Exploring parking related traffic in urban areas using GPS data

A case study of the city of Tilburg, the Netherlands

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Preface

This thesis is the last and foremost part of my Master's Program in Construction Management at the University of Eindhoven. My thesis would not have been successfully conducted without the constant and considerable support of many people. They have been by my side these past two years and they made it possible for me to achieve my academic goals as well as the completion of this thesis paper. Without them, I would definitely not be able to reach my scientific and personal goals in the most desired degree. I am extremely satisfied with the outcome hence I owe a great appreciation to both my professors and my family.

To start with, I would first like to express my gratitude to my family and especially my parents who have been constantly encouraging me all of this time and showed the appropriate understanding and patience. The fact that I was given the opportunity to study and obtain a Master's degree is solely because of them. They have covered most of the expenses and never limiting my choices. They have never discouraged me; on the contrary, they have always supported my decisions and silently helped in the achievement of my aims. Secondly, I would never be able to start this thesis if it was not for my supervisor dr.ing. Peter van der Waerden (TU/e) who through our cooperation had provided me with valuable information as well as with comments as he had read and reviewed my drafts. His intellectual input was totally substantial and I have gained great knowledge from him during or continuous meetings and discussions.

Apart from this, John Swaans was the one who facilitated my research since enabled the communication and cooperation between me and the town hall/council of Tilburg. I could not neglect the help of Tilburg's administration for the important information they shared with me in order for me to be given the relevant and most accurate information/data so as to evolve my thesis accordingly. I have experienced an excellent collaboration within a friendly and energetic environment. Finally, I want to thank the graduation committee, prof.dr.ir. Bauke de Vries, dr.ing. Peter van der Waerden, dr. Qi Han, and Ing. John Swaans for their support and guidance during the execution of my graduation thesis.

This thesis can be interpreted as the continuous efforts made not only by me but also by my professors and family. Entering the Technological University of Eindhoven was the initial milestone for a prosperous career in Engineering especially in the sector of Construction Management. The present thesis represents one of my many aspirations in the field of Engineering and I hope that I will soon apply all this knowledge I have gained these two years always reminding myself of those responsible for this rewarding experience. Everything and everyone involved in the writing of this thesis is part of a lifetime's dream which has just started to unfold.

Summary

In recent years, the increase in the use of car has raised major concerns to transport planners and local authorities. Cities become more and more dense, followed by complex traffic patterns. Parking is an important aspect of mobility which provides people with access to their destinations. A significant share of traffic in congested downtowns is related to parking. In addition, the increase of parking demand requires more parking spaces; however, this is limited by land area. Lately, serious attention has been paid lately to the subject of parking. Though, the lack of reliable information about parkers' behavior makes it complicated to develop effective parking policies, assess the accessibility of destinations and the environmental effect of traffic, and support the allocation of parking demand.

Traditionally, travelers' trip information has been mainly collected through travel surveys and stated preference surveys. In this way, information is obtained about drivers' attitudes and perceptions, as well as the parking supply, and parking demand itself. However, observing travelers' route choice is usually difficult using conventional methods of data collection.

A relatively new and rich data source for collecting activity travel data consists of the GPS technology, though; the experiences in studying parking behavior are still limited. Using GPS technology, more complete trip information with enhanced data quality can be collected while the respondents' burden is reduced. However, at this moment, this information it is practically difficult to be accessed, collected, and analyzed. The need for participants' recruitment and the burden of the equipment cost allow small GPS-based travel surveys to be conducted due to the high costs. In addition, the processing of the excessive amount of data, and the inaccuracy are still some considerable issues. Therefore, municipalities and parking companies who are interested to know how the traffic is distributed through their streets and how accessible their parking locations are, require a significant amount of effort to collect this information.

This has led to the conclusion that once GPS technology is practically difficult to be accessed for the time being, as the *primary aim* of this research, is to develop a simpler and practical approach for parkers' route choice estimation. On the other hand, considering the promising capabilities of the GPS technology, as the *additional aim of this study,* the auspicious potentials of the GPS technology and the way this can be utilized to provide insights into the parkers' route choice is also demonstrated.

Estimating drivers' route choice behavior requires alternative route choice sets to be generated. Path generation processes create a set of alternative routes under hypothetical scenarios about drivers' behavior. The shortest path-based methods are the most straightforward methods assuming that drivers opt to minimize their route based on some travel costs. However, there are many factors that might influence drivers' route choice. Previous studies revealed that one of the most important factors is travel time.

Considering the above, a methodological framework is developed and applied to address the study's aims. The data-analysis technique of the shortest path algorithm offered by TransCAD

(GIS) is used to create additional route choice sets between O-D pairs. The hypothesis that is being tested is that parkers' opt to minimize either travel time or travel distance. The city of Tilburg, the Netherlands is used as a case study for the implementation of the research framework. Secondary GPS data of 83 car trips that have destination the city's center are used in the analysis which was extracted from the B-Riders stimulation program. The road network in TransCAD (GIS) is improved by identifying one-way, pedestrian roads, and ensuring that link connectivity represents as much as possible the real transportation network. The analysis is based on 3 types of routes, the observed routes and the shortest alternatives based on time and distance. The observed routes from the GPS data are reconstructed and assigned to the available parking facilities. The route choice set based on travel distance is created between the O-D pairs considering the length of the networks' segments. The route choice set based on travel time considers posted speed limits and the influence of street characteristics on the average travel speed. The alternative route choice sets are compared to the observed routes to evaluate the suitability of each route choice set. Through the comparison, information about the road type composition for each route is also obtained. Based on this information, the paired samples t-test was conducted in SPSS to determine if there are significant differences between observed routes and shortest alternative routes.

The results show significant statistical differences between the observed and shortest path routes based on the average travel time and distance. In particular, the observed routes are not optimized once they significantly exceed the shortest alternative routes based on time and distance by 13.4% and 16.2%, respectively. Remarkably, the shortest path based on time correctly estimates on average the 75% of the observed routes' total travel distance compared to only 52% in the case of the shortest distance routes. Therefore, it is also perceived, that drivers consider time more than distance as their path selection criterion. Regarding the road type composition, shortest time routes significantly underestimated the use of local roads once this road category provides lower speeds. Moreover, the shortest distance routes significantly underestimate and overestimate the use of ring-road and local road, respectively.

The practical application of the shortest path approach based on time is demonstrated through a traffic assignment model considering a specific parking facility. The traffic assignment model seems to be promising regarding future development. However, there are shortcomings that need to be considered and improved. In particular, the comparison of the estimated traffic flow to the actual traffic flow revealed that the use of some streets is missed. This might imply that other factors such as congestion, number of turns, number of traffic lights etc. might influence parkers' route choice. In addition to this, drivers might also express their time effort as a function of familiarity with the network, time of the day, road conditions, congestion etc. which are factors that were not considered in this study due to time restrictions. Therefore, it is recommended that a more extensive data collection should be employed in order to provide more solid evidence of the traffic assignment model's performance and the magnitude of the shortcomings of its application. Finally, it can be said that the combination of GPS data with the capabilities of a GIS can provide great insights into drivers' route choice. As it has been seen, in addition to the positional information, temporal information can be captured by GPS receivers and can be used to derive patterns about how traffic or the occupancy level of a parking facility differentiates by time and day of the week.

Abstract

This study mainly develops and applies the shortest path approach based on time and distance for route choice analysis of car drivers. Person-based GPS data is analyzed in an attempt to develop a more practically accessible approach that can be used, for the time being, in the place of the GPS tracking approach to estimate, to the best possible extent, the parker's route choice in a timely and costly manner. GPS data was extracted from the B-Riders stimulation program which took place in the province of Noord-Brabant, the Netherlands. The study presents the applied methodology, the way the data has been collected, organized and analyzed, and the findings of the study. The main hypothesis being tested in this study is that car drivers choose routes in order to minimize either the total travel time or distance for "non-daily shopping" trip purpose. All the trips have a destination to the central area of Tilburg, the Netherlands. A GPS data set of 83 car trips is analyzed in TransCAD (GIS). Combining GPS and GIS can provide great insights into car drivers' route choice decision making. The comparison of the observed routes to shortest alternative paths based on time and distance revealed that observed routes are significantly longer than the shortest paths. However, it appears that shortest path routes based on time correctly identify on average 75% of the observed routes' total travel distance compared to 52% in the case of shortest distance routes. These findings suggest that drivers consider time more than distance as their path selection criterion. It is also implied that more research is required to define if other factors affect parkers' route choice. In addition, there is also space to improve as well as to reconsider the way travel time and distance attributes were expressed in this study. Finally, the practical application of the shortest path approach based on time is demonstrated through a traffic assignment model for a specific parking facility. The estimated traffic flow was compared to the actual traffic flow. The performance of the shortest path algorithm considering travel time shows good potential for further development. Therefore, more data is required in order to provide robust evidence about the performance of the traffic assignment model and the magnitude of the possible shortcomings of its application.

Table of contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1. Research Motivation

Nowadays, the increase of the global population has raised major concerns to governmental authorities. At the same time, urbanization has become a contemporary tendency as a significant growing share of the population lives and moves in cities. At the same time, the increase in car use has an aftereffect the heavily congested streets. This phenomenon is more intense in dense city centers (Van der Waerden et al., 2015b) which consist of areas of utmost human interactions followed by intricate traffic patterns linked to intense commuting, commercial transactions and leisure/cultural activities (Van Ommeren et al., 2012).

Parking is an important aspect of mobility once all the vehicles require a storage location when they are not being used (Rodrigue et al., 2006). Lately, serious attention has been paid to drivers' parking behavior by the local authorities and researchers (Van der Waerden et al., 2015b). Previous studies revealed that a significant share of traffic in congested downtowns (8 - 71 percent) comes from cruising for parking (Shoup, 2006). This phenomenon was found to be directly related to unnecessary fuel consumption, pollutant and noise emissions, implications on traffic flow, and to increase of collision rates (Kaplan & Bekhor, 2011). At the same time, this situation becomes more intensified once the parking supply cannot satisfy the increase in the parking demand. In addition, increasing the parking spaces is restricted by limited land area (Teknomo & Hokao, 1997).

Reliable information about drivers' travel and parking behavior is therefore vital for the competent authorities who assess the accessibility of destinations and the environmental effects of traffic. For planning purposes, understanding parkers' behavior can support the allocation of parking demand according to the parking location and improve the effectiveness of the parking facility's usage (Teknomo & Hokao, 1997). But where is this information collected from, how practically difficult is the data collection, and how reliable the information is?

In recent years, there has been an increased interest in understanding travel behavior and the factors behind drivers' route choice decision making. Route choice modeling can facilitate the comprehension and the analysis of drivers' behavior. Understanding drivers' route choice gives the possibility for more realistic traffic forecasts, which can lead to the formulation of effective policies and infrastructure design. Though, the uncertainty about the drivers' perceptions of the route characteristics and the lack of the drivers' knowledge about the composition of the road network and their preferences, are the main issues in route choice modeling (Prato, 2009).

Travelers' route choice decisions are usually difficult to observe with conventional methods of data collection (Papinski & Scott, 2011). Empirical evidence on travel behavior has been collected mainly through field observations and travel surveys. A relatively new and rich data source for collecting activity travel data consists of the GPS technology (Montini et al., 2012). Data can be collected in an economical and timely manner (Papinski et al., 2011) while at the same time the respondents' burden is reduced and the data quality is enhanced (Van der Waerden et al., 2012).

GPS tracking method is superior to conventional methods of travel related data collection once it can provide more complete and accurate trip information. However, for the time being, this information is still practically difficult to be collected and analyzed. Large-scale GPS-based travel surveys need to be conducted to collect adequate real-time traffic evidence regarding parkers' route choice. This requires recruiting participants and providing them with the necessary equipment (buy GPS loggers) (Montini et al., 2012). Providing participants GPS devices can also hide some other challenges such as some people forget to carry the device, charge it, or even leave it in the car which can affect the overall accuracy of the data (Bierlaire et. al., 2010). In addition, dealing with the excessive amount of data is also a considerable issue (Anyang, 2010). Also, one could argue that GPS-related information can be easily obtained by telephone companies, or car navigation companies. However, due to privacy issues, trip information is not completely provided, for instance, the parts of the trip that include drivers' origin and destination locations.

Consequently, from a practical point of view, competent authorities such as municipalities require a significant amount of time and effort to collect and analyze this information. This has lead to the conclusion that as long as the GPS technology is practically difficult to be accessed, there is a *current need* to develop a simple approach that can be used to estimate parkers' route choice, for the time being.

This is currently approached bearing in mind that GPS technology can be more advanced and accessible in the near future, as it consists of an under-developed and very promising technology which can be potentially exploited accordingly. Consequently, it would be unreasonable to entirely neglect it in this study. To this extent, taking into consideration the promising capabilities of the GPS technology and the limited experiences with the use of GPS data to identify parkers' behavior, there is an *additional need* to gain insights into the way GPS data can be used to study parkers' route choice and into the valuable information this method offers.

1.2. Background

This thesis consists of an extension of a previous study that has been conducted under the scope of the Research & Development course provided by the Eindhoven University of Technology (Georgiou, 2017). According to this study, the suitability of GIS to analyze parking search behavior of drivers was explored. In addition, the spatial component of parking search behavior was investigated using only the O-D pairs from the GPS tracks of 190 car trips. The data used in this study corresponded to the city center of Tilburg, the Netherlands. For the execution of the study, TransCAD, a GIS transportation software package tool was utilized. Briefly, the approach which has been followed refers to the connection of each O-D pair via the shortest route based on length minimization. In order to achieve this, many tools and functions offered by TransCAD were used. Finally, the most used roads were identified based on the assumption that people start to search within an 800 meters radius from their final destination. The study suggests that the combination of GPS technology and GIS consists of a promising way that can be used to analyze parking search behavior.

One of the previous study's possible limitations is the difference between the shortest routes and the observed routes. More specifically, there is a possibility that drivers have logically opted for the shortest route which minimizes the travel time even if they would travel a longer distance. Moreover, some inaccuracy issues of the GPS data also observed which can verify previous studies' assertions.

All in all, the simplified O-D pairs approach was developed to a certain extent based on the shortest path approach using length as the path selection criterion. However, more improvement is needed in order to develop a promising approach that can be used to estimate the drivers' route choice by using only the O-D pairs from the total GPS registrations of a trip. The efficiency of the shortest path approach can be then examined through the comparison of the observed routes (GPS tacks) to shortest path alternative routes.

1.3. Problem Definition & Research Objectives

The problems are derived from the findings of the literature review as well as from the current practical standpoint of the use of GPS technology as a data collection method for route choice analysis.

The main problems regarding the GPS data that were identified in general were the following:

1. The lack of empirical evidence on parking behavior using GPS data (Van der Waerden et al., 2015b; Van Ommeren et al., 2012)
2. The assertions regarding the issues of GPS data such as:

2.1 Labor intensive process of data collection (Montini et al., 2012)

2.2 Inaccuracy issues occurred due to several sources (Anyang, 2010; Bierlaire et al., 2010; Stopher et al., 2005; Van der Waerden et al., 2012)

2.3 The huge amount of data requires automated and sophisticated post-processing procedures in order to derive the information needed (Anyang, 2010; Montini et al., 2012)

The current thesis has a two-fold character. Considering the *motivation* of this research and given the *literature review* presented in Chapter 2, two aims are defined. The *primary aim* is to develop a more practically accessible approach that can be used, for the time being, to estimate to the best possible extent the parker's route choice in a timely and costly manner. That is derived from the *current need* for a simplified approach that can be used to estimate the traffic flow towards parking locations.

As aforementioned, the GPS technology is a relatively new and rich data source (Montini et al., 2012). Its' promising capabilities over conventional methods are a scientifically proven fact, therefore, it would be unreasonable to neglect it. However, there are still limited experiences on parking behavior with the use of GPS data. Therefore, the *additional aim* is to focus on how information about parking related traffic can be derived from the GPS data in combination with the capabilities of a GIS, and draw attention to the valuable insights that can be gained.

The approach being developed is based on the data analysis technique of the shortest path algorithm which is offered by TransCAD (GIS). As already stated in the Background sub-chapter, the shortest path approach used in the previous study will be further developed considering not only the travel distance but also the time component when generating the shortest paths between O-D pairs. From the comparison of the observed routes to the shortest alternative routes, the efficiency of the shortest path approach will be investigated. In addition to this, focusing on the GPS data, the car trips are assigned to the parking facilities and the actual traffic flow is determined from the GPS registrations. The traffic flow is then aggregated to provide information about the most used roads.

Finally, Chapter 5 presents a traffic assignment model which consists of the practical application of the shortest path method for estimating the traffic flow caused by parkers approaching a specific parking facility.

1.4. Research Questions

Given the needs and the subsequent aims of this study, as these were presented in the previous paragraph, the following research questions are formed:

Main research question:

1. *To which extent can full GPS tracks be replaced by just O-D points and shortest paths (length, time)?*

Additional research question:

2. *How GPS technology and GIS can be utilized to provide insight into the parking-related traffic and what kind of information can be obtained?*

1.5. Research Framework

In order to execute this thesis in a methodological and systematic way, a conceptual framework was formed as depicted in Figure 1.1. The conceptual framework can be divided into 4 sections, beginning with the ***problem definition*** which is then followed by the ***literature review***, ***practical application*** and ends up with the ***final conclusion*** part.

Problem Definition

The problem definition is based on the research's motivation as well as on the findings of the literature review which was conducted in order to define the main problem within the topic's context. Finally, the research objectives are defined which are then translated into research questions.

Literature Review

A literature review is conducted in order to formulate the base of this research according to which assumptions will be made. In addition, the review of the literature consists of the start of this thesis and provides insights in regards to the state-of-art scientific knowledge surrounding the subjects of parking and route choice modelling. In addition, background information is collected in terms of the problems that derive from the parking behaviour, the solutions applied, and the methods used up to date to address these subjects. This chapter is conducted focusing on scientific publications, books, and thesis similar to this study's topic. At first, the GIS and GPS technology are introduced as they consist of the main means for the thesis' execution. Finally, these findings can be considered as the theoretical framework for the thesis objectives' achievement.

Practical Application

During the practical application, the necessary data is collected, organized, and prepared for the analysis. At the same time, the road network in TransCAD (GIS) is improved by applying directional restrictions, travel time features, and identifying pedestrian and bike roads not accessible by cars, in order to consider a network that represents as much as possible reality. Therefore, the GPS data is imported and analyzed in TransCAD (GIS) where observed routes are reconstructed and then compared to shortest alternatives based on time and distance. In addition, the observed routes of the two parking facilities that received the most car trips are used as examples based on which the traffic captured from the GPS data is assigned to the road network. The results are presented and checked against the research questions to verify that these have sufficiently been answered. Finally, a traffic assignment model is presented which consists of a possible practical application of the shortest path method which is used to estimate the real traffic flows of parkers on the road network in TransCAD (GIS).

Final Conclusions

Finally, based on the analysis results and the findings of the literature review, the final conclusions are presented and the research questions are answered and discussed. The possible shortcomings of the research are included as well. Also, the recommendations for future work are discussed.

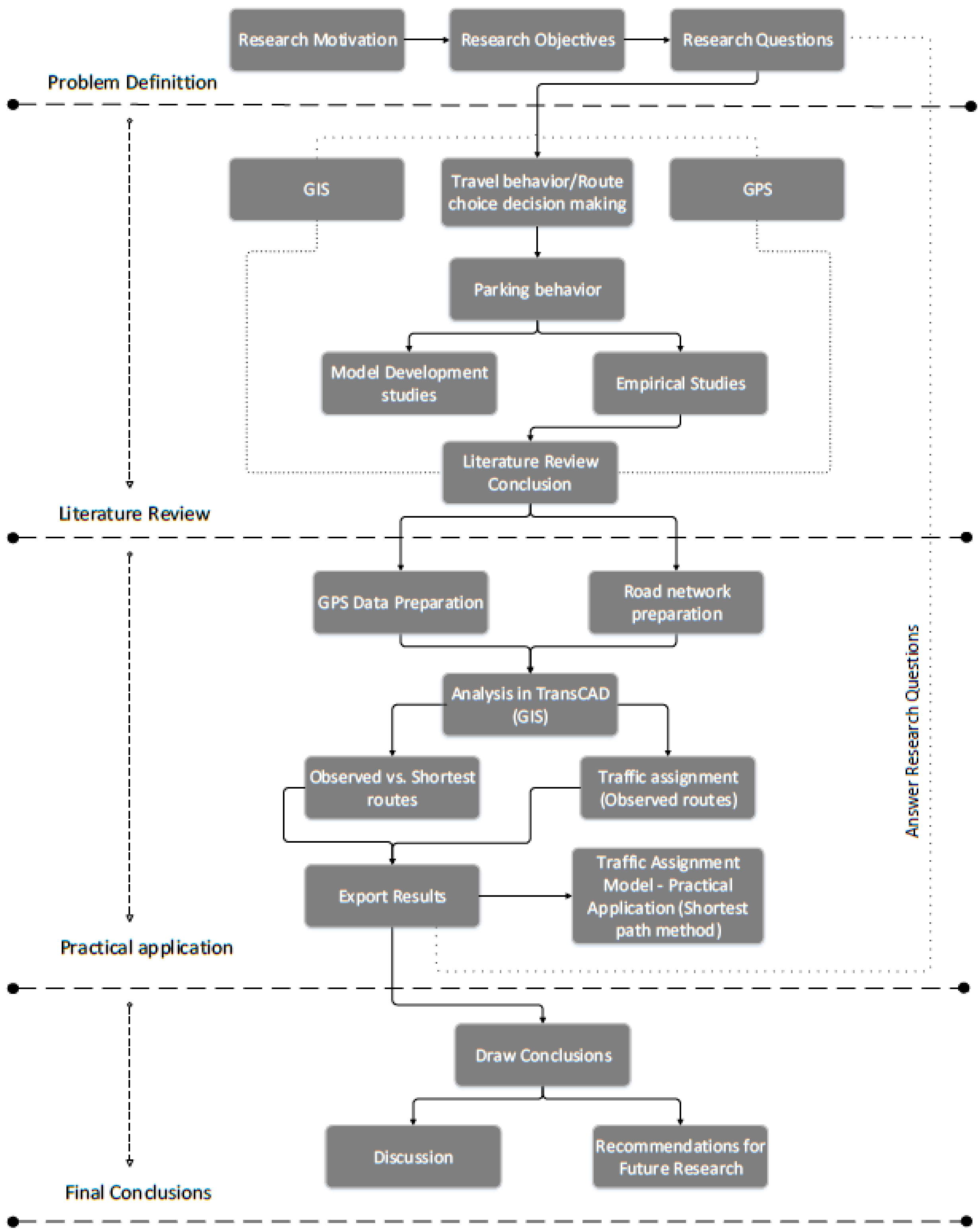


Figure 1 1: Research Framework

1.6. Contributions

Practical Contributions

The traffic assignment model is used to facilitate the investigation of the parking-related traffic. Therefore, an overview can be given regarding the way the drivers approach specific parking facilities in a timely and costly manner, and minimizing the effort required to the best possible extent. This information is of utmost importance to the competent authorities in order to evaluate whether or not streets have been designed to receive this parking-related traffic. Moreover, the results can also be used as assessment criteria for the accessibility of destinations and parking facilities. In addition, the study's outcome could be served as a decision support tool to apply solutions in order to eliminate as much as possible unnecessary car movements within the central vulnerable traffic areas. Also, another stakeholder interested in drivers' parking behavior consists of the parking companies which are concerned if their parking facility is still accessible for people and from which directions. All in all, through this study the means and procedures required to collect, analyze, and translate GPS data into valuable information about travelers' route choice behavior are highlighted.

Theoretical & Scientific Contributions

From a scientific point of view, this research reinforces the currently limited empirical studies on drivers' parking behavior with the use of GPS technology as a data collection method. In addition, the evidence on travelers' route choice decision making process is also enhanced through this study. Moreover, through the literature review, it was made clear that the route choice problem has been largely approached using the hypothesis that drivers tend to minimize the total travel time and distance (Papinski & Scott, 2011). However, some studies addressed that minimizing the aforementioned attributes may not be the only path selection criteria that people consider regarding the route choice decision making. To this extent, through this project, this assertion is also being tested, once the adopted hypothesis is that people opt to minimize travel time and distance.

1.7. Reading guide

The report consists of 5 chapters followed by the conclusions part and the recommendations and future research as well as the general discussion.

