In recent years, with the fast adoption of technologies such as mobile telecommunication networks and Global Positioning System, there emerged various data sources providing information about the traveler behavior. While GPS based probe vehicles are used to estimate traffic characteristics (Bertini and Tantiyanugulchai, 2004; Rakha and Van Aerde, 1995), Zhao (2000) studied the possible uses of mobile phone locater technologies in TIS and TMS.

2.4. Global Positioning System

Global Positioning Systems are satellite-based radio positioning systems that provide instantaneous information about time, three dimensional position and velocity to receivers located on the surface of the earth. The Navigation Signal Timing and Ranging Global Positioning System (NAVSTAR), operated by the US Department of Defense, is the first of such systems widely available to civilian users. The Russian system, GLONASS, is similar in operation and may prove complimentary to the NAVSTAR system (Dommety and Jain, 1996). In addition, European Union is building a Global Positioning System called Galileo, as an alternative to NAVSTAR and GLONASS. In literature, Global Positioning System is often used to refer NAVSTAR (Dommety and Jain, 1996; Taylor and Blewitt, 1999; Zhao, et al., 2003). In the following sections, Global Positioning System (GPS) is used to refer to NAVSTAR, specifically.

The Global Positioning System is a constellation of 24 active satellites that orbit the Earth. System aims instantaneous determination of position and velocity using a GPS receiver. GPS service is available for free use in civilian applications. System is designed to provide three or more visible satellites from almost any point located on Earth Surface. GPS has two sets of services providing different accuracy levels. Standard Positioning Service (SPS), which can be accessed without any restriction, provides a predicted (at 95 percent probability) 100 meters horizontal accuracy, 156 meter vertical accuracy and 167 nanoseconds time accuracy, while Precise Positioning

Service (PPS), which requires authentication to access, provides a predicted (at 95 percent probability) 17.8 meter horizontal accuracy, 27.7 meters vertical accuracy and 100 nanoseconds time accuracy. GPS signals provided for PPS are degraded using filter Selective Availability (SA) to provide less accurate SPS service to civilian users until midnight May 1st 2000. SA was turned of by a Presidential Order on May 1st 2000 (White House, 2000). “Since SA error has been removed a low cost stand-alone GPS receiver will always provide a position within approximately 20 m of the true position. However, the position error is often much lower than this” (Taylor, et al., 2001).

GPS receivers communicate with other electronic devices via serial communication using the protocol “0183” developed by National Marine Electronics Association (NMEA). NMEA 0183 protocol defines several formats of text data, which are usually referred as “NMEA Sentences”, and contains various GPS data for various purposes (Rouhbakhsh, 2003).

2.5. Studies on Map-Matching

In general, vehicles are restricted to travel on road networks; however, positioning systems are not inherently capable of locating vehicles on the road networks. Positioning system receivers are affected by various noise sources resulting in position information that may not locate vehicle on the road network (Scott and Drane, 1994). Therefore, the raw positioning data may need to be refined to archive a precise mapping on road network. The algorithms developed in this field are referred as Map-Matching algorithms. Most of the studies are based on systems collecting data from GPS receiver equipped vehicles (Basnayake, 2004; Ochieng and Quddus, 2003; Scott and Drane, 1994). The roads are usually represented with their center-lines in digital road maps. Most of the studies report that the success of map-matching operation highly depend on the accuracy and the precision of digitized road map (Scott and Drane, 1994).

Most basic approach to the problem is to run a geometry search for the track datum to find the nearest point located on road network, commonly referred as nearest point (NP) query. This is also known as point-to-point matching. A more advanced approach is point-to-curve matching which is based on a geometry search returning the nearest curve to the track datum. Another geometric approach, curve-to-curve matching, compares the vehicle's trajectory against known roads (Bernstein and Kornhauser, 1996).

Besides the geometric techniques, raw track data can be refined prior to geometric matching by utilizing vehicle dynamics. "Kalman filtering is widely used in various system state estimations and predictions. It is a kind of linear minimum mean-square error filtering process using state-space methods. The two main features of Kalman formulation and problem solution are vector modeling of the dynamic process under consideration, and recursive processing of the noisy measurement data." (Zhao, et al., 2003). Ocak (2001) presented a software implementation of Kalman Filter on a M.S. Thesis. In his study he post-processed Differential GPS data with Kalman Filter and evaluated the improvements that can be observed.

There are studies on positioning systems equipped with additional improvements. Basnayake (2004) proposed techniques to improve map-matching using High Sensitivity GPS receivers. Scott and Drane (1994) and Ochieng and Quddus (2003) proposed algorithms for improving map-matching utilizing Dead Reckoning (DR) sensors integrated to GPS. Study of Zhao et al. (2003) presents extended map-matching techniques over Kalman Filters to be used with low-cost DR sensors with GPS receivers. Taylor and Blewitt (1999) studied map-matching techniques with data collected by differential GPS equipped vehicles. Taylor et al., (2001) proposed map-matching techniques utilizing the directions and restrictions (network tracing) over a network.

2.6. Shortest Path Problem

The term *shortest path algorithms* is commonly used as a general term to identify a set of algorithms that are capable of solving problems including least-length path, least-time path or least-cost path. In this study term *link weight* is used to generalize link attributes; link length, link travel time, link travel cost that are employed in cost functions. Shortest path algorithms are based on graph search algorithms (graph is defined later). They aim to find a sub-path (which is called a sub-graph in mathematics literature) satisfying the minimum length, time or cost (which is called weight in mathematics literature) between a source node and a destination node.

Shortest path algorithms have been a subject of extensive study for a long time. These studies resulted in several algorithms for several purposes. They can be classified according to the types of problems they solve. Source and sink (used interchangibly with destination node) definitions result in subclasses as single-source single-sink problems, single-source all-sinks problems, all-sources single-sink problems, all-sources all-sinks problems (in this study these problems are referred as *one-to-one*, *one-to-all*, *all-to-one*, *all-to-all* respectively) and other variations. Shortest path algorithms also vary according to the assumptions of attributes of networks in problem definitions. Shortest path algorithms may handle networks whose link weights (link-travel speeds, link-travel costs, etc.) are static over the time, or change as a function of time. In this study, the term *static shortest path algorithm* is used to define algorithms which are developed to handle the problem on networks with constant link weights over time. The term *time-dependent shortest path algorithm* is used to define algorithms those developed to handle the problem on networks with time-varying link weights over time. Labelling techniques proposed inside the algorithms also classify them into two sets, *label setting algorithms* and *label correcting algorithms* (Cherkassky, et al., 1994; Zhan and Noon, 2000). Shortest path algorithms can be classified into extensive categories considering other criterion which are not mentioned in this section, considering the scope of the study.

Dijkstra (1959) and Moore (1957) proposed algorithms for static shortest path problems in late 50's. These algorithms for the shortest path problem find shortest paths from the source to all destination nodes (one-to-all). Their works differentiate on the labeling techniques while Dijkstra's method uses label-setting steps (defined later), Moore's method uses label-correcting steps. Those algorithms differ mainly in the data structures used for managing the set of labeled nodes and selecting candidate nodes for scanning. Label-setting algorithms assign one label as permanent after each iteration while labels can be updated during iterations in label-correcting algorithms. In label-setting algorithms, total weight of shortest path from source to sink is determined once the sink is scanned and permanently labeled. So there is no need to scan all nodes to calculate a one-to-one shortest path. In label-correcting algorithms, all nodes should be scanned to find the shortest path, so computation complexity of 'one-to-one' and 'one-to-all' is equal.

Experimental evaluations of label-setting and label-correcting algorithms has been studied by Cherkassky et al. (1994) and Zhan and Noon (1998). Although study of Cherkassy et al. (1994) does not point a single algorithm as best-performing for all classes of shortest path problems, it concludes that Dijkstra's one-to-one label setting algorithm is more efficient than one-to-one label-correcting algorithms on networks with non-negative links. The computational study of Zhan and Noon (2000) has concluded that Dijkstra's algorithm implemented with approximate buckets (DIKBA) is the best-performing algorithm in the group of label-setting algorithms, and Pallottino's graph growth algorithm implemented with two queues (TWO-Q) is the best-performing algorithm from the group of label-correcting algorithms. Study shows that while computing one-to-one problems DIKBA implementation of Dijkstra's label-setting algorithm perform better than Pallottino's label correcting algorithm if a destination node is 'sufficiently' close to a given source node, while it is outperformed by Pallotino's algorithm if a destination node is 'sufficiently' far away from a given source node (Zhan and Noon, 1998).

Time-dependent shortest path problem has been studied by Cooke and Halsey (1966) as early as 1966. They studied the problem of finding the least-time paths between all cities to a destination city (*all-to-one*) where the time of travel between city i and city j depends on the time of departure from city i. They proposed solution for a network on which travel times for links are defined by arbitrary functions of discrete times. Later Dreyfus (1969) has extended Cooke and Halsey's study and proposed a solution based on Dijkstra's label setting algorithm. He adapted label-setting algorithm to determine the least-time path through a network with link travel times depending on the departure time.

Validity of Dreyfus's solution was questioned by Kaufman and Smith (1993) . In their study they showed that label-setting and label-correcting algorithms are valid for solution only if they have First-In-First-Out (FIFO) consistency property. *FIFO networks* are a subclass of networks in which vehicles or commodities travel along links in a First-In-First-Out manner. FIFO consistence on this case can be translated as "a traveler can not arrive sooner if he leaves later". Another limitation of Dreyfus's solution is, only one single departure time is considered, a *one-to-one* solution. A *one-to-all* solution on time-dependent shortest path problems is covered by Leurent and Aguilera (2005). In their proposed algorithm each link has been divided into its subsets according to the unique value set for link delay function, identified by time intervals, each subset is referred as "atom" in the study. Proposed algorithm computes minimum-cost paths for all departure times from a single source node.

Dreyfus's (1969) solution, which is valid for networks with *link weights* defined by arbitrary functions, can solve limited number of cases. Orda and Rom (1991) proposed an algorithm for least-cost path problem in networks, link costs and link travel times of which are both functions of time. Their application, based on functions using continuous time, shows the possibility of infinite paths with finite minimum total cost (valid for networks containing loops). Their study includes three time dependent costs, which are link travel times, link costs and node parking times. Unlike the previous studies referred, Orda and Rom include weights on nodes referred as "parking costs" in their solution.

Horn (2000) studied approximate methods for estimating least-time shortest path problem. To meet the potential lack of information about the network conditions it is presumed that estimates of the average speed on individual network links are available at pre-defined sample time intervals. The assumptions made by Horn (2000) imply a condition of FIFO consistency.

Besides the static shortest path algorithms and time-dependent shortest path algorithms, there have been studies for solving shortest path problem on networks where link-weights are stochastic. Hall (1986) demonstrated shortcomings of Dijkstra's algorithm based solutions on non-stationary networks with variable link lengths.

Heuristic functions are also employed in shortest path problems to improve computational time. Hart et al. (1968) proposed A-star (A*) algorithm which extends Dijkstra's algorithm by utilizing a heuristic estimation function to rank nodes during iterative scan. Function estimates the distance left to the destination node, and scans the nodes in the order of returned values from heuristic function. Liu's (1997) study show that A*, a best-first search using heuristic estimate, performed best amoung popular search algorithms.

CHAPTER 3

METHODOLOGY

This chapter focuses on the methods and approaches to develop a model to estimate traffic characteristics using track data collected from GPS-equipped vehicles. As the first step, a digital representation of the traffic network is needed, which can be generated using GIS tools and stored in a geographic database. Next step is to develop a map-matching method that associates the GPS track data with the selected traffic network. Finally, matched GPS data are processed to produce travel time information for the network segments which are used in the solution of the time-dependent shortest path problems.

3.1. Traffic Network Development

In this section, the methods to create a spatial-database representing a traffic network are presented. A geographic database defining a road map is processed to create a custom GIS-T database to fulfill the requirements of this study.

As defined earlier in Section 2.1, the term network describes an interconnected set of nodes, where nodes and links represent relations between entities on varying subjects, e.g. social networks, traffic networks, internet, etc. Each dicipline has its own criteria when defining a node and interconnecting links.

In traffic networks, nodes represent:

- a topologic change in network, such as physical intersections of roads.
- a seperator for a change in characteristic of traffic, such as a start of a speed restriction zone, a speed bump, a bus stop etc.

- an imaginary point that associates external measures to the traffic network, such as assumed origin/destination points as in the case of a parking lot, centroid of a traffic analysis zone, shopping centers, boundary points that extend to other networks.

3.1.1 Creating A Network Using GIS Tools

Physical representation of a network can be created in different ways. GIS packages provide user-friendly environments for creating digital representations of networks. These packages provide interfaces, which seamlessly integrate remotely sensed imagery that can be used as a base-map for network representation creation. The generated representation and associated characteristic parameters are stored in a geographical data structure, which mainly consists of "Links" and "Nodes". These components will be discussed in further detail below.

a. Links

In traffic network representations, links represent the traffic flows between nodes. Links are generated using the digital road map stored in the spatial database, at compile time defined in Section 3.1.2. A digital road map for area of interest is generated using a GIS Package. Generated data are stored in a spatial-database. Links on the network are represented by geographic data features. In geographic data features, spatial representations *(geometries)* are stored as *multicurves* in spatial field. A multicurve, as defined by OpenGIS, is a geometry collection that consists of multiple curve geometries, where a curve, is a geometry, consisting of sequential control points. The sequential order of control points determine the *physical direction* of a curve, which is the order followed during control point addition in the creating of physical representations of links.

A link represents a single direction of flow, so two distinct links are required to represent a bi-directional flow between two nodes, such as a bi-directional traffic flow on a street. However, bi-directional flow between two nodes is represented using a single geographic data record, which is converted into two distinct links in compile time

(See Section 3.1.2). Physical direction of a curve may differ from the travel direction of the link it represents. The information on travel direction(s) of a link compared to its physical direction can be stored in an additional integer field, using the values “0”, “1” and “2”, standing for a traffic flow in “two directions”, “in the direction of the link” and “reversed direction”, respectively. The format of a link table is shown in Table 3.1.

Table 3.1 Link table design

Field Name	Type
ID	Numeric
Geometry	Spatial
Direction	Numeric

b. Nodes

A node map can be generated and stored in geographical data format. Each node on a network is represented by a single geographic data feature, which includes a coordinate pair defining its position on a coordinate system.

There may be multiple nodes at exactly the same point with different types and purposes, such as a point that represent both an origin and a destination node. Maintainability of the system highly depends on the integrity of data, so such nodes can be represented by a single geographic data feature with attribute fields defining several properties for multiple characteristics. For a traffic network, nodes are classified into four categories according to their characteristics represented by an integer values as follows:

Code 0: A bus stop.

Code 1: A speed bump.

Code 2: An imaginary node behaving as a trip origin or a destination.

Code 3: Road intersections and interchanges.

The node types are stored in the same node data table with additional three numeric fields, as shown in Table 3.2. Link intersections are not generally included in GIS data file, and generated in compile time, while GIS data are processed to generate a traffic network data structure.

Table 3.2 Node table design

Field Name	Type
ID	Numeric
Geometry	Spatial
NodeType	Numeric
Var1	Numeric
Var2	Numeric
Var3	Numeric

3.1.2 Creating Digraph From GIS Data

A digraph, as described in Section 2.1.1, is a mathematical model for representing a network. GIS provides tools for creating and modifying physical representation of a network. Some commercial GIS packages also provide indices that handle the topological relations between geometric features and include tools to query on topologically indexed data. In this study, a digraph data structure is designed to handle the topological relations while preserving the spatial references for further GIS operations.

Digraph data define nodes, links and their topological relations. The data for the links and nodes are kept in the *link table* and *node table,* respectively. Network data, which are stored in GIS data files, are extended by topological relation tables to represent a digraph. Conversion requires several steps. First, the link data, stored as a set of *multicurve* objects, are read to create a node set that defines the start point and the end point of each link. An algorithm named *CreateNodes* is developed for this process and can be found in Appendix A, Figure A-1.

Following the creation of nodes, the next step is to fill the link set of the digraph, which is performed via an algorithm named *CreateLinks* (Appendix A, Figure A-2). *CreateLinks* algorithm traces *link table* and nodes, which are created by *CreateNodes* algorithm, to create a set of links. The following step is to create and store the topological relations between links and nodes in an adjacency matrix, as described in the algorithm named *CreateAdjacencyMatrix* (Appendix A, Figure A-3). Once the topological relations are defined, the next step is to associate nodal attributes, which are stored in *node table*, with the node set created in algorithm *CreateNodes* (See the algorithm *SetNodesAttributes* in Appendix A, Figure A-4). As a result of these steps, a digraph data structure modeling a traffic network is populated. Once a traffic network is ready, the next step is to add the travel characteristics for the links and nodes. Major attributes include travel times, average speeds, capacity information for links and waiting/dwell time and number of originating trips for the nodes if there are any. Some of these measures can be obtained from GPS track logs, which require matching of the GPS data to the associated network component that is discussed Section 3.2.

3.2. Mapping Track Data onto a Traffic Network

The matching of the track data onto a traffic network requires a) matching of the track data point to a network component (a link or a node), and b) a directional mapping to form the route of the vehicle equipped with a GPS receiver. The first step is a basic point-to-curve matching, which is a spatial search method that matches the closest link in the nearest neighborhood to the track datum. This step includes an alignment matching, where the direction of the link is compared with the instantaneous direction vector obtained from GPS data. The second step traces consecutive track data to create routes, which are sets of space and time-continuous track data of each vehicle. Routes are projected on the traffic network to control connectivity and consistency of the mapped track data.

In addition to geographic position, track data provide the temporal information of the vehicle, including an instantaneous motion vector. These temporal data are needed for a time-dependent traffic analysis to decide which time window the derived characteristics will represent. Thus, a sorting algorithm based on the time of the observance of GPS track data is to be included in the process of mapping of those data to the associated link or node.

Level 1: Point-to-Curve Matching

In this step, the raw data collected with GPS (referred as *track data*) are associated with links according to their euclidian distance to links and their intantenous alignment with respect to north, which is also provided by GPS. First, an area defining extends of the network is created to trim total track data. Track data falling outside of extends are not mapped.

For the track data falling within the selected study area, mapping is done in several steps. Let Φ^i denote the GPS track datum at i^{th} time-epoch. To map the i^{th} track datum to the nearest link, nearest link is found by calculating the shortest distances to the control points of the links. Unless an efficient search algorithm is used, this step requires calculation of all control points on all the links resulting in a decreased complexity (APPENDIX B). As an alternative, a search based on Minimum Bounding Rectangle (MBR) intersection method is employed. For large networks, advanced spatial indexing methods, such as R-Tree, can be used to minimize calculation time. Steps of this procedure can be summarized as follows:

Step 1. Create a set of MBRs for each link.
Initizalize each member of set of $\gamma^i = -1$.

Step 2. Select a track datum to be matched with network links (Φ^i).

Step 3. Define a rectangular neighbourhood $R_{\Phi i}$ for the track datum Φ^i using a predefined proximity value.

Step 4. Find the eligible set of MBRs, $S_{\Phi i} = \{j \in$ links where MBR_j intersects $R_{\Phi i}\}$
If intersection set is empty, leave Φ^i unmatched.

Step 5. For every $j \in S_{\Phi i}$ calculate the shortest distance between Φ^i and the links on set S. Set γ^i to closest j. Set φ^i to projected position of Φ^i on the link j.