Introduction

Chapter 1 serves as the introductory part of this study. This chapter introduces the problem definition and the objectives of the thesis. The research questions are also addressed along with the research design, and the practical and scientific importance of this thesis.

Literature Review

Chapter 2, the Literature review, introduces the basic concepts that are required for the reader's understanding. It describes the various concepts related to the parking and travel behaviour (route choice) subject found in the literature as well as the previous studies conducted on this topic. Subjects such as the parking related issues, the way route choice behaviour has been approached, and the data collection methods are discussed. In addition, the methods used up to date to approach these subjects and some interesting results are also presented. Finally, the utility of GIS and GPS to explore parking search as well as to execute this thesis is also addressed.

Methodology

Chapter 3 elaborates on the methodology that has been established for the execution of this study considering the discussion and the findings of Chapter 2. It also provides a sequential stepwise procedure for answering the research questions and therefore achieving the aims that have been defined in Chapter 1.

Analysis

Chapter 4 presents the analysis followed by the results obtained from the methodology's implementation. The analysis and the results are supported by maps, graphs, and statistics to provide a better understanding of the outcome.

Traffic Assignment Model - Practical Application

In Chapter 5, the reader is guided through the parking-related traffic assignment model which is based on the findings of Chapter 4. More specifically, the outcome that is occurred by answering the two research questions is combined in order to finally end up with a practical application of the shortest path approach. It starts by briefly discussing the outcome of the research questions where the main idea behind it is demonstrated. Finally, the practical application is presented, and the results and the possible shortcomings are discussed.

Conclusions, Recommendations and Future Research

Chapter 6 summarizes the main accomplishments and findings of the conducted thesis. Also, ideas for future research as well as for further improvements are presented.

Discussion

To conclude this research, in the final Chapter 7, a general discussion takes place addressing the limitations and weaknesses of this study.

Chapter 2

Literature Review

2.1. Introduction

Historically, parking related problems seem not to be a recent issue. Behrendt (1940), in one of the first papers for parking, indicated that problems arise from the rapid growth of automobile traffic in combination with the attitude of people to park as near as possible to their destination. Once parking became a real problem for city planners, measures to improve traffic flow were started to be implemented. These measures refer to the widening of streets and/or providing off-street parking to accommodate the increased number of cars. Once these activities turned out to be insufficient to relieve traffic the strategy was then oriented towards policy regulations.

Through the years, with the increase of transportation demand also the need for effective measures for parking related problems emerged. Taking into consideration the implications that "parking" has, reliable information is therefore vital for the competent authorities (Van der Waerden, et al., 2015b). Therefore, in the recent years, the need for modeling drivers' route choice behavior has grown aiming to understand and give answers to the motives which govern drivers' route choice decision making (Papinski & Scott, 2011). In parallel, under the same scope researchers started to pay attention to drivers' parking behavior. To this extent, an insight into the parkers' behavior can facilitate the establishment of more effective parking policies and determine the additional traffic which is caused by parking. However, the main problem of detecting the presence and the level of parking-related traffic in dense inner city areas remains largely unsolved (Hampshire et al., 2015).

Among the methods used to collect route choice information in order to study the travelers' behavior, a relatively new and rich data source for collecting travel related data is GPS technology. Although GPS data seem to be superior to conventional methods of travel related data collection, from a practical standpoint this information is currently difficult to be collected and analyzed. Researchers, municipalities, parking companies and other competent authorities require a significant effort to conduct a GPS-based survey to collect this information including people recruitment, equipment costs etc. The post-processing procedures of the excessive amount of raw GPS data are also a big issue.

As mentioned in Chapter 1, for the execution of this thesis GPS data of car drivers is analyzed in GIS. The study has a twofold character. On the one hand, the GPS technology is approached from a practical point of view and how accessible it is for the time being. On the other hand, despite its current drawbacks, the capabilities of this relatively new technology regarding route choice are a scientifically proven fact. Therefore, considering the enthusiasm around the GPS technology and its promising current and future capabilities for tracking drivers and capturing trip information like never achieved before, it would be illogical if this study neglects it.

Consequently, the *primary aim* is to develop an approach based on the shortest-path method for route choice modeling considering two different variables, the travel time and travel length. The shortest paths are then compared to their observed route to examine to which extent the former can adequately describe the parker's route choice and if this consists of a more practically convenient and simplified approach which can be used for the time being in the place of GPS data. The *additional aim* is to provide insight into the way GPS traces can be combined with the capabilities that a GIS offers in order to investigate parkers' route choice.

Therefore, this chapter intends to give answers to the following research questions based on the literature suggestions regarding these fields:

1. What is "parking" in general, how the problems developed, how researchers approach this field and which solutions have been given until now?
2. What are the "state of the art" approaches used in modeling drivers' route choice?
3. Which methods are used to collect drivers' travel-related data?
4. What is GIS and how is it used to explore route choice behavior?

It starts by discussing the subject of parking in general (section 2.2) focusing on the parking related implications (section 2.2.2) and the solutions given through time (2.2.4). The current understanding of driver's parking behavior is addressed in section 2.2.3. Section 2.3 provides an overview of the methodological approaches used to gain insight into individuals' route choice (section 2.3.1) while section 2.3.2 focuses mainly on the approaches within the parking behavior context. Section 2.3.3 describes the data collection methods for measuring travelers' behavior. More emphasis is given to the GPS technology (section 2.3.3.3) highlighting its promising capabilities and advantages over the conventional methods of travel-related data collection. The limitations of the GPS technology are also underlined. Section 2.4 introduces the Geographic Information System (GIS) addressing its' powerful capabilities for route choice modeling. Finally, section 2.5 is regarding the conclusion.

2.2. Parking, implications, and solutions

2.2.1. Parking - A retrospect of the past history

Parking itself is a central concern in urban and transport planning causing direct and indirect negative externalities such as congestion, possession of a substantial amount of land, safety issues, land use separation, etc. (Feitelson & Rotem, 2004). It is remarkable to mention that in the literature many studies even before the half of the last century had started to explore the implications of parking and proposed measures to combat them. Chronologically speaking, around 1935 the problem of the disproportion between the number of curb spaces and the number of cars became clear to the municipalities ("Parking Strabgles Everything," 1950). Also, the land used for parking was addressed to reduce the open areas available for recreation and ecosystem services, thus having deleterious visual effects (Feitelson & Rotem, 2004). The oldest study found belongs to Behrendt (1940) who addressed the emergence of new city planning problems due to the rapid growth of the automobile traffic. From this point onwards, parking related issues for instance the space allocation of parking, parking related congestion in central business districts, parking management policies, and parking demand and supply were some of the popular topics for many researchers after the beginning of the automotive era (Arnold & Gibbons, 1996; Behrendt, 1940; Davis et al., 2010; Feitelson & Rotem, 2004; Hongbing & Zhaokang, 2011; Ligocki & Zonn, 1984; Locklin, 1948). Some of these problems are briefly discussed below.

At a first glance, the common problem that many of these studies addressed is the land occupancy of parking. In order to regulate parking supply, urban planners usually set minimum parking requirements (Feitelson & Rotem, 2004). Shoup, (1999) in a study according to which the minimum requirements in the US were analyzed, found that these were excessive. Also, a case study on 10 office buildings conducted in California, US, revealed the oversupply of parking to be almost twice than what was actually needed (Li & Guo, 2014). Similarly, in a study conducted in the city of Olympia, Washington, the overbuilding of parking was also confirmed with 51% more parking spaces than they were required (Arnold & Gibbons, 1996).

From the traffic point of view, through the literature many studies have addressed that private car and cruising for parking is widely accepted to be a significant contributor to congestion especially in dense city centers (D'Acierno et al., 2006; Gallo et al., 2011; Kaplan & Bekhor, 2011; Montini et al., 2012; Shoup, 2006; Van der Waerden, et al., 2015b). Moreover, it has also been proved that a significant share of cars in streets is cruising for parking which in turn causes significant delays (Shoup, 2006). The same study also revealed that the average share of traffic due to cruising is 30%.

2.2.2. Parking related implications

A common phenomenon that can be observed in dense city centers is cars moving around looking for a free parking spot. Nowadays, cruising for parking becomes more and more intense in urban areas and causes significant economic and environmental implications in large cities. These implications refer to as adding more pressure to the already congested traffic, unnecessary fuel consumption, and noise and air pollution (Kaplan & Bekhor, 2011). In addition, the decrease in the parking space availability will probably cause the increase of the number of cars searching for a free parking spot in the future (Van der Waerden et al., 2015b). It is also remarkable to mention that even if the demand is not increasing but remains stable the decrease of the supply itself is also an important issue due to the fact that municipalities take out of the transport system parking facilities. More specifically, parking lots and parking garages are closed down and on-street parking is forbidden, therefore the supply is decreased. To this extent, several side effects arise such as the decrease of accessibility and attractiveness of destinations as well as implications on the livability of visitors and residents (van der Waerden, et al., 2015b). In addition to this, a study based on accident data collected in 10 US cities found the increase in collision rates is related to the effort of drivers to find a free parking spot. More specifically, 49% of midblock accidents in major streets, 68% in collector streets and 72% along local streets were related to an effort to find a parking by the drivers (Karlin-Resnick et al., 2015)

2.2.3. Current understanding of parking behavior

Considering a car trip, although it may seem to be just a movement from an origin point A to a destination point B; it actually involves some in-between actions taken by the car driver. Galo et al., (2011) developed a model according to which they distinguished a car trip into 4 parts as followed:

- Walking access time (home to personal car)
- On-board time (trip to destination zone)
- Parking search time (cruising for parking)
- Walking egress time (parked car to destination)

When car trips come to their end cars need to be parked somewhere. The way drivers behave when they are about to find a free parking place can be seen common decision problem according to which drivers are evaluating all the parking possibilities that they are passing (Polak & Axhausen, 1990) considering a variety of factors in order to decide whether to park or continue to find the next opportunity that might satisfy their needs (Shoup, 2006). Drivers' decision is influenced by the parking tariff, parking duration, fuel and time spent for searching, the number of passengers, availability of parking spaces, and walking time (e.g. Shoup, 2006; Teknomo & Kazunori, 1997).

To reiterate, a very common phenomenon in urban areas is drivers who unnecessarily move around in cities looking for a free parking spot. This phenomenon causes noise and air pollution, add to the existing traffic (Kaplan & Bekhor, 2011), and decrease the accessibility and attractiveness of the destinations (Van der Waerden et al., 2015b). A detailed exploration of drivers' strategies regarding their parking behavior has been conducted in Karlsruhe, Germany, according to which not every car trip includes a "cruising" part (Polak & Axhausen, 1990). Some of these strategies are presented below:

- Strategy I: There might be drivers who have access to an almost guaranteed parking space, for instance, a private or a disabled parking space, thus they directly head to this parking without having to look for a free parking spot.
- Strategy II: Some drivers who can accept long walking distances usually collect a set of parking opportunities beforehand which almost always can guarantee a parking spot (usually off-street) without additional search. Therefore, there is no sign of cruising for parking once the decision of where to park has been pre-determined.
- Strategy III: Some drivers might opt to travel to the desired location and go directly for on-street parking nearby while they can be succeeded or not. To this extent, they start to seek

for a free parking place by making circles around their destination. Most of the times, this kind of strategy include short walking distances and long search times.

- Strategy IV: It was also addressed that some drivers might approach their destination using a pre-defined route which offers parking possibilities; however, if their search turns out to be unsuccessful then they illegally park near the destination for short stay. This type of strategy is associated with long searches.
- Strategy V: If the parking duration is short then drivers after a short search park illegally accepting the risk of having a fine in an exchange for short search and walking time.
- Strategy VI: Drivers know a fixed sequence of on-street and cheap off-street opportunities which can always assure a parking regardless of the type of parking. Drivers who use this kind of strategy do not use expensive off-street parking facilities and usually, they reject multi-storey and underground facilities.

The subject of parking can be approached from different perspectives. Throughout the literature, it is clear that researchers have attempted to understand parkers' behavior. To this extent, attention has been given to drivers' parking type preference and to the factors that influence their decision making in terms of route choice.

Studies have found that drivers whose activity is shopping, business or recreation most of the times prefer to park on a multi-storey parking facility while people who go to work prefer to leave their car on a parking surface (Teknomo & Kazunori, 1997). Studies on parking type choice behavior indicate that the two most important factors that drivers consider in order to choose a parking type are the time they spend searching as well as the walking distance to their destination (Polak & Axhausen, 1990). The behavior of choosing a parking facility can be seen as an evaluation process according to which the drivers consider a set of possible parking opportunities which they determine based on their characteristics (parking fee, type, capacity etc.). These characteristics are combined with the trip features, for instance, the destination, arrival time, trip purpose etc. to finally choose a parking facility (Thompson & Richardson, 1998). Shoup (2006) in an empirical study based on data collected from twenty cities throughout the US he produced a model of how drivers choose whether to pay or cruise and concluded that where curb parking is underpriced some drivers are more likely to cruise rather than pay to park off-street, however, if curb and off-street parking prices are equal then cruising time will be close to zero. Another interesting finding regarding the planned routes (from preference surveys) and observed routes (from GPS data) of 31 participants was that drivers choose their route to approach their destination in order to minimize the total travel time and traffic lights/signs, as well as to maximize route directness (Papinski et al., 2009).

Another interesting aspect in the context of parking that is relatively new within the scientific community is the parking search behavior of the drivers. Through the literature, it can be seen that there is a grown interest recently. However, the experiences on the parking search behavior of drivers is still limited (Van der Waerden, 2015b) due to the fact that until lately researchers have neglected it as a source of congestion once it is hidden in the general traffic flow (Shoup, 2006).

Cruising for parking can be distinguished into two components. The first component refers to as the spatial component of parking search behavior indicating the street segments used for searching. Some studies' findings have shown that it seems that there is less cruising in streets near the parking facilities while at the same time searching is more common where there is a presence of shops (Van der Waerden et al., 2015b; Van Ommeren et al., 2012). Also, the higher the parking tariff the more people tend to search for a cheaper opportunity (Shoup, 2006). In addition, the socio-demographic characteristics of drivers also seem to be linked to cruising for parking, for instance, low-income drivers are expected to cruise more and the vice versa (Van Ommeren et al., 2012).

The second component refers to as the temporal component which is the time spent for searching (Van der Waerden et al., 2015b). Shoup (2006) reported a review of 16 studies conducted in 11 cities in the US according to which the average cruising time ranges between 3.5 and 13.9 minutes. Looking at the situation in Europe, one can say that the aforementioned indications of cruising time have no such a difference while there are strong indications that indeed most of the drivers spend unproductive time searching for free parking spaces or waiting in a queue. However, few European examples which indicate the issues that arise from parking could be found in the literature. Surveys conducted in British cities over the 90's century indicated that 25% of the total travel time of trips in central urban areas was spent on parking search. More specifically, a research in London reported that between 30% and 40% of the total traveled distance of the trips that ended in the central area of the town corresponded to parking search (Bonsall & Palmer, 2004). Polak & Axhausen (1994) indicated that in Frankfurt, Germany 40% of the total travel time can be spent on searching for a parking space. A recent study in the city of Amsterdam, Netherlands regarding cruising for parking has resulted in a very small average search time (36 seconds) compared to Shoup's findings (3.5 – 13.9 min) while evidence of cruising observed in 30% of the total trips (Van Ommeren, et al., 2012). This phenomenon was mainly explained as the effectiveness of the paid parking introduction by the Dutch municipalities since 1990. Another recent study conducted in the city of Turnhout, Belgium reported a higher average parking search time (1 min and 18 sec) than Van Ommeren (36s) which corresponds to 14% of the total travel time (Van der Waerden, et al., 2015b). Also, Montini et al., (2012) in a study conducted in Zurich found that parking search in the central business district is less than 4 minutes for 80% of the cases and the distance driven from the assumed search start point range between 1100 to 1400 meters. In addition, throughout a controlled group of GPS traces, Karlin-Resnick et al., (2015) found an average search time of 62 seconds.

2.2.4. Solutions to parking related problems

One of the first reactions by the city planners against these unprecedented problems caused by the rapid growth of the automobile traffic were the widening of the streets and highway construction. However, these turned out to be insufficient to relieve the traffic congestion in the downtown sections simply due to the fact that the problem was where to put these cars when they come to rest (Behrendt, 1940). From this point on, many ideas were put on the table and implemented in some cities, for instance, the prohibition of curb parking in main cross streets, the parking time restriction using parking meters and parking zones in order to increase turnover and ensure availability of parking space (Hampshire et al., 2015). However, the parking problem was characterized as an incurable disease which had left untreated (Parking Strangles Everything, 1950).

According to (Marsden, 2006) parking policies first emerged from the need to manage the concerns of safety and traffic flow obstruction on streets with parking pricing and supply restrictions to be the most widely accepted methods to limit car use. This has led to policies in order to manage parking on the highway as well as to consider parking standards at new developments and to provide off-street public car parks.

In Philadelphia and Pittsburgh parking authorities have been established which had the right to condemn private property for parking lot purposes. Many cities then made a turn towards the establishment of off-street parking places as a way to mitigate the side-effects of the curb parking prohibition (Parking Strangles Everything, 1950). In the city of Buffalo, the US, over a three year period 50 buildings were demolished within the central district and the property has been transformed into a parking lot (Behrendt, 1940).

Furthermore, a solution that could directly affect and easily handle motorists was the parking pricing policies to which many studies paid serious attention to the effect pricing policies have on drivers' behavior and decision, and therefore the distribution of congestion (Anderson & de Palma, 2004; D'Acierno et al., 2006; Gillen, 1978; Kelly & Clinch, 2006; Miller & Everett, 1982; Shoup, 2006; Teknomo & Kazunori, 1997). Pricing policies in many large cities in Europe were adopted to basically force users' mode choice towards public transport, and to minimize parking search time and its externalities such as air pollution, and other additional costs (D'Acierno et al., 2006). Some of the behavioral studies found regarding the parking pricing policy are briefly discussed below.

A model developed by Shoup (2006) predicted that where curb parking is underpriced some drivers are more likely to cruise rather than pay to park off-street, however, if curb and off-street parking prices are equal then cruising time will be close to zero. Van Ommeren et al., (2012) added that further reduction of cruising time can be achieved by stronger within day differentiation of parking fees. Moreover, Willson & Shoup (1990) studied the effect of parking subsidies on employee's travel choices and concluded that reduction of parking subsidies increase solo driving. Also, a similar study in Los Angeles, US, predicted that 34% fewer automobiles would drive to work if workers have to pay to park as compared when they park free (Wilson, 1992). Thus, we can see that the sensitivity of parking demand and the drivers' behavior in response to parking pricing fluctuation was extensively explored (Caicedo, 2012; Calthrop et al., 2000; Kelly & Clinch, 2006; Mei et al., 2010; Ottosson et al., 2013). Moreover, time-varying and location-dependent parking fees were also issues that were examined (Arnott et al., 1991; Zhichun et al., 2007). Another good example of the effectiveness the parking pricing policies consists of a study conducted in San Fransisco under a parking pricing optimization program which aimed to reduce cruising for parking. The impact that the "SFpark" program had on cruising refer to decreases of approximately 25-50 % (Karlin-Resnick et al., 2015).

Along with the gradual technological developments of the last decades, new ideas and solutions arise as well. According to Hössinger et al., (2014) as an attempt to solve the problem of the unnecessarily high amount of parking search traffic especially in rush hours in the centers of large cities accurate information systems were used to navigate drivers to the closest free parking space. The last two decades many cities were started implementing the so-called PGI systems (parking guidance information) to manage the parking demand (Geng & Cassandras, 2012). To this extent, real-time information about the degree of occupancy is provided to drivers using the so-called variable message signs (VMS) in order to guide drivers with directional signs to the available parking space. However, many studies addressed the side-effects of parking guidance information systems, for instance, the high cost of the sensors as well as their controversial effects once they indirectly support car use (Hössinger et al., 2014). Wang & He (2011) addressed the problem that occurs when the number of vacant spaces within a parking lot is limited during rush hours. To this extent, when the parking availability information is published by the smart parking system then the prospect drivers moving towards this precious spot would increase, thus causing additional congestion. This phenomenon is known as the "multiple-car-chasing-single-slot" . Moreover, Rodier et al., (2005) conducted a smart parking participant survey in San Fransisco, US, and found that 37% of the responders have actually seen the message signs with the parking information while only 32% of these responders changed their decision based on this information. In a similarly conducted study to assess the impact of PGI to the behavior of drivers, it was found that 30% of the responders were unaware of the message signs existence while 18% had used them once. However, Polak & Axhausen (1994) in a case study for measuring the effectiveness of a PGI system in a central business district in Frankfurt, Germany, they found that search times were decreased during high demand periods for instance on Saturdays while at the same time changes in the parking search behavior of drivers were observed.

Advanced ICT-based automation management solutions have already been used by the parking lot industry in response to the increased parking demand. These solutions refer to digital monitoring and recording, license plate recognition and automatic payment kiosks (Lee et al., 2015). A new contribution to the smart parking management consists of the reservation system which allows travelers check the parking availability and reserve one via the internet or cell phone up to 2 weeks in advance of their trip. This system was successfully implemented in various European and Japanese cities (Rodier et al., 2005). Geng & Cassandras (2012) proposed and implemented a smart parking system according to which it assigns and reserves the optimal parking place to the driver considering a variety of factors such as proximity to destination, parking cost as well as ensuring at the same time that the overall capacity of the parking is efficiently utilized. Finally, through a pilot implementation project of their proposed system, they concluded that significant amount of time, fuel and congestion can be saved.

2.3. Methodological approaches, measuring methods, and limitations

2.3.1. Observing route choice

There has been an increased interest in recent years in order to understand the factors that govern route choice decisions (Papinski & Scott, 2011). Gaining an insight into commuters' choice behavior became one of the most significant missions in travel behavior modeling (Tang & Cheng, 2016). However, observing and understanding activity-travel patterns and route choice decision making is often difficult using the conventional methods of data collection due to the complexity of the human behavior, the lack of the drivers' knowledge about the composition of the road network, the lack of knowledge of their preferences, and the uncertainty about their perceptions of the route characteristics.

Therefore, modeling traveler's route choice facilitates the analysis and understanding of this behavior and is essential while it gives the possibility to predict travelers' behavior under certain hypothesis and forecast the future traffic conditions on a given transportation network. Other travel choice models, for instance, mode choice (car, train, bicycle, etc.) and destination choice (cities, apartments, regions, traffic analysis zones, etc.) include only few alternatives. However, in route choice the routes are hidden in the road network and need to be extracted from the big amount common links that comprise a road network. In order to achieve this, the path generation process is required to create a set of alternative routes based on which one route that represents the route choice behavior under hypothetical scenarios is selected. Route choice modeling approaches focus on fuzzy logic, artificial neural networks, cognitive psychology, and discrete choice approaches (Prato, 2009).

Within the context of discrete choice modeling approach, the choice set generation can be achieved using methods that are classified into probabilistic approaches, constraint enumeration algorithms, deterministic shortest path methods, and stochastic shortest path methods (Prato, 2009).

The shortest path problem is a well-known combinatorial optimization problem which has extensively been studied and has a multi-disciplinary range of applications. Real world problems where the shortest path algorithms are constantly in use are among others web-based services (e.g. Google maps) which help people with travel directions, constructing public transportation itineraries provided by many websites nowadays (e.g. train, airline industry) combining multiple optimization criteria (e.g. time, cost). In addition, internet service providers (ISPs) perform every day shortest path calculations for packets' routes (Santos, 2009).

The most simple route choice model is based on shortest path-based methods. As mentioned, there are two methods for generating shortest paths, deterministic and stochastic with the former to be the most common approach for route choice models (Papinski & Scott 2011). Stochastic shortest path methods include the simulation approach and the doubly stochastic generation approach.

A popular deterministic method consists of the shortest path algorithm which is the most straightforward approach for generating a route choice set. The behavioral assumption behind the shortest path algorithm is that drivers choose their route in order to minimize the paths' general cost and to avoid tremendously costly alternatives (Prato, 2009). In addition, another example of a deterministic method is the labeled paths (Frejinger et al., 2009) which assume that drivers have different objectives such as minimizing travel time, prefer routes with familiar landmarks, or feel discomfort with greatly congested roads and highways, while others might prefer scenic routes regardless of the total travel time. To this extent, links are labeled based on certain criteria/objective functions (Prato, 2009). Another method consists of the link elimination (Frejinger et al., 2009) which aims to make sure that there are no similarities among the shortest path alternatives. This is achieved by eliminating part or all of the shortest paths links which have used in previous shortest path searches. Finally, the link penalty method works in a similar way like the link elimination, however, this time the shortest paths' links are imposed to a penalty instead of being removed (Prato, 2009).