Step 6. Set i = i+1 and go to step 2.

Notations used in this chapter are given in Table 3.3. Geometric definitions used in the steps above are shown in Figure 3.1.

Table 3.3 Notations used in map-matching and travel time estimation algorithms

Notation	Definition
x	X coordinate of position of vehicle
y	Y coordinate of position of vehicle
υ	Instantaneous motion vector of vehicle
Φ^{t_j}	Set of {x, y, t, υ} representing track datum recorded at time t_j.
γ^{t_j}	Matched link for track datum Φ^{t_j}
φ^{t_j}	Projected point of Φ^{t_j} on σ^{t_j}
Γ_i	Successor link(s) to link i
$\Gamma^{-1}{}_i$	Predecessor link(s) to link i
Γ_{ir}	Successor link to node i on route r
$\Gamma^{-1}{}_{ir}$	Predecessor link to node i on route r
Γ_φ	Node defining the end of link where φ located on
$\Gamma^{-1}{}_\varphi$	Node defining the start of link where φ located on
SPL_{ij}	Set of links defining the shortest path between node/point i and j
SPN_{ij}	Set of nodes defining the shortest path between node/point i and j
$Dist_{ij}$	Length of SPN_{ij}
Con_{ij}	Connectivity between links i and j
$Speed^{jk}$	Average travel speed on the shortest path connecting point φ^{t_j} and φ^{t_k} where travel duration is $\Delta t = t_j - t_k$
R	Set of routes.

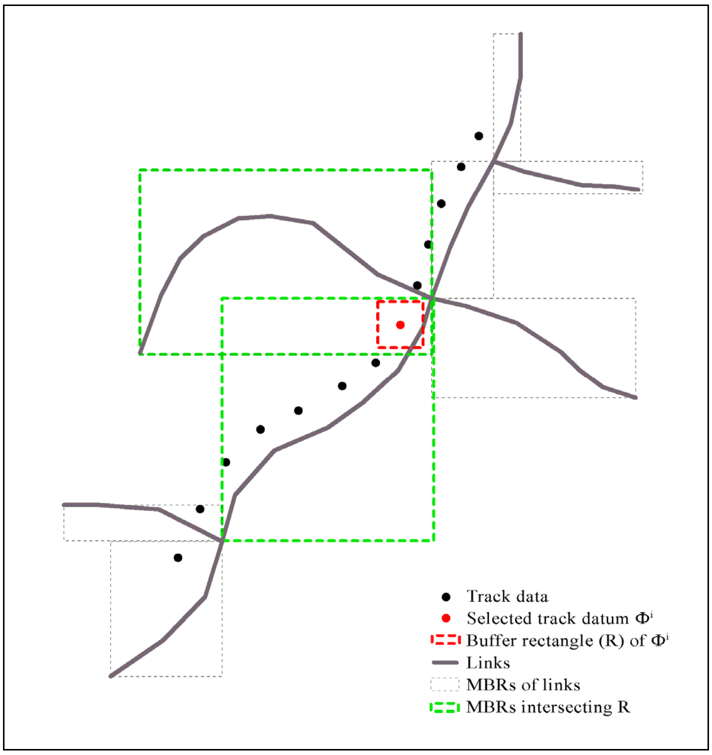


Figure 3.1 Spatial-search based on MBR-intersection

To find the eligable MBRs, additional information (speed and course) provided in a GPS track datum can be utilized. Instantaneous course data provided by GPS can be used to eliminate links which have an opposite flow direction with course of track datum. However course data recorded while vechicle is traveling in low speeds are ignored due to decreased relevance. If instantaneous speed is bigger than the minimum confident speed limit, intantaneous course is compared with the tangent of the link at the projected point link j. If they are in the same direction j is added to the eligable set of MBRs "S". See APPENDIX B Figure B-1 and B-2 for pseudo codes developed for PTC matching and MBR-intersection search respectively.

It should be noted that PTC mapping step matches track data to links using basic spatial techniques, ignoring the topologic characteristics of the traffic network. Not all of the track data are provided with its alignment data, such as track data of a parking vehicle. Missing alignment data or any error in the alignment data may lead to incorrect mappings, which should be checked for the consistency and coherence by route-based assignment tasks.

Level 2: Route-based Matching

As the scope of this study is to find the characteristics of a traffic network, we have to check if all the links, which are travelled during a trip, are matched by a GPS track datum. For the unmatched links we estimate the links travelled by tracing the track log of a vehicle with respect to network topology.

During a simple PTC matching, there might be mismatched links due to link geometries which can be corrected by a Route-based Matching (RBM). If there are persistent mismatching or inconsistency in matching of track data is detected using network topology, further assesment of the problem is possible via RBM.

Basic steps of RBM can be summarized as follows:

- Select a track datum.
- Set the first track datum as the start point of a route "r" and initialize j = 0.
- Check if the next track datum $\Phi^{t_{j+1}}$ falls on route r.
- If track datum is accepted as a part of r, $r = r \cup \Phi^{t_{j+1}}$.
- Otherwise try to correct the matching of Φ^{t_j} and $\Phi^{t_{j+1}}$.
- If correction is not possible, stop r at Φ^{t_j}, start new route r with $\Phi^{t_{j+2}}$.

There are multiple criteria to accept a datum to a route. First, duration between two consecutive track data should be checked to see if there are long breaks, which shows possible discontinuity in GPS data collection process. If so, instead of offering any possible route, the current route is closed, and a new route with new start time is initiated. Secondly the locations of the consequent track data are checked to see a) if they are on the same link in a consistent order, b) if not, whether they are on adjacent links. The second measure to check consistency is the location of two consequent track data. They can be on the same link, but the locations have to be checked to see if they are in the expected order with the direction of the link.

If two consecutive data are not on the same link or adjacent links, the possibility of finding a path reachable from the last point datum in the route to next via the network connectivity has to be searched. If there exists at least one such subpath, the datum is accepted to the route. For all topological accessibility controls, the track speed between two track data has to be checked against a reasonable limit. Schematic representation of the steps explained above is shown in Figure 3.2. See Appendix C for flow charts showing the algorithms developed for RBM.

3.3. Estimation of Travel Characteristics

So far, GPS track data for a vehicle are matched with traffic network. Next step is to derive link travel characteristics from the track log information. Travel characteristics of the vehicles can be represented by cost functions of links and/or nodes in a traffic network. If time-dependent analysis is needed for network analysis, the travel characteristics have to be time-dependent as well. Travel cost of a link can be defined in many ways, such as travel time, travel cost (in monetary terms), fuel consumption, etc. For this study, the cost is measured in terms of travel time. To estimate the time-dependent costs for network links, time-dependent link travel times need to be calculated. If a more precise analysis of spatio-temporal distribution of the link travel times is needed, the different link costs can be defined for selected time-of-day and every day-of-week analysis-windows.

Any length of analysis-window can be selected to study the time-dependent nature of the travel characteristics in a network, as long as the traffic conditions within these analysis-windows can be assumed to be homogenous. However, the analysis-windows can be customized based on the network and demand specifics. For example, if the travel characteristics are not changing frequently within a day, windows of time-dependent analysis can be selected in a more aggregated way such as morning peak, noon-off peak and evening peak windows in a day. Similarly, weekday and weekend days can be studied separately. If needed, weekdays can be categorized as mid-week days (Tuesday-Thursday) versus week start/end days (Monday, Friday).

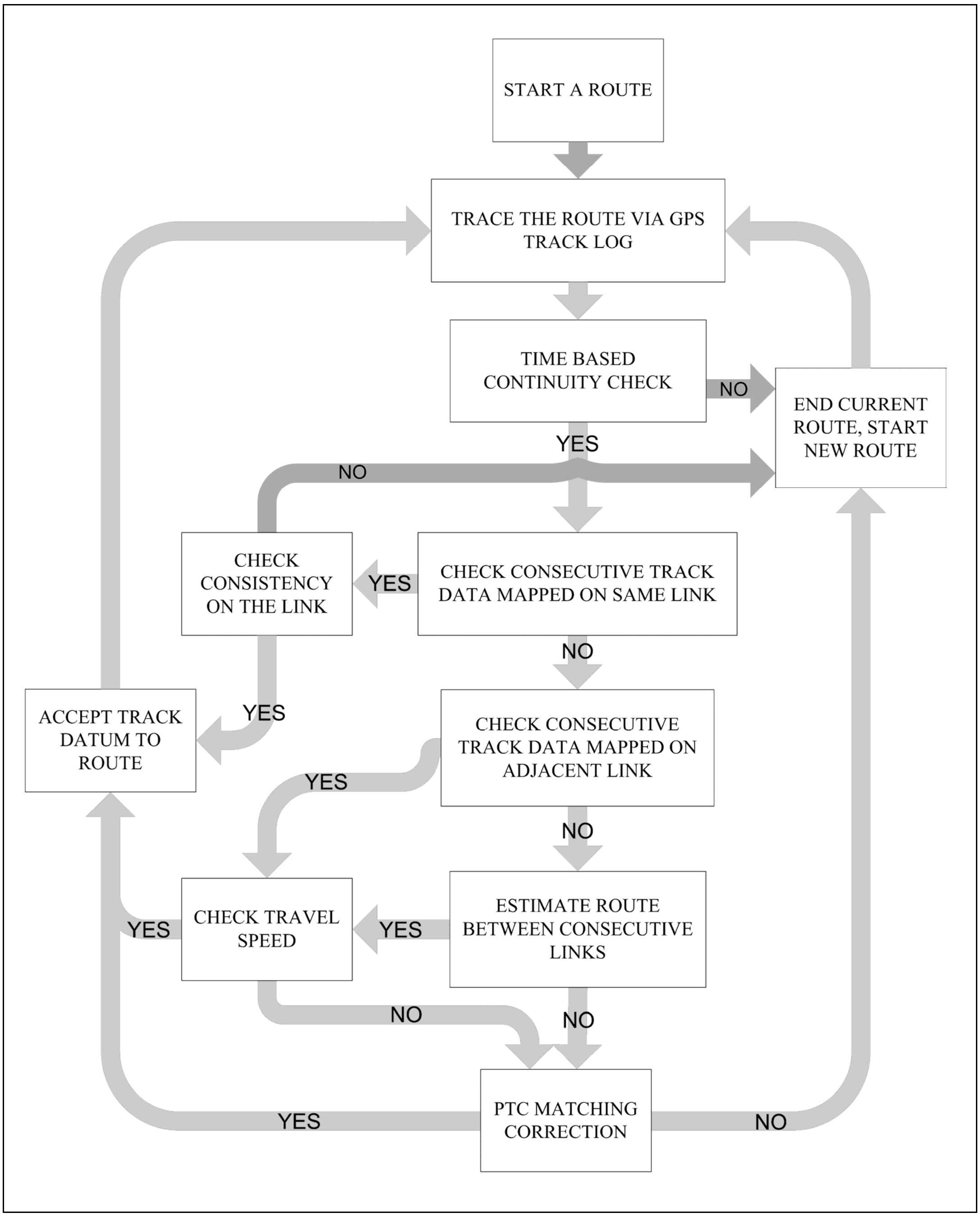


Figure 3.2 Schematic representation of RB matching

3.3.1 Link Travel Time Estimation

Link travel time is defined as the time required for a vehicle to enter and exit a link. For this, an enter time (t_{in}) and an exit time (t_{out}) have to be determined using map-matched tracked data. We can detect or estimate these t_{in} and t_{out} (Figure 3.3).

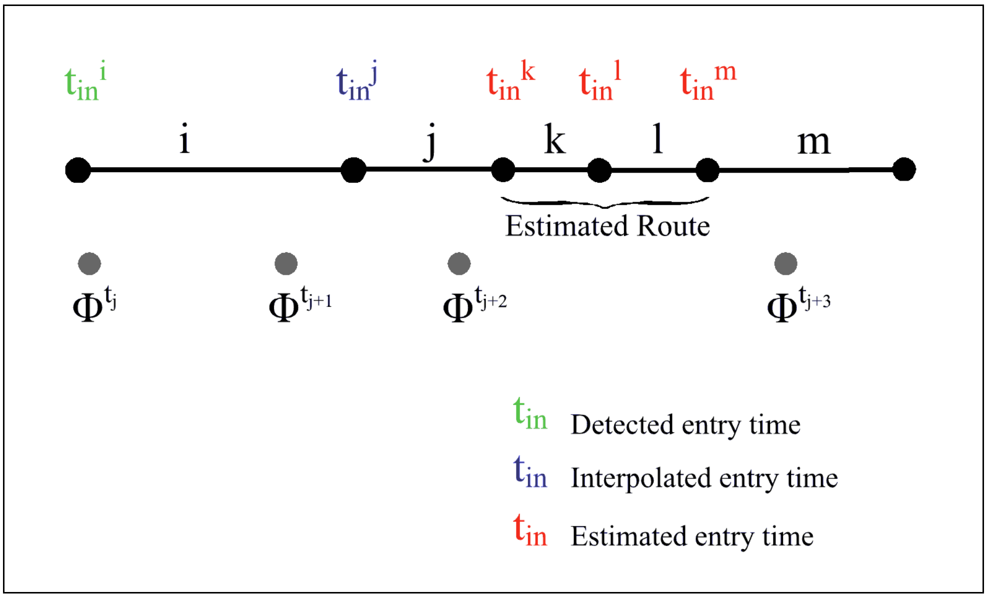


Figure 3.3 Link entry-time calculation

An Algorithm to Estimate Link Travel Times

Each track datum ($\Phi_{\alpha}^{t_j}$) of each route ($\forall r \in R$) is examined in order of track time (t_j). Enter and exit times for each link are caculated using linear interpolation. Link travel time estimation mapping follows the steps given below to estimate travel times (Figure 3.4).

Step 1. For each $r \in R$, compare each consecutive track data $\Phi_{\alpha}^{t_j} \in R$.

Step 2. Check conditions A and B.

Condition A: If consequent track datum is mapped on the same link proceed to Step 1 to fetch next $\Phi_{\alpha}^{t_j} \in R$

Condition B: A shortest path connecting the points φ_α^{tj} and φ_α^{tj-1} on mapped links is calculated. t_{in}^{ir} and t_{out}^{ir} time values are calculated by linearly interpolating t_j and t_{j-1} with the link lengths and $Dist_{SPL\varphi_{\alpha tj}\varphi_{\alpha tj-1}}$

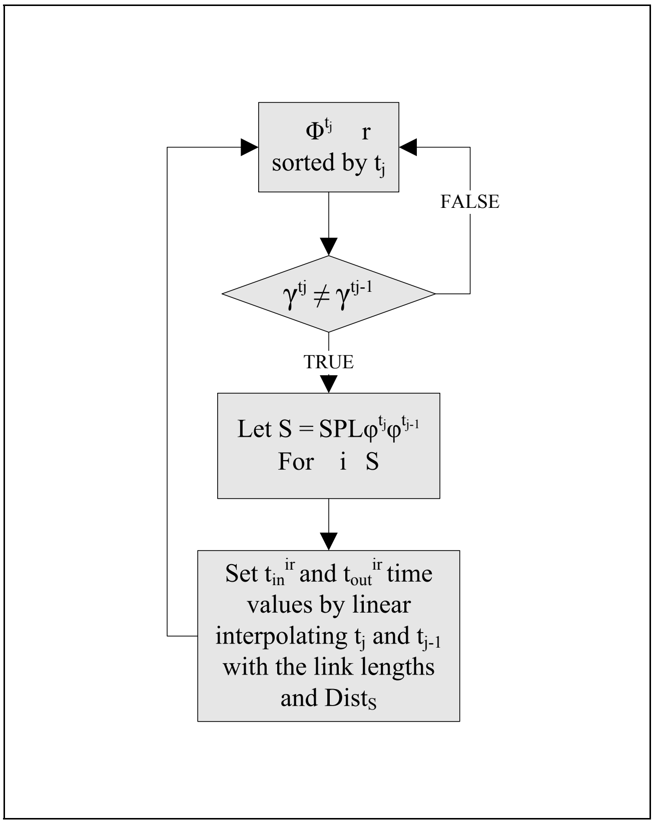


Figure 3.4 Link cost assignment using linear interpolation

3.4. Time-Dependent Traffic Characteristics

In the previous sections, the information collected from vehicles has been processed to create the link-based travel data (Figure 3.5). Link-based travel data (shortly link-travel data), which include entry and exit times, should be processed to create a database consisting of time-based traffic network information for datawarehousing. Data can be analyzed in any selected time window (T), such as time-of-day and every day-of-week.

Determined time window can be divided into sub-windows, which is referred as *time-interval* (τ), depending on the requirements of analysis.

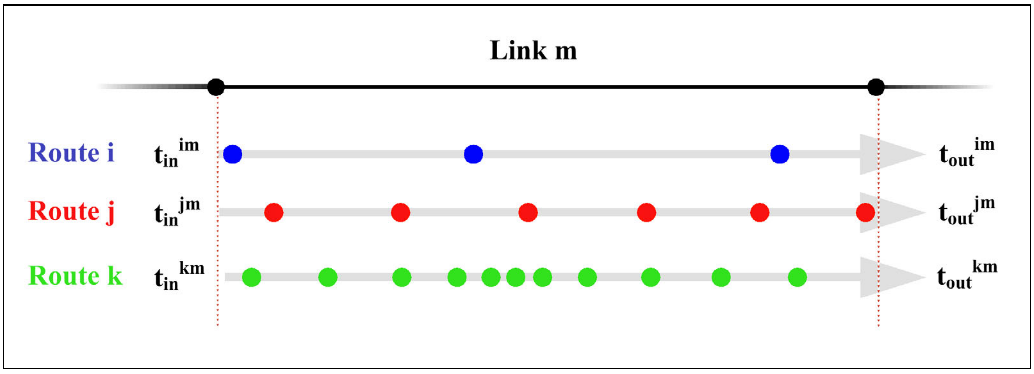


Figure 3.5 Possible GPS track data mappings on a link

Link-travel data are used to calculate travel times of links along routes. Cost of link m along route i (c_m^i) is equal to the duration of travel between entry ($t_{in}^{i,m}$) and exit ($t_{out}^{i,m}$) times. Cost data (c_m^i) are assigned to time-intervals (τ) when entry time of link-travel ($t_{in}^{i,m}$) falls into respective time-interval. Sets of costs of links for each time-interval are populated with travel link-travel data. Finally, single cost information per time-interval is calculated from the set of costs of each link. Cost information for a link at a single time-interval consist of, average of cost values in the respective time-interval, sample standard deviation of these cost values, minimum cost value among these cost values and maximum value among these cost values. A cost information table calculated for a time-interval is shown in Figure 3.6.

$$C_m = \left\{ \begin{array}{c} \tau=0 \\ \tau=1 \\ \tau=2 \\ \cdots \\ \tau=n \end{array} \right. \begin{bmatrix} \bar{c}_{m\tau_1} & \delta_{Cm\tau_1} & \min_{Cm\tau_1} & \max_{Cm\tau_1} \\ \bar{c}_{m\tau_2} & \delta_{Cm\tau_2} & \min_{Cm\tau_2} & \max_{Cm\tau_2} \\ \bar{c}_{m\tau_3} & \delta_{Cm\tau_3} & \min_{Cm\tau_3} & \max_{Cm\tau_3} \\ \cdots & \cdots & \cdots & \cdots \\ \bar{c}_{m\tau_n} & \delta_{Cm\tau_n} & \min_{Cm\tau_n} & \max_{Cm\tau_n} \end{bmatrix}$$

Figure 3.6 Time-dependent cost information of link m.

Cost information database provides time-dependent cost information for time-dependent network analyses. The columns of the information are designed to serve various network analysis methods for various purposes. While $\overline{c}$ column can be used for network analyses with deterministic cost assumption, the sample standard deviation column, δ, with $\overline{c}$ column can be used for network analyses with stochastic cost assumption. The information stored in columns min and max can be used for best-case and worst-case analyses respectively. Data warehousing for further analyses can be performed on cost information database.

Solutions for shortest path problems are trivial. As reviewed in Section 2.6, there have been various studies for both deterministic and stochastic shortest path problem. Solution to be used depends on the requirements, such as temporal precision, computational simplicity, etc. Time-dependent shortest path problems should be solved by a time-dependent shortest path algorithm unless both departure and arrival times fall into the same analysis-window. Lower calculation times can be achieved with the use of static shortest path algorithms in the shortest path queries where arrival time is expected to be in the same analysis-window with the departure time.

CHAPTER 4

CASE STUDY

The case study environment used to test the proposed methology is the road network of Middle East Technical University campus, located in Ankara, Turkey. This section outlines the details about the case study environment and results derived from the test scenario that is run in the environment.

4.1. Study Area

Study area of this thesis is the Middle East Technical University (METU) campus. METU is a public university founded in 1956. METU land is located on the Ankara-Eskişehir highway in Ankara, Turkey (Figure 4.1). The METU land, covering 4500 hectares of area including Lake Eymir, is about 20 kilometers from the center of Ankara (METU, 2006). Campus has an estimated population of 30,000. As present, built-up area of the land, which is referred as METU Campus, is about 250 hectares, which covers the northern part of the land. The road network, which this study is based on, connects the facilities located in the campus and the gateways to Ankara. Campus is connected with Ankara road network through three gates, A1 on Ankara-Eskişehir highway, A7 on Bilkent Road and A4 on district of 100.Yıl. Although there are more connection nodes to Ankara network, they have restricted accessibility for authorized official fleet. Campus will also be connected to Ankara through the Kızılay-Çayyolu heavy rail system, which is under construction at present. Kızılay is the central business district of Ankara.

Figure 4.1 Location of METU campus in Turkey and Ankara

Campus traffic network

METU has a road network, mostly serving to campus area, located in the northern part of the overall METU land. For the required network analysis, a digital map representing road network of METU is generated. To get most accurate travel time estimates from methods given in Section 3.3, routes derived from track data should be mapped into digital map successfully. Success of map-matching methods highly depend on the accuracy and precision of the digital road map. To create such digital road map, a high precision satellite image of the campus area is used. This satellite imagery is provided by Inta Spaceturk. The imagery product has a 2-meter or better horizontal precision (root mean square error) as a result of rectification process conducted by using ground control points collected using Differential GPS receivers.

Campus network is created by using “MapInfo Professional V8.5” GIS package. Almost all features affecting traffic flow, including speed bumps and parking lots, are digitized to have a digital map for general purposes. Digital road map consists of 451 polyline records, each of which represents a single or a two directional traffic flow. Records are converted into links during digraph generation, resulting in 683 links, each represents a single direction of traffic flow (Figure 4.2). Four types of nodes are registered in the network:

- External nodes: The connection points with the rest of the Ankara network are represented using “external nodes”. One can use external nodes to represent the effect of Ankara network, by reflecting the demand generated on these points. Since, the effect of generated demand by the external network on travel times can be measured by the methods of this study, no exceptional calculations based on external nodes are performed.
- Bus stops: These are stops used by transit vehicles of METU, which are called “Ring buses”.
- Speed bumps: While this study does not study the effects of speed bumps on traffic flow, digitized road map includes these points for further analyses.

- Parking lots: Parking lots are represented as nodes, too. With the "External Nodes", these behave as origin or destination nodes for trips, which are generated in campus by non-transit vehicles.
- Intersection nodes: These are the nodes created on intersection points of links.

Network includes 375 nodes, 144 of which are created during digitization step. Rest of the nodes, which are Intersection Nodes, generated automatically during digraph generation. Numeric distribution of nodes by type is shown in Table 4.1.

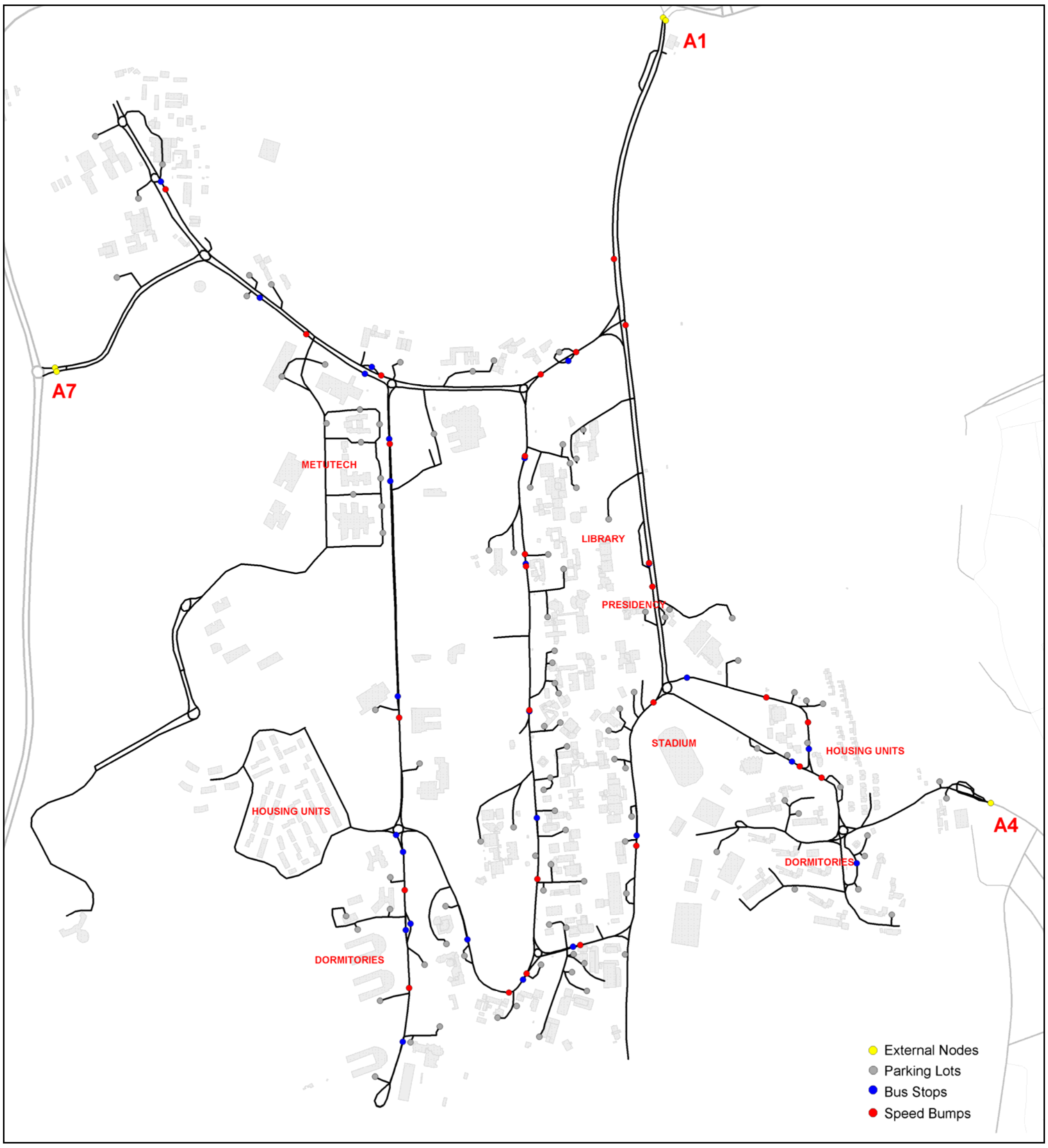


Figure 4.2 Road network and built-up area of METU campus

Table 4.1 Distribution of nodes by type

Node type	Number of occurrence in the network
External nodes	6
Bus stops	26
Speed bumps	24
Parking Lots	180
Intersection Nodes	213

4.2. GPS Track Data

In this study, GPS track data are obtained from two types of sources, a fleet tracking system with historic logs and handheld GPS receivers. METU has its own assigned fleet which serves to fulfill transportation needs in the campus. Some of the vehicles on this fleet are tracked by directorate of transportation affairs, using vehicle telematics systems based on GPS receivers and mobile data services. Vehicles are tracked with the fleet tracking service, named as “TAKİPONLİNE”, which is provided by Inta Spaceturk. “TAKİPONLİNE” uses Turkcell GSM network for real-time data transfer from field, utilizing mobile data services standard General Packet Radio Services (GPRS). The tracking data are kept in database for up to one year of time for analyses. Inta provided the data as a delimited text file, structure of which is shown in the next section.

A set of controlled data for the study area is collected using handheld GPS receivers. Data are collected by a scheduled transit vehicle and by a car, which traveled on predefined routes. Magellan GPS receivers with models 400 and XL provided NMEA sentences to logging devices through serial port with one-second epochs. Structure of GPS log files is discussed in the next section.

Data Specification

In this section, structure of log files provided by fleet tracking system and handheld GPS are defined respectively. Both of the data are provided as delimited text files, encoded by ISO/IEC 8859-1 standard. Screen shot of the provided data-file is shown in Figure 4.3.

```
210137326|10014|727745,4|488665,4|1|322|21.11.2006 02:52:42
210137346|10014|727749,6|488673,3|0||21.11.2006 02:52:51
210144909|10014|727740,1|488672,4|2|11|21.11.2006 03:53:14
210144928|10014|727743,2|488687,1|6|1|21.11.2006 03:53:23
210144949|10014|727741,3|488698,6|5|325|21.11.2006 03:53:33
210144983|10014|727738|488714,5|14|290|21.11.2006 03:53:43
210145006|10014|727697,6|488726,9|10|315|21.11.2006 03:53:53
210145034|10014|727695,9|488730,7|0||21.11.2006 03:54:03
210145738|10014|727695,6|488732,1|2|329|21.11.2006 03:58:41
210145764|10014|727690|488761,9|16|339|21.11.2006 03:58:50
210145791|10014|727634,8|488758,3|22|249|21.11.2006 03:59:00
210145816|10014|727669,1|488694,8|34|147|21.11.2006 03:59:10
210145841|10014|727717,6|488597,8|43|151|21.11.2006 03:59:20
210610357|10017|727731,3|488683,7|0||22.11.2006 02:08:11
210610392|10017|727729,3|488680,8|2|137|22.11.2006 02:08:31
210610418|10017|727728,9|488679,1|1|162|22.11.2006 02:08:41
210610435|10017|727729,3|488679,6|0||22.11.2006 02:08:51
210610455|10017|727729,9|488680,8|1|160|22.11.2006 02:09:02
210610478|10017|727732,7|488685|0||22.11.2006 02:09:11
210610716|10017|727735,2|488690,8|1|85|22.11.2006 02:10:52
210610735|10017|727735,7|488697,6|0||22.11.2006 02:11:01
210610843|10017|727733,8|488704|1|153|22.11.2006 02:11:51
210610867|10017|727732,7|488701,9|0||22.11.2006 02:12:01
210610914|10017|727734|488693,8|3|173|22.11.2006 02:12:21
210610937|10017|727735,3|488695,5|0||22.11.2006 02:12:31
```

Figure 4.3 Fleet tracking system log file

Fleet tracking data log is kept in Inta Spaceturk (Inta) "TAKİPONLINE" database, located in the datacenter in their Bilkent office. Table 4.2 summarizes brief definitions of columns of the delimited text file provided by Inta.

Two sets of data are provided with two distinct time epochs. First set of data includes the track logs of METU fleet, logged from Oct. 25, 2006 to Nov. 16, 2006, with 30-second epochs. This set consists of 703,666 track data, 331,447 of which fall inside of the defined study area. Second set of data is the track log of four scheduled vehicles from METU fleet, collected from Oct. 25, 2006 to Nov. 16, 2006, with 10-second epochs. This set consists of 47,560 track data, 35,294 of which fall inside the defined study area. Data are originally retrieved in Geographic coordinates. Later, these coordinates are re-projected using Lambert Conformal Conic (LCC) projection on WGS84 ellipsoid before inserting into database. The parameters used for LCC projection can be found in Table 4.3.

Table 4.2 Raw track data column details

Column No.	Content
1	Record id. An auto-increment field, assigned in order of time that the record is inserted.
2	Vehicle id. Each associated with a unique plate id.
3	X component of the coordinate of a vehicle during corresponding tracking time. (Coordinate system defined below)
4	Y component of the coordinate of a vehicle during corresponding tracking time. (Coordinate system defined below)
5	Vehicle speed during corresponding tracking time. (In kilometers per hour)
6	Vehicles alignment with respect to north during corresponding tracking time.
7	Time of tracking. In 12 hours “d/m/Y h:M:S (AM/PM)” format. E.g. “8/20/2006 2:10:41 AM”

Table 4.3 Parameters used in raw track data for Lambert Conformal Conic Projection

Parameter	Value
False Easting	1003827.11 meters
False Northing	-1183453.08 meters
Standard Parallel One	37.5
Standard Parallel Two	40.5
Units	Meter
Origin Latitude	25.0
Origin Longitude	36.0

Second type of sources, that is used to obtain track data, is by handheld GPS receivers. GPS receiver data are logged in laptop computers. The data are transferred via serial communication as NMEA sentences. Screenshot of GPS log file is shown in Figure 4.4.

```
$GPRMC,120156.23,A,3953.4378,N,03247.4066,E,15.3,353.3,181106,04,E*4E
$GPGGA,120157.22,3953.4421,N,03247.4060,E,2,08,1.8,00924,M,,,,*23
$GPRMC,120157.22,A,3953.4421,N,03247.4060,E,15.5,353.5,181106,04,E*43
$GPGGA,120158.23,3953.4465,N,03247.4053,E,2,09,1.5,00924,M,,,,*21
$GPRMC,120158.23,A,3953.4465,N,03247.4053,E,15.8,352.1,181106,04,E*45
$GPGGA,120159.22,3953.4508,N,03247.4044,E,2,07,3.0,00923,M,,,,*23
$GPRMC,120159.22,A,3953.4508,N,03247.4044,E,15.6,350.6,181106,04,E*42
$GPGGA,120200.22,3953.4549,N,03247.4032,E,2,06,4.0,00923,M,,,,*2E
$GPRMC,120200.22,A,3953.4549,N,03247.4032,E,15.2,344.3,181106,04,E*4D
$GPGGA,120201.23,3953.4588,N,03247.4014,E,2,06,3.7,00922,M,,,,*26
$GPRMC,120201.23,A,3953.4588,N,03247.4014,E,14.5,335.5,181106,04,E*42
$GPGGA,120202.22,3953.4622,N,03247.3991,E,2,09,1.6,00922,M,,,,*28
$GPRMC,120202.22,A,3953.4622,N,03247.3991,E,13.3,328.7,181106,04,E*4F
$GPGGA,120203.23,3953.4651,N,03247.3963,E,2,08,2.5,00921,M,,,,*23
$GPRMC,120203.23,A,3953.4651,N,03247.3963,E,12.6,320.7,181106,04,E*4A
$GPGGA,120204.22,3953.4676,N,03247.3932,E,2,08,2.6,00921,M,,,,*27
$GPRMC,120204.22,A,3953.4676,N,03247.3932,E,12.4,312.3,181106,04,E*4A
$GPGGA,120205.22,3953.4697,N,03247.3897,E,2,08,2.4,00920,M,,,,*24
$GPRMC,120205.22,A,3953.4697,N,03247.3897,E,12.6,304.0,181106,04,E*4C
$GPGGA,120206.22,3953.4715,N,03247.3857,E,2,08,2.4,00920,M,,,,*20
$GPRMC,120206.22,A,3953.4715,N,03247.3857,E,12.8,298.9,181106,04,E*4B
$GPGGA,120207.22,3953.4733,N,03247.3812,E,2,09,1.6,00920,M,,,,*24
$GPRMC,120207.22,A,3953.4733,N,03247.3812,E,15.4,298.6,181106,04,E*4B
$GPGGA,120208.22,3953.4755,N,03247.3761,E,2,09,2.1,00919,M,,,,*2E
$GPRMC,120208.22,A,3953.4755,N,03247.3761,E,16.8,300.0,181106,04,E*46
```

Figure 4.4 NMEA sentences in GPS log file

Two types of NMEA sentences are logged:

- RMC: This set of data is defined as "Recommended Minimum Specific GPS/TRANSIT" by NMEA. It is designed to contain minimum set of GPS data for general-purpose usage. Data provided by RMC are shown in Table 4.4.
- GGA: This set of data is defined as "Global Positioning System Fix Data" by NMEA. It defines a set of data containing parameters that effect the accuracy of GPS receiver. Data provided by GGA are shown in Table 4.5.

While all the data required in map-matching steps can be obtained from RMC sentences, GGA sentences are logged for possible further analyses.

Table 4.4 NMEA RMC sentence data definition

Data Type	Sample Value	Description of value
Sentence Type	$GPRMC	Type of the sentence is RMC
Time of fix	120105.21	12:01:05 P.M. (Greenwich Main Time)
Navigation	A	A = OK, V = warning
Latitude	3953.3482,N	39^o 53' 34.82" Northern Hemisphere
Longitude	03247.4426,E	32^o 47' 44.26" Eastern Hemisphere
Speed over	15.7	15.7 Knots
Course	314.1	True Course of 314 degrees
Date of fix	181106	November 18,2006 (Greenwich Main Time)
Magnetic	04,E	Magnetic Variation
Checksum	*40	Required for validation

Table 4.5 NMEA GGA sentence data definition

Data Type	Sample Value	Description of value
Time of Fix	120202.22	12:02:02 A.M. Greenwich Main Time
Latitude	3953.4651,N	39^o 53' 46.51" Northern Hemisphere
Longitude	03247.3963,E	32^o 47' 46" Northern Hemisphere
Fix Quality	2	0 = Invalid 1 = GPS fix 2 = DGPS fix
Number of Satellites in Use	08	8 satellites are in view
Horizontal Dilution of Precision	2.5	Relative accuracy of horizontal position
Altitude	00921,M	921.2 meters above mean sea level
Height of the geoid above WGS84 ellipsoid	-34.0	34 meters below WGS84 ellipsoid
Time since last DGPS update	Blank	No last update
DGPS reference station id	Blank	No station id
Checksum	*75	Required for validation

4.3. Verification of Map-Matching Process

The verification of the map-matching processes is done against the controlled data collected using handheld GPS. Two predefined routes are used to collect controlled data with one-second epochs. These routes are referred as "Route #1" and "Route #2" (Figure 4.5).