The key assumption of traffic assignment models is that individuals tend to minimize as much as possible their travel effort (Papinski & Scott, 2011). According to Wardrop (1952) drivers seek to minimize the total travel time. Traditionally, the most common path selection criteria that individuals use consist of the time and distance attributes (Golledge et. al., 2001). Most of the studies on travel behavior adopted the assumption according to which individuals seek to minimize time, cost, or distance. Papinksi et al., (2009) in an overview of the most studied route choice attributes also confirmed that travel time, distance and cost have been given a great attention in previous studies.

However, beyond the travel time or distance drivers also take into account other criteria for instance avoiding stops, monetary costs, (Tang & Cheng, 2016), avoiding congestion (Papinski & Scott, 2011) minimizing obstacles (traffic lights, stop signs), maximizing aesthetics, minimizing number of street segments, avoiding hazardous areas, and minimizing intermodal transfers (Golledge et al., 2001). A good example consists of Papinski et al., (2009) study according to which the outcome of a stated preference survey suggests that participants opt to minimize travel time when they travel from home to work. However, the same study's results also revealed that drivers not only seek to minimize travel time but also they tend to avoid congestion and select routes which are as direct as possible.

2.3.2. Parking behavior

Taking a glance at the parking subject, previous studies within the parking context can be distinguished into empirical studies and studies for model development. The former, aims to give answers into parking behavior of the drivers by observing and measuring (collecting data) the phenomenon, for instance, using survey data, GPS data etc. The studies which aim in model development mainly consists of an extension of network based assignment models or agent-based models (Van der Waerden, 2015b).

Modeling approaches can vary from discrete choice models which used to study the effect of parking pricing policies on the en-route parking behavior of the drivers regarding the choice between parking type, parking facilities, driving route, and their response to en-route parking information (PGI) (Kaplan & Bekhor, 2011; Teknomo & Kazunori, 1997; Axhausen & Polak, 1991; Lambe, 1996; Bonsall & Palmer, 2004;) simulations for the traffic effect of parking search behavior as well as its environmental cost (Benenson et al., 2008; Dieussaert et al., 2009; Gallo et al., 2011; Guo et al., 2013; Thompson & Richardson, 1998) to possibility theory for the evaluation of the effects of various parking pricing policies on parking users' behavior (Ottomanelli et al., 2011).

The second group of studies, as mentioned above, aim to give empirical insight into the subject of parking behavior by providing a more quantitative explanation of this phenomenon. These studies have mainly been focused on the amount of cars moving around seeking for parking paying little attention on which streets are used and how much time is spent on searching (Kaplan & Bekhor, 2011). From what has been found in the literature good examples of empirical studies on parking behavior consists of the ones conducted by Hampshire et al., (2015), Karlin-Resnick et al., (2015), Shoup (2006), Van der Waerden et al., (2015b), and Van Ommeren et al., (2012) which their findings presented before.

2.3.3. Measuring travel behavior

Collecting data about driver's travel behavior has been mainly achieved through stated or revealed preference surveys and direct observations (e.g. video, GPS tracking). These methods are briefly presented below.

2.3.3.1. Survey approaches

As far as we know, the most common method used to obtain behavioral and theoretical understandings of the travelers' route choice in most of the studies found in the literature was mainly through survey approaches. More specifically, information about drivers has been collected using travel surveys, and stated preference surveys (e.g. questionnaires and interviews) in order to collect information about driver's attitudes and perceptions as well as information about the parking supply and demand itself (Gallo et al., 2011; Shoup, 2006; Teknomo & Kazunori, 1997; Van der Waerden et al., 2006; Van der Waerden et al., 2015b; Van Ommeren et al., 2012; Weis et al., 2011;). In addition, socio-demographic information can be collected along with the chosen route, chosen parking, and travel and search time estimations.

2.3.3.2. Manual data collection and visual techniques

It is also remarkable to mention that except from the survey approaches of collecting data about travelers behavior in some studies the researcher used to follow the car until it is finally parked so as to observe the trip characteristics in real time (e.g., Wright & Orram, 1976). Moreover, another study used in-car observations by filming the driver while he/she was driving in order to collect information about route choice decisions as well as to film the streets in order to define the most used roads the drivers used to approach his/her final destination and park (Laurier, 2005). In addition, aerial observation has been used in some studies to record and observe traffic via video cameras (e.g. Salomon, 1986).

2.3.3.3. Global Positioning System (GPS)

In the late 1990s, global positioning system (GPS) devices began to be used as a method for measuring personal travel (Stopher et al., 2008). GPS stands for the geographical positioning system which is a constellation of satellites that emit precisely timed signals. Through a GPS receiver, these signals are detected and the user's exact position on the Earth's surface can be calculated in three dimensions (longitude, latitude, elevation) (Lin et al., 2014).

Therefore, with the aid of a GPS logger, it is possible to find out the location and speed of a vehicle at a certain time. The GPS logger takes the difference of relocation between two consecutive measurements and calculates the vehicle speed for each time interval. Therefore, even if the car is not moving, GPS logger will still register speeds which usually do not exceed 1km/h (Haberkorn, 2011).

The specifications of different GPS recorders can vary in terms of sensitivity, position accuracy, velocity accuracy, memory etc. Moreover, the user can set the GPS logger to receive measurements at a specific time interval, for instance, every 1 or 3 seconds. The outcome of a GPS recorder consists of a .csv (comma separated value) file containing information in columns and has the structure which is depicted in Table 2.1 below:

Table 2 1: Outcome of a GPS logger (Haberkorn, 2011)

INDEX	An upward numbering of the records/measurements
RCR (ReCord Reason)	Indicates whether the positions were recorded as a condition of time, speed and/or distance. For a normal recording, the "T" value will appear in the data.
DATE	The date of recording
TIME	The time of the recording
VALID	Indicates whether enough satellites determined the position and if so, the value will be "SPS". However, if not enough satellites were found the value will be set to "Estimated"
LONGITUDE	Longitude
N/S	North/South
LATITUDE	Latitude
E/W	East/West
HEIGHT	Height in meters
SPEED	Speed in km/h
PDOP	Position Dilution of Precision. It is the combination of both the horizontal and vertical components of position error caused by satellite geometry. Values between 2 and 4 indicate excellent accuracy
HDOP	Horizontal Dilution of Precision (degree of horizontal accuracy)
VDOP	Vertical Dilution of Precision (degree of horizontal accuracy)

NSAT	Number of satellites used to determine the position/number of satellites found
DISTANCE	Distance in meters from the previous measurement

GPS technology and travel behavior

Personal travel and the way it changes is something that policy makers and transportation planners are concerned about (Batelle et al., n.d.). Observing drivers' route choice is a very difficult process especially if the factors that might influence decision-making are being investigated (Papinski & Scott, 2011). In recent years, studies have shown an emerging interested in using GPS tracking data to observe trip information (Papinski et al., 2009) once data can be collected in an economical and timely manner (Papinski &Scott, 2011) while at the same time the respondents' burden is reduced and the data quality is enhanced (Van der Waerden et al., 2012)

GPS technology consists of a relatively new and rich data source which has been applied to track and understand driver's activity-travel patterns and route choice decision making (Montini et al., 2012). To this extent, various studies can be found in the literature which used GPS to measure household travel information (Batelle et al., n.d.), study route choice decision making (Papinksi et al., 2009; Papinski & Scott, 2011), and even to assess the accuracy of household travel surveys (Stopher et al., 2007). Therefore, studies have shown its promising capabilities according to which GPS data can supplement conventional methods, for instance, existing diary data recorded (Papinski & Scott, 2011).

Reconstructing the observed routes is a powerful way to provide the driver's actual route in terms of links and nodes. The use of a Geographic Information System (GIS) is of vital importance once it can support the travel behaviour research. GIS gives the opportunity to the researcher to view, manage, process, analyze, and visualize data which are related to positions on the surface of the earth (Mitchell, 1999) within an analytical and programming environment (Papinski & Scott, 2011).

Therefore, matching the collected GPS points to a road network required to be able to observe study travellers' behaviour. To this extent, previous studies have developed map matching algorithms that can correctly identify the travelled links with 78.5% success. Thus, automated map matching algorithms can decrease the burden regarding other trip reconstruction approaches, for instance, the revealed or stated preference surveys and therefore allow more time to the researcher to spend on other aspects (Papinski & Scott, 2011).

An interesting study on individuals' route choice behavior that fits best the scope of the current thesis is the one conducted by Papinski & Scott (2011). According to this study, the route choice of travelers was investigated using GPS data and a GIS-based tool. The main challenge was to test the hypothesis that workers opt to minimize travel time or distance home to work commutes. In order to achieve this, shortest paths were generated between origin destinations which were then compared to the observed route. The shortest paths based on distance were generated considering network connectivity, turn restrictions (one-way roads), and impedances (travel distance). For the shortest path based on time posted speed limits and estimated network travel times were used. The observed routes were manually map-matched to the road network in ArcGIS. In total 237 observed routes collected in the city of Halifax, Canada has been analyzed. Their results suggest that observed routes are significantly longer than their alternatives (shortest paths based on time and distance), thus they don't accurately represent the observed routes for home to work commutes. Consequently, this implies that algorithms used to generate shortest paths might not capture individuals' real world route choice decisions. Therefore they concluded that workers may consider other route attributes for their route choice. At the same time, they mentioned that the kilometers traveled per vehicle are being underestimated by policy makers thus the emission levels and pollutants caused by vehicles are also likely to be underestimated.

Global Positioning System and parking behavior

To reiterate, the GPS technology consists of a relatively new data source for collecting information about travellers' behavior. To the best of our knowledge, in the literature, there are limited examples of studies that used GPS data to collect information about travelers in order to study the subject of parking. Though, an increased interest can be observed lately. However, most of the studies found within the context of parking mainly studied the cruising behavior of drivers which has been explained before (Hampshire et al., 2015; Kaplan & Bekhor, 2011; Karlin-Resnick et al., 2015; Montini et al., 2012; Van der Waerden et al., 2012; Van der Waerden et al., 2015b).

In spite of the promising capabilities of the GPS technology as a data collection method these studies also revealed the disadvantages regarding the parking behavior related information provided by the GPS logger. For instance, the time that people start to search is still unknown and hidden in the raw data as explained above. Also, due to the fact that GPS data is only a registration, it does not give any feeling of the users and their actions that might indicate the search effort (e.g. the information acquired from video data).

To this extent, studies have tried to combine the GPS tracks with other data collection methods in order to reveal the hidden aspects of parking search behavior that can't be observed from raw GPS data. In particular, through the literature it can be seen that some studies attempted to couple the typical self-reported surveys with a GPS-based field experiment in order to get complete and accurate travel diaries by retrieving detailed information with high degree of accuracy about parkers' behavior (Kaplan & Bekhor, 2011; Montini et al., 2012; Papinski et al., 2009). An interesting example consists of Papinski et al., (2009) study according to which the route choice decision making of 31 users was explored using GIS to demonstrate the individuals' planned routes collected from a traditional travel survey and then compare them to the observed routes derived from the GPS devices. Their findings also suggest that GPS data coupled with diary data provides new great insights into trip planning behavior, for instance, spontaneous en-route decisions that can be taken from drivers who deviate from their planning route.

In addition to survey methods, GPS data has also been coupled with data collected via video camera that has been fixed in the car in order to capture and analyze the passenger's head movements that might indicate a sign of searching (Hampshire et al., 2015; Karlin-Resnick et al., 2015). More specifically, by drivers verbally indicate when they start to search. In addition, this verbal sign is combined with the indications of the video data (upper body movements of the driver) and the fluctuations in the travel speed (acceleration-deceleration) in order to derive consisted patterns of the way that people search for parking and when people start to search. Consequently, this combination can provide robust indications of the parking search behavior process.

Except the coupling of the GPS data with other methods of data collection, also attempts to study the parkers' behavior using only GPS data have been observed in the literature (Montini et al., 2012; Van der Waerden et al., 2012; Van der Waerden et al., 2015a). Van der Waerden et al., (2012) through a pilot study they examined if GPS trip loggers can be used to sufficiently capture drivers' parking search behavior. From the few cases that were explored (9 car trips) it seems that parking search behavior can accurately be determined. As an extension of the aforementioned study, Van der Waerden et al. (2015b) explored both the temporal and spatial component of parking search behavior based on empirical data collected in the city of Turnhout, Belgium. Their findings confirmed the assertions according to which the use of GPS consist of a promising and rich data source that could be used to describe car drivers' search behavior both in terms of time and location.

As it can be seen, GPS technology can provide valuable information regarding users' position in different time intervals accompanied by speed and distance which can be then used to analyze parking search behavior. However, the time that people start to search is still unknown.

Limitations of Global Positioning System (GPS)

As already mentioned, GPS technologies are becoming more and more useful in terms of the collection, manipulation and analysis of travel behavior data (Van der Waerden et al., 2012) With the help of GPS technology accurate information about travel time and trip speed is collected in a short period of time and in an economical manner (Papinski & Scott, 2011). However, despite the advanced deployment of GPS technology the last years and its hopeful capabilities to replace conventional methods of collecting data, some issues regarding instrument reliability, battery consumption, urban canyon effects, post-processing of the data still exist (Montini et al., 2012; Papinski & Scott, 2011; Van der Waerden et al., 2012).

To this extent, although GPS collected data seems to be a very promising source of information which can be used to analyze travel behavior; studies have addressed the drawbacks of its reliability. More specifically, one of the limitations of GPS regarding its accuracy is the position determination under tree coverage and underground (Zandbergen & Barbeau, 2011). Also, the movements of satellites as well as the reflection of satellite signals on objects especially between large buildings in urban areas (Van der Waerden et al., 2012) consist of a major limitation in regards to the accuracy and reliability of GPS data causing disturbances in movements' tracking (Zandbergen & Barbeau, 2011) resulting in a few meters errors (Van der

Waerden et al., 2012). A study regarding the positional accuracy of collected data using GPS-enabled mobile phones revealed that the maximum horizontal error observed was 20 meters when performing outdoor testing (Zandbergen & Barbeau, 2011).

A comparison of the data collection methods

Compared to conventional methods of parking-related data collection GPS data seems to have a major advantage over interviews and questionnaires (Montini et al., 2012). In particular, the most recent technologies for GPS devices indicate the potential to replace many conventional methods of data collection that are flawed because of known errors and inaccuracies (Stopher et al., 2008). More specifically, GPS data is based on objective time and distance calculations while interviews/surveys are based on participants' estimations, therefore, their disadvantage consists of the risk of retrieving inaccurate or incomplete data due to partial memory recall. In addition, the data collected from traditional questionnaires can lead to a biased estimation of walk distances (underestimation) while only the main activity is reported (Montini et al., 2012). On the other hand, GPS data can reveal intermediate activities for instance window shopping.

From a cost perspective, the advantage of a self-reported behavior survey lies in the ability to conduct a large-scale survey at a relatively modest cost. In contrast, GPS data collection is characterized by the labor intensive process of the data collection. In particular, it requires recruitment of participants who will then provide information of their daily commutes by using the GPS logger. Consequently, these procedures can be related to high costs and respondents' burden In addition to this, there is always the risk that participants forget to carry the logger or sometimes forget to turn the logger off thus additional from car movements are also registered (e.g. train, bus), and therefore, lead to a misrepresentation of the study's outcome. Moreover, the post-processing procedures that are required for the huge amount of data collected from GPS loggers is also an important issue.

A novel data collection method that has been explained above is the one that uses video data collected from in-car, aerial observation or by following a car until it is parked. However, it can be strongly argued that these methods consist of very labor-intensive processes which also require a significant amount of time, effort and cost to collect as well as to process the data in order to extract the relevant information from the aerial images and the video tapes. Finally, the disadvantage of these video and visual techniques relies on the extremely limited information obtained in terms of geographic scope which can then be provided by GPS data.

2.4. Geographic Information System (GIS)

Many people think of Geographic Information Systems (GIS) as any recent computer system which uses advanced technology in order to present a set of data on a map. However, viewed historically, the first GIS application dates back to 1854 when a map with 48 districts was made to map cholera outbreaks and avoid its expansion ("What is GIS ", 2015).

By and large, the need to capture, display, and process spatial information for different purposes was developed through the years into an invaluable system that serves today many disciplines among others planning and engineering, transportation/logistics, agriculture, medicine, meteorology and business management. GIS generally facilitates the information management of whatever is located on earth (Mitchell, 1999).

The GIS system has the ability to dynamically combine and process information from a variety of sources which have common geographical components using a layering technique ("What is GIS", 2015). This diversity of information can be presented in an easy to understand graphical format (Van der Waerden & Timmermans, 1996). These layers might hold information that refer to transportation, water features, elevation, land use, boundaries etc. ("What is GIS", 2015). Figure 2.1 below illustrates the principle behind the GIS system where real world information from different sources is stored as thematic layers each carrying its own attributes and can be linked together by geography.

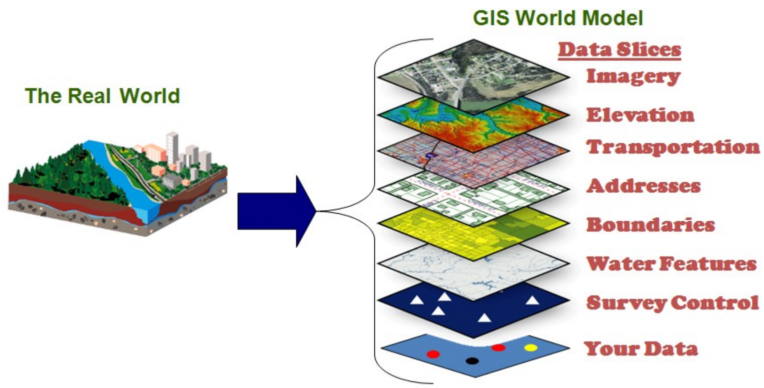


Figure 2 1: Geographic Information System – Thematic Layers

In GIS, two models can be used to represent geographic features on the map: the Raster and the Vector model (Mitchell, 1999). The former can store information about the features in cells. For instance, satellite images, photogrammetry, and scanned maps are cell-based data. The latter includes lines, points, and polygons that are created by digitizing the base data (the process of converting the map's coordinates into digital format by tracing the lines along geographical features) (Bolstad, 2008). Thus, the Vector model is specifically used to store data for discrete boundaries for instance roads, borders, and land parcels and, therefore, fits better the transportation field by which features can be represented by lines, points, and areas. The reason behind it is that the network analysis which is one of the main approaches regarding the transportation analysis is operated by using a network which consists of links (representing roads) interconnected by points (representing the intersections of roads) (Rodrique et al., 2006).

2.4.1. GIS and Transportation planning

At the present time, GIS is being served by many powerful tools which have been efficiently designed to facilitate spatial analysts' job to link data with geography in order to visualize, decide, predict and take actions. The wide range of GIS tools is incorporated in different software packages such as ArcGIS, ArcMap, and TransCAD.

Geographic Information Systems support several transportation planning activities of many planning agencies and institutions by offering a variety functions that are used for spatial and transportation analysis (Van der Waerden & Timmermans, 1996). These activities refer to the management and maintenance of the existing transportation system and to anticipate possible transportation infrastructure problems (Meyer, 1986). By this end, GIS-T comes to enhance the current approaches of GIS with unique developed analysis methods and models that fit the transportation issues offering a variety of functions for transportation modeling, network analysis, route analysis, and traffic assignment. These functions are accompanied by an effective range of powerful tools and analysis techniques including among others shortest path calculations, map based calculations, buffer analysis, traveling salesman analysis etc. (Van der Waerden & Timmermans, 1996).

2.4.2. GIS and route choice behavior

Studies within the context of parking behavior were supported by GIS in order to display and analyze data, proving its' invaluable importance (Karlin-Resnick et al. 2015; Montini et al. 2012; Papinski et al. 2009; Papinksi & Scott 2011; Van der Waerden et al. 2015b). Travel behaviour research is also supported by Geographic Information Systems (GIS) once it allows the user to view, query, interpret and visualize spatiotemporal data (Papinski & Scott, 2011). The GIS strength can be seen in its unique ability to relate spatial and attribute data (non-spatial data) into a spatial context using an integrated manner in order to draw conclusions that could have never be seen by just observing the raw data itself (Rodrique et al., 2006).

Among the wide range of GIS's abilities one of utmost importance is the ability to visualize the routes taken by car drivers using the recorded routes from the GPS device (GPS tracking data) and perform an analysis. Van der Waerden et al., (2015b) they have used TransCAD, a transportation GIS software package tool, to relate the GPS data with the streets segments so as to calculate the number of times each road segment was used as well as to relate this numbers with characteristics of the street segments. Montini et al., (2012) used POSDAP which is an open source of GPS data analysis in order to extract parking search related characteristics. In addition, Papinski et al., (2009) addressed the valuable insight that can be given into the route choice process by combining GPS and GIS. In particular, they recorded the routes of participants using the ESRI's ArcMap by displaying both the road network and other land use features. Finally, Karlin-Resnick et al., (2015) in their study used PostGIS, an open source software, to make their analysis of the GPS collected traces.

2.5. Conclusions

This chapter provided a better understanding of different aspects regarding the thesis topic. This was achieved by examining subjects that are required for the understanding of this research, and providing a review of previous studies within the context of parking and route choice.

Through the Literature Review chapter the following research questions have been answered and extensively discussed. The most essential findings are briefly discussed below.

1. What is “parking” in general, how the problems developed, how researchers approach this field and which solutions have been given until now?
2. What are the “state of the art” approaches used in modeling drivers’ route choice?
3. Which methods are used to collect drivers’ travel-related data?
4. What is GIS and how is it used to explore route choice behavior?

Regarding the route choice modeling, observing and understanding the route choice decision making of drivers is not simple due to the complex nature of the human behavior. However, it does worth the effort once it gives the opportunity to study and predict the future traffic conditions as well as the travelers’ behavior under certain hypothesis. Basically route choice researchers confront two major challenges. The first refers to the creation of a set of alternative routes between origins and destinations in order to choose the route that best satisfies the study’s hypothetical scenarios. In order to do so, the second challenge is to evaluate the attributes of the route choice set (Papinski & Scott, 2011). As aforementioned, researchers used a variety of approaches to generate a set of alternative routes between origins and destinations. Among the methods for generating a route choice set, the most straightforward approach is the shortest path algorithms, with travel time being the most popular path selection criterion (Wardrop, 1952).

Geographic Information Systems support many transportation planning activities by offering a variety of functions. The shortest path algorithms are one of these analysis techniques. The shortest path approach is being served by many GIS tools among others TransCAD and ArcGIS. With the capabilities of GIS to combine, analyze and observe information of entirely different nature great insight can be obtained about drivers’ route choice. All the studies that were found within the context of parking behaviour and route choice (with the use of GPS data) were supported by GIS in order to display and analyze this GPS-related information, something that proves its importance.

All in all, regarding the use of the GPS technology as a data collection method it has been addressed that it can provide important information about the drivers’ behavior by observing their route in an economic, accurate, and timely manner while at the same time the burden of participants is eliminated significantly. Moreover, studies also addressed the GPS technology’s advantage over the conventional methods of data collection such as the stated or revealed preference surveys due to their limitations. For instance, through stated preference surveys people need to answer hypothetical questions which make respondents overly optimistic. Therefore, respondents need to imagine possible alternative routes rather than directly experience them, thus the factors that indeed influence route choice might not be considered in the data the respondents provide. In addition, there is a case that respondents might give the interviewer the respond they believe he/she would like to hear.

Although GPS data seems to be superior to conventional methods of travel data collection, this information is practically difficult to be collected and analyzed for the time being. For instance, a significant amount of time and effort is required to collect and analyze this GPS-related information. Therefore, there is a need to recruit people, provide them with GPS receivers, and of course burden the equipment cost (buying GPS loggers). In addition, dealing with the excessive amount of data that is collected is also something that is being discussed. Moreover, issues about the accuracy of the GPS technology are also addressed in the literature. More specifically, instrument reliability, battery consumption, urban canyon effects, are some issues that still exist. One can also say that GPS related information can be found by the car navigation companies and telephone companies. However, navigation companies and telephone companies which have in their dispose travelers' information from GPS data might not fully provide the required information due to users' privacy issues. More specifically, the parts of the trip that include information about the origin and destination of the drivers are not provided.

Moving from GPS loggers to smart phones GPS data collection was partly the solution for issues such as when people forget to carry the device, or charge it, once nowadays people manage both to charge and carry their phone. However, the GPS function on phones can consume a great deal of energy. Moreover, due to the limited storage space and the expensive cost to transmit the data, the data cannot be recorded at short time intervals. In addition, due to the fact that most of the people usually carry the phone in their bag or pocket weakens the signal, and therefore, affect the accuracy.

Chapter 3

Methodology

3.1. Introduction

Given the research motivation presented in chapter 1 and the findings of the literature review (chapter 2) the research questions were derived. To reiterate, the current thesis has a two-fold character.

First of all, it was made clear that there is a current need to simplify the GPS tracking approach, in terms of the time, cost, and effort required by parties such as municipalities and parking companies in order to capture and study parker’s route choice. Therefore, as the *primary aim* of this study is to develop a more practically accessible approach that can be used, for the time being, by the municipality and parking companies to estimate to the best possible extent the parker’s route choice in a timely and costly manner.

Second of all, it is a scientifically proven fact that the GPS technology consists of a relatively new and very rich data source with promising capabilities over conventional methods of data collection. Therefore, although this study examines an alternative approach that can be used for the time being in the place of GPS tracks; it would be illogical if the promising capabilities of the GPS technology are neglected. As aforementioned, there are still limited experiences on parking behavior with the use of GPS data. Therefore, the *additional aim* is to focus on how information about parking related traffic can be derived from the GPS data in combination with the capabilities of a GIS, and draw attention to the valuable insights that can be gained.

Consequently, taking into consideration the aforementioned, the following research questions were introduced.

Main research question:

1. *To which extent can full GPS tracks be replaced by just O-D points and shortest paths (length, time)?*

Additional research question:

2. *How GPS technology and GIS can be utilized to provide insight into the parking-related traffic and what kind of information can be obtained?*

In chapter 1, the research framework (Figure 1.1) divided into 4 parts was presented illustrating the necessary steps for the execution of this study. In short, in the first part the research questions were defined based on the literature review and research motivation. In the second part, the literature review provided the background information on the subject of parking and route choice in terms of the current understanding, methods used to approach these subjects, the findings of previous studies, strengths and weaknesses etc. The third part refers to the methodology that was adopted to approach the research questions. To this extent, the necessary data is collected. Most of the analysis part takes place in TransCAD (GIS) where the data-analysis technique of the shortest path algorithm is applied to create the alternative route choice sets (time, distance) for the comparison to the observed routes. In addition, the traffic assignment is achieved using the variety of functionalities that TransCAD (GIS) offers. To generate the results, the use of tools such as SPSS and Excel facilitate the process. Finally, the fourth part consists of the conclusion part. The results from the analysis and literature review are used to answer and discuss the research questions. In addition, the recommendations for future research based on the experience acquired through this study are given.

3.2. Research approach

This section describes in detail the way the study has been conducted in order to answer the research questions which were described above. In this study three types of routes are examined, the observed, and the shortest routes based on time and distance. First, in section 3.2.1 the data-analysis technique of the shortest path algorithm is introduced. This technique is offered by TransCAD (GIS). The Geographic Information System and its utility have been extensively described in chapter 2. The observed routes and the way these are reconstructed from the GPS data are described in section 3.2.2. The routes' comparison methods are introduced in section 3.2.3. Section 3.2.4 introduces the traffic assignment procedure and how this is approached using TransCAD (GIS). Finally, the way in which the necessary data is collected is then described in section 3.3.

3.2.1. Shortest path method

Route choice modeling facilitates the understanding of the incentives behind the drivers' complex behavior. In particular, it is gives the possibility to estimate drivers' behavior under certain hypothesis and predict the future traffic conditions on a given transportation network. In order to do so, through the path generation process a set of alternative routes is created from which the route that represents the driver's route choice behavior is selected under certain hypothetical scenarios. The generation of the choice set is achieved using a diversity of methods which are classified into probabilistic approaches, constraint enumeration algorithms, deterministic shortest path methods, and stochastic shortest path methods (Prato, 2009). Route choice modeling confronts two main challenges. The first refers to the creation of a set of alternative routes between origins and destinations in order to choose the route that best satisfies the study's hypothetical scenarios. The second challenge is to evaluate the attributes of the route choice set. Among the methods for generating route choice sets, the shortest path method is the most common and straightforward approach for route choice models (Papinski & Scott, 2011; Prato, 2009).

A simple representation of the principle behind the shortest path approach can be found in Figure 3.1 below. Shortest path refers to the shortest possible path that connects two specific points (in this case 1 and 2) from a network which consists of many stages (nodes). This is achieved considering the attributes of the network. These attributes might refer to values (e.g. time, distance etc.) and/or link directional restrictions. Finally, taking into consideration the network's features the possible shortest path can be calculated that minimizes the path's total value accumulation and at the same time satisfies the segments' directional restrictions (if these are applied).

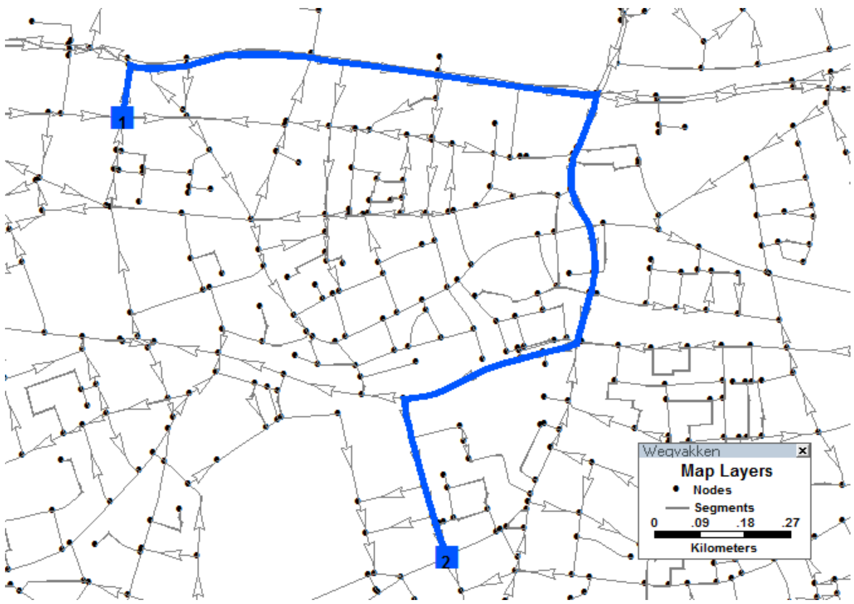


Figure 3 1: Shortest path principle

In this study, the data-analysis technique of the shortest path algorithm offered by TransCAD software package tool is used to create the set of alternative routes between origins and destinations.

Regarding the networks' attributes, there are different types of path selection criteria such as the turn minimization, fewer obstacles (e.g. traffic lights), avoiding unsafe areas, and minimizing intermodal transfers. The most studied selection path criteria are travel time and distance (Papinski & Scott, 2011). The findings of a travel survey regarding the route choice decision of the drivers revealed that half of the respondents stated that minimizing the travel time is the most significant factor that affects their decision (Papinski et al., 2009). In addition, minimizing distance was also stated by the respondents during the interview.

In the current thesis, due to the time constraints the two basic networks attributes are used to create the alternative route choice sets are the distance and time. The former refers to the shortest path which minimizes the travel distance. The latter refers to the travel time minimization between an origin and destination point.

3.2.2. Observed Routes Reconstruction

As aforementioned, this study examines 3 types of routes, the observed routes derived from the GPS data, and the shortest routes based on time and distance as section 3.2.1 described above. This section describes the methodology followed for the observed routes.

What makes GIS so powerful is the ability it has to combine spatial and non-spatial data. TransCAD uses three types of data files, the line, point, and area file. These line file can be used to build up a transportation network. The line file is comprised of two different layers, the segment layer which represents the roads of a network and a special point layer (nodes) which represents the intersections between these segments (Van der Waerden & Timmermans, 1996). All three data files are not connected to each other once they are entirely three different files. The GPS tracks are stored in a point file. Although, the point and line file can be projected at the same time, still they are not connected to each other. Therefore, the line file needs to be connected to the point file in order to transform the GPS tracks into segments and notes (connection with road network). In this way, the actual routes can be observed and make the necessary network calculations.

A powerful way to reconstruct the observed routes is by using map matching algorithms which can correctly identify up to 78.5 % of the links traveled. To this extent, automated map matching algorithms can decrease the researcher's burden compared to other trip reconstruction approaches, for instance, the revealed or stated preference surveys, therefore, it allows more time to the researcher to spend on other aspects (Papinski & Scott, 2011). However, due to the lack of the necessary means and time in this study, it was decided that the observed routes will be manually reconstructed. Although it is a time-consuming procedure, the manual reconstruction of the observed routes ensures that these have been correctly identified eliminating any error that could occur from using a map matching algorithm. Figure 3.2 depicts the combination of the point (GPS tracks) and the line file (nodes + links) in TransCAD (GIS).

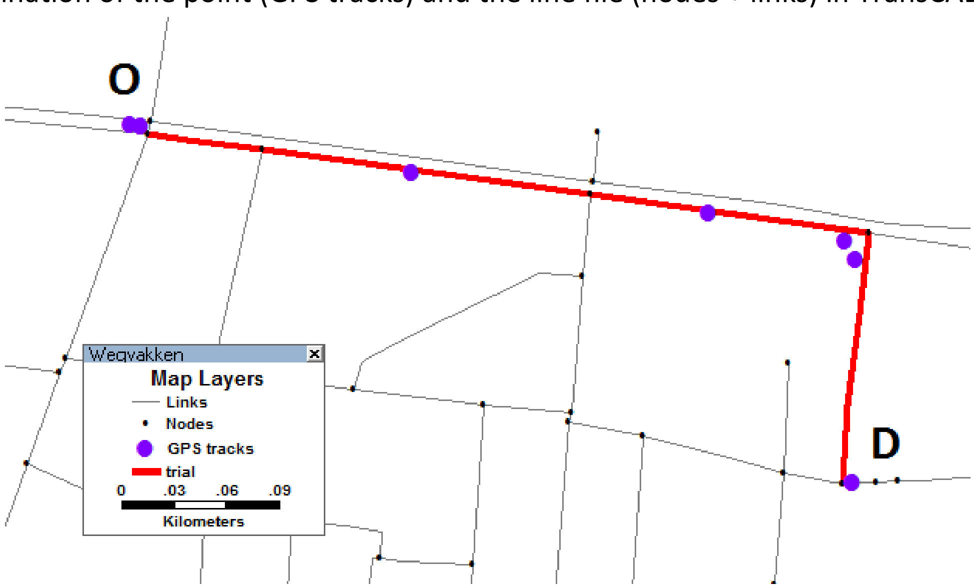


Figure 3 2: Combination of point and line file in TransCAD (GIS)

3.2.3. Comparison of Observed and Shortest routes

The main research question will be approached through the comparison of the observed routes (from the GPS tracks) to two alternative route choice sets generated using the shortest path method. As already mentioned, the two route choice sets refer to the network attributes of time and distance. Therefore, the main hypothesis that is being tested is that travelers seek to minimize either travel time or distance. Figure 3.3 below depicts the principle behind the comparison of the observed (a) routes to their alternative shortest paths based on distance (b) and time (c).

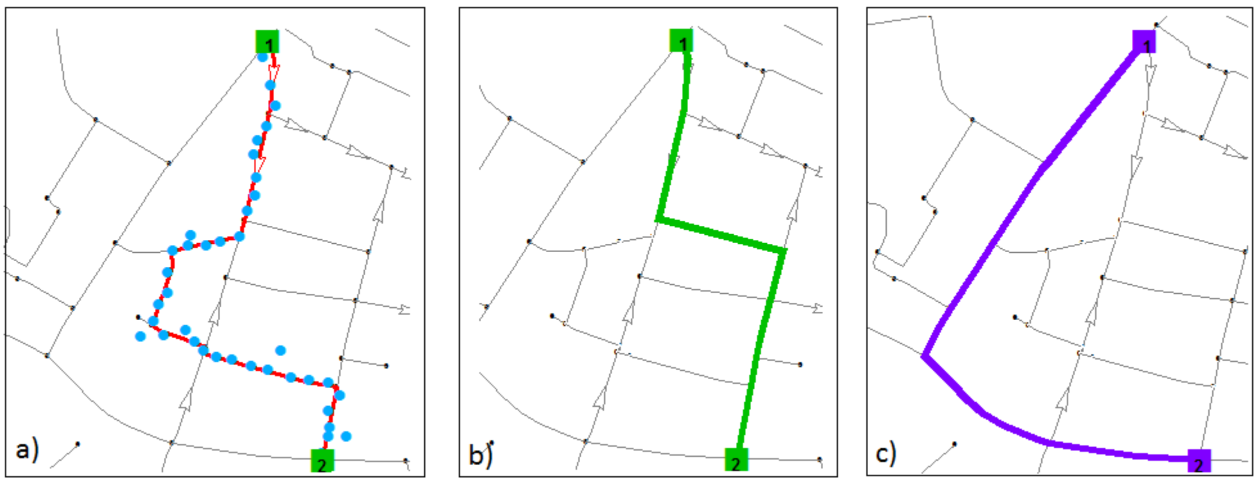


Figure 3 3: Observed (a) and shortest routes based on distance (b) and time (c)

For the comparison two different approaches have been adopted and are described below. In this study, the comparison is based on network calculations of the time and distance attributes.

3.2.3.1 Approach 1

The first approach refers to measuring the common distance covered between observed and shortest alternative routes from the network. Figure 3.4 depicts an example of this process according to which the shortest path (marked with orange) and the observed route (marked with red) can be compared. In this way, the effectiveness of the alternative route choices will be assessed using a quantitative approach (determine the percentage of the common distance covered between the observed routes and their shortest alternatives).

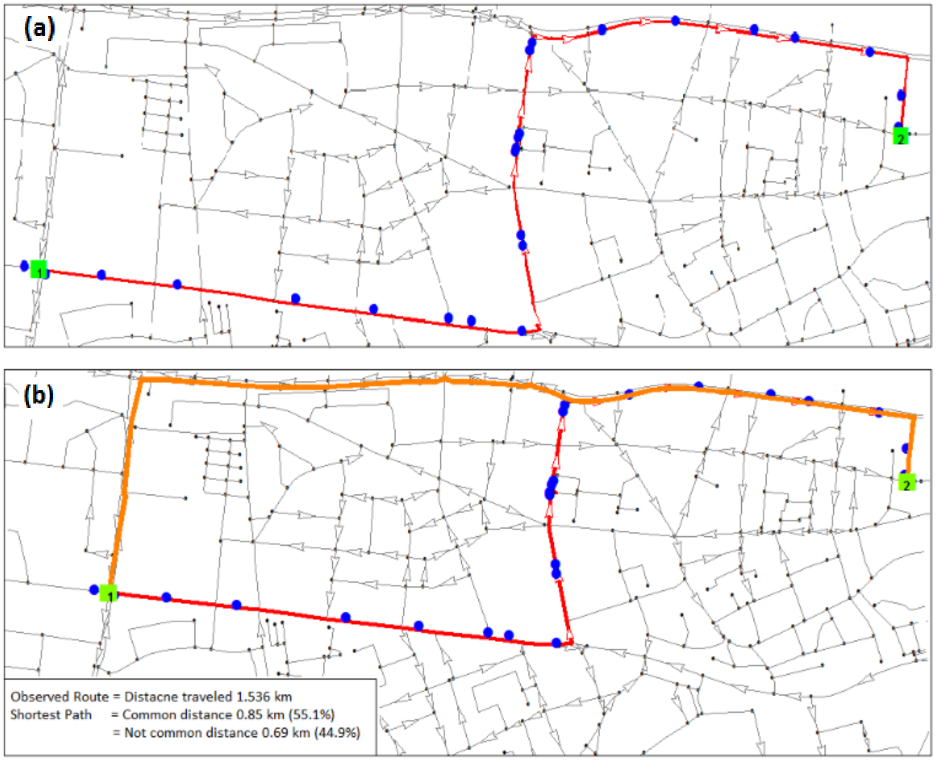


Figure 3 4: Approach 1 – Observed and shortest route comparison

3.2.3.2 Approach 2

A second approach was adopted for the comparison of the observed routes to their shortest alternative routes in order to reinforce with more evidence the outcome of the first approach. The second approach is depicted in the example of Figure 3.5 below. More specifically, a buffer of 20 meters is created around each shortest path. The value of 20 meters is based on the horizontal error found in a study regarding the positional accuracy of GPS-enabled mobile phones (Zandbergen & Barbeau, 2011). The maximum horizontal error found in this study was 20 meters when performing outdoor testing. Thereafter, the number of GPS points that fall within this buffer can be counted. Then, the percentage of points that fall within in the buffer compared to the overall GPS points can be calculated.

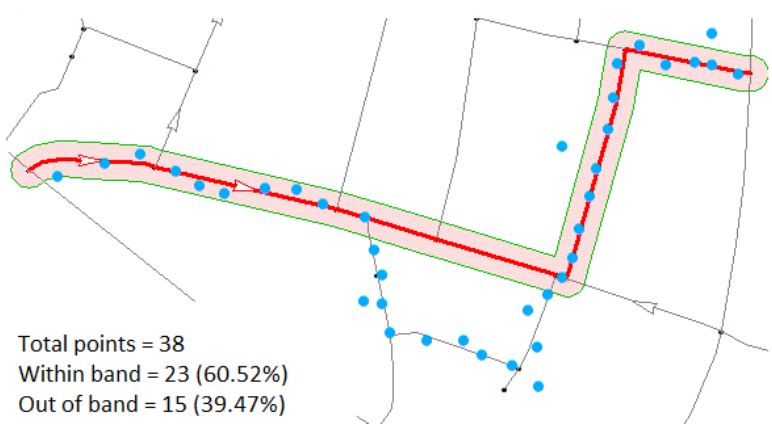


Figure 3 5: Approach 2 – Observed (GPS tracks) and shortest route comparison

Finally, quantitative information about the observed and shortest routes can be collected through TransCAD (GIS) based on network estimations in terms of:

- Common distance travelled (Approach 1)
- No. GPS points within the buffer (Approach 2)
- Total traveled time
- Total traveled distance
- Road type composition (ring-road, main, local)

3.2.4. Traffic Assignment Model

As discussed in the Literature review chapter, among the wide range of functions that TransCAD (GIS) offers, the possibility for traffic assignment is one of them. Traffic assignment is the process of allocating traffic between a set of origins and destinations to the specified transportation system. This is done through algorithms which under least travel-cost criteria choose a specific route to connect each O-D pair (Gonzales-Ayala, 1999). The majority of the methods in the literature refer to the O-D matrix estimation and link flow simulation (Caggiani & Ottomanelli, 2011). The fundamental purpose of assigning traffic on a road network is to reproduce the pattern of vehicle movements according to a set of constraints. In general, the main goals of a traffic assignment process are to (Singh, 2015):

- Provide estimates of travel costs between origins - destinations
- Estimate the volume of traffic on the networks' links and acquire aggregate network measures,
- Analyze the travel pattern between an origin destination pair
- Identify heavily traveled or congested links as well as the routes used between origin – destination pairs so as to collect important traffic data for future intersections design

In this study, parking related traffic is explored. Under the current research, the stepwise procedure illustrated in Figure 3.6 below, is used for the traffic assignment application. Traffic is reproduced on the road network through the generation of trips between the O-D pairs. The desired outcome of the traffic assignment is the traffic flow estimation on the network and the aggregation of traffic volume in terms of the most used roads. This can provide an estimation about the heavily congested links occurred from trips towards a parking facility. To this extent, an O-D trip matrix is created including the trips that correspond to the specific parking facility.

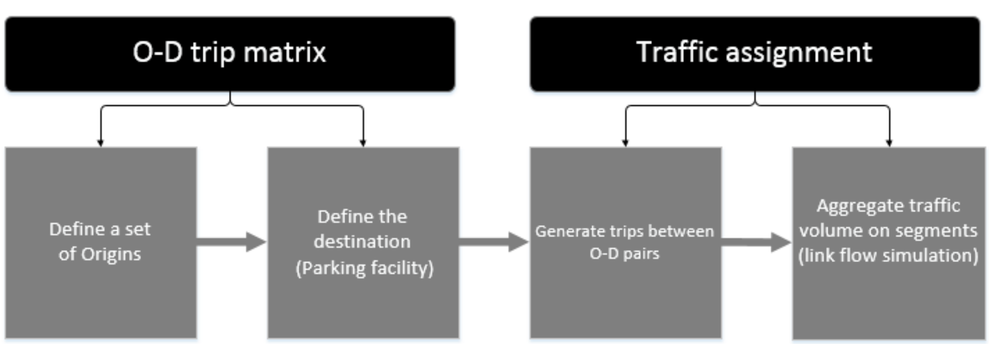


Figure 3 6: Traffic assignment procedure

In order to achieve this, the traffic assignment function of TransCAD (GIS) will be used. TransCAD (GIS) offers a diversity of traffic assignment routines for traffic flow estimation, amongst others the All-or-Nothing, Stochastic Loading, Incremental Assignment and Capacity Restraint (Van der Waerden & Timmermans, 1996). The common requirements of all methods are an O-D matrix and a node-link network. However, the selection of a particular method depends mostly on the available data. The method that fits the best the purpose of this study is the “All-or-Nothing” which assigns traffic on links without considering the links’ capacity and congestion, which are data that is not available in the current study. Compared to other methods (e.g. user equilibrium assignment) this method distributes the trips between O-D pairs on a single path between them using travel time as a fixed input without dependence on link’s congestion (Gonzalez-Ayala, 1999).

3.3. Data Collection

This section describes how the necessary data is gathered. The data can be divided in two categories. The first refers to the GPS data collection and it is covered by section 3.3.1. The second category refers to the necessary information collected about the road network in terms of its’ attributes (time, length, directional restrictions, road categorization etc.) and is explicitly presented in section 3.3.2.

3.3.1. GPS data

There are different sources that GPS data can be collected from. GPS loggers can be used to track the route choice of individuals. Participants should then be provided with GPS devices which should be carried on board whenever they travel, thus tracking their travel route. This method requires participants’ recruitment as well as a significant amount of capital in order to acquire the GPS loggers. In addition, studies which compared different data collection methods have shown the effectiveness of moving towards smart-phone GPS data collection strategies and car navigation systems (Papinki et al., 2009) as more convenient methods. In this way, issues such as when people forget to charge or carry the GPS device can be eliminated with the use of smart-phones. However, there are still issues such as the expensive data transmission cost, accuracy (when smart-phones are in a pocket or bag), energy consumption required, limited phone storage space (data cannot be recorded at a high rate) etc. (Bierlaire et al., 2010).

Nevertheless, in this study, due to the time constraints based on which this research should be carried out, GPS data could not be collected during the study’s execution period. As already mentioned, car navigation systems companies, as well as mobile phone companies due to privacy issues do not fully provide this GSP-related information. More specifically, parts of the trips that contain information about the origin and destination of the car driver cannot be provided.

For that reason, this study uses secondary GPS data which was not specifically collected for the purpose of this research. However, this was a convenient dataset that has been used to conduct this study. More specifically, the data has been provided by the Eindhoven University of

Technology. The GPS data was gathered in the context of a bicycle stimulation program (B-Riders) by the province of Noord-Brabant. The aim of this program was to stimulate people in order to use the bicycle more often than the car for their commutes (B-Riders-2016). In total, 2345 individuals participated in the "B-Riders" program in 2014, and their trip information was collected. According to this program, people were asked to install an application on their mobile device which would then register their movement by tracking their GPS coordinates. This application could be turned on/off manually when they start and finish their bike trip. However, users who set the application to be turned on automatically when they were moving also sent in information regarding their different commutes within the day. These additional commutes referred to trips with travel mode car, train, bus etc.