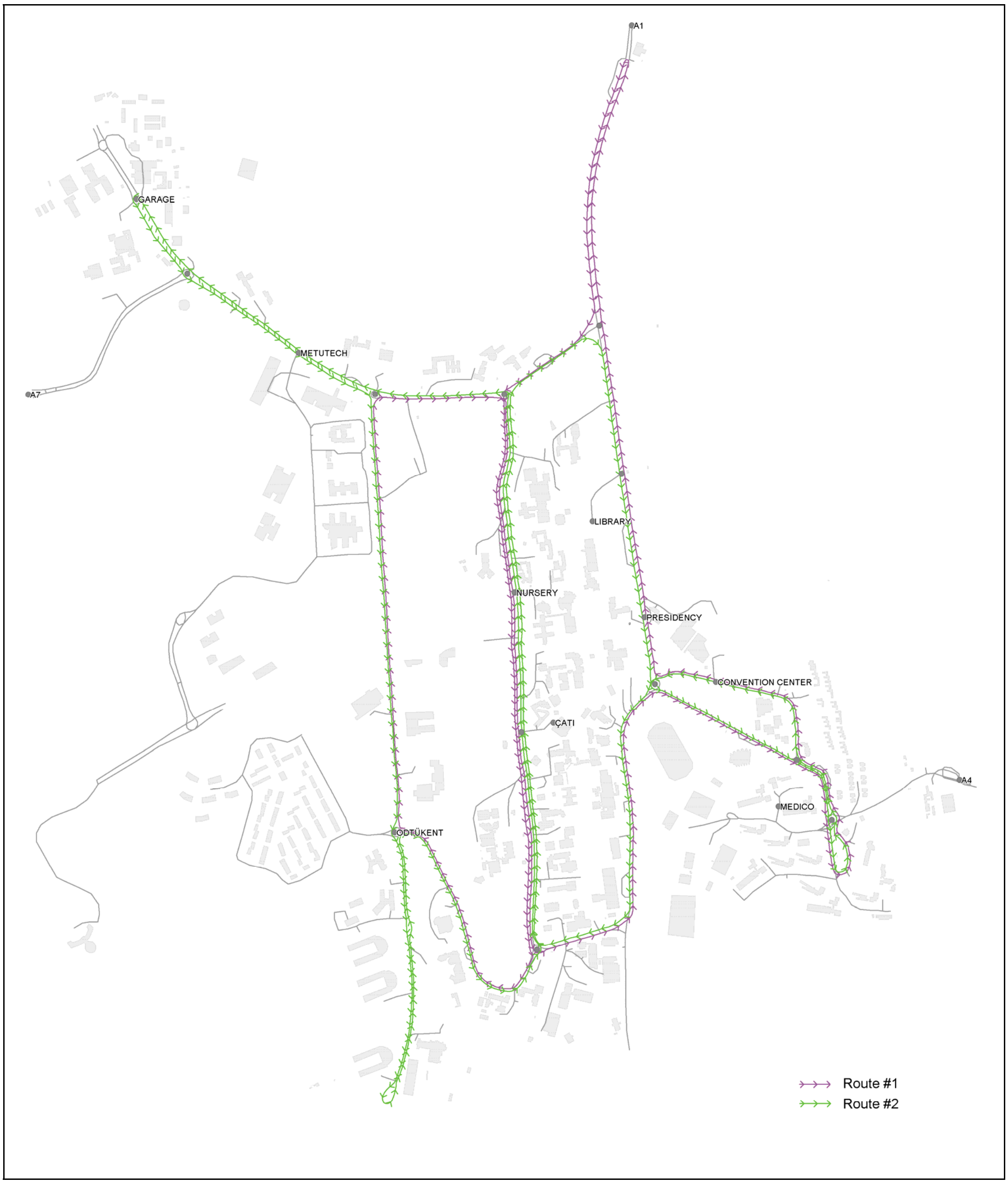


Figure 4.5 Controlled track data

The verification is done in two levels; first level compares the results derived from Point-to-curve (PTC) matching step with route-based (RB) matching step. A close-up map presenting results of PTC matching is shown in Figure 4.6. A close-up map comparing the results of PTC matching and RB matching is shown in Figure 4.7.

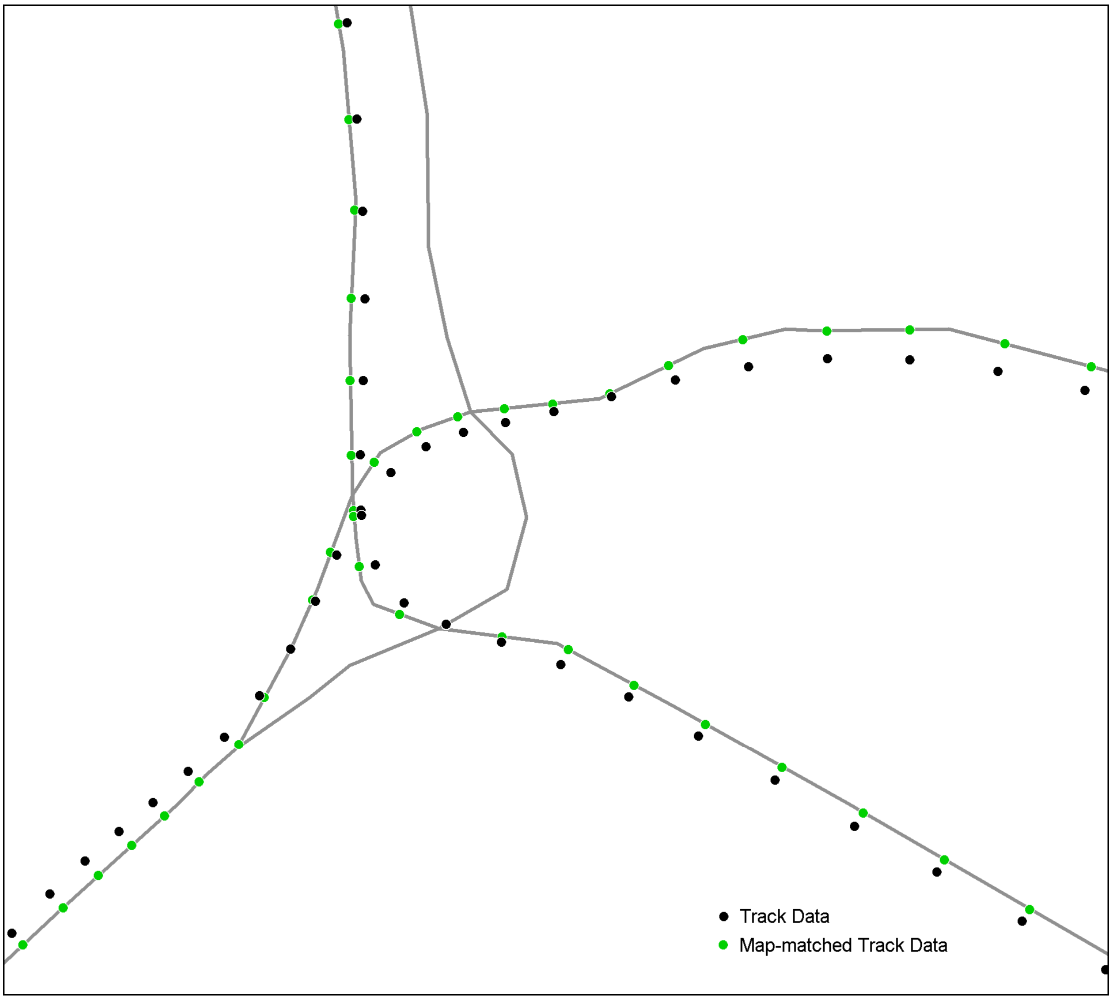


Figure 4.6 Point-to-curve matching

Route #1 consists of 1168 track data. In PTC matching, no track datum is failed to fall in the proximity of links, so all of the track data are matched. In RB matching step, in topology-based control, 18 track data are detected as mismatched. All of the mismatched track data are corrected through correction steps utilizing topological relations of matched links. Therefore, no sub-routes are created; a single route is generated from the track data, which belongs to Route #1. In manual control, it is observed that the routes generated from track-data completely match the actual route followed to collect track data for Route #1.

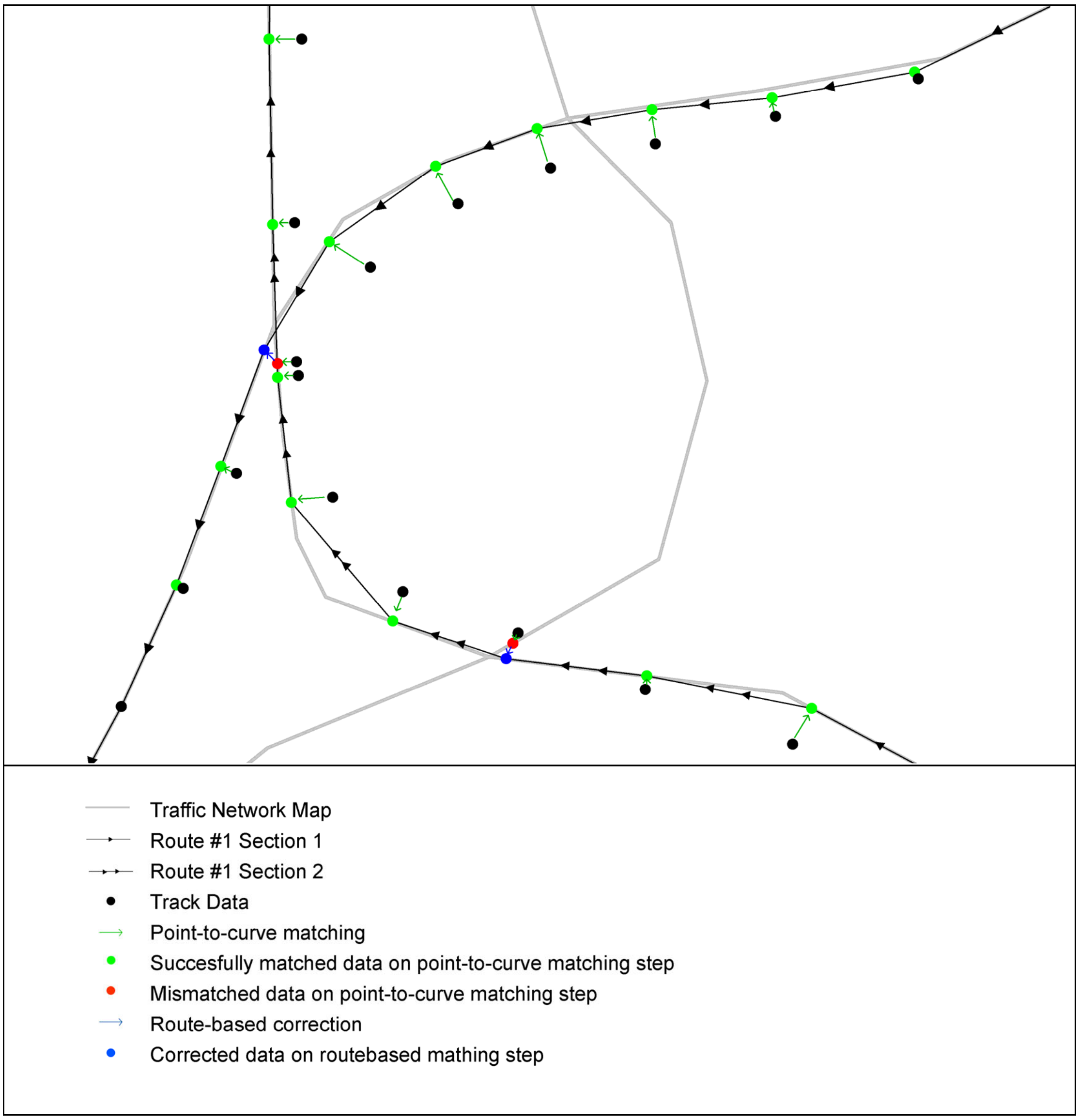


Figure 4.7 Route-based matching

Route #2 consists of 1280 track data. In PTC matching all of the track data are matched with links. In RB matching step, 68 matched data are detected as incompatible with topology of the network, they are marked as mismatched. 65 of the mismatched data are corrected in RB matching step. Three track data, two of which are consequent, cannot be corrected. First case of mismatch of track datum on the controlled route is referred as "Mismatch A" while the second case of mismatch of consequent data is referred as "Mismatch B".

In Mismatch A case, tracked vehicle on the controlled route traveled through a road segment, which is not represented on traffic network. Therefore, topologic relation controls in RB matching step are failed and absence of the connecting link prevents the possible corrections. Current sub-route ended at the last verified track data; while a new one is started at the first verified successor track data (Figure 4.8 A).

In Mismatch B, two consequent data are mapped on a link, which connects controlled route to a parking lot. Method proposed for RB matching cannot correct the nodes, since the correction steps require predecessor or successor link to be mapped correctly. Therefore, the current sub-route has been ended at the last topologically verified track data and a new sub-route is started from the first topologically verified track data (Figure 4.8 B).

4.4. Estimation of Traffic Network Characteristics

Traffic networks have time-dependent characteristics. These characteristics can be modelled using various cost measures assigned to links or nodes. In this study, methods that calculate travel link times as cost measures, are proposed. In the previous sections, data are processed to create a time-dependent route database, which provides appropriate information for travel-time calculation. In this step, results derived from various total time windows (T) and various durations of analysis-windows (τ) are evaluated. During the evaluations, three sets of data are included in calculations; fleet-tracking data with 10-second epochs, fleet-tracking data with 30-second epochs and tracking data collected with handheld GPS on transit vehicles with 1-second epochs. 87 percent of the track data fall between 07:00 AM and 07:00 PM. Any time window, extends of which is defined outside these limits result in analysis-windows without a single link travel time estimate. Therefore, interval of 07:00 AM – 07:00 PM is used as the daily time window.

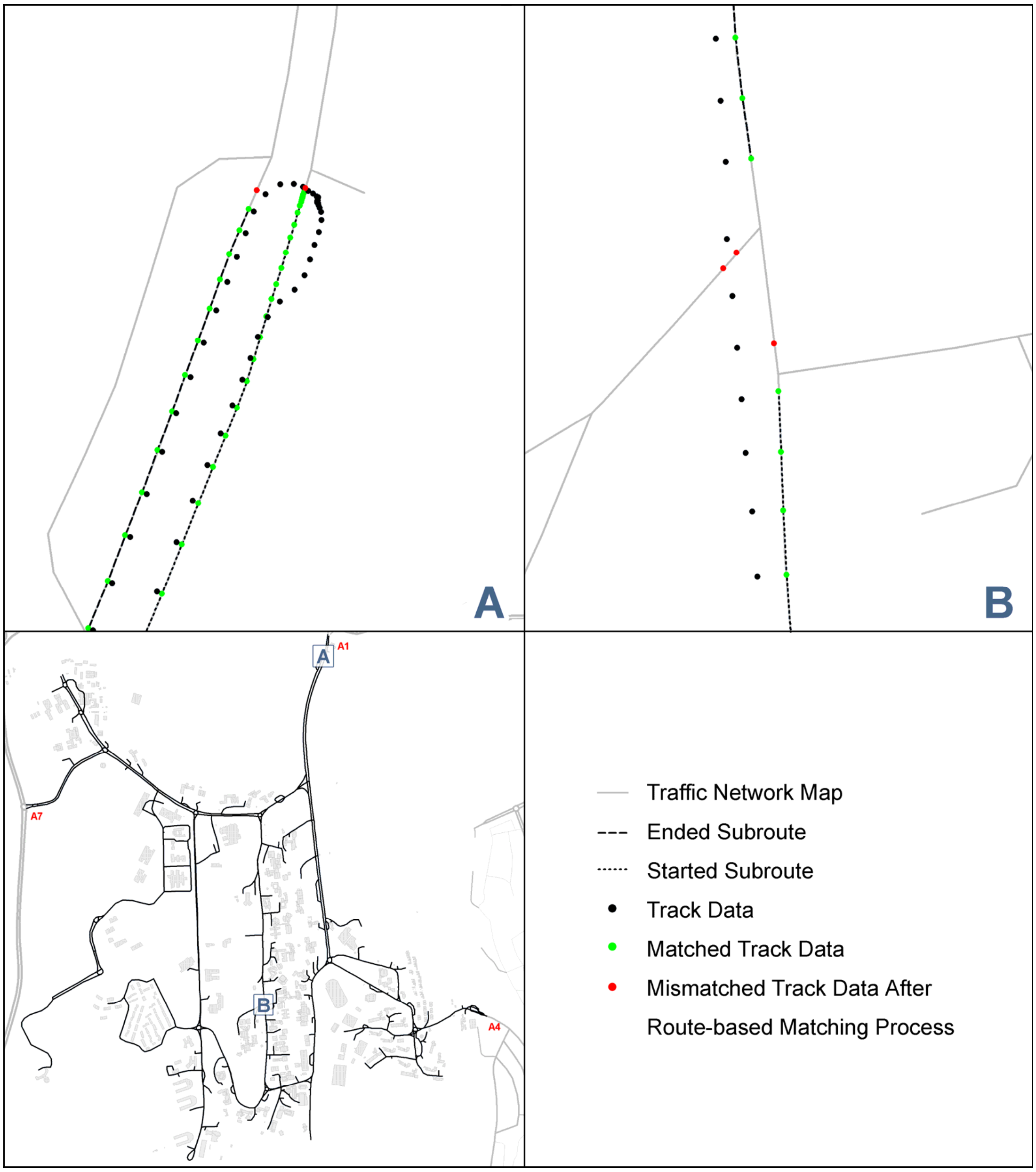


Figure 4.8 Mismatched track data after route-based matching process

In the determined time window, time-dependent cost tables are calculated for a range of durations of analysis-windows. This step aims to find out a duration that does not ignore the temporal changes in traffic network while satisfying a reliable number of link travel time estimates per analysis-window. Traffic conditions through a time-window (τ) is assumed homogenous. Cost tables for durations of 30, 45 and 60 minutes are calculated.

For better presentability, reduced sets of nodes and links are created for a selected network analysis scenario, which are defined later in Section 4.5. Number of nodes is reduced from 375 to 22 nodes, 10 of which are topology intersection nodes. A review of the rest of nodes are given in Table 4.6. Number of links is reduced from 683 to 45. Then, a set of link-travel data based on the simplified network is calculated with the map-matched route data created with the detailed METU traffic network (Figure 4.9).

Table 4.6 Nodes in the simplified METU network

Node Alias	Details
A1	Gate connecting Campus to Eskişehir Highway
A4	Gate connecting Campus to district of 100. Yıl
A7	Gate connecting Campus to Bilkent Road
PRESIDENCY	Node for Presidency and Student Affairs buildings
GARAGE	Node for shelter and maintanence center for METU fleet
METUTECH	Node for technopark including over 96 firms with over 1000 employies
NURSERY	Node for Nursery
ÇATI	Node for a major restaurant
LIBRARY	Node for library and museum
ODTÜKENT	Node for housings of academic staff
CONVENTION CENTER	Node for shopping-center and convention center
MEDICO	Node for health center

During the calculations, pseudo links, such as the ones connecting parking lots with main arteries are ignored. As the track data mostly come from the transit vehicles, there are relatively less track data matched with pseudo links and the costs calculated for these links have relatively less effect on traffic analyses. The only ones kept in METU network are links with ID's 38, 39 for "LIBRARY" and 40 and 41 for "ÇATI".

Time-dependent cost table, as defined in Section 3.4, is populated using link-travel time data, based on the link entry-time information. Time-dependent cost table contains mean, sample standart deviation, sample size, minimum and maximum values for each populated time-interval for each link.