Van der Waerden & Feng (2015) conducted a study using the aforementioned GPS dataset of the "B-Riders". The goal of the study was to contribute to the ways that large GPS traces can be translated into activity-travel diaries so as to generate useful information. The authors used a computer-software named TraceAnnotator (TA) for the post-processing of the phone GPS data. This tool was developed in the context of previous projects conducted by the Urban Planning group of Eindhoven University of Technology. The software's tasks were to recognize the transport mode and the activity purpose as well as to classify the traces into trips and activities. This is achieved by taking into account some variables, for instance, average speed, acceleration, deceleration, and the distances to different networks like cycle ways, motorways, and footways. Finally, the GPS traces were translated into journeys (O-D trips) and stages (travel mode classification). Consequently, the produced O-D as well as the full GPS tracks of initially 190 car trips were provided and used as a convenient dataset to apply the aforementioned methodology and conduct this study.

3.3.2. Road network

The transportation network is undoubtedly the basic data file required in order to execute the analysis in TransCAD. The road network file is basically a line file which consists of two different layers, the segment and node layer. The former refers to the actual lines of the network which represent the road segments while the latter refers to the nodes (intersections) that connect these segments. The transportation network of the Netherlands was obtained through the National Road File (NWB-Wegen) which is a digital geographic database provided by the Ministry of Interior (Ministerie van binnenlandse Zaken en Koninkrijksrelaties) in open source and contains almost all roads in the Netherlands including pedestrian roads and cycle paths. In addition to the road segments, the file also contains some additional valuable characteristics for the analysis, for instance, street names, length, and coordinates.

However, additional information about the road network needs to be collected. A shortest path is generated between two points considering the road networks' attributes. As aforementioned, there is a diversity of possible attributes that can be considered. In this study two route choice sets are created, based on the time and distance attributes. Serious attention has been paid to develop a good quality's road network by implementing its real characteristics to the best possible extent. The road network needs to represent as much as possible reality due to the fact that shortest paths will be generated based on the network's features.

The next paragraphs describe the necessary information that has been collected for the road network regarding the two route choice sets. Section 3.3.2.1 refers to the information collected for the shortest distance routes creation. In the same way, section 3.3.2.2 describes the necessary information for the creation of the shortest time routes.

3.3.2.1. Shortest path based on the travel distance

Shortest path approach is directly influenced by the road network and its characteristics. In their study, Montini et al. (2012) explored the parking search behaviour of the drivers in Zurich, Switzerland with the use of GPS data. Their analysis was based on the comparison of the route choice with the shortest possible path which was calculated using Dijkstra's algorithm with distance as cost. Therefore, in order to generate the shortest possible path they considered one-way streets and streets' length as the features of the network which influence the calculation of the shortest path based on travel distance. Hampshire et al., (2015) also included in their study the shortest possible path as the length of the most efficient path that drivers could have taken to reach their final destination as this was calculated by Google Maps. Another interesting study conducted by Karlin-Resnick et al., (2016), according to which the network calculations of the shortest path between various points and the final destination was accomplished taking into account one-way streets and turn restrictions using OpenStreetMap data. Finally, as mentioned in the literature review chapter Papinski & Scott (2011) generated shortest paths based on distance considering network connectivity, turn restrictions (one-way roads), and impedances (travel distance).

Consequently, one-way roads, street length, and turn restrictions seem to adequately fulfil the requirements that a road network should have so as to efficiently calculate the shortest path based on travel distance. Therefore, it was decided that in the current thesis the shortest path that minimizes the travel distance of the car trips should take into account the road network's characteristics such as one-way roads and of course length values.

3.3.2.2. Shortest path based on the travel time

Travel time can be seen as a broader and more complex aspect to implement in the road network compared to the travel distance described above due to the diversity of factors that could influence travel time. Except for current traffic conditions, undoubtedly, one of the main factors that have a direct influence to the travel time is speed. Despite the lack of empirical evidence in the literature about the urban features that influence driving speed (Groot et al. 2006) there are still studies that prove the relation of the urban design and street characteristics with the fluctuation of the driving speed (Brundell-Freij & Ericsson, 2005; Daisa & Peers, 1997; Duy & Kubota, 2013; Elliott et al., 2003; Groot et al., 2006; Maghelal et al., 2008; Marshall et al., 2008).

More specifically, drivers are stimulated to increase or decrease their speed according to their interaction with the urban environment. In general, urban design features that cause a feeling of safety usually tend to stimulate drivers to increase the driving speed while in the case where a feeling of possible risk is induced then the driving speed is decreased (Groot, et al. 2006). To this extent, evidence from previous studies in regards with how street characteristics and road design affects the average travel speed needs to be collected. This information is presented below.

3.3.2.3. Street Characteristics

On-street parking

The urban feature that seems to induce most the feeling of unsafety to drivers and therefore causes a decrease of the average driving speed is the presence of on-street parking. A study regarding the driver's speed choice found a significant speed difference in streets which provided on-street parking compared with streets without on-street parking. The presence of on-street parking, especially in streets which are part of the main destinations of a city, help people to recognize that they have reached their final destinatoin and therefore they slow down (Marshall et al., 2008). Daisa & Peers (1997) presented the influence of the "effective" street width as a function of curb-to-curb width. Their findings are illustrated in Figure 3.7 below where the narrower the street width the more influence it has on the driving speed. In particular, in Figure 3.7(a) depicts a case based on which a wide street induce drivers to increase speed. In constrast, in Figure 3.7(d) a narrow street with high parking density causes the reduction of drivers' speed. In a similar way, Figures 3.7 (b) and (a) depict cases with low and moderate effect on speed respectively.

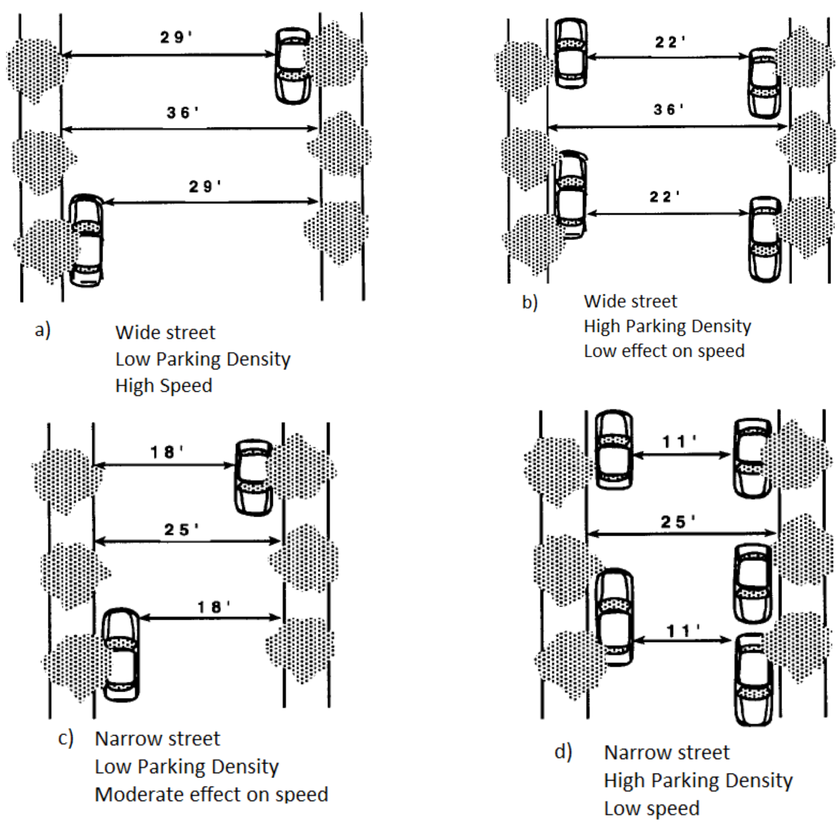


Figure 3 7: Influence of on-street parking on average travel speed, (Daisa & Peers, 1997)

Presence of trees

In addition to this, the so-called street tree effect seems to also influence driver's speed choice because one can see the environment as not a movement function. A study which compared drivers' speeds in tree-lined streets and streets without curbside trees indicated a reduction in driving speeds in the case of the presence of trees for both faster and slower drivers (Maghelal et al., 2008). The difference between the two cases can be seen in Figure 3.8 and 3.9 below. The former illustrates a road section where the road width is greater than the optical height. In this case, the authors claim that rather than a reduction of speed is observed. On the other hand, Figure 3.9 depicts a case according to which slower speeds are expected compared to the previous case due to the fact that the optical height is much smaller than the road width. The assertion about the influence of trees on the drivers' speed choice was also confirmed from the results of an experimental study which used virtual reality to derive participants' reactions in terms of the driving speed when they interacted with a series of street profiles including a variety of different street characteristics (Groot et al., 2006).

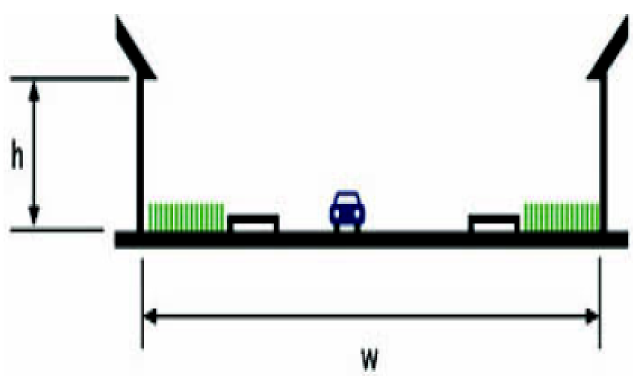


Figure 3 8: Street without curbside trees (Maghelal et al., 2008)

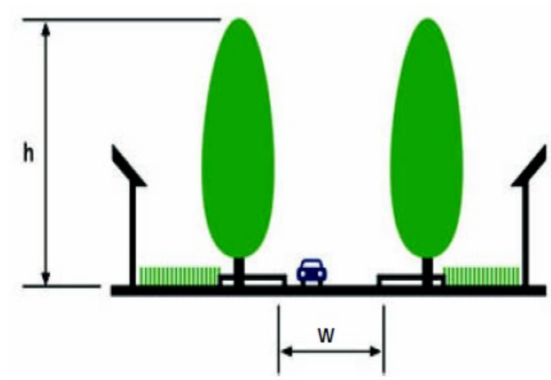


Figure 3 9: Street with curbside trees (Maghelal et al., 2008)

Bike lanes

Moreover, the introduction of bike lanes has been also found to have an influence on the driving speed of individuals. However, an interesting fact is the differentiation of this influence according to the type of the bike lane. For instance, when the bike lane is integrated with the road network and is separated with only a marking line (white line) then the drivers come closer to cyclists, therefore, the likelihood of a serious event is increased causing them to decrease their speed (Groot et al., 2006). However, the difference in the speed is small due to the fact that drivers could consider the speed suitable for passing a cyclist (Elliott et al., 2003). On the other hand, when there is a presence of a segregated bike lane (elevated) from the rest road network then drivers might have a feeling of safety, therefore, urging them to increase their speed.

Buildings

The main feature of an urban environment is buildings. The distance of the building façade to the road (setback) as shown in Figure 3.10 seems to play an important role to drivers' speed choice. Regardless their height, the presence of buildings on one or both sides of the road has the aftereffect of narrowing the visual field of the driver and tend to reduce the average travel speed (Elliott et al., 2003). At the same time, drivers can judge the area as an area with residential function and less as a movement function, therefore, inducing drivers to slow down. An interesting finding is that the distance of the buildings from the road seems to affect speed. More specifically, the smaller the distance the bigger is the reduction in speed (Groot, 2005). Perhaps the reason is that drivers correlate the frequency of buildings and their distance from the road with the likelihood of the presence of pedestrians, kids playing, or other hazards (Elliott et al., 2003).

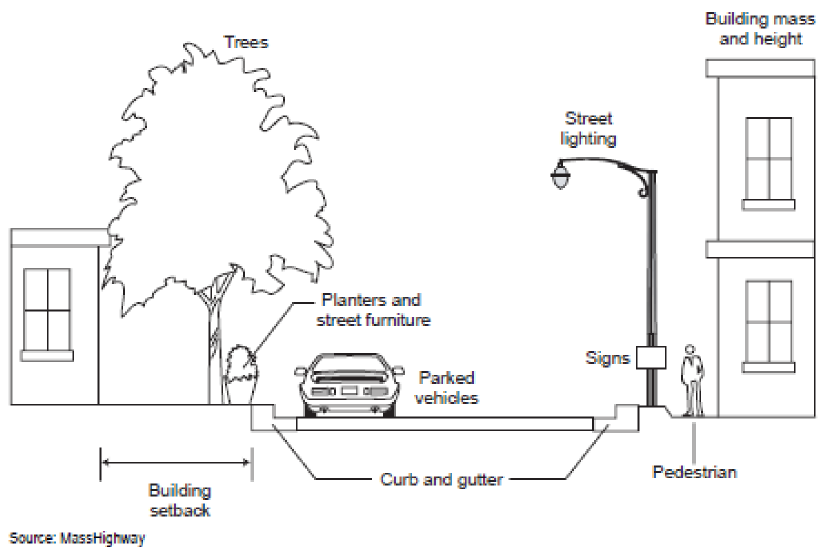


Figure 3 8: Influence of building setback on average travel speed (Elliott et al., 2003)

Road Surface

Finally, also the road surface seems to play an important role in drivers' speed choice. For instance, studies revealed that a rough road surface can reduce driving speeds. The reason is the discomfort of the driver which is caused by the noise and vibration that come from the friction of car wheel and the road anomaly-surface. Compared to asphalt material; brick, and imprinted surfacing can induce drivers to reduce their speed (Elliott et al., 2003).

All in all, the presence of on-street parking, trees, buildings, bike lanes tend to narrow physically and visually (limit the visibility) the road, induce the feeling of fear, and thus tend to increase the level of concern for a possible unexpected event, for instance, with pedestrians, childs, car or other risks (Groot et al., 2006).

Table 3.1 below summarizes the above mentioned street characteristics and their influence on the average travel speed.

Table 3 1: Influence of urban design features on average travel speed

Attribute	Influence on Average Travel Speed
	Decrease (km/h)
Residential Buildings	
Small Setback (2m)	2.4
Large Setback (4m)	1.2
Large Setback (6m)	-
Trees	
Optical Height > Optical Width	2.3
Optical Height < Optical Width	-
Road Humps	19
Road Surface	
Asphalt	-
Brick	6.4
Bus lane	1.6 - 3.2
Bike lane	
Marking line	1.6
Elevated	0.6
On-street parking	6

The profiles of the aforementioned street characteristics can be found in Appendix A. These profiles were collected through Google Maps and depict the road network's characteristics which have been discussed above. Based on these profiles, the adjustment of the posted speed limits that correspond to each road can be achieved.

Chapter 4

Analysis

4.1. Introduction

In the previous chapter, the methodology and techniques that are used for the execution of this project were explained. Thereby, the data collection as well as how the additional required information has been obtained was also described. To this extent, this chapter elaborates on the implementation of the methodological framework using as a case study the city of Tilburg, the Netherlands. Section 4.2 introduces the study area and the required information for the implementation of the methodology presented in the previous chapter. At this point, the necessary data for further elaboration is acquired for the case of Tilburg, and analyzed in order to answer the research questions.

The *main research question* is approached by section 4.3.1 which refers to the comparison of the observed routes to their shortest alternatives. The hypothesis that is being tested is that car drivers opt to minimize either travel time or travel distance. The *additional research question* is approached in section 4.3.2. This section focuses on the GPS data itself. The observed routes of the 83 car trips are related to the available parking facilities of Tilburg and then the parking related-traffic is assigned to the road network.

4.2. Data Preparation

4.2.1. Description of dataset

In this thesis, the city of Tilburg, the Netherlands is used as a case study for the implementation of the methodological framework presented in the previous chapter and to solve the research questions set in chapter 1. In particular, Figure 4.1 depicts the study area which is the city center (marked with blue) where most of the main parking facilities are located. As mentioned before, this study uses secondary GPS data. More specifically, the GPS data has been collected within the context of a bike stimulation program (B-Riders). Although the concept of this program was to capture movements of bike trips, the participants have also registered trips that correspond to train, car and bus travel modes. Within the context of a previous study conducted by Van der Waerden & Feng (2015), the aforementioned dataset has been used for the application of a computer-software named (TraceAnnotator) where GPS traces were translated into journeys (O-D trips) and stages (travel mode classification).

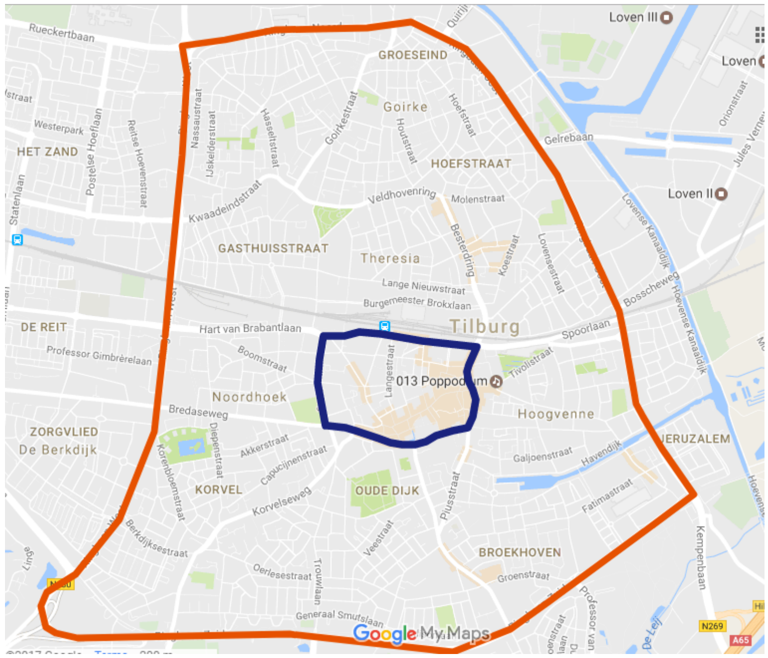


Figure 4 1: Study area: Tilburg, the Netherlands (Source: Google Maps)

To this extent, using this convenient dataset, car trips with final destination the central area of Tilburg were extracted, organized, and prepared for the execution of this thesis. In total, GPS data of 83 trips have been used in the analysis. The purpose of the selected trips corresponds to "nondaily shopping". Although the destination of the trips is the city of Tilburg, many of them are originated from different locations in the Netherlands, such as Eindhoven, Breda, and Hertogenbosch etc. In total, 52 trips (63%) correspond to participants (visitors) with a home location other than Tilburg while 31 trips (37%) refer to participants who can be defined as residents. However, the familiarity of the participants with the city it is an unknown factor.

The following Figure 4.2 illustrates the journey data that includes the O-D pairs. Each participant corresponds to an ID, the "persno". Each trip has a unique ID, the "Casenum1". The columns "lonfrom", "latfrom", "lonto", and "latto" contain the origin and destination coordinates respectively. In addition, as it can be seen, the travel year, month, and day of each trip is also included.

	travyr	travmn	travdy	Casenum1	Casenum	persno	jourseq	purfrom	purto	lonfrom	latfrom	lonto	latto	distance	method
1	2014	9	17	1083	1564	2401	1	home	nietdagelijk...	4.948183280000	51.619953680000	5.091910290000	51.56045158000	15555.69	CAR
2	2014	5	9	3640	1983	2413	1	home	nietdagelijk...	4.749691400000	51.608280600000	5.082127523900	51.56069720811	33582.43	CAR
3	2014	4	14	3815	1983	2413	3	nietdagelijkse	nietdagelijk...	5.292954258437	51.690847441812	5.082601994137	51.56080087622	24730.59	CAR
4	2014	7	9	7318	1707	2424	2	betaaldwerk	nietdagelijk...	5.095973582943	51.559628346052	5.081622117796	51.55447715406	1524.79	CAR
5	2014	9	24	7546	1707	2424	1	home	nietdagelijk...	5.090396449231	51.555043189150	5.095599151651	51.55956443659	689.27	CAR
6	2014	8	12	12368	2744	2437	1	home	nietdagelijk...	5.042146174242	51.543839396957	5.083791660150	51.55461005871	4301.57	CAR
7	2014	8	21	12583	2744	2437	3	dagelijkse	nietdagelijk...	5.042077885955	51.543714738272	5.087818996986	51.55773240146	4784.08	CAR
8	2014	1	9	13139	2227	2443	3	betaaldwerk	nietdagelijk...	5.291471570000	51.687842590000	5.086232250000	51.55995070000	24182.54	CAR
9	2014	5	8	19691	363	2459	1	home	nietdagelijk...	5.176196280000	51.469656280000	5.091929650000	51.56146638000	12461.93	CAR
10	2014	9	5	30269	1404	2482	4	recreatie	nietdagelijk...	5.328179458156	51.674248860218	5.082941148430	51.55908913817	27093.10	CAR
11	2014	4	8	30377	1404	2482	3	betaaldwerk	nietdagelijk...	5.079219667241	51.555263134651	5.093326400000	51.55943380000	1471.03	CAR
12	2014	3	13	30539	1404	2482	5	dagelijkse	nietdagelijk...	5.094739347696	51.567367650569	5.081107774749	51.56030572951	1535.22	CAR
13	2014	5	16	32714	886	2485	2	dagelijkse	nietdagelijk...	5.461425984013	51.739345391354	5.083189937723	51.56013768653	41854.26	CAR
14	2014	4	25	33691	2140	2486	3	nietdagelijkse	nietdagelijk...	5.110894500000	51.564412900000	5.092635700000	51.55759000000	1949.19	CAR
15	2014	9	26	33722	2140	2486	1	home	nietdagelijk...	4.988571083983	51.575840100947	5.088935581410	51.55560763569	10238.35	CAR

Figure 4 2: Journey data

The following Figure 4.3 depicts the O-D pairs projected on the road network in TransCAD (GIS).

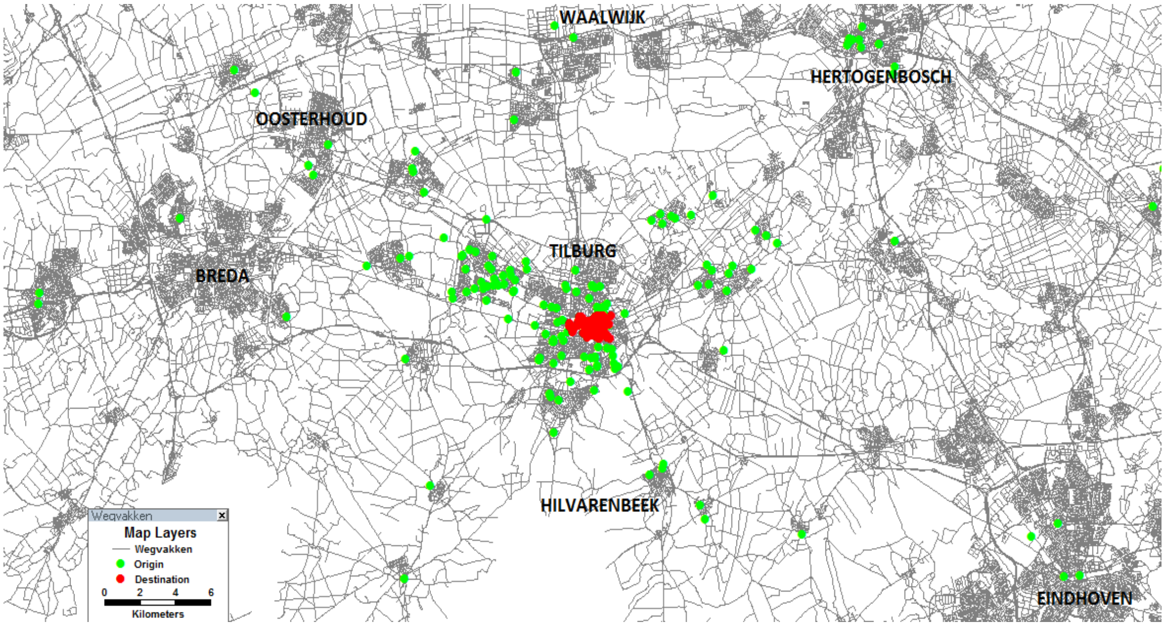


Figure 4 3: Overview of Origin – Destination pairs in TransCAD (GIS)

The respective GPS traces of the O-D pairs are shown in the next Figure 4.4. The trace data includes the GPS registrations that comprise the full trajectory of a trip. The "pernum" column includes the participants' ID which is the same column as "persno" of Figure 4.2 above. Each row represents a GPS registration which corresponds to a pair of coordinates (longitude and latitude). The visualization of the data would demonstrate the entire route of each trip.

	A	B	C	D	E	F	G	H	I
1	pernum	identification	month	day	hour	minute	second	lon	lat
2	2413	6746182014	4	14	10	52	39	4.778217	51.5956
3	2413	6746182014	4	14	10	53	12	4.77934	51.59512
4	2413	6746182014	4	14	10	54	48	4.779626	51.5952
5	2413	6746182014	4	14	10	57	43	4.842787	51.603
6	2413	6746182014	4	14	11	1	43	4.982047	51.57717
7	2413	6746182014	4	14	11	5	43	5.050566	51.56634
8	2413	6746182014	4	14	11	9	41	5.08478	51.55995
9	2413	6746182014	4	14	11	11	41	5.085115	51.55998
10	2413	6746182014	4	14	11	12	45	5.084581	51.56021
11	2413	6746182014	4	14	11	12	46	5.084581	51.56021
12	2413	6746182014	4	14	11	12	48	5.084581	51.56021
13	2413	6746182014	4	14	11	13	1	5.084581	51.56021
14	2413	6746182014	4	14	11	13	43	5.086958	51.55981
15	2413	6746182014	4	14	11	13	46	5.087431	51.55978
16	2413	6746182014	4	14	11	13	52	5.088497	51.55984
17	2413	6746182014	4	14	11	14	12	5.090652	51.55968
18	2413	6746182014	4	14	11	14	30	5.090797	51.55967
19	2413	6746182014	4	14	11	14	38	5.090797	51.55967
20	2413	6746182014	4	14	11	15	40	5.092944	51.55942
21	2413	6746182014	4	14	11	15	51	5.095254	51.55954

Figure 4 4: Trace data

4.2.2. Required Information

In addition to the GPS data and the observed routes, information about the area of Tilburg needs to be collected. This information is explicitly described in the following paragraphs.

4.2.2.1 Road network

Prior to the analysis, the road network in TransCAD (GIS) needs to be improved so as to represent as much as possible reality. First of all, the road network in TransCAD is carefully checked to determine if the network file represents the real transportation network of Tilburg. In this way, possible inaccuracies can be avoided, for instance including roads that do not exist or pedestrian roads that cannot be traversed by car which could then lead to misrepresentation of the analysis' outcome as well as to low performance of the shortest path algorithm. In addition, information about two-way roads and directional restrictions was found in Google Maps. Figure 4.5 depicts the implementation of two-way, one-way, and pedestrian roads in TransCAD (GIS).

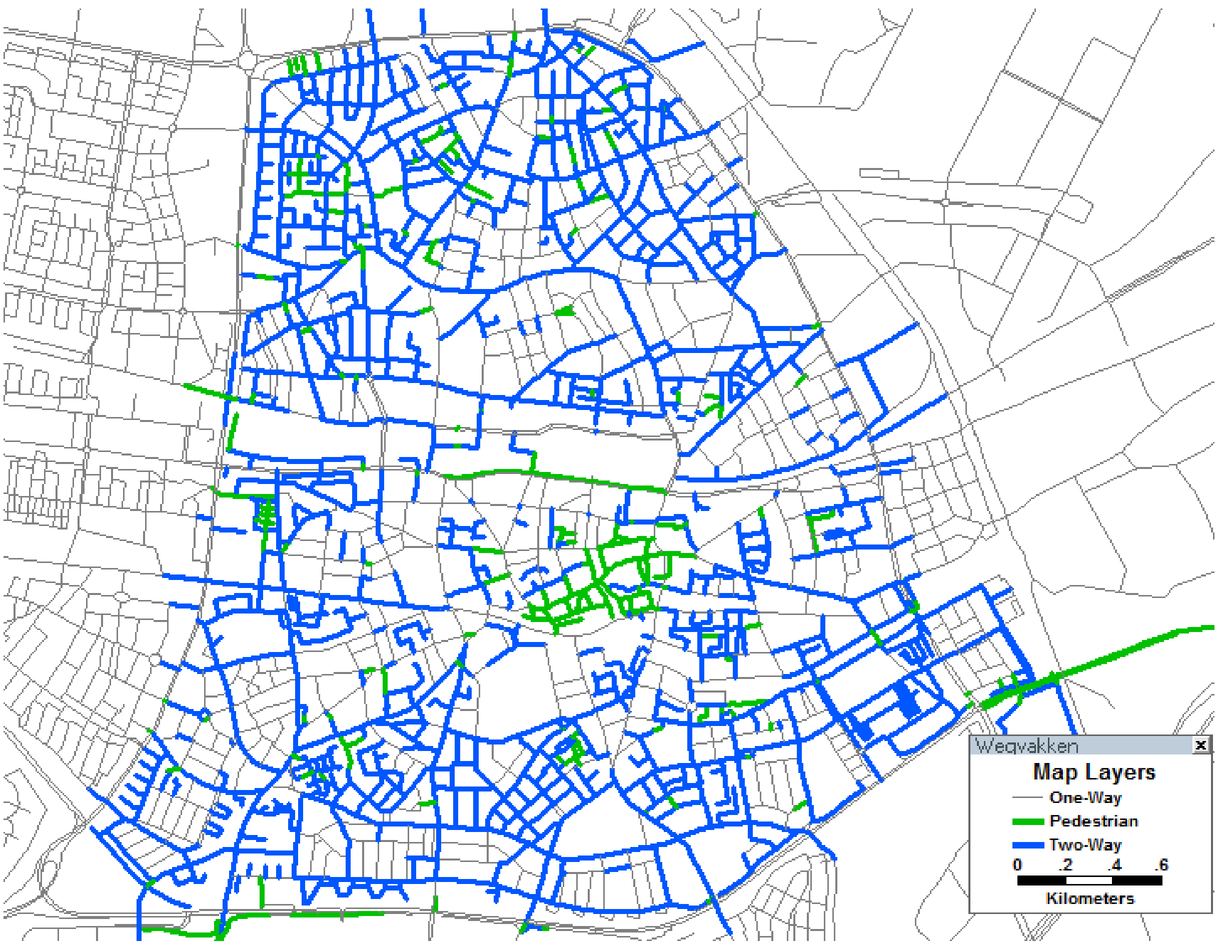


Figure 4 5: Road network in TransCAD (GIS) – Two-way, One-way, and Pedestrian roads

As mentioned in the methodology chapter, for the shortest path approach based on time, first the posted speed limits of the roads need to be defined. The speed limit of each road is directly related to the road design and its function. According to the Institute of road safety research (Janssen, 1994), the roads in the Netherlands are distinguished into “Through” roads including the motorways which are related to a speed limit of 120 and 100 km/h, and “Distributor“ roads which their main function is to distribute traffic from the outer area into the cities. The latter type of road is usually related with a speed limit of 70 and 50 km/h. Finally, the “Access” roads within the cities have the main function to make parcels and buildings accessible and correspond to a 30km/h speed limit. The road type categorization of Tilburg was provided by the Municipality and implemented in the road network in TransCAD (GIS) as Figure 4.6 depicts below. Thereby, considering the road type categorization, the respective posted speed limits were easily defined as Figure 4.7 illustrates.

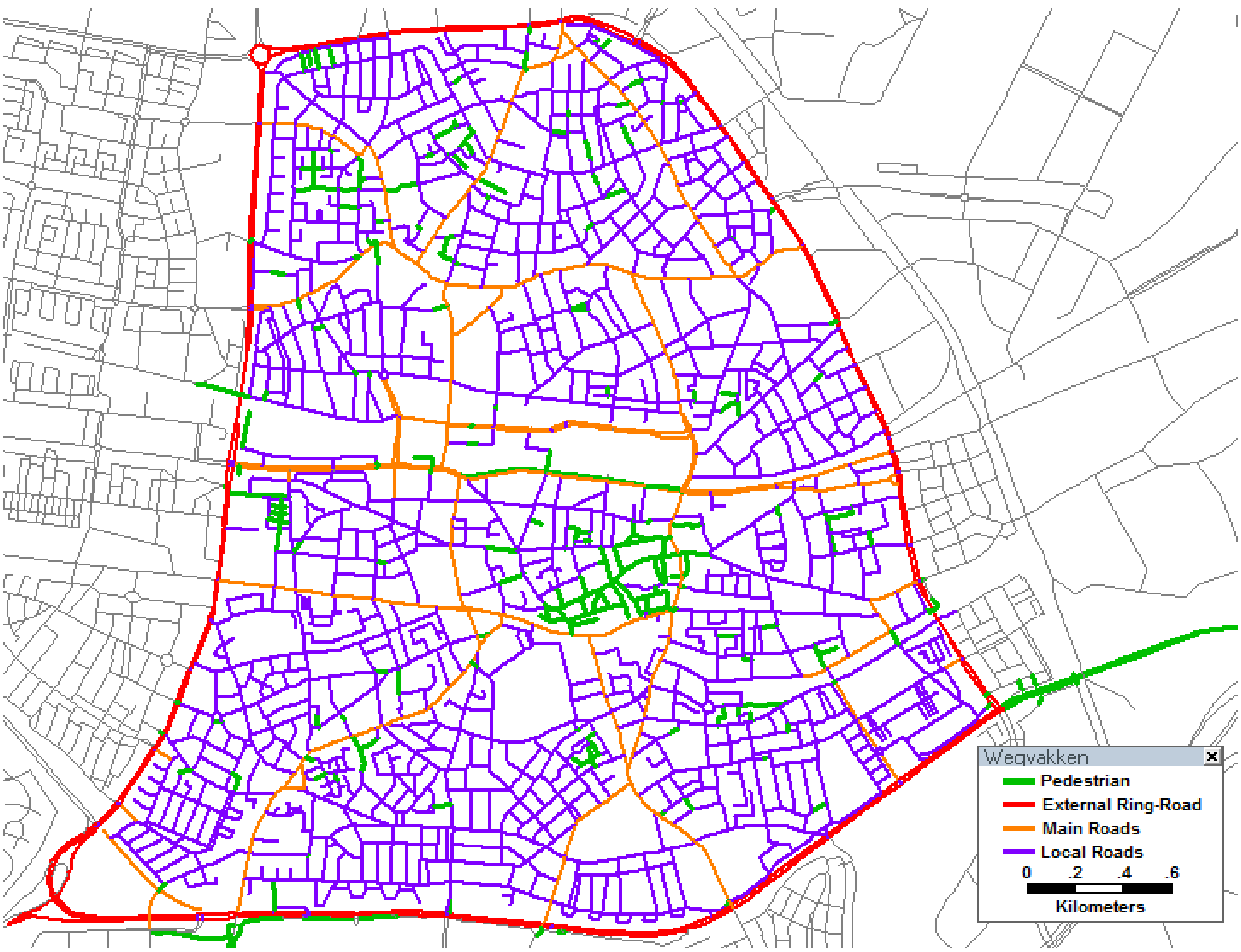


Figure 4 6: Road network in TransCAD (GIS) – Road type categorization

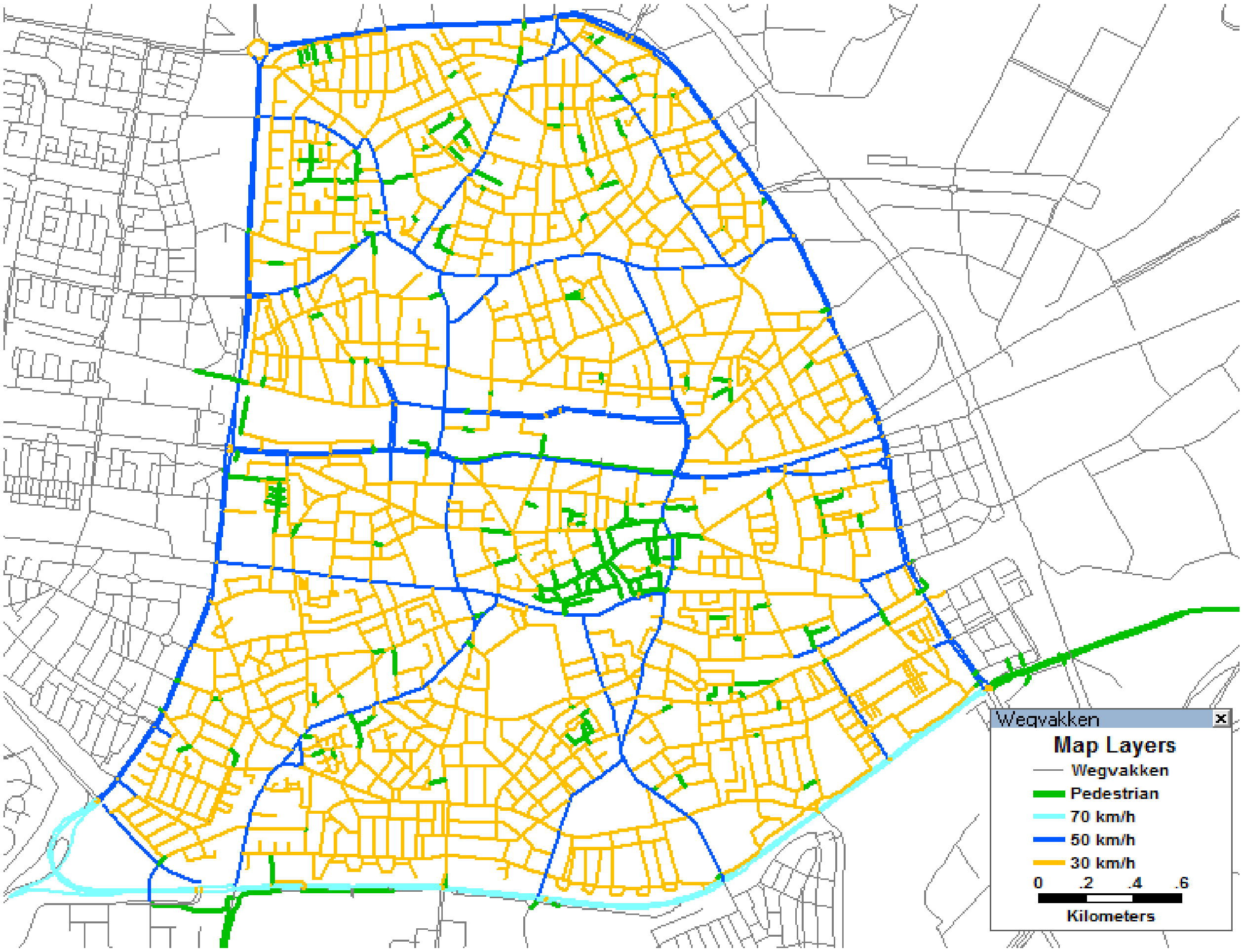


Figure 4 7: Road Network in TransCAD (GIS) – Categorization based on posted speed limits

4.2.2.2 Influence of the street characteristics on average travel speed

After the road network has been categorized based on road type and the posted speed limits were defined, the implementation of the urban features' influence on the average travel speed takes place. To begin with, the transportation network of Tilburg is observed through Google Maps and the streets' characteristics are recorded based on the street profiles presented in Appendix B. More specifically, the speed limit of each road segment is assumed to be the reference point. For instance, if a road is designed with an upper-speed limit of 70 km/h then this value is accordingly reformed (decreases or remains stable) based on the influence of the urban design features on drivers' speed choice. Finally, the travel time of each road segment is calculated by dividing its' length by the average travel speed as this was estimated considering the influence of the urban design features mentioned above.

4.2.2.3 Parking Facilities

Information regarding the parking facilities that can be found in and around the central area of Tilburg has been provided by the municipality. Figure 4.8 depicts the parking facilities available near the city centre. These parking facilities refer to parking garages where local people, as well as visitors, can park their car. In total there are 8 parking garages in and around the city centre. The green and purple areas (zone B01 and B02) divide the centre area into two zones. Together, these zones cover the area within the centre of Tilburg and some streets which are adjacent to it.

Figure 4 8: Parking facilities in and around the city centre (Blankendaal et al., 2017)

Parking garages are not the only parking opportunities available within the city. Parking along a street at a parking meter or on a parking lot are also possible choices. However, most of the on-street parking places are only available for people who hold a parking permit which refers to the inhabitants. The following Figure (4.9) depicts the area according to which people need a permit to park. Parking locations marked with “P” indicate the places where visitors are allowed to park. These refer to parking garages as well as open parking spaces (on-street parking areas). The colours of each area indicate the working time of the permits, as the map legend depicts.

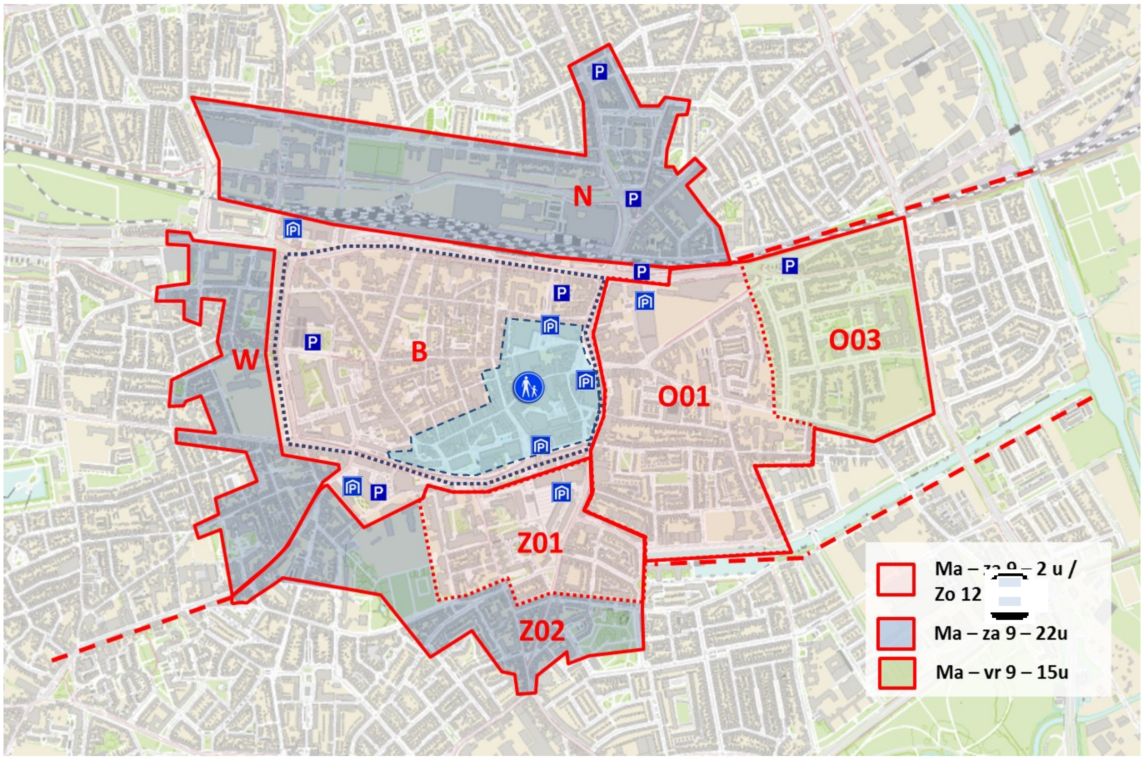


Figure 4 9: Area where parking permit is required (Blankendaal et al., 2017)

Table 4.4 shows the capacity of the main parking facilities in the city of Tilburg, as well as the capacity that on-street parking provides. In total parking spaces consists of 4.635 public parking spaces of which 957 refer to on-street parking while the rest 3.678 are provided in parking garages.

Table 4 1: Parking facilities and capacities (Blakendaal et al., 2017)

Parking location	Parking Type	Parking capacity
Tivoli	Garage	695
Pieter Vredeplein	Garage	621 (+130 reserved)
Heuvelpoort	Garage	378
Emmapassage	Garage	298
Koningsplein	Garage	419
Knegtel	Garage	560
Schouwburg	Garage and Outdoor Surface	519
Rankenstraat	Underground	58
Total		**3.678**

Zone name		Parking capacity
B01	On-street Parking	520
B02	On-street Parking	437
Total		**957**

In total, eight main parking facilities can be identified within the central area of Tilburg namely: Tivoli, Emmapassage, Pieter Vredeplein, Heuvelport, Koningsplein, Schouwburg, Knegtel, and Rankenstraat. The parking garage with the greatest capacity is Tivoli providing 695 spaces followed by Pieter Vredeplein (621), Knegtel (560), Schouwburg (519), Koningsplein (419), Heuvelport (378), Emmapassage (298) and Rankenstraat (58). As it can be seen from Table 3.3 above, Pieter Vredeplein's total capacity reaches 751 (621 + 130) parking spaces. From these parking spaces, 130 are reserved by specific permit holders. These spaces are located in a closed area and are only accessible by the permit holders. Interestingly, the parking garage of Rankenstraat is only available for permit holders who reserved the available parking spaces.

4.3. Application and Results

After the required information regarding the city of Tilburg was collected and implemented in the road network in TransCAD (GIS), the routes choice sets (time, distance) are created using the data-analysis technique of the shortest path algorithm. For the shortest path based on the distance, one-way roads and turn restrictions were considered in the network. For the shortest path based on the time, the travel times were calculated considering posted speed limits and the influence of the urban features on the average travel speed.

The hypothesis that is being tested is that drivers use either time or distance as their path selection criteria in order to optimize their trip. Therefore, the analysis is based on the comparison of three types of routes, the observed routes from the GPS traces and their shortest alternative paths (time and distance). Information about total traveled time, total traveled distance, and distance traveled by road type is collected for each route type based on network estimations. The analysis is facilitated utilizing both the environment of TransCAD (GIS) and Microsoft Excel to perform the necessary calculations.

The shortest paths are generated between the origin and destination points and compared to the observed routes based on two approaches as mentioned in the methodology chapter. The comparison of the 83 observed routes to the shortest alternative paths based on time and distance is depicted in Appendix B. The outcome from the two approaches is presented in section 4.3.1. Using SPSS and the paired-samples t-test observed and shortest routes are tested for significant differences regarding the time and distance variables. The outcome as well as some general statistics about the routes is presented in section 4.3.1.1. In section 4.3.1.2 the road type composition (percentage of distance traveled by road type) is depicted. Finally, in section 4.3.2 using the observed routes from the GPS tracks, the car trips are assigned to the parking facilities available in the city of Tilburg. The parking related traffic is assigned to the road network and the traffic volume is aggregated and presented in terms of most used roads.

4.3.1. Comparison of observed to shortest alternative routes

As mentioned above, for the comparison of the observed to their shortest alternative routes two approaches were adopted.

Approach 1

As mentioned in the methodology chapter, based on this comparison approach, the common distance traveled between an observed and a shortest route is calculated. The results suggest that in the case of travel time being the selection path criterion, on average, 75% of the observed routes' total traveled distance can be correctly captured. In contrast, when observing the shortest path based on distance only 52% of the observed route total traveled distance can be captured by the shortest alternative route.

Approach 2

The second approach refers to the number of GPS points that fall within a 20 meters buffer around the shortest path. The results were similar to the first approach's outcome. In particular, again the shortest path based on time is closer to the observed routes than the shortest distance paths. More specifically, 76% of the total points fall within the buffer around the shortest time route while only 55% in the case of the shortest distance route.

4.3.1.1 Analysis in SPSS

To begin with, the information collected through the network calculations in TransCAD (GIS) for each route type is analyzed in SPSS. The following table (4.2) contains some general statistics (mean and standard deviation values) by route type for different variables.

Table 4 2: Statistics for observed routes and shortest paths based on time and distance

Variables	Observed route (mean ± std.)	Shortest Path based on time (mean ± std.)	Shortest Path based on distance (mean ± std.)
Distance (km)	3.043 ± 1.24 (16.2% ↑)	2.917 ± 1.099	2.617 ± 0.907
Time (min)	4.2 ± 1.7 (13.4%↑)	3.701 ± 1.33	5.1917 ± 2.31
% of route based on road type			
% distance on ring-road	1.039 ± 1.192	0.979 ± 0.947	0.321 ± 0.453
% distance on	1.671 ± 0.812	1.765 ± 0.804	1.400 ± 0.814

main road			
% distance on local road	0.333 ± 0.4091	0.162 ± 0.208	0.895 ± 0.731

Using SPSS, and more specifically the paired samples t-test significant differences between observed and shortest alternative routes for variables such as distance and time are tested. In addition, differences between observed and shortest paths are also examined in terms of the road type composition, for instance, the use of the external ring-road, main, and local roads.