Figure 4.9 Simplified METU network with selected subset of nodes

Due to lack of historical data, cost tables for 30-minute analysis-windows, failed to provide link travel time estimates (samples) for each of the links. Calculated values in table showed that, 12 out of 45 links have at least one analysis-window without any sample. When analysis-window is extended to 45 minutes, number of links with at least one analysis-window without any sample is decreased to 10. In 60-minute analysis-window, number of links with at least one analysis-window without any sample is decreased to 7 (Table D-1). Cost values calculated with 60-minute analysis-windows are used to detect time-dependent changes on traffic conditions, including the detection of peak hours (Figure 4.10). Also, cost table with 120-minute analysis-window is calculated to find out whether the detected peaks in 60-minute analysis-windows can also be detected on 2-hour cost table. Cost tables with 2-hour analysis-windows are calculated for data with both 30-second and 10 or less seconds of epochs. These cost tables are given in Tables 4.7 and 4.8. The pseudo-links (38, 30, 40 and 41) and links without travel-time estimates (31, 45 for “MEDICO”) are excluded in referenced tables.

Morning, mid-day and late-afternoon peaks can be detected on all of the cost tables calculated with 30, 45, 60 and 120-minute analysis-windows. As it can be seen in Figure 4.10, on link 28, the entrance link to the campus from gate “A1”, a morning peak is detected while on link 27, the exit link, a late-afternoon peak can be detected. Since the tracked vehicles are usually used for transit purposes and usually have predefined routes to dedicate, analyses on track data do not provide adequate link-travel time estimates for some links including the ones adjacent to “A4” and “A7” gates.

The available data do not indicate such strong peaks as the ones detected on links to and from gate “A1”. Link 42 (Figure 4.10), the exit link of “A7” gate, has higher link-travel time values during mid-day hours, which is originating from “METUTECH”. This may show that “A7” is serving as a gateway for mid-day activities, such as lunch. Also it can be observed that the travel times of links connecting departments to node “CONVENTION CENTER” increase in mid-day hours.

Some of the tracked vehicles are scheduled transit buses which dwell for drop-offs and pick-ups on the links with bus-stops. The coefficients of variation of travel-time estimates increase on the links with bus-stops with respect to the adjacent links without bus-stops. Link 10, on which a major bus-stop exists, has higher variances in most of the analysis-windows, in comparison to adjacent links 8 and 26, on which there are no bus-stops. Similarly, Link 5 with a bus-stop has higher variances in comparison to its adjacent links 3 and 7, which have no bus-stops on.

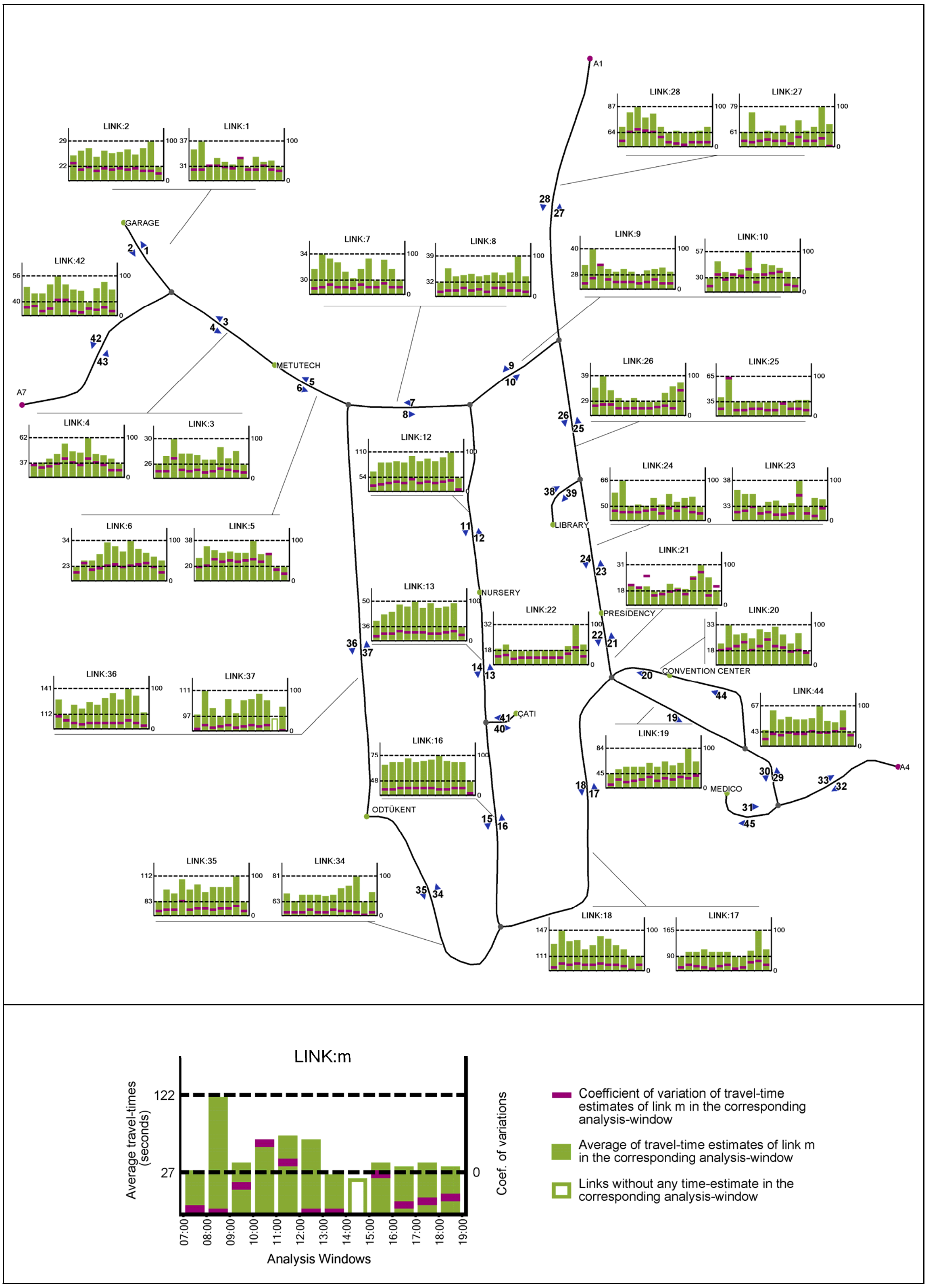


Figure 4.10 Average link travel costs and their variations in 60-minute analysis-windows

Table 4.7 Time dependent cost table for simplified METU network

Analyzed Data: 30-second epoch fleet tracking data; Analysis-window=2-hour; Unit of values: seconds																		
LINK ID	τ_1						τ_2						τ_3					
	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	36,9	12,0	32,6	1563	11	160	31,1	11,0	35,5	660	10	148	31,8	11,6	36,5	664	1	162
2	26,4	11,7	44,4	588	10	181	26,0	7,9	30,6	532	10	85	27,3	8,4	30,7	533	4	111
3	28,0	5,4	19,4	1741	18	116	29,2	11,3	38,8	715	19	175	28,2	5,7	20,1	702	19	64
4	38,7	11,1	28,5	520	26	156	45,0	14,3	31,8	553	13	134	54,5	21,6	39,6	548	27	170
5	34,3	12,4	36,2	1734	12	126	32,1	16,4	51,2	699	12	187	31,8	15,6	49,1	689	14	119
6	25,5	9,3	36,6	579	10	125	28,0	8,8	31,3	617	17	83	33,2	12,4	37,3	598	18	93
7	34,1	5,9	17,4	1691	18	66	33,1	7,1	21,5	619	23	101	32,1	5,4	16,8	613	12	67
8	35,9	6,3	17,6	391	25	60	34,5	6,5	18,9	351	13	65	35,3	6,5	18,3	223	11	70
9	41,0	10,5	25,6	109	22	80	33,5	20,4	61,0	197	19	184	31,1	7,4	23,6	238	19	67
10	44,1	22,8	51,8	461	17	122	36,7	15,2	41,5	540	18	214	51,8	28,4	54,8	532	22	179
11	69,0	0,0	0,0	1	69	69	69,1	8,2	11,8	64	52	92	66,8	7,2	10,7	11	57	80
12	87,3	18,8	21,5	1593	49	195	89,3	21,9	24,5	657	49	202	96,4	26,1	27,1	692	51	211
13	42,9	7,2	16,7	1598	30	84	46,5	9,8	21,1	653	31	96	48,6	9,7	19,9	674	31	99
14	80,0	0,0	0,0	1	80	80	47,9	7,4	15,4	66	36	72	47,6	7,3	15,4	7	40	60
15	79,0	0,0	0,0	1	79	79	76,5	11,1	14,5	59	57	98	74,1	10,4	14,1	8	62	97
16	68,7	9,9	14,4	1476	44	112	71,3	13,3	18,7	595	47	131	72,0	12,7	17,7	573	46	123
17	102,7	12,1	11,8	90	81	142	106,6	13,7	12,9	98	80	147	103,2	11,0	10,7	57	84	132
18	145,0	23,5	16,2	1042	94	272	131,5	20,9	15,9	393	95	209	127,9	19,0	14,8	378	89	223
19	50,2	10,1	20,1	226	12	128	56,8	9,9	17,4	693	13	141	61,3	13,8	22,5	661	13	182
20	31,7	14,6	46,0	386	5	78	29,0	16,1	55,5	643	5	142	30,3	15,0	49,6	652	5	113
21	21,1	10,0	47,5	223	4	66	19,0	9,0	47,3	230	4	134	20,6	7,6	36,9	225	7	58
22	22,0	5,5	24,8	1486	4	59	19,1	3,8	20,0	720	4	74	19,6	5,9	30,2	641	8	141
23	35,5	8,6	24,1	200	10	66	35,2	14,4	41,0	231	10	218	34,7	9,7	27,9	224	12	149
24	65,1	16,0	24,6	1467	12	239	52,1	11,6	22,3	704	21	167	54,9	13,8	25,2	633	12	152
25	51,3	42,2	82,4	178	24	352	37,2	6,1	16,4	219	25	57	36,2	5,9	16,3	212	25	68
26	38,9	10,5	27,1	1459	18	106	32,8	7,2	21,8	689	20	94	31,7	6,4	20,3	631	21	86
27	64,8	10,2	15,7	142	48	100	62,2	8,4	13,5	95	51	94	66,5	14,8	22,3	81	49	160
28	83,7	31,0	37,1	982	57	261	87,5	35,4	40,5	167	56	215	79,3	29,8	37,5	132	54	235
29	29,6	7,5	25,3	285	20	95	29,6	7,3	24,8	348	19	94	27,9	4,6	16,6	407	20	52
30	25,4	11,1	43,7	162	11	159	26,0	4,0	15,2	522	14	52	26,5	4,3	16,4	549	19	53
32	37,0	7,0	18,9	81	26	73	40,0	10,2	25,4	6	30	59	37,5	2,1	5,7	2	36	39
33	37,6	18,2	48,3	25	27	122	57,5	33,2	57,7	19	31	145	74,6	32,7	43,8	25	43	186
34	64,5	5,8	9,1	62	56	90	68,0	12,6	18,5	68	57	150	67,0	6,1	9,2	54	55	81
35	93,4	15,0	16,0	137	63	151	103,5	37,9	36,6	241	66	466	103,2	19,2	18,6	313	69	160
36	116,0	29,5	25,4	254	87	267	121,9	15,8	13,0	268	88	181	128,3	20,3	15,8	350	90	273
37	115,9	22,1	19,1	133	85	234	102,5	17,5	17,1	77	82	194	103,7	13,4	12,9	66	77	146
42	47,0	13,2	28,2	177	18	161	49,6	8,1	16,4	64	36	77	52,5	18,4	35,1	61	13	126
43	65,8	46,9	71,3	15	17	131	41,3	19,9	48,0	3	19	57	35,0	32,5	92,9	2	12	58
44	63,9	26,9	42,1	382	11	232	55,7	16,8	30,2	608	27	161	56,6	18,8	33,3	631	10	168

Table 4.7 Time dependent cost table for simplified METU network (cont'd)

Analyzed Data: 30-second epoch fleet tracking data; Analysis-window=2-hour; Unit of values: seconds																		
LINK ID	τ_4						τ_5						τ_6					
	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	32,2	15,2	47,1	538	10	245	32,7	11,1	34,0	683	11	110	30,9	8,9	28,9	311	8	65
2	27,4	8,2	29,9	448	10	78	27,4	7,8	28,3	623	10	97	29,7	8,0	27,1	1034	13	85
3	28,0	5,3	18,8	567	18	64	28,6	6,0	20,8	737	17	77	28,1	4,5	15,9	461	18	55
4	52,8	23,0	43,7	477	26	190	48,5	17,9	36,9	663	26	145	42,1	7,0	16,7	1059	29	91
5	32,1	18,9	58,9	568	15	190	29,3	16,2	55,4	731	14	180	20,8	4,9	23,6	458	15	56
6	31,0	11,2	36,2	516	18	89	31,1	13,2	42,4	727	7	119	28,0	10,6	37,9	1112	19	118
7	32,7	6,6	20,1	502	21	104	32,4	7,1	21,9	608	11	130	32,0	5,3	16,6	450	18	62
8	35,2	5,6	16,0	259	27	58	35,7	6,0	16,8	401	10	66	39,5	6,0	15,2	1035	14	64
9	29,7	5,1	17,1	247	20	50	31,0	6,5	21,1	306	16	79	31,5	5,0	15,8	445	19	46
10	41,0	16,8	40,9	403	19	149	44,2	22,8	51,5	642	21	175	36,8	7,2	19,6	1112	22	97
11	70,0	8,2	11,7	62	56	88	64,3	9,5	14,8	10	55	82	64,6	5,8	9,0	8	57	76
12	96,6	24,0	24,8	445	53	212	95,0	22,6	23,7	555	52	228	102,4	27,4	26,8	50	59	194
13	49,4	10,2	20,7	440	31	88	48,0	9,6	20,0	535	30	102	48,5	9,3	19,2	71	36	91
14	49,4	7,9	16,0	64	35	74	41,1	4,1	10,1	9	36	47	55,3	21,3	38,5	4	42	87
15	76,9	8,8	11,4	57	62	100	61,7	4,4	7,1	21	57	72	62,5	6,4	10,2	2	58	67
16	74,5	13,0	17,5	395	47	108	70,6	11,2	15,9	505	44	120	66,5	10,1	15,2	66	50	97
17	108,6	15,5	14,3	97	83	164	101,7	18,2	17,9	60	81	165	141,8	36,6	25,8	56	85	229
18	137,1	27,1	19,8	255	94	249	129,2	19,5	15,1	351	93	198	110,4	12,5	11,3	5	98	131
19	61,4	14,3	23,2	508	10	116	63,2	16,0	25,3	704	13	139	83,1	25,4	30,6	633	10	303
20	29,7	19,1	64,3	502	4	139	26,3	11,8	44,9	756	4	90	27,9	12,4	44,3	471	4	144
21	22,7	15,8	69,4	259	11	177	30,5	23,9	78,4	397	4	215	25,1	7,2	28,7	631	4	58
22	20,1	3,5	17,5	462	14	34	20,6	5,3	25,7	724	4	65	31,3	14,3	45,7	1150	12	110
23	34,7	8,1	23,4	254	24	101	35,0	12,6	36,0	409	11	227	35,2	5,1	14,4	798	11	94
24	54,8	14,5	26,4	464	32	136	55,5	17,5	31,5	712	11	157	54,7	11,4	20,9	1147	11	165
25	36,3	6,6	18,3	253	25	98	36,0	7,1	19,9	408	24	120	37,4	6,6	17,6	958	27	93
26	30,8	7,1	23,1	467	20	109	31,3	6,8	21,6	700	20	67	35,2	7,7	21,9	1151	20	141
27	64,3	8,9	13,9	40	53	96	65,7	10,4	15,8	185	52	108	86,7	44,9	51,7	648	51	470
28	64,9	6,4	9,8	88	56	91	66,5	5,9	8,9	139	54	87	69,0	10,2	14,7	142	54	149
29	29,3	7,6	25,9	362	5	97	28,6	6,0	21,0	603	18	69	26,7	5,1	18,9	189	5	54
30	26,8	4,4	16,3	449	19	54	27,7	7,0	25,3	664	19	85	29,9	5,4	18,0	367	12	54
32	34,3	3,5	10,3	8	29	39	35,3	3,8	10,7	3	31	38	35,0	3,7	10,5	28	29	45
33	38,1	20,9	54,8	7	25	84	38,3	6,3	16,5	23	30	62	41,8	5,3	12,8	200	27	66
34	72,4	18,4	25,4	54	56	191	77,7	9,5	12,2	63	58	96	72,1	6,8	9,5	37	61	100
35	99,6	19,1	19,1	245	70	227	102,1	20,5	20,1	269	68	176	106,8	29,1	27,3	156	70	189
36	135,3	21,7	16,0	259	86	198	136,7	24,3	17,8	308	92	257	132,4	20,6	15,5	89	100	186
37	112,1	18,0	16,0	61	88	175	107,3	13,1	12,2	102	85	159	104,0	14,9	14,4	6	88	131
42	48,5	5,3	11,0	11	39	59	44,5	10,9	24,5	43	18	71	65,2	36,0	55,2	143	13	228
43	N/A	0,0	0,0	0	N/A	N/A	97,0	0,0	0,0	1	97	97	35,0	31,1	88,9	2	13	57
44	59,6	24,4	41,0	488	8	211	53,6	18,8	35,1	754	11	214	60,1	27,5	45,7	563	8	263

Table 4.8 Time dependent cost table for simplified METU network

Analyzed Data: 10-second epoch fleet tracking and 1-second epoch handheld data; Analysis-window=2-hour; Unit of values: seconds																		
LINK ID	τ_1						τ_2						τ_3					
	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	33,8	9,1	26,9	24	21	56	35,7	6,7	18,8	18	27	52	36,7	9,0	24,6	20	25	60
2	25,2	3,8	15,1	20	17	33	25,2	3,1	12,4	13	21	32	27,1	8,4	30,9	18	19	52
3	23,1	2,4	10,3	28	17	32	22,7	2,4	10,7	18	18	30	23,0	2,4	10,2	20	19	27
4	40,1	5,3	13,2	15	29	49	46,5	8,0	17,3	13	32	55	53,2	17,5	32,8	22	30	91
5	38,9	11,7	30,0	32	20	62	36,6	17,1	46,7	19	19	67	43,1	15,2	35,3	20	21	77
6	21,8	2,5	11,7	15	18	27	26,0	7,8	29,9	15	18	41	35,0	14,9	42,4	23	19	76
7	26,9	1,8	6,6	31	23	31	28,3	4,0	14,1	20	24	36	27,6	2,9	10,4	18	22	32
8	31,3	1,7	5,3	12	28	33	37,2	6,6	17,7	5	28	46	30,5	1,9	6,1	8	27	33
9	54,2	15,8	29,2	5	28	66	34,7	7,3	21,2	11	28	53	34,7	3,2	9,3	3	31	37
10	40,2	16,4	40,9	14	28	78	38,7	11,3	29,2	15	29	76	52,2	26,1	49,9	21	29	147
11	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
12	95,0	20,4	21,5	24	58	144	91,6	13,6	14,9	18	71	113	103,9	29,6	28,5	27	64	178
13	43,5	9,7	22,3	27	31	69	46,7	6,5	14,0	19	37	60	54,5	8,6	15,8	24	42	72
14	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
15	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
16	64,6	8,9	13,8	25	49	85	60,8	12,8	21,1	17	47	95	59,2	8,4	14,2	11	50	74
17	101,0	0,0	0,0	1	101	101	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
18	174,0	46,9	26,9	12	129	288	136,8	24,3	17,8	4	113	166	118,4	8,1	6,8	8	104	130
19	54,4	15,9	29,2	9	40	92	62,2	13,1	21,1	13	42	93	63,6	13,9	21,9	18	40	90
20	36,3	12,0	33,0	6	15	49	27,2	13,9	51,1	16	14	65	34,7	17,6	50,8	17	17	69
21	19,0	4,8	25,5	5	14	27	18,4	1,3	7,3	5	17	20	24,7	6,4	26,1	3	20	32
22	17,5	2,6	14,7	32	15	25	17,5	2,8	16,1	13	14	24	16,8	2,0	12,1	18	14	22
23	31,3	2,5	8,0	4	30	35	32,0	0,8	2,6	4	31	33	40,5	4,9	12,2	2	37	44
24	67,1	17,8	26,6	31	38	97	50,8	6,8	13,3	15	38	60	54,9	10,1	18,4	21	38	82
25	111,4	60,5	54,3	5	48	185	39,6	5,3	13,3	7	36	51	40,7	1,2	2,8	3	40	42
26	33,2	12,8	38,4	31	20	73	26,8	4,4	16,5	15	21	37	26,6	2,7	10,3	21	23	35
27	63,0	0,0	0,0	1	63	63	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
28	85,8	35,3	41,1	18	63	201	67,5	4,4	6,6	4	63	73	N/A	0,0	0,0	0	N/A	N/A
29	25,5	2,1	8,1	6	23	28	25,0	2,0	8,0	14	22	29	25,6	3,0	11,9	17	22	34
30	25,0	2,6	10,4	9	21	29	26,9	4,4	16,2	14	20	38	25,1	2,2	8,7	19	22	31
32	32,6	1,8	5,6	5	31	35	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
33	34,4	1,1	3,3	5	33	36	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
34	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	69,0	0,0	0,0	1	69	69
35	94,3	9,3	9,8	3	84	102	96,0	15,4	16,1	9	77	129	106,2	14,9	14,1	10	90	139
36	107,0	0,0	0,0	1	107	107	143,4	31,2	21,7	7	116	204	139,5	10,4	7,4	10	116	150
37	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	100,5	4,9	4,9	2	97	104
42	46,7	4,8	10,2	11	40	56	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
43	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
44	71,5	16,4	23,0	6	39	85	61,2	18,0	29,4	16	36	94	60,9	9,8	16,1	17	44	77

Table 4.8 Time dependent cost table for simplified METU network (cont'd)

Analyzed Data: 10-second epoch fleet tracking and 1-second epoch handheld data; Analysis-window=2-hour; Unit of values: seconds

LINK ID	τ_4						τ_5						τ_6					
	$\overline{c}$	s_c	δ_c	n_c	min_c	max_c	$\overline{c}$	s_c	δ_c	n_c	min_c	max_c	$\overline{c}$	s_c	δ_c	n_c	min_c	max_c
1	38,3	7,3	19,1	19	27	56	36,8	12,8	34,7	24	26	80	30,0	4,7	15,7	18	22	41
2	25,9	2,5	9,7	18	20	30	25,7	5,5	21,5	23	18	44	28,1	6,8	24,3	10	22	44
3	23,1	2,5	10,9	20	18	28	24,1	2,3	9,5	26	21	30	24,8	2,7	11,1	21	22	30
4	59,0	17,6	29,9	23	31	91	51,1	15,9	31,0	25	32	93	41,4	5,9	14,3	14	32	56
5	45,8	18,4	40,2	25	18	69	37,6	19,1	50,9	26	19	91	23,0	2,8	12,0	21	19	32
6	35,8	13,3	37,1	27	19	63	30,4	15,1	49,8	27	19	70	23,4	5,8	25,0	14	19	43
7	27,6	4,0	14,4	25	22	42	28,9	5,9	20,4	22	21	52	28,0	3,3	11,7	21	25	40
8	32,8	3,6	11,1	11	27	40	31,0	2,5	8,1	9	26	34	37,8	6,2	16,3	12	31	53
9	31,0	2,3	7,5	8	28	36	32,1	2,6	8,1	8	27	35	33,4	2,7	8,0	21	28	41
10	44,3	15,1	34,2	25	29	94	53,7	29,4	54,8	20	29	128	38,1	4,7	12,5	16	33	51
11	50,0	0,0	0,0	1	50	50	52,0	0,0	0,0	1	52	52	50,0	0,0	0,0	1	50	50
12	96,8	9,9	10,3	29	61	111	98,6	18,2	18,4	24	72	141	74,0	29,7	40,1	4	52	117
13	50,5	6,4	12,7	26	41	68	45,9	8,1	17,5	20	36	64	41,5	7,0	17,0	4	33	50
14	36,0	0,0	0,0	1	36	36	41,3	4,6	11,2	3	36	44	36,0	0,0	0,0	1	36	36
15	45,0	0,0	0,0	1	45	45	62,5	0,7	1,1	2	62	63	55,0	0,0	0,0	1	55	55
16	67,8	7,0	10,3	19	54	78	64,8	8,3	12,8	18	51	82	56,5	11,6	20,6	4	47	73
17	95,0	0,0	0,0	1	95	95	102,0	0,0	0,0	1	102	102	N/A	0,0	0,0	0	N/A	N/A
18	153,4	26,4	17,2	11	124	214	122,9	7,4	6,0	7	111	132	111,0	0,0	0,0	1	111	111
19	61,2	16,0	26,2	26	12	87	67,0	16,6	24,7	21	48	113	76,3	16,5	21,6	12	48	101
20	34,3	16,1	46,9	28	5	69	26,5	7,6	28,7	18	15	38	18,2	5,8	31,8	19	14	32
21	16,9	1,4	8,0	8	15	19	20,2	1,2	5,8	6	19	22	22,2	6,4	28,6	17	16	35
22	16,8	3,7	22,1	25	13	31	17,7	2,1	11,9	20	15	23	30,5	24,8	81,3	17	17	122
23	30,0	3,4	11,2	4	28	35	30,3	1,2	3,8	3	29	31	31,6	2,1	6,5	14	28	36
24	56,0	9,7	17,3	24	37	82	59,3	15,2	25,7	21	42	106	55,1	9,1	16,4	16	37	74
25	36,7	5,9	16,0	9	26	43	37,5	3,1	8,2	6	35	43	44,0	12,5	28,5	22	30	73
26	27,6	4,8	17,5	25	22	42	28,3	3,9	13,8	20	24	39	32,6	8,8	26,9	16	25	60
27	54,0	0,0	0,0	1	54	54	N/A	0,0	0,0	0	N/A	N/A	69,2	10,7	15,5	5	56	81
28	N/A	0,0	0,0	0	N/A	N/A	57,0	0,0	0,0	1	57	57	72,5	15,7	21,6	4	64	96
29	25,4	3,7	14,4	27	19	37	25,9	2,5	9,7	20	20	32	25,7	2,8	10,8	15	22	31
30	25,0	1,9	7,5	25	21	28	25,1	1,4	5,4	22	24	29	26,6	1,6	6,2	10	25	29
32	26,0	0,0	0,0	1	26	26	N/A	0,0	0,0	0	N/A	N/A	32,6	2,1	6,4	5	29	34
33	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	37,0	3,5	9,6	5	31	40
34	65,0	0,0	0,0	1	65	65	N/A	0,0	0,0	0	N/A	N/A	59,0	0,0	0,0	1	59	59
35	101,5	11,6	11,5	10	86	124	89,7	7,7	8,6	13	72	100	92,5	10,5	11,4	4	78	102
36	143,3	10,7	7,4	15	129	162	136,4	23,7	17,4	15	105	185	105,0	0,0	0,0	1	105	105
37	88,0	0,0	0,0	1	88	88	104,5	6,4	6,1	2	100	109	103,0	0,0	0,0	1	103	103
42	N/A	0,0	0,0	0	N/A	N/A	40,0	0,0	0,0	1	40	40	53,3	6,1	11,5	3	48	60
43	N/A	0,0	0,0	0	N/A	N/A	50,0	0,0	0,0	1	50	50	N/A	0,0	0,0	0	N/A	N/A
44	62,6	23,4	37,3	28	19	116	53,0	13,8	26,1	20	38	95	45,1	8,7	19,4	18	36	67

4.5. Test Scenario

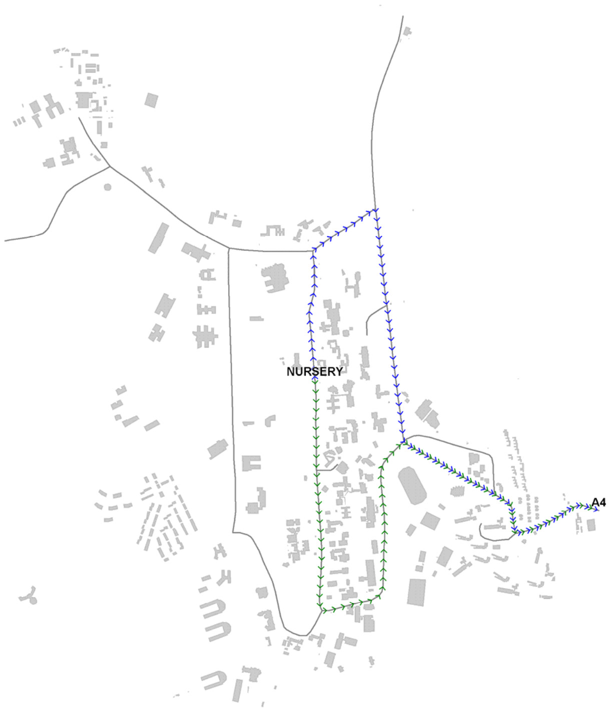
The scope of the thesis is defined to create time-dependent traffic characteristic data, specifically link-travel times, from tracking data of GPS equipped vehicles. For this purpose, a subset of nodes is selected for an analysis to demonstrate a sample usage case for generated time-dependent cost table.

In the test scenario, time-dependent cost tables are used to calculate all-to-all shortest paths. Queries performed at various departure times from 7:00 AM to 7:00 PM between the nodes defined in simplified METU network. Analysis-window length is selected as 1-hour to have adequate link time estimates per window. Calculated shortest paths between node pairs are checked against time to figure out variations due to temporal characteristic changes on the network.

METU campus network is a less-connected network with few links and therefore has less path alternatives in comparison to urban networks. Due to this, one-to-one shortest path queries between 22 nodes offer few alternative routes.

The shortest paths calculated between node pairs (origin and destination respectively) "NURSERY – LIBRARY", "LIBRARY – ODTÜKENT", "NURSERY - A4", "NURSERY – CONVENTION CENTER", "NURSERY – MEDICO" and "ODTÜKENT – NURSERY", "ÇATI - LIBRARY" varied over time. The varied results presented the significance of the link-travel time changes that take place in the network in a time-dependent manner. Temporal increases in the travel times of certain links resulted in variations in the calculated routes.

As it may be observed in Figure 4.10, links 26 and 24 generate morning and late-noon peaks, while link 21 generate only late-noon peak, so the shortest paths using these links in off-peak hours, do not use these links in peak hours. As shown in Figure 4.11, the calculated shortest paths from "NURSERY" to "A4" do not use link 26 and the its adjacent links, between hours from 9:00 to 10:00 (τ=3), 13:00 to 14:00 (τ=7) and 17:00 to 19:00 (τ=11 and τ=12).

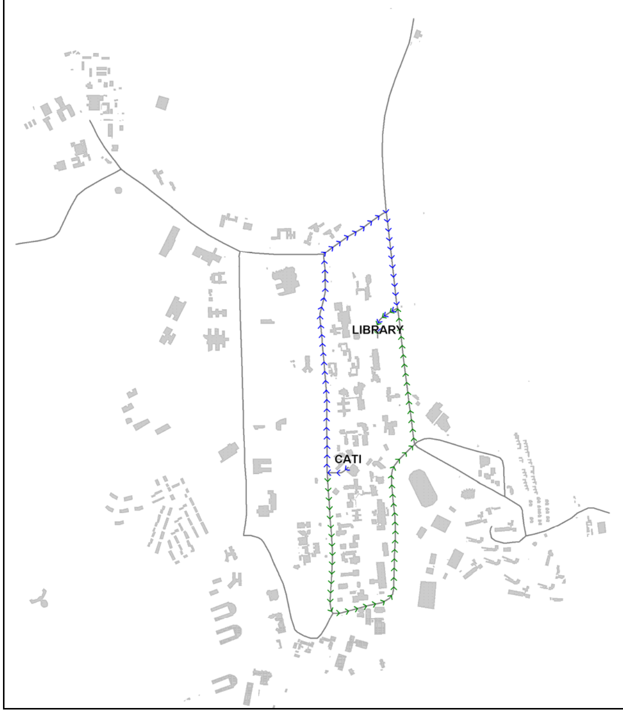


ORIGIN: NURSERY DESTINATION: A4

Shortest Path #1

Shortest Path #2

Analysis Window		Shortest Path
1	7:00 - 8:00	2
2	8:00 - 9:00	2
3	9:00 - 10:00	1
4	10:00 - 11:00	2
5	11:00 - 12:00	2
6	12:00 - 13:00	2
7	13:00 - 14:00	1
8	14:00 - 15:00	2
9	15:00 - 16:00	2
10	16:00 - 17:00	2
11	17:00 - 18:00	1
12	18:00 - 19:00	1



ORIGIN: ÇATI DESTINATION: LIBRARY

Shortest Path #1

Shortest Path #2

Analysis Window		Shortest Path
1	7:00 - 8:00	1
2	8:00 - 9:00	1
3	9:00 - 10:00	1
4	10:00 - 11:00	1
5	11:00 - 12:00	2
6	12:00 - 13:00	2
7	13:00 - 14:00	2
8	14:00 - 15:00	2
9	15:00 - 16:00	1
10	16:00 - 17:00	1
11	17:00 - 18:00	1
12	18:00 - 19:00	1

Figure 4.11 Shortest path results with respect to hour-of-day

Similarly, links 12 and 13 have lower travel time values only in early-morning and late-noon. The calculated shortest paths from “ÇATI” to “LIBRARY” use “Shortest Path #2” instead of “Shortest Path #1” from 11:00 to 15:00, during which link-travel times increase on links 12 and 13.

CHAPTER 5

CONCLUSION

This chapter focuses on the conclusive results of the study. Main contribution and observed limitations are also discussed. Section 5.1 summarizes the conclusive results achived by the methods proposed, and discusses the practical use of methods in our daily lives. Section 5.2 presents recommendations based on the observations of the study for future work.

5.1. Conclusions

This study aimed to derive time-dependent link cost information from global positioning data collected from vehicles, with the help of GIS tools. GIS tools provided a user-friendly environment especially during the development of the digital map, representing the network of the study area. Application programming interfaces of GIS tools provided a convenient development environment during the creation of abstract data structures for the specific requirements of this study.

The proposed map-matching method, which is strongly bounded with the topology, created map-matched routes. Proposed link-travel time estimation method requires a consequent set of track data matched to corresponding link successfully. Created routes are checked against topology to detect mismatches.

Shortest path analyses are performed on the network to compare the results with respect to time. These analyses show that the time-dependent shortest path results may differ even on such a less-connected network with long links. Due to limited availability of historic data, some links failed to have a travel time estimation on each analysis window. In this study, available tracked vehicles are transit buses, most of which have predefined routes to dedicate. Therefore, some of the links, which are used by predefined routes, have more track data to matched with than the ones which are not located on predefined routes. Similarly, allocation of track data on links may not represent how commonly they are used with regular vehicles.

These results showed that GPS-equipped vehicles promise opportunities to measure the time-dependent characteristics of traffic networks. Methods of this study can be used to create low-cost traffic datawarehousing systems that analyze various time-dependent measures of a traffic network.

5.2. Recommendations

There have been some limitations observed about the methodology proposed in this study. To have a general-purpose time-dependent link travel time table, dwelling times occurred during the routes of transit vehicles should be detected and travel times should be refined by eliminating these durations. Without detection of dwelling times, calculated travel-times will not reflect the actual behavior of non-transit vehicles, so calculated cost tables will not be applicable for non-transit vehicles.

The proposed map-matching methods present a network-topology based verification and correction. Other map-matching advancement methods studied in the literature, such as Kalman Filters, can be integrated to increase the success of map-matching process. Also other GPS-provided data, such as number of satellites in view and precision, can be used to improve results. With these data, uncertainty caused by GPS precision can be taken into account. While the network selected as case study is modeled as a planar-topology, 3D-topology structure can help improving the results of both map-matching step and traffic analyses based on the time-dependent cost table.

The proposed methodology can be used to monitor the characteristics of a traffic network under a selected specific condition, such as emergency conditions. Data collected from vehicles during an emergency state can provide historic information about traffic network under emergency conditions for future reference. Also the methods proposed in this study can be improved to create a real-time traffic monitoring system, including real-time measurements of travel-time and incident detections. Real-time traffic data can be served to travelers using internet web interfaces or in-car navigation systems.

REFERENCES

Basnayake, C. "Automated Traffic Incident Detection Using GPS-based Transit Probe Vehicles." The University of Calgary, 2004.

Bernstein, D., and Kornhauser, A. "An Introduction to Map Matching for Personal Navigation Assistants." New Jersey TIDE Center, New Jersey Institute of Technology, 1996.

Bertini, R. L., and Tantiyanugulchai, S. "Transit Buses as Traffic Probes: Empirical Evaluation Using Geo-Location Data." In *Journal of the Transportation Research Board*, 35-45. Washington, D.C: National Research Council, 2004.

Cherkassky, B. V., Goldberg, A. V., and Radzik, T. "Shortest paths algorithms: Theory and experimental evaluation." Paper presented at the 5th Annual ACM-SIAM Symposium on Discrete Algorithms (SODA 94), Arlington,VA 1994.

Christofides, N. *Graph Theory: An Algorithmic Approach*. New York: Academic Press, 1975.

Cooke, K. L., and Halsey, E. "The shortest route through a network with time-dependent internodal transit times." *Journal of Mathematical Analysis and Applications* 14 1966: 492-98.

Diestel, R. *Graph Theory*. New York: Springer, 1997.

Dijkstra, E. "A Note on Two Problems in Connexion with Graphs." *Numerische Mathematik* 1 1959: 269-71.

Dommety, G., and Jain, R. "Potential Networking Applications of Global Positioning Systems (GPS)." CS Dept, The Ohio State University, 1996.

Dreyfus, S. E. "An appraisal of some shortest path algorithms." *Operations Research* 17 1969: 395-412.

Fletcher, D. *Geographic information systems for transportation: A lookforward*, *Transportation in the New Millenium: State of the Art and Future Directions*. Washington, DC: Transportation Research Board, CD-ROM, 2000.

Goodchild, M. F. "Geographic Information Systems." *Journal of Retailing* 67 (1) 1991: 3-15.