In general, the test examines if there is statistical evidence according to which the mean difference between a pair of variables (in our case observed vs. shortest routes) is significantly different from zero. The paired-samples t-test provides evidence in terms of the p-value (significance) and t-value. The p-value indicates the probability of observing results which support the null hypothesis (assumes that mean difference between a paired sample is zero). This value is usually set to 0.05 (5% or less) based on which the null hypothesis can be either accepted ($p > 0.05$) or rejected ($p < 0.05$) (conclude that the means of the two compared variables are significantly different). The t-value is used to measure the magnitude of the difference between paired samples. That means, the bigger the size of t-value the bigger the evidence against the null hypothesis.

Table 4.3 below lists the p-values and t-values as these were occurred from the paired samples t-test in SPSS providing evidence according to which it can be concluded whether the null hypothesis is rejected or accepted. The values in bold indicate the variables which significant differences have been found when comparing their mean value. The resulted t-values and p-values for each variable are shown below (p-values are within the parentheses).

Table 4 3: Paired samples t-test outcome

Variables	Observed vs. SP distance	Observed vs. SP time
-	t-value (p-value)	t-value (p-value)
Distance (km)	**6.538 (0.000)**	1.980 (0.051)
Time (min)	**5.824 (0.000)**	**4.998 (0.000)**
% of route based on road type		
% distance on ring-road	**6.732 (0.000)**	0.593 (0.555)
% distance on main road	1.509 (0.135)	**2.255 (0.027)**
% distance on local road	**8.087 (0.000)**	**4.196 (0.000)**

As it can be seen, when comparing the shortest paths to their observed route some of the combinations revealed significant differences for the attributes of distance and time. Regarding the distance (km) variable, the results of the paired samples t-test for the pair “observed vs. SP distance” were significant, $t = 6.538$, $p < 0.05$ (0.000), indicating that the null hypothesis is rejected and therefore there is a significant difference in distances between the observed routes and the shortest distance paths. Interestingly, when the observed routes are compared to their shortest time routes based on the distance traveled the results revealed that there are no significant differences.

In the case of “Time (min)” variable, the results of the paired samples t-test were significant for both pairs, $t = 5.824$ and $t = 4.998$ respectively, with $p < 0.05$ (0.000). Thus, the null hypothesis is rejected and therefore it can be concluded that there are significant differences between the observed routes and their shortest alternative paths (time and distance).

Consequently, these results indicate that the observed routes are not optimized and that observed routes are longer than their shortest alternatives both in terms of travel time and distance. Interestingly, when examining the t-values of the two variables (time, distance) it can be seen that although there are significant differences for both variables compared to the observed routes, the t-values indicate that the shortest path based on time is more efficient than the shortest path based on distance. That is because the t-value of the former is smaller than the latter’s, therefore, for the shortest path based on distance there is greater evidence against the null hypothesis. More specifically, from table 4.2 above, it can be derived that the observed routes exceed their corresponding shortest routes in travel time and distance by 13.4% and 16.2% respectively.

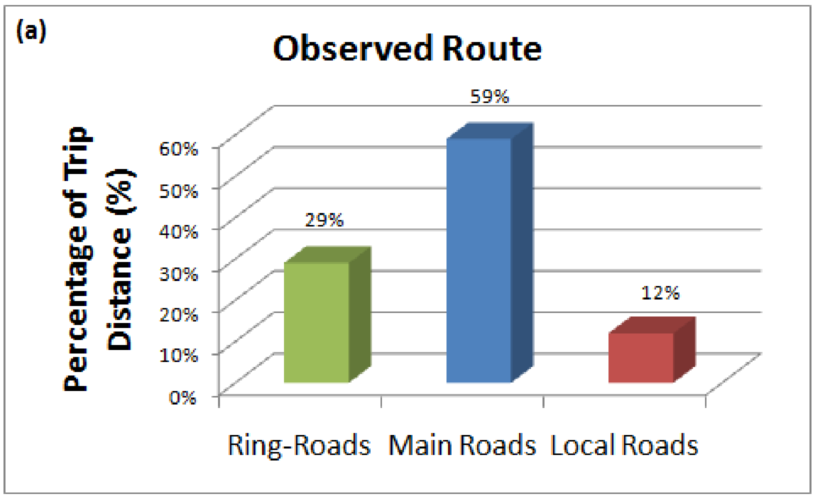
4.3.1.2 Road type composition

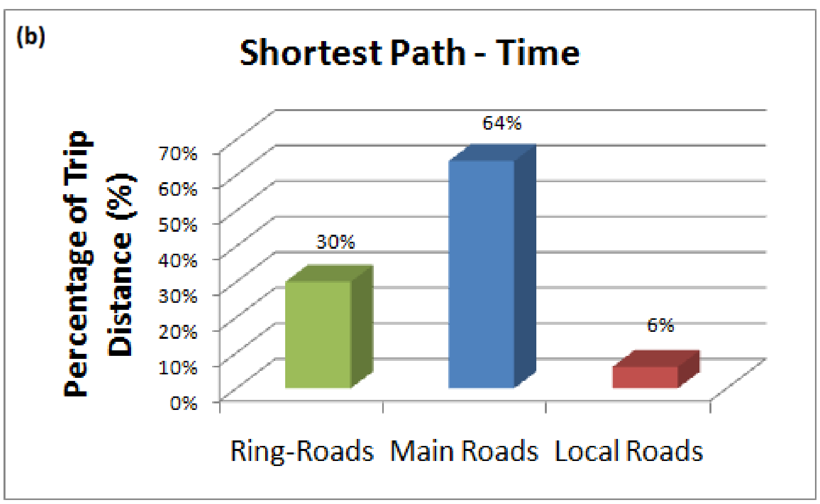
The road type composition for each route and mainly the observed route was also determined and compared. As it was expected, the results of the paired samples t-test indicate that there is a difference in the composition of road type usage between the shortest distance routes and the shortest time routes (see Table 4.3). The road type composition has been measured in terms of the distance travelled by each road type (estimated from network).

The Figure 4.10 below highlights the differences between the road types as these have occurred from mean calculations. In particular, for the shortest time routes, the ring road and the main road type are used the most as these types of roads provide higher speeds, possessing on average 30% and 64% respectively. As it was expected, the local road type only comprises a minimal portion of usage (6%). In contrast, for the shortest distance routes the usage of local roads is on average higher than the usage occurred for the case of shortest time routes (6%), reaching 33% of the total travel distance. The ring road is used the least possessing 12% of the total travel distance. Interestingly, main roads comprise 55% of the total route’s distance.

Looking at the observed routes, these remarkably tend to follow the ring road and the main roads (29% and 59% of the route distance respectively) and to a lesser extent the local roads (12% of route distance). These findings alone come to support the effectiveness of the policy that the municipality has adopted according to which traffic occurred from visitors towards the city centre is preferable to be distributed mainly through the main roads of the city. This kind of traffic mainly refers to people approaching the main destinations of the city such as main parking facilities, stations, and centre.

All in all, in the case of ring-roads the average trip distance covered by shortest time approach is very close to the observed routes (30% and 29% respectively, see Figure 4.10 a and b). In contrast, the shortest distance approach underestimates this type of road by 17% (29% for the observed routes compared to 12% for the shortest time). At the same time, the main roads are slightly overestimated by the shortest time approach by 5% reaching 64% of the total trip distance compared to 59% for the observed routes. As it was expected the local roads are underestimated by the shortest time approach (6% compared to 12%) while the shortest distance routes overestimate them to a larger extent (33% compared to 12%).





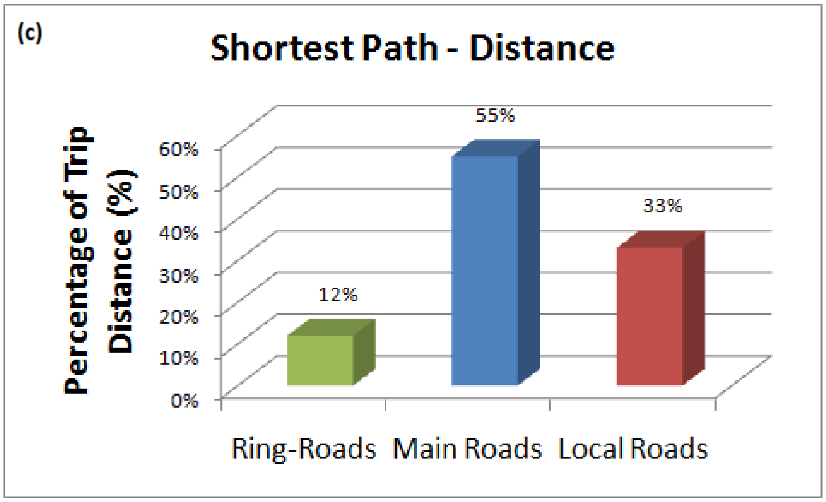


Figure 4 10: Trip distance by road type for observed (a), shortest time (b), and distance (c) routes

4.3.2. Parking-related actual traffic flow

In the following sections the GPS traces of the 83 car trips are used to assign the trips to the parking facilities available in Tilburg. Therefore, the car trips ended at a specific parking facility are isolated and their GPS tracks are used to assign traffic on the road network. Finally, the traffic flow towards the parking facility is aggregated in terms of the most used roads. The procedure followed in TransCAD (GIS) is explicitly described below.

4.3.2.1 Car trips and parking facilities

To begin with, taking into consideration the parking opportunities available in Tilburg (garages, on-street, lots) the 83 car trips have been assigned to a parking facility. The GPS tracks (point file) of the trips are combined with the road network (line file) in TransCAD (GIS) and the destination point is used as an approximation in order to determine where the drivers have parked their car. The following table (4.4) depicts the frequency of the trips assigned to the main parking facilities found in the central area of the city. An overview of the trip frequency by parking type is first given.

As it can be seen, the majority of the trips (49 trips, 59%) were assigned to the parking garages available in the central area of Tilburg. Trips have also been found to end at parking lots and on-street parking but the frequency of these types of parking was fewer reaching 18 and 16 trips respectively. Interestingly, taking a glance at how many times each parking facility is used it can be said that the most used parking garage consists of Pieter Vredeplein and Schouwburg followed by Koningsplein, Emmapassage, and Tivoli. The parking facilities of Knegtel, Heuvelpoort and Rankenstraat have minimal usage.

Table 4 4: Frequency of trips by parking type and parking facility

Parking Type	Frequency	Percent (%)
On-street	18	21.7
Parking garage	49	59.0
Parking lot	16	19.3
Total	83	100.0
Parking facilities	**Frequency**	**Percent % (n=49)**
Tivoli	6	12.24
Pieter Vredeplein	15	30.61
Heuvelpoort	1	2.04
Emmapassage	7	14.28
Koningsplein	8	16.32
Knegtel	1	2.04
Schouwburg	11	22.44
Rankenstraat	0	0
Total	49	100

A recent study has been funded by the Municipality of Tilburg and conducted by Spark, a parking consultancy firm in the Netherlands, based on which the occupancy level of the parking facilities at different times of the week was studied. The examined parking facilities were the parking garages available in and around the city center, and the on-street parking spaces. Based on their findings, the parking facilities with the highest occupancy level were the Pieter Vredeplein, Emmapassage and Schouwburg. Although the small sample of car trips used in this thesis (83 trips), the parking facilities of Pieter Vredeplein and Schouwburg have the highest frequency as Table 4.4 indicates.

4.3.2.2. Traffic assignment

The combination of the trip data provided by GPS technology with the capabilities of a GIS is a powerful way to project, observe and analyze travelers' route choice behavior. In this section, the parking facilities of Pieter Vredeplein and Schouwburg are selected to be analyzed as these have the highest frequency of car trips reaching 15 and 12 car trips respectively. Despite the small frequency of the car trips, the purpose here is to demonstrate the way drivers' route choice can be approached using the capabilities of a GIS (in this case TransCAD) and the traces collected from GPS. In addition to this, not only the positional data of drivers but also the temporal data is used to highlight the valuable information that GPS technology can offer.

To begin the process, the GPS tracks of the car trips that correspond to each parking facility are imported in TransCAD (GIS) as a point file. The GPS tracks are manually map matched in order to provide the exact routes in terms of the links and nodes of the underlying road network (line file). The GPS registrations of the car trips assigned to the parking facilities are depicted in the Figures 4.11 and 4.12 below.

Parking garage: Schouwburg

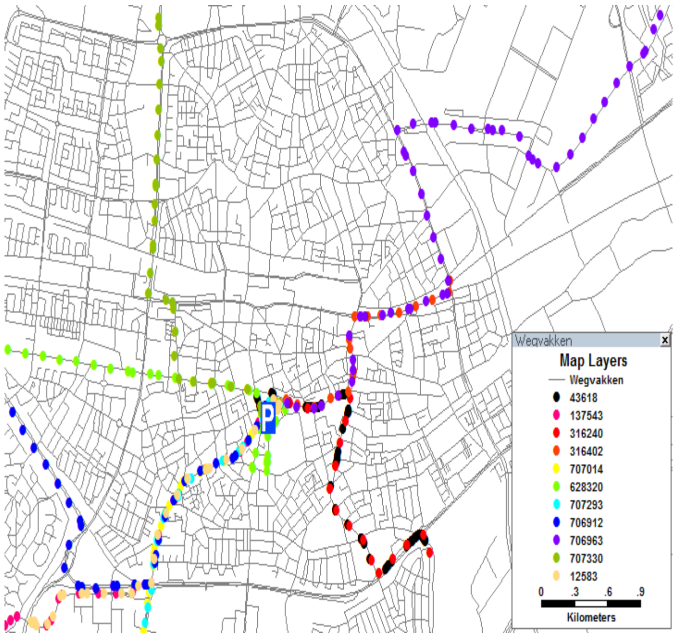


Figure 4 11: Schouwburg – GPS tracks and manual route reconstruction

Parking garage: Pieter Vreedeplein

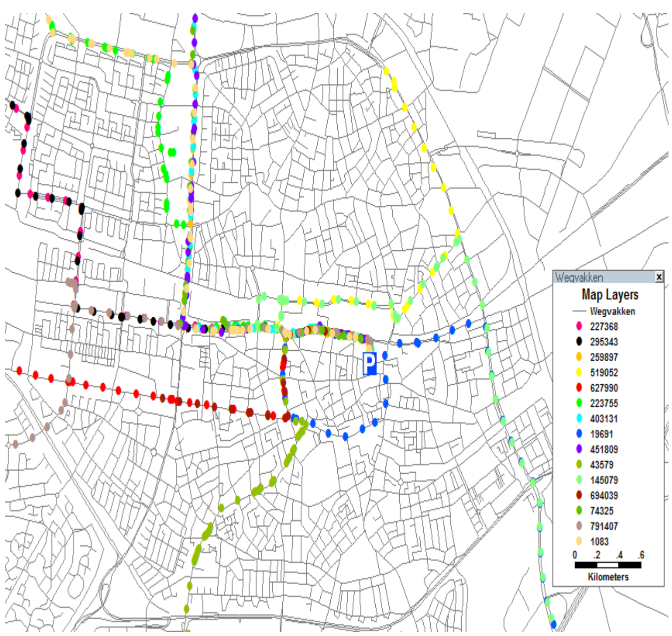


Figure 4 12: Pieter Vreedeplein – GPS tracks and manual route reconstruction

4.4.2.1. Traffic flow aggregation

After the observed routes are reconstructed from the GPS tracks, the way they reach the parking facilities was depicted above. In this section, the traffic flow that is occurred from the car trips of each parking facility is aggregated in terms of most used roads. More specifically, each observed route is represented by the networks' segments (with a specific id) as Figure 4.13 shown below.

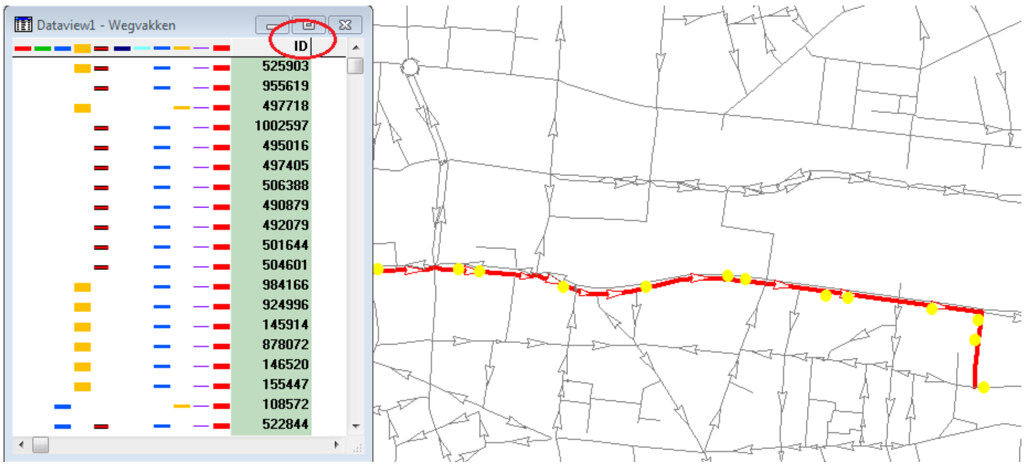
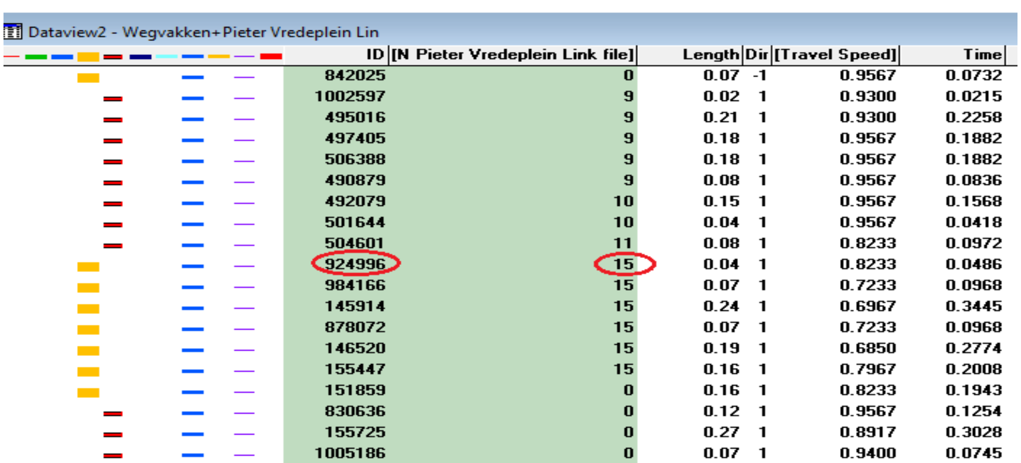


Figure 4 13: Link file dataview

For each route, the ID's of the segments that is comprised of are collected. When combining the file which consists with all the street segments' IDs of the observed routes with the line segment file of the road network it is able to aggregate their frequency. Therefore, the number of times that each road segment is used can be determined. An example is depicted in Figure 4.14 below where the column "N Pieter Vreedeplein Link file" includes the number that each road segment is used. For example, the number "15" means that the link with ID = "924996" is used 15 times.


Dataview2 - Wegvakken+Pieter Vredeplein Lin

ID	[N Pieter Vredeplein Link file]	Length	Dir	[Travel Speed]	Time
842025	0	0.07	-1	0.9567	0.0732
1002597	9	0.02	1	0.9300	0.0215
495016	9	0.21	1	0.9300	0.2258
497405	9	0.18	1	0.9567	0.1882
506388	9	0.18	1	0.9567	0.1882
490879	9	0.08	1	0.9567	0.0836
492079	10	0.15	1	0.9567	0.1568
501644	10	0.04	1	0.9567	0.0418
504601	11	0.08	1	0.8233	0.0972
924996	15	0.04	1	0.8233	0.0486
984166	15	0.07	1	0.7233	0.0968
145914	15	0.24	1	0.6967	0.3445
878072	15	0.07	1	0.7233	0.0968
146520	15	0.19	1	0.6850	0.2774
155447	15	0.16	1	0.7967	0.2008
151859	0	0.16	1	0.8233	0.1943
830636	0	0.12	1	0.9567	0.1254
155725	0	0.27	1	0.8917	0.3028
1005186	0	0.07	1	0.9400	0.0745

Figure 4 14: Join view of line segment file and link file

To this extent, TransCAD allows the user to create thematic maps which give an overview by illustrating the most used roads to approach the parking facilities. As it was logically expected, the closer to the parking facility street segments the more these are used. The resulted thematic maps are presented in the Figures 4.15, 4.16 below illustrating the number of times each road segment is used to approach each parking facility. The numbers depend on the number of cases that correspond to each facility with a minimum value of 0 times.

Parking facility: Schouwburg (11 car trips)

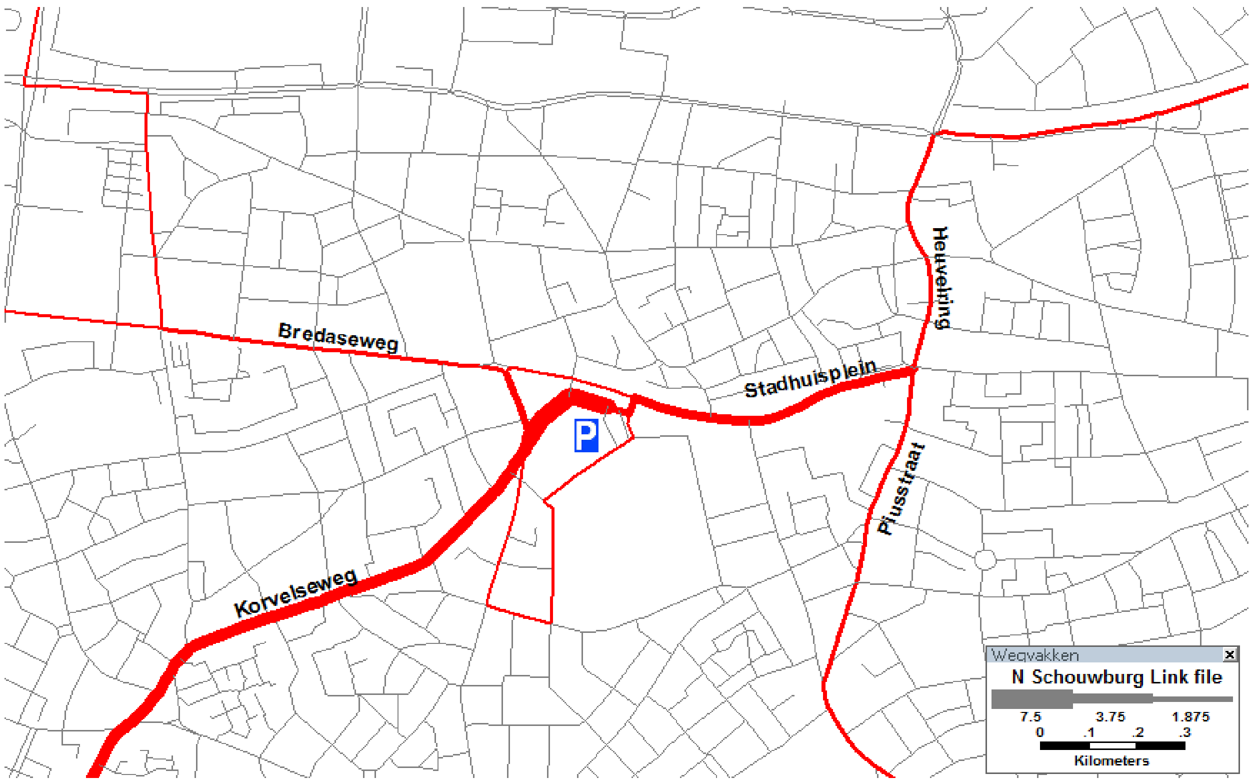


Figure 4 15: Schouwburg – Scaled symbol theme map in TransCAD (GIS)

General comments:

Regarding the parking facility of Schouwburg, the observed routes of 11 car trips in total were analyzed. At a first glance, it can be said that this parking facility can be accessed from 3 main directions. Figure 4.15 above suggests that the most used roads that people use to access Schouwburg consist of Korvelseweg from the south, Bredaseweg from the west, and Stadhuisplein (part of ring road) from east. When approaching the city center and more specifically Schouwburg parking from the east side of Tilburg it seems that drivers use the streets Piustraat and Heuvelring to reach the central ring road (specifically Stadhuisplein) in order to access the parking facility. Regarding the trips which are approaching from the west side of Tilburg the traffic always end up either in Bredaseweg or Korvelseweg streets. Almost half of the trips (5 out of 11) approach from the southwest side of Tilburg justifying the fact that most of the traffic concentrated on Korvelseweg Street. Remarkably, it can be seen that people use mostly the main roads to access the parking facility of Schouwburg.