Goodchild, M. F. "GIS and transportation: Status and challenges." *GeoInformatica* (4) 2000: 127-39.

Hall, R. "The fastest path through a network with random time-dependent travel time." *Transportation Science* 20 (3) 1986: 182-88.

Hart, P. E., Nilsson, N. J., and Raphael, B. "A formal basis for the heuristic determination of minimum cost paths." *IEEE Transactions on System Sciences and Cybernetics* SSC-4 (2) 1968: 100-07.

Hazelton, M. L. "Estimating Vehicle Speed from Traffic Count and Occupancy Data." *Journal of Data Science* 2 2004: 231-44.

Horn, M. E. T. "Efficient modelling of travel in networks with time-varying link speeds." In *Networks*, 80-90, 2000.

Kaufman, D., and Smith, R. L. "Fastest paths in Time - Dependent Networks for Intelligent Vehicle-Highway Systems Application." *IVHS Journal* Vol 1 1993: 1-11.

Leurent, F., and Aguilera, V. "An atomic dijkstra algorithm for dynamic shortest paths in traffic assignment " Paper presented at the Meeting 2005 of the EURO Working Group on Transportation, Poznan, Poland 2005.

Liu, B. "Route Finding by Using Knowledge About the Road Network." *IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans* 27 1997: 436-48.

METU. 2006. In, http://www.metu.edu.tr/about/misguide.php, last accessed September, 2006.

Miller, H. J., and Shaw, S. L. "GIS-T Data Models." In *Excerpts from Geographic Information System forTransportation: Principles and Applications*, 53-84: Oxford University Press, 2001.

Moore, E. F. "The shortest path through a maze." Paper presented at the International Symposium on Theory of Switching, Part II 1957.

Ocak, Mustafa. "GPS and DGPS Error Sources and Developing a DPGS Post Processing Software." Middle East Technical University, 2001.

Ochieng, W. Y., and Quddus, M. "Map-Matching in complex urban road networks." *Brazilian Journal of Cartography (Revista Brasileira de Cartografia)* 55(2) 2003: 1-18.

Orda, A., and Rom, R. "Minimum weight paths in time-dependent networks." *Networks* 21 (3) 1991: 295-319.

Patterson, P. E. "An evaluation of the capabilities and integration of aggregate transportation demand models with GIS technologies." Paper presented at the Annual Conference of the Urban and Regional Information Systems Association, Edmonton, Alberta 1990.

Petty, K., Bickel, P., Jiang, J., Ostland, M., Rice, J., Ritov, Y., and Schoenberg, F. "Accurate Estimation of Travel Times from Single-Loop Detectors." *Transportation Research, Part A* 32 A No.1 1998: 1-17.

Rakha, H., and Van Aerde, M. "Accuracy of vehicle probe estimates of link-travel time and instantaneous speed. ." Paper presented at the Annual Meeting of ITS America, Washington DC 1995.

Rouhbakhsh, N. "Improving the accuracy of DR GPS-based vehicle navigation systems." Department of Electrical & Electronic Engineering, University of Aucland, 2003.

Scott, C. A., and Drane, C. R. "Increased accuracy of motor vehicle position estimation by utilizing map data: vehicle dynamics, and other information sources." Paper presented at the Vehicle Navigation and Information Systems Conference, Yokohama, Japan 1994.

Taylor, G., and Blewitt, G. "Virtual differential GPS & road reduction filtering by mapmatching." Paper presented at the ION'99, Twelfth International Technical Meeting of the Satellite Division of the Institute of Navigation, Nashville, USA 1999.

Taylor, G., Uff, J., and Hamadani, A. "GPS positioning using map-matching algorithms, drive restriction information and road network connectivity." Paper presented at the NavSat 2001 Conference, Nice, France 2001.

Thong, C. M., and Wong, W. G. "Using GIS to design a traffic information database for urban transport planning." *Computers, Environment and Urban Systems* 21 No.6 1997: 425-43.

Transport Canada. 2005. In, http://www.its-sti.gc.ca/en/what_is_its.htm, last accessed June, 2006.

White House. "Statement by the President Regarding the United State's Decision To Stop Degrading Global Positioning System Accuracy. White House Press Announcement, May 1." 2000.

Wiggins, L., Dueker, K., Ferreira, J., Merry, C., Peng, Z., and Spear, B. "Application challenges for geographic information science: Implications for research, education and policy for transportation planning and management." *URISA Journal* 12 2000: 52-59.

Zhan, F. B., and Noon, C. E. "A comparison between label-setting and label-correcting algorithms for computing one-to-one shortest paths." In *Journal of Geographic Information and Decision Analysis*, 2000.

Zhan, F. B., and Noon, C. E. "Shortest Path Algorithms: An Evaluation Using Real Road Networks." *Transportation Science* 32 1998: 65-73.

Zhao, L., Ochieng, W. Y., Quddus, M. A., and Noland, R. B. "An Extended Kalman Filter algorithm for Integrating GPS and low-cost dead reckoning system data for vehicle performance and emissions monitoring." *The Journal of Navigation* 56 2003: 257-75.

Zhao, Y. "Mobile phone location determination and its impact on intelligent transportation systems." *IEEE Transactions on Intelligent Transportation Systems* 1 (1) 2000: 55-65.

APPENDIX A

DIGRAPH ALGORITHMS

This section represents pseudo codes used to generate a digraph structure from a digital map representing a road network. Sequence of the algorithms presented in Section 3.1.2.

1. Let N=∅ be the set of nodes
2. For each data row as R in link table
3. Let C be first element of the geometry field of R
4. Let startnode be the first element in control points set of C
5. Let endnode be the last element in control point set of C
6. If startnode $\notin$ N then add startnode to N
7. If endnode $\notin$ N then add endnode to N
8. Go to step 2

Figure A-1 Algorithm for creating nodes (CreateNodes)

1. Let L=∅ be the set of links
2. For each data row as R in link table
3. Let C be first element of the geometry field of R
4. Let D be the direction field of R
5. If D=1 then insert C into L
   Else If D=2 then, Let ‘C be C with reversed control point order, insert ‘C into L
   Else If D=0 then, Let ‘C be C with reversed control point order, insert C and ‘C into L
6. Go to step 2

Figure A-2 Algorithm for creating links (CreateLinks)

1. Let N be the set of node created in *CreateNodes*
2. Let M be a 2 dimensional array with n(N) x n(N)
3. Set all elements of M to -1
4. For all N1 $\in$ N
5. For all N2 $\in$ N
6. If C$\in$L and start point of C equals N1 and start point of C equals N2 Then set M(i to j) to C
7. Go to step 5
8. Go to step 4

Figure A-3 Algorithm for creating adjacency matrix (CreateAdjacencyMatrix)

1. Let N be the set of nodes created in *CreateNodes*
2. Let P be the set of nodes in node table
3. For all p$\in$P
4. If n$\in$N and n has same physical location with p Then

   If NodeType field of p=2, n connected to a single n'$\in$N through 2 links with distinct directions Then let m=n, add m to N. Set attributes of m and n with appropriate fields of p

   Else set attributes of n with appropriate fields of p
5. End If
6. Go to step 3

Figure A-4 Algorithm for assigning attributes to nodes (SetNodesAttributes)

APPENDIX B

POINT-TO-CURVE MATCHING ALGORITHMS

This section briefly presents the pseudo codes developed for minimum bounding rectangle (MBR) search and point-to-curve (PTC) matching.

Let d be maximum acceptable distance between a link and track datum for a successful association. (This parameter should be optimized taking GPS performance and network characteristics into account.)

Let G be the set of GPS track data.

Let L be the set of links on the network.

1. For each $t \in G$.
2. Find the closest links to t using FindNearestNeighbour algorithm defined at Figure B-2
3. Compare the alignment data associated to t with the alignment of the link tangent on the point that the t projects onto link.
   If the difference is under a specified threshold, assign link to t.
4. Else test consecutive closest links until the distance between t and link fits into a specified maximum distance.
5. Go to step 1

Figure B-1 Algorithm for node-to-curve matching

Step 2 of the MapGPSData algorithm is a computationally extensive task if all the links on the network are scanned for distance calculation to a *track datum*. Complexity is O(nmp) where n, m and p are the number of track data, number of links in the network and average number of control points in links respectively. To narrow the scanned links steps shown in Figure B-2 are followed.

Steps 1-7 of the algorithm *FindNearestNeighbour* provides a set of links (**L**) with distances to our *track data*. MBR intersection applied in Step 4 reduce the number of links to be scanned for distance, without excluding any links that have a distance to *track data* less than **d**. **L** may also include links with distances longer than **d**. But steps will generate an **L** that is a subset of G with smaller number of elements, if MBR derived from **d** does not contain the MBR of all elements on **G**. Following method decreases complexity to O(nm)+O(nlp) where l is the number of candidate links derived from Step 3. Parameter l does not scale with n or m.

1. Let M be the set of minimum bounding rectangles of each link in set G.
2. Let B be the minimum bounding rectangle (MBR) of a Euclidian circle whose center point is track data and radius is d.
3. Let L be the set of links where derived M intersects B
4. For each link on L
5. Let p be the set of control points l
6. Find link to sample distance by calculating point-to-point and point-to-line distances using consecutive sample points on p.
7. Go to step 4.

Figure B-2 Algorithm for search based on MBR-insection

APPENDIX C

A ROUTE-BASED MATCHING ALGORITHM

An algorithm that performs the checks discussed Section 3.2 is developed. The notation is used in this algorithm is given in Table 3.3. Route based mapping follows the steps to estimate a valid route for each vehicle, α .

Step 1. Initialize a new route r.

Step 2. Find the start time and location for the new route r. If the time between two consecutive track data, consequent *track data* $\Phi^{t_{j-1}}$ and Φ^{t_j} have a long time period (e.g. exceed predefined duration denoted by MAXINTERVAL), set the second data as the start point of a new route r. This value should be optimized in order to minimize mismatches on route-based mapping. Minimum and average link lengths are inputs considered while deciding this value. If $t_j - t_{j-1}$ < MAXINTERVAL not met, go to step 7, else proceed to next step.

Step 3. Check if the mapping of the two consecutive track data are consistent with the network connectivity. The possible mapping of two track data can be one the following cases:

Case A. Two consequent track data are mapped on the same link, where position of predecessor track data (t_j) on the mapped link is smaller than position of successor track data (t_{j+1}) on the same link with a predefined error margin given as MAXREVDISTANCE. If ($\varphi^{t_j} - \varphi^{t_{j-1}}$ < MAXREVDISTANCE) is not met, go to step 7, else proceed to next step.

Case B. Two consequent track data are mapped on the links γ^{t_j} and $\gamma_\alpha^{t_{j-1}}$ where γ^{t_j} is one of the predecessor links of γ^{t_j} topologically.

Case C. Two consequent track data are mapped on links that are not adjacent but connected with a "reasonably long path". To define the reasonable limit for this step, the shortest path connecting the mapped links γ^{t_j} and $\gamma^{t_{j-1}}$ is calculated. However the returned path may not reflect the actual path of vehicle travelling from γ^{t_j} to $\gamma^{t_{j-1}}$, in an urban network shortest path function between γ^{t_j} and $\gamma^{t_{j-1}}$ always be expected to return a result. All the result are also controlled against a maximum travel speed given as MAXSPEED. Shortest paths, which require a travel speed exceeding MAXSPEED between t_j and t_{j+1} are ignored.

Step 4. If any of the three cases in the previous step is observed, current track datum, Φ^{t_j}, is appended into current route r and and next track datum is processed. Otherwise enhance the data history information as described in Step 5.

Step 5. Enhanced consistency check for the mapping:
Check track data with times t_{j-1} and t_{j-2}, if any of the cases A, B or C is met, track data with time t_j are remapped on the next best matching link and go to Step 2 to check the connectivity else proceed to next step.

Step 6. Check the track data with times t_j and t_{j-2}. If A, B or C is met, track datum with time t_{j-1} is remapped on the next best matching link and go to Step 2 to check the connectivity else proceed to next step.

Step 7. Terminate current route r, append r to set routes “R”. Initiate a new route r. Go to step 1.

The aforementioned algorithm is summarized in Figure C-1.

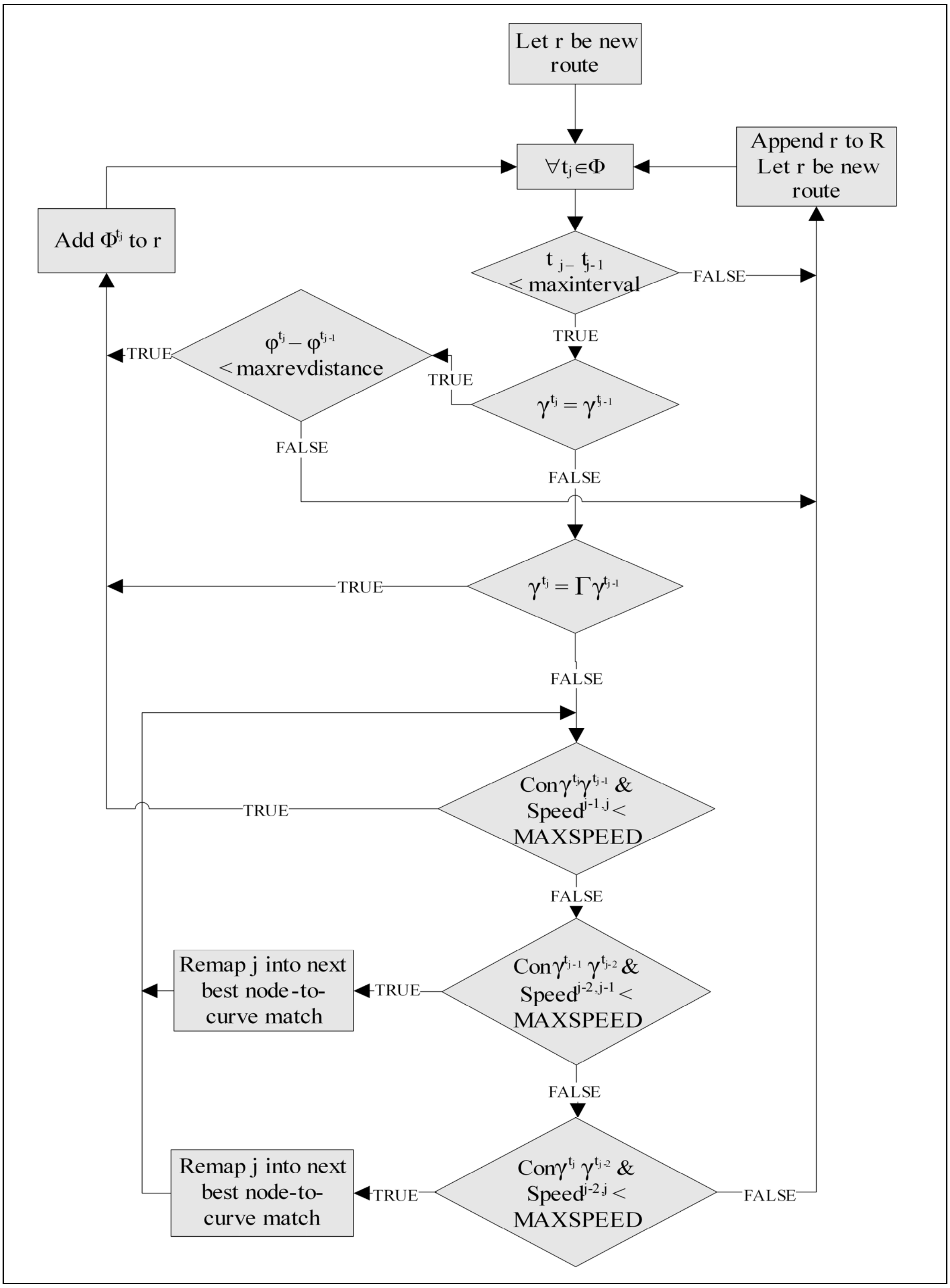


Figure C-1 Route-based map-matching algorithm

APPENDIX D

TIME DEPENDENT COST TABLES

Time dependent cost tables with 60-minute analysis-windows are given in this section. Time-windows for the cost tables are from 7:00 AM to 7:00 PM.

Table D-1 Time dependent cost table for simplified METU network

Analyzed Data: All Ring Data with 1, 10 and 30-second epochs; Analysis-window=1-hour; Unit of values: seconds																		
LINK ID	τ_1						τ_2						τ_3					
	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	35,9	10,0	27,8	176	12	71	37,5	10,9	29,0	601	13	93	31,8	12,2	38,5	160	16	148
2	25,8	11,6	44,8	103	10	119	27,1	7,7	28,4	183	12	83	27,8	10,1	36,4	145	14	85
3	27,1	4,5	16,7	187	17	43	28,2	5,2	18,5	676	18	57	30,2	15,1	50,1	182	18	175
4	37,3	12,1	32,3	86	26	118	39,6	9,6	24,3	182	27	105	43,3	12,8	29,6	156	13	134
5	27,2	9,2	33,9	187	14	67	36,2	13,4	36,9	691	14	126	32,9	18,0	54,6	180	12	187
6	23,6	4,8	20,2	103	18	42	26,8	12,3	45,8	200	10	125	26,6	7,8	29,3	176	18	69
7	32,4	5,1	15,8	181	23	48	34,0	5,8	17,2	670	22	54	33,6	8,3	24,6	164	25	101
8	32,4	3,6	11,2	80	25	45	36,7	5,9	16,1	126	28	57	34,3	5,7	16,6	109	13	51
9	33,1	4,5	13,7	9	27	41	40,0	11,9	29,6	53	22	66	33,4	20,1	60,2	49	23	165
10	30,0	5,0	16,5	83	20	52	48,5	22,0	45,3	156	25	117	37,5	12,4	33,0	148	22	125
11	N/A	0,0	0,0	0	N/A	N/A	69,0	0,0	0,0	1	69	69	70,8	9,9	14,0	24	56	92
12	70,2	10,3	14,7	161	52	99	89,5	17,4	19,5	629	52	147	88,0	19,1	21,7	175	53	160
13	40,2	4,8	11,9	156	31	55	43,7	7,8	17,8	644	30	84	45,5	7,8	17,1	177	33	73
14	N/A	0,0	0,0	0	N/A	N/A	80,0	0,0	0,0	1	80	80	46,8	6,5	13,9	25	39	60
15	N/A	0,0	0,0	0	N/A	N/A	79,0	0,0	0,0	1	79	79	74,7	11,2	15,0	21	57	94
16	66,5	9,2	13,8	139	44	88	69,4	10,5	15,1	599	47	112	69,9	12,3	17,6	168	47	109
17	93,6	6,5	6,9	16	81	105	108,0	14,6	13,5	30	81	142	109,0	14,5	13,3	31	86	142
18	130,6	11,2	8,6	105	102	167	147,5	24,7	16,7	401	97	288	133,5	18,7	14,0	116	99	186
19	45,2	4,3	9,4	60	34	59	53,7	11,3	21,1	68	12	92	57,9	9,5	16,4	180	13	89
20	23,1	9,2	39,7	42	14	51	33,8	14,4	42,7	166	5	78	28,6	13,5	47,0	172	5	79
21	21,2	10,6	50,0	30	14	61	21,4	10,0	46,5	83	4	66	21,4	15,9	74,1	60	4	134
22	20,4	4,4	21,5	159	14	40	22,6	5,7	25,4	583	4	59	19,2	3,2	16,4	189	4	31
23	36,8	7,6	20,7	29	29	61	36,1	9,5	26,2	71	10	66	36,1	12,4	34,3	62	10	108
24	59,3	14,1	23,8	157	33	114	66,4	14,1	21,2	575	12	117	52,1	11,3	21,6	180	21	87
25	41,9	8,2	19,5	28	29	63	65,6	64,7	98,6	68	29	352	37,0	6,1	16,4	54	28	53
26	35,5	8,6	24,2	157	21	67	39,4	10,8	27,3	570	20	73	34,2	9,3	27,3	172	20	94
27	63,3	8,7	13,8	43	48	86	76,3	8,8	11,6	15	59	89	63,0	9,2	14,6	37	51	94
28	70,7	10,3	14,5	80	57	121	84,3	31,2	37,0	386	59	261	87,7	40,7	46,4	54	58	215
29	28,7	10,0	34,7	37	20	79	29,7	5,2	17,6	118	21	50	29,4	5,4	18,4	98	22	53
30	23,8	3,3	13,8	56	11	34	26,1	3,7	14,3	43	18	35	27,0	4,4	16,2	140	17	40
32	27,5	0,7	2,6	2	27	28	38,1	8,4	22,1	44	26	73	N/A	0,0	0,0	0	N/A	N/A
33	33,3	2,0	5,9	18	29	37	122,0	0,0	0,0	1	122	122	42,3	10,8	25,6	4	31	55
34	70,0	5,7	8,1	2	66	74	64,9	6,2	9,5	31	56	90	69,1	5,5	8,0	14	63	82
35	84,9	8,9	10,5	20	74	110	98,6	16,1	16,4	54	69	151	93,5	14,1	15,1	64	70	128
36	129,9	42,4	32,6	23	88	254	112,4	23,0	20,5	98	89	225	124,1	18,6	15,0	74	95	204
37	99,0	4,1	4,1	4	95	103	112,0	17,8	15,9	59	85	162	102,5	8,0	7,8	17	85	116
42	50,3	10,4	20,7	28	36	78	46,4	11,1	23,9	43	23	83	46,8	5,4	11,5	12	38	55
43	110,0	0,0	0,0	1	110	110	52,0	37,3	71,8	5	18	95	57,0	0,0	0,0	1	57	57
44	46,3	9,1	19,6	43	34	69	64,7	20,4	31,6	161	11	124	56,1	16,0	28,5	161	27	122

Table D-1 Time dependent cost table for simplified METU network (cont'd)

Analyzed Data: All Ring Data with 1, 10 and 30-second epochs; Analysis-window=1-hour; Unit of values: seconds																		
LINK	τ_4						τ_5						τ_6					
ID	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	33,6	12,3	36,8	157	11	99	32,4	11,3	35,0	161	1	75	32,0	10,7	33,3	172	13	90
2	25,4	6,3	24,6	125	10	56	27,3	8,6	31,6	143	4	67	26,7	7,2	26,8	135	13	57
3	28,4	6,2	21,7	167	19	61	28,4	5,3	18,5	166	19	49	28,3	6,3	22,1	181	19	64
4	47,6	17,3	36,4	127	23	122	58,0	27,3	47,0	134	27	170	50,9	19,3	37,8	145	28	150
5	31,4	14,8	47,3	168	15	94	32,5	16,9	52,1	164	15	96	31,4	14,7	46,9	176	15	119
6	29,5	9,7	32,9	136	17	83	34,2	13,4	39,1	142	19	93	32,6	13,2	40,5	161	19	81
7	33,1	6,5	19,5	151	24	58	32,2	5,5	17,1	147	24	52	31,3	5,0	16,0	154	12	46
8	34,8	7,6	21,9	66	28	65	35,0	5,5	15,6	58	27	58	34,3	6,3	18,3	65	11	64
9	31,7	7,9	24,9	53	21	68	30,4	5,9	19,5	58	21	48	31,4	6,0	19,1	55	21	56
10	36,3	16,8	46,2	145	21	177	40,4	16,6	41,3	116	23	126	57,7	33,0	57,2	152	22	172
11	68,0	0,0	0,0	1	68	68	N/A	0,0	0,0	0	N/A	N/A	67,2	7,6	11,4	5	57	77
12	92,3	24,2	26,2	164	55	202	87,9	18,0	20,5	147	52	152	104,1	32,1	30,8	187	57	211
13	49,1	11,7	23,8	159	33	96	48,0	10,0	20,7	143	33	86	50,4	10,4	20,7	186	31	99
14	44,3	7,2	16,3	3	36	49	N/A	0,0	0,0	0	N/A	N/A	49,0	5,2	10,6	3	43	52
15	68,0	2,8	4,2	2	66	70	N/A	0,0	0,0	0	N/A	N/A	77,4	11,5	14,9	5	68	97
16	72,7	14,0	19,2	146	47	131	69,9	12,2	17,5	123	49	113	71,0	12,4	17,5	145	46	114
17	116,3	10,4	9,0	4	103	126	106,3	7,0	6,6	11	97	122	105,9	14,1	13,3	19	84	132
18	134,9	24,4	18,1	77	95	203	122,7	18,4	15,0	78	89	205	128,7	17,5	13,6	96	100	198
19	57,3	10,1	17,6	151	39	93	57,8	11,6	20,2	151	13	94	63,1	17,1	27,1	167	17	182
20	29,2	17,5	60,0	132	14	139	26,7	10,4	39,0	151	5	63	32,1	15,4	48,0	159	7	94
21	18,4	4,4	23,9	50	12	32	18,5	5,0	27,1	45	8	32	22,7	8,2	36,1	62	12	42
22	19,2	3,7	19,3	165	14	48	18,7	3,3	17,7	137	9	33	19,9	3,7	18,4	173	14	34
23	33,6	5,8	17,1	49	24	56	34,7	7,5	21,5	42	15	60	34,9	5,4	15,5	61	22	58
24	52,6	11,2	21,4	169	34	84	52,1	12,3	23,7	137	14	105	56,4	15,3	27,1	171	15	152
25	38,3	5,5	14,3	52	28	53	37,7	6,8	18,1	39	28	68	36,6	6,2	17,0	58	28	66
26	31,6	6,0	19,0	170	20	50	30,1	5,2	17,4	137	22	47	31,7	6,1	19,2	169	21	53
27	64,0	12,2	19,1	10	51	94	61,9	8,3	13,4	8	51	73	67,3	9,3	13,8	28	54	86
28	78,7	33,1	42,0	21	56	182	82,5	32,7	39,7	32	54	184	71,2	16,9	23,7	33	55	129
29	30,6	11,6	38,0	84	19	94	27,6	4,6	16,7	105	20	39	27,8	4,4	15,8	102	20	46
30	25,8	3,4	13,2	121	14	37	25,8	4,1	15,7	124	19	39	25,9	3,4	13,2	145	20	44
32	43,7	14,6	33,4	3	30	59	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A
33	65,0	39,0	60,0	6	38	142	78,0	35,2	45,2	4	53	129	71,3	1,5	2,1	3	70	73
34	69,2	9,8	14,2	15	57	98	69,1	4,9	7,0	9	63	76	68,7	5,1	7,5	18	62	81
35	110,9	44,1	39,7	64	69	338	98,4	16,1	16,3	63	73	160	104,0	18,1	17,4	93	69	159
36	121,0	15,3	12,6	69	96	166	127,4	17,0	13,3	83	96	178	124,6	18,7	15,0	92	90	187
37	97,3	9,9	10,1	16	82	121	107,7	14,4	13,4	16	89	136	99,6	9,3	9,3	20	77	120
42	52,2	9,4	18,0	10	43	73	56,4	23,4	41,6	15	38	126	52,1	22,6	43,3	10	13	97
43	N/A	0,0	0,0	0	N/A	N/A	58,0	0,0	0,0	1	58	58	12,0	0,0	0,0	1	12	12
44	57,8	20,1	34,8	128	35	161	56,1	17,7	31,6	153	10	154	56,1	17,2	30,7	150	24	130

Table D-1 Time dependent cost table for simplified METU network (cont'd)

Analyzed Data: All Ring Data with 1, 10 and 30-second epochs; Analysis-window=1-hour; Unit of values: seconds																		
LINK	τ_7						τ_8						τ_9					
ID	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	33,8	19,9	59,1	175	10	245	31,1	9,1	29,3	100	13	62	33,7	9,1	27,1	179	11	73
2	26,9	8,5	31,6	130	10	78	27,7	8,1	29,3	112	10	70	26,3	8,0	30,3	151	11	79
3	27,6	4,5	16,1	184	18	45	27,6	4,7	17,2	104	18	43	29,2	6,9	23,4	192	19	76
4	48,8	15,4	31,6	135	26	111	62,7	30,4	48,4	117	28	190	48,2	17,7	36,8	162	29	145
5	31,2	16,0	51,4	190	16	80	38,9	20,9	53,8	102	16	118	30,2	14,6	48,3	183	15	86
6	30,4	10,8	35,4	153	18	65	34,4	13,0	37,8	121	18	89	31,2	13,2	42,4	177	7	86
7	32,4	7,9	24,4	169	21	104	33,7	6,1	18,1	96	25	51	31,0	5,3	17,0	143	11	48
8	34,8	4,3	12,2	81	27	48	35,7	7,4	20,9	42	27	56	34,9	7,8	22,4	77	10	66
9	30,4	5,2	17,2	91	23	49	28,4	4,6	16,1	28	21	38	31,2	5,9	19,0	69	22	61
10	36,9	9,3	25,1	112	22	60	45,9	20,1	43,8	118	19	149	44,7	21,3	47,6	144	22	128
11	70,6	7,7	10,9	25	57	85	50,0	0,0	0,0	1	50	50	52,0	0,0	0,0	1	52	52
12	91,5	18,3	20,0	133	59	173	97,8	24,5	25,0	135	58	212	91,0	20,3	22,3	159	52	190
13	47,2	9,6	20,4	133	34	88	50,0	9,2	18,4	134	33	86	47,3	9,3	19,7	157	30	79
14	51,0	8,5	16,7	26	36	74	36,0	0,0	0,0	1	36	36	36,0	0,0	0,0	1	36	36
15	75,5	7,5	9,9	20	62	94	45,0	0,0	0,0	1	45	45	59,0	0,0	0,0	1	59	59
16	71,6	12,9	18,0	120	49	105	75,3	12,1	16,1	112	50	108	70,1	11,0	15,6	143	47	109
17	106,1	16,5	15,5	32	85	164	90,7	4,5	5,0	3	86	95	93,9	8,6	9,2	17	81	112
18	140,4	27,8	19,8	80	99	247	137,5	19,3	14,1	59	98	199	129,0	19,2	14,8	108	96	198
19	57,5	11,2	19,5	159	12	88	66,0	15,8	24,0	116	15	116	60,0	12,8	21,3	166	36	96
20	29,9	19,4	64,7	179	5	139	33,5	15,8	47,1	93	6	79	29,0	13,4	46,1	177	14	76
21	20,8	7,6	36,8	100	11	46	19,7	5,7	29,0	27	13	33	26,1	18,3	70,0	73	13	125
22	19,7	3,5	17,8	139	13	31	19,4	3,5	17,8	116	13	31	19,6	3,3	17,0	161	13	35
23	34,0	5,0	14,8	94	25	50	34,4	6,0	17,3	26	24	50	38,5	25,1	65,4	70	26	227
24	52,5	9,7	18,5	137	36	87	59,0	18,1	30,7	116	37	136	53,9	13,3	24,7	157	33	142
25	35,7	4,8	13,5	98	27	49	36,1	5,3	14,6	27	26	51	37,4	11,4	30,5	75	24	120
26	29,9	5,0	16,7	138	21	45	30,2	6,0	19,9	118	20	50	30,2	6,5	21,4	156	22	61
27	62,3	4,8	7,8	14	54	69	70,9	18,2	25,7	7	54	96	63,9	8,7	13,6	28	52	84
28	65,1	8,3	12,8	28	56	91	68,0	6,2	9,1	8	56	75	65,0	4,3	6,7	32	57	78
29	28,2	7,8	27,8	139	19	97	29,9	7,9	26,4	72	17	72	28,4	6,4	22,7	155	18	62
30	25,7	3,7	14,6	141	19	43	27,0	4,8	17,8	106	21	54	27,5	8,2	29,9	173	20	75
32	34,5	2,1	6,1	2	33	36	33,3	6,4	19,3	3	26	38	N/A	0,0	0,0	0	N/A	N/A
33	27,0	0,0	0,0	1	27	27	N/A	0,0	0,0	0	N/A	N/A	43,7	15,9	36,4	3	34	62
34	69,3	9,3	13,4	18	58	100	74,0	7,8	10,5	4	65	84	76,0	9,8	12,9	19	58	96
35	96,2	16,0	16,7	71	71	151	102,0	16,3	16,0	69	73	150	100,8	20,1	19,9	85	70	176
36	131,5	18,9	14,4	71	86	174	137,1	22,4	16,3	73	100	198	130,4	20,9	16,0	91	92	194
37	107,4	13,3	12,4	19	92	146	108,1	16,6	15,3	7	88	133	111,1	13,3	12,0	32	85	143
42	49,2	6,0	12,1	5	44	59	48,3	3,8	7,8	3	44	51	40,6	6,9	17,1	8	30	50
43	N/A	0,0	0,0	0	N/A	N/A	N/A	0,0	0,0	0	N/A	N/A	50,0	0,0	0,0	1	50	50
44	56,8	21,9	38,6	180	16	129	67,6	22,9	33,9	86	37	168	55,3	18,6	33,6	176	33	150

Table D-1 Time dependent cost table for simplified METU network (cont'd)

Analyzed Data: All Ring Data with 1, 10 and 30-second epochs; Analysis-window=1-hour; Unit of values: seconds																		
LINK ID	τ_{10}						τ_{11}						τ_{12}					
	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c	$\bar{c}$	s_c	δ_c	n_c	min_c	max_c
1	32,5	12,6	38,9	181	15	91	32,9	9,9	30,0	95	8	65	31,4	7,7	24,4	71	17	52
2	28,1	7,1	25,4	231	12	63	29,4	7,4	25,1	449	13	85	22,8	3,9	17,3	10	17	29
3	27,8	6,4	22,9	200	19	77	28,7	4,9	17,0	156	19	55	26,9	4,2	15,6	70	21	46
4	46,7	15,5	33,3	235	26	103	42,9	7,4	17,3	463	30	91	37,0	6,3	17,1	6	29	47
5	30,5	21,2	69,4	206	16	180	21,5	6,0	27,8	154	15	56	20,6	3,5	17,1	70	15	32
6	30,0	13,6	45,2	257	18	109	28,1	10,2	36,4	480	19	106	26,3	6,0	22,8	9	19	39
7	33,4	9,2	27,5	178	25	130	32,4	5,7	17,6	153	23	61	31,1	5,3	16,9	68	24	53
8	35,5	4,9	13,8	162	26	52	39,7	5,6	14,0	448	23	62	34,3	3,8	11,2	6	28	38
9	31,9	8,1	25,4	100	21	79	32,5	5,1	15,6	151	22	46	30,5	4,6	15,0	70	19	40
10	42,2	21,7	51,4	228	22	175	37,0	6,9	18,6	485	24	84	31,1	4,4	14,0	7	25	38
11	63,5	7,8	12,2	2	58	69	64,0	3,6	5,6	4	61	69	50,0	0,0	0,0	1	50	50
12	100,5	25,4	25,2	149	61	228	110,0	30,4	27,6	25	70	194	54,5	3,5	6,5	2	52	57
13	47,7	9,5	20,0	131	34	83	50,3	11,8	23,5	29	36	91	36,5	4,9	13,6	2	33	40
14	44,3	0,5	1,1	4	44	45	N/A	0,0	0,0	0	N/A	N/A	36,0	0,0	0,0	1	36	36
15	62,2	4,0	6,4	13	57	72	N/A	0,0	0,0	0	N/A	N/A	55,0	0,0	0,0	1	55	55
16	69,0	12,0	17,4	130	50	120	69,5	12,4	17,9	25	50	97	48,5	2,1	4,4	2	47	50
17	112,0	24,3	21,7	19	81	165	165,1	39,4	23,9	19	85	229	113,8	17,0	14,9	12	89	139
18	122,6	14,6	11,9	72	101	174	111,0	0,0	0,0	1	111	111	113,3	16,6	14,7	3	98	131
19	64,3	17,7	27,5	212	20	137	84,2	21,8	25,9	259	12	178	66,4	20,8	31,3	21	10	119
20	23,7	8,0	33,9	210	4	57	29,4	10,9	37,1	177	4	54	18,3	5,7	31,0	50	4	48
21	31,2	26,8	85,9	139	4	215	25,9	6,6	25,6	261	4	50	19,2	9,2	47,8	34	13	58
22	21,5	6,4	29,9	241	13	65	32,2	14,9	46,3	497	14	122	22,3	5,2	23,2	15	16	37
23	33,8	5,9	17,5	154	11	51	35,5	4,6	13,0	333	11	71	35,2	11,0	31,1	34	28	94
24	56,5	19,0	33,7	241	11	127	57,0	11,9	21,0	499	11	129	50,5	9,3	18,3	15	33	63
25	35,9	6,0	16,7	161	25	53	38,9	7,6	19,5	397	28	76	39,1	5,3	13,5	35	30	53
26	33,2	7,8	23,6	240	21	67	35,9	6,9	19,3	499	22	71	37,0	24,0	64,9	17	26	129
27	66,9	10,6	15,9	81	52	106	79,8	17,5	21,9	281	56	146	69,0	0,0	0,0	1	69	69
28	67,1	7,6	11,3	33	56	87	67,8	8,7	12,9	33	57	103	71,0	8,9	12,5	41	56	96
29	28,8	5,6	19,4	169	20	62	27,1	3,3	12,2	54	20	36	24,5	4,3	17,4	51	5	33
30	27,4	6,1	22,3	180	19	85	30,2	6,0	19,7	155	12	54	27,3	4,0	14,5	27	20	34
32	37,5	0,7	1,9	2	37	38	33,3	3,0	9,0	4	30	37	33,1	2,6	7,8	9	29	36
33	38,1	3,3	8,5	14	31	45	42,0	4,3	10,3	92	27	52	38,8	5,4	14,0	6	32	47
34	81,4	7,8	9,5	12	66	94	63,5	0,7	1,1	2	63	64	71,0	5,0	7,1	16	59	79
35	101,9	18,4	18,0	75	71	162	112,4	27,2	24,2	56	70	178	83,2	9,5	11,4	16	70	95
36	141,2	30,1	21,3	91	92	257	135,1	21,5	15,9	35	100	186	116,3	9,0	7,7	4	105	127
37	107,3	16,3	15,2	17	91	159	N/A	0,0	0,0	0	N/A	N/A	103,5	0,7	0,7	2	103	104
42	49,8	7,9	15,8	21	39	71	53,6	12,0	22,5	61	13	98	48,7	5,2	10,8	6	43	55
43	N/A	0,0	0,0	0	N/A	N/A	13,0	0,0	0,0	1	13	13	57,0	0,0	0,0	1	57	57
44	52,9	19,9	37,6	221	11	214	64,4	29,7	46,1	210	11	263	43,1	12,1	28,0	52	8	101