Parking facility: Pieter Vredeplein (15 car trips)

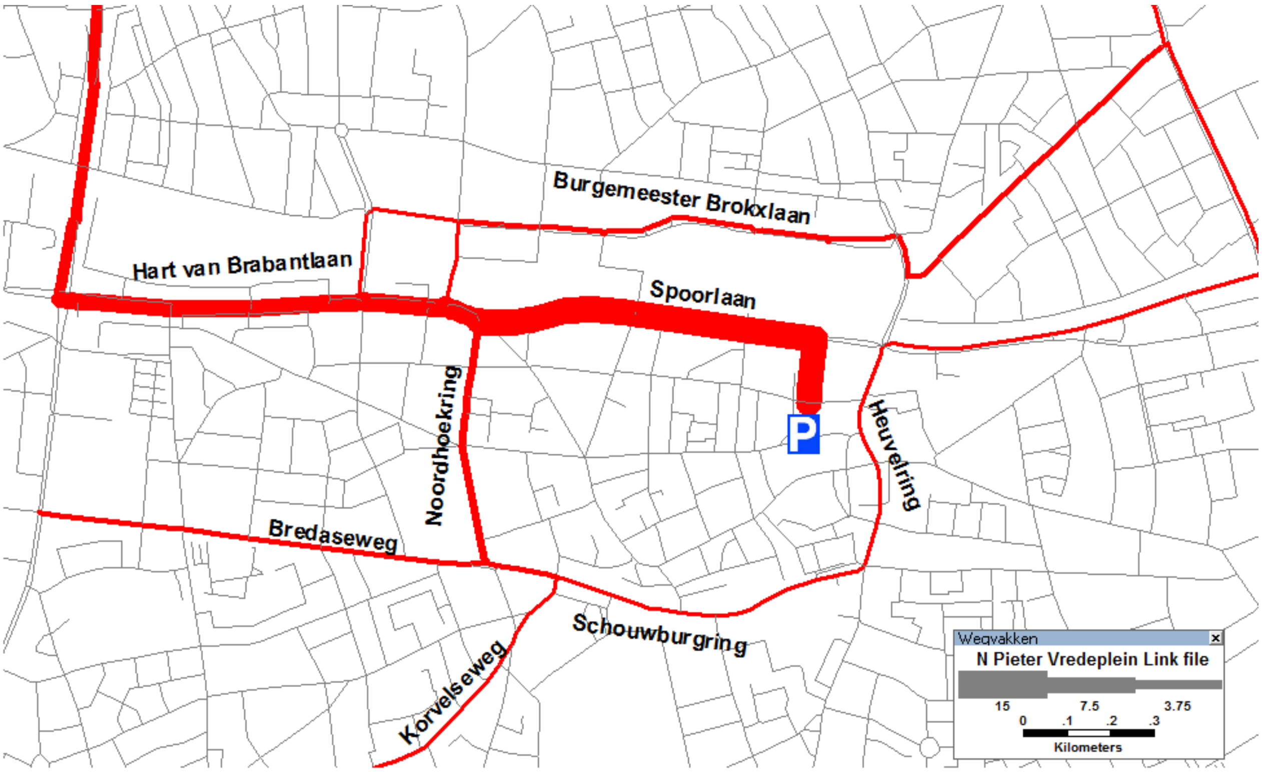


Figure 4 16: Pieter Vreedeplein – Scaled symbol theme map in TransCAD (GIS)

General comments:

In the case of Pieter Vredeplein, the observed routes of 15 car trips have been analyzed. The scaled symbol map of Figure 4.16 shows that the road of Spoorlaan is the only street that gives access to the parking facility and therefore is the most used street as the scaled symbol map depicts above. Observing the trips that approach the city center from the west side of Tilburg the main roads of Hart van Brabantlaan, Bredasaweg and Korvelseweg are used to access the central ring road (Spoorlaan and Noordhoekring) which then gives access to Pieter Vredeplein. On the other hand, interestingly when cars approach the parking facility from the east side of Tilburg they are forced to make a kind of circle in order to park to Pieter Vredeplein. More specifically, it is observed that cars approaching from the east side are forced by the road network itself to either use the central ring road (Heuvelring - Schouwburgring - Noordhoekring - Spoorlaan) or the Burgemeester Brokxlaan to drive the circle around the parking facility and finally access it. Remarkably, in all car trips, the drivers use only the main roads in order to approach the parking facility.

Additional information obtained

The drivers' spatial information is not the only information which can be obtained through a GPS receiver. However, valuable background information also accompanies the x,y coordinates of a traveler. This information refers to the temporal component which can provide great insight into many aspects. More specifically, the time point of each registration is also captured by the GPS receiver. This can lead to gain insight into the drivers' commutes considering different time periods within the day in order to observe their movements in terms of both spatial and temporal aspect (where and when they go).

Taking as an example the parking facility of Pieter Vredeplein the way this information can be used is depicted. The time aspect of the day has been divided into 3 periods while the days within a week have divided into 2 groups. The resulted groups are the weekday morning (06:00 – 12:00), weekday afternoon (12:00 – 18:00), weekday evening (18:00 – 00:00), weekend morning (06:00 – 12:00), weekend afternoon (12:00 – 18:00), weekend evening (18:00 – 00:00). Thereafter the trips which correspond to Pieter Vredeplein have been distributed into these groups based on the time point they have parked. Figure 4.17 depicts the frequency of parked cars per time period within a week. For the group "weekday evening" none car trips was found in the dataset. Unfortunately, as mentioned before the number of trips used in this study was limited. Consequently, more evidence is required in order to be able to provide a more robust overview of the occupancy level of a specific parking facility and derive patterns of the way this differentiates within the week.

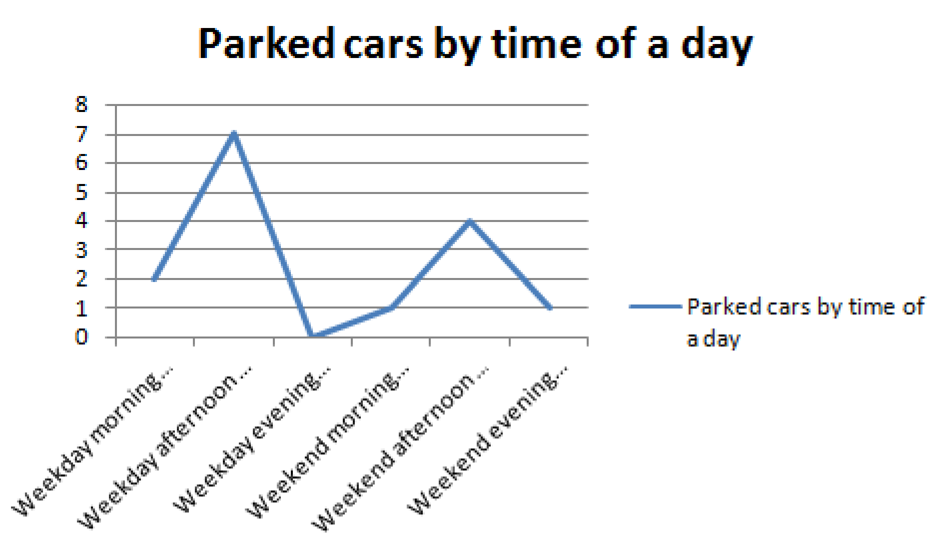


Figure 4 17: Parked cars by time of day

Chapter 5

Parking-Related Traffic Assignment Model Application

5.1. Introduction

In this section, a traffic assignment procedure is used to model parking-related traffic based on the findings of the previous chapter. In general, a traffic assignment can be seen as the process of allocating traffic between origins and destinations on a specified road network. The fundamental aim of assigning traffic on a road network is among others the estimation of the traffic which is accumulated on each segment and node of the road network. This is achieved through algorithms which under some travel-cost criteria they choose specific routes on the road network to connect the O-D pairs (Gonzales-Ayala, 1999).

To this extent, in this study parking-related traffic is assigned on the road network demonstrating the practical application of the shortest path method for estimating the parkers' route choice, always bearing in mind the possible drawbacks of this method. For the implementation of the traffic assignment procedure, the parking facility of Pieter Vreedeplein was selected once it has the highest car trip frequency. Considering the outcome of the analysis chapter, the shortest path based on travel time is used to generate routes between origins and a specific destination (parking facility). In order to achieve this, the procedure described in the methodology chapter (see Figure 3.6) is applied and explained in the following paragraphs. In section 5.2, the required information for the traffic assignment application is discussed. Finally, considering the occupancy level of the selected parking facility on a given day, the traffic assignment procedure is applied and the outcome is presented in section 5.3.

5.2. Required Information

For the implementation of the traffic assignment procedure, the parking facility of Pieter Vreedeplein is selected as it possesses the highest trip frequency with 15 trips. The required information consists of an O-D trip matrix and a link-node network created from the line file considering the time attributes of links. Thereby, the traffic assignment is conducted and the O-D pairs are connected via the shortest path method based on travel time in TransCAD (GIS).

5.2.1. O-D trip matrix

As mentioned above, the parking facility of Pieter Vredeplein was selected; therefore, it consists of the destination point of all the trips. In chapter 4, and more specifically in the case of Pieter Vreedeplein parking facility, the analysis of the 15 trips provided information about the way the drivers approach, enter the city, and finally park their car. The following Figure 5.1 depicts the main distributor roads of Tilburg and the entry points that were defined from the 15 observed routes based on which people use to access the city and then approach the parking facility. In addition, the percentage of the trips that correspond to each entry point is determined.

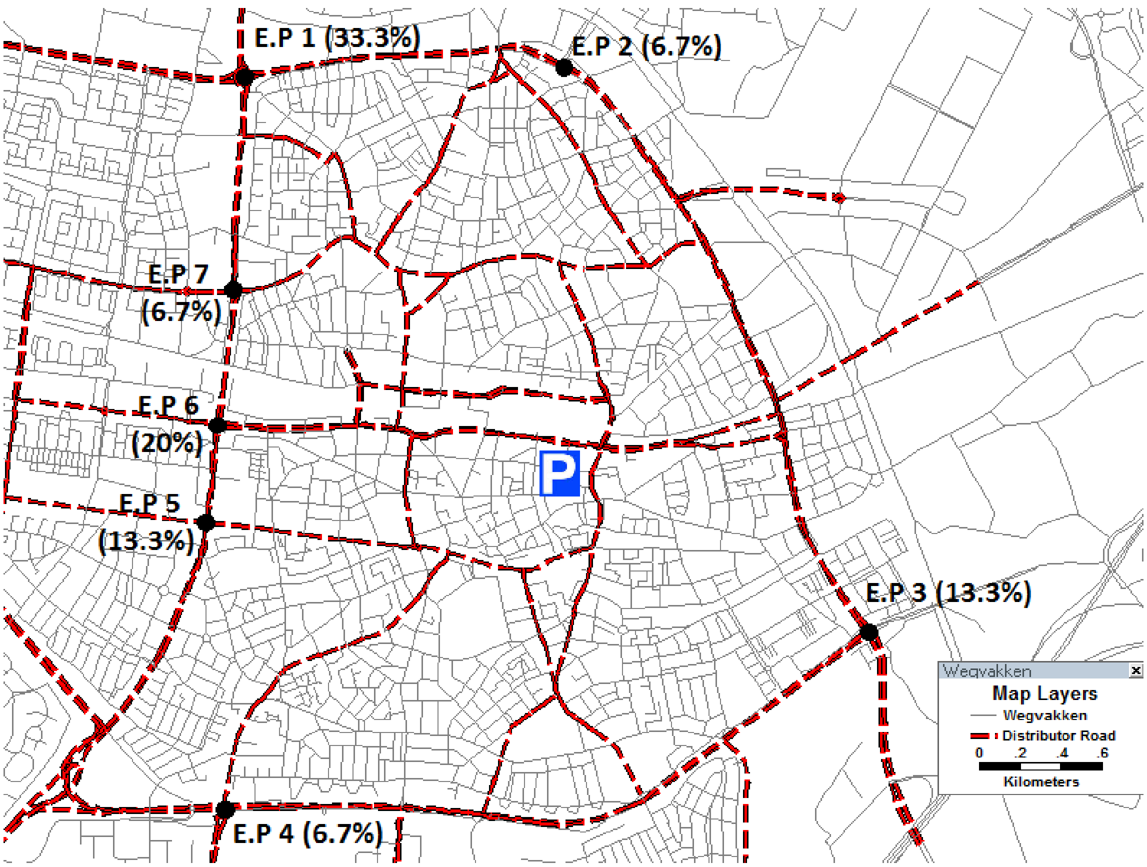


Figure 5 1: Distributor roads and entry points

Considering that the occupancy rate on a working-day evening at Pieter Vredeplein is on average 188 trips (Blankendaal et al., 2017), the number of trips is then proportionally distributed to the entry points as Figure 5.2 depicts below. All the trips have a common final destination the parking facility of Pieter Vreedeplein.

Finally, after the entry points are defined and the occupancy level of the parking facility is distributed to the entry points, the O-D matrix is created. The created Origin-Destination matrix consists of a column and a row representing the node features of the network. To this extent, the column of the matrix is created based on the nodes that represent the entry points (origins) and the row based on the node that represents the parking facility (destination). This matrix is then filled with the number of trips as this was distributed to each entry point (see Figure 5.2). In this way, the estimated traffic flow on the network will provide an overview of the use of the segments towards the parking facility. The O-D trip matrix is depicted in Figure 5.3 below.

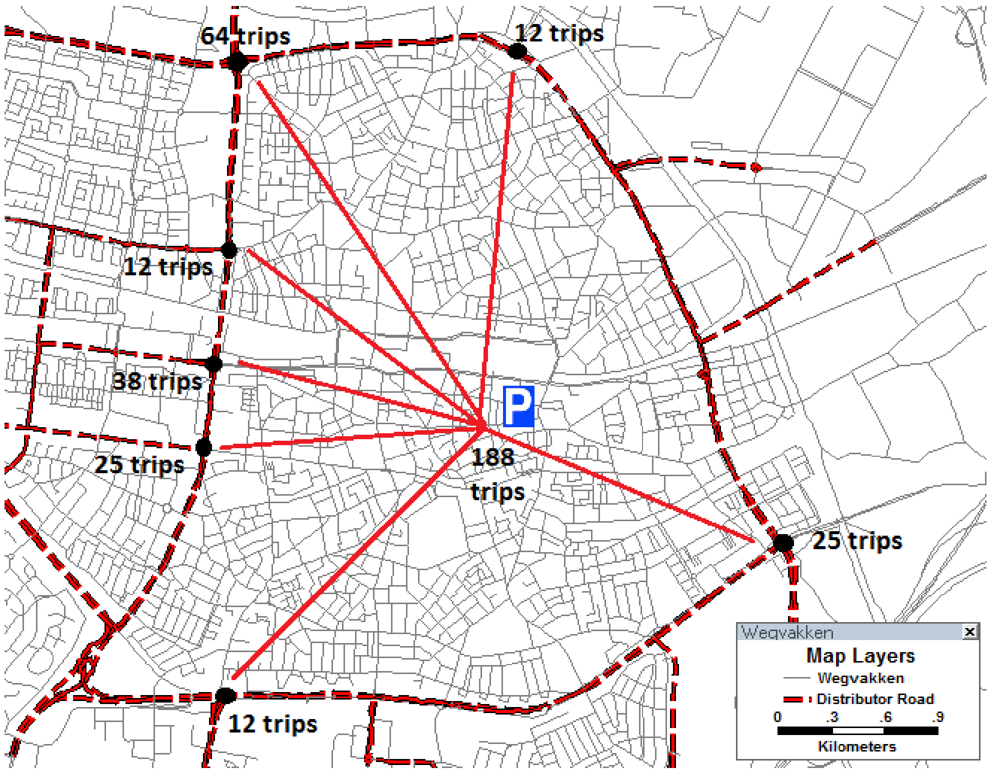


Figure 5 2: Distribution of occupancy level to entry points

Matrix1 - Endpoints Matrix File (final)

	153805
95771	12.00
243093	64.00
245362	38.00
257898	12.00
280582	25.00
323139	12.00
576722	25.00

Figure 5 3: O-D trip matrix

5.3. Application and Results

5.3.1. Traffic flow allocation between O-D pairs

After the O-D matrix has been defined, using the traffic assignment function of TransCAD (GIS) the O-D pairs are connected via the shortest path route considering travel time as the path selection criterion. The networks' attributes such as one-way roads, as well as pedestrian and bike roads (not accessible by car), are also considered. To this extent, the traffic flow is estimated on the road network.

5.3.2. Traffic volume aggregation

The traffic assignment can provide valuable information about the traffic flow assigned to the road network. In this study, information was derived regarding the estimated traffic flow on the network in terms of the total number of times each road segment is used. Therefore, this can provide an estimation about the most heavily congested links occurred from car trips traveling towards the parking facility. The scaled-symbol map (Figure 5.4) as this was created in TransCAD (GIS) shows the estimated traffic flow that occurred from the traffic assignment. The flow is represented by line width.

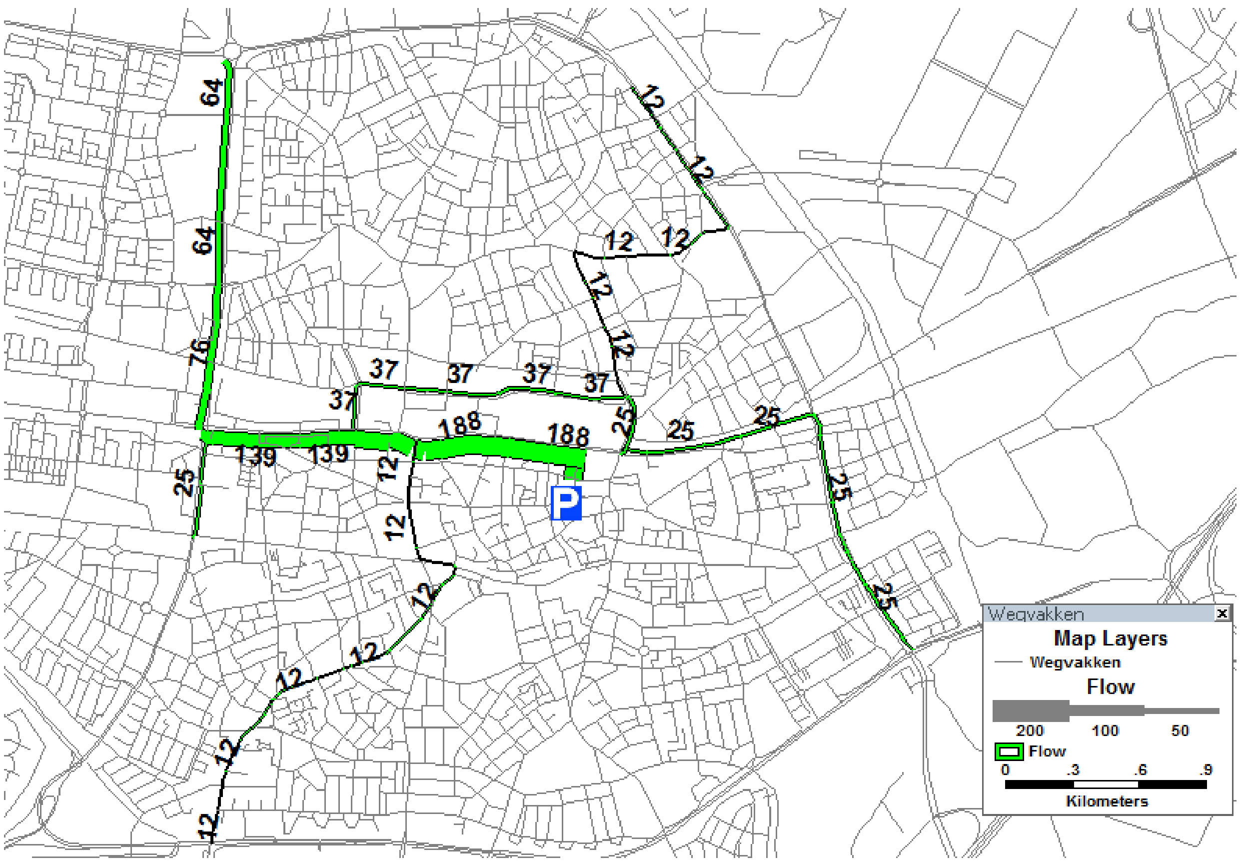


Figure 5 4: Estimated traffic flow in TransCAD (GIS)

When examining the differences between the actual traffic flow (Figure 5.5a) and estimated traffic flow (Figure 5.5b), the former revealed that the use of some streets is missed (marked in blue). The numbers in Figure 5.5 indicate the number of times the road segments are used. Undoubtedly, the limitations of the incorrectly estimated traffic volumes need to be considered. These limitations refer to the performance and accuracy of the shortest path algorithm which was used to assign traffic on the road network in a try to estimate parkers' route choice. The misrepresentation of the traffic assignment can lead to incorrect estimation of the congestion on some streets and therefore on some intersections. To this extent, it can be said that more data is required in order to provide more solid evidence about the performance of the shortest path method used in this study, and the magnitude of its inaccuracy and the subsequent consequences.

In addition, it is remarkable to mention that due to time constraints, factors such as road conditions, traffic conditions, participants' familiarity with the network etc. have not been considered in the current traffic assignment model. These factors might affect drivers' instant route choice decision making. Therefore, this directly implies that further research is required into the factors that influence parker's route choice decision making.

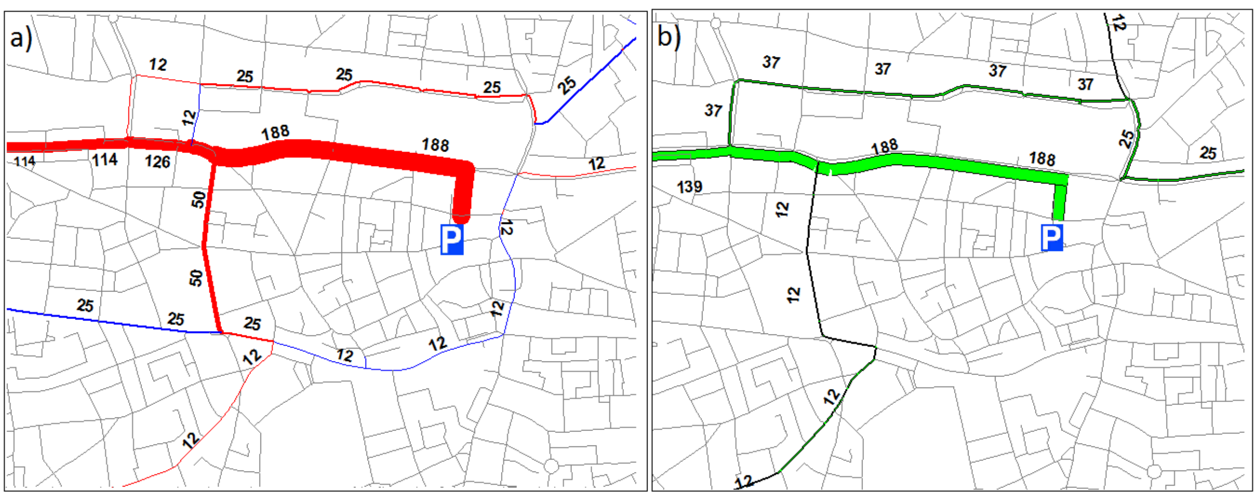


Figure 5 5: Actual traffic flow (a) and estimated traffic flow (b)

Chapter 6

Conclusions, Recommendations & Future work

6.1. Introduction

In this chapter of the graduation report the conclusion of the project is performed. In addition, this chapter also provides some recommendations for future work. Section 6.2 presents the general conclusion of the study supported by the main results. It starts by summarizing the research project, the research motivation and the subsequent research questions. Finally, the recommendations and future work are presented in section 6.3.

6.2. General Conclusion

This section describes the final conclusion supported by the main results of this graduation study.

To reiterate, this thesis had a twofold character. On the one hand, the *primary aim* of this study as discussed in Chapter 1, was to develop an alternative approach based on the shortest path method that can be used, for the time being, in the place of GPS data as long as from a practical point of view the GPS technology is currently difficult to be accessed. By this end, a traffic assignment model that can be used to estimate parkers' route choice was examined.

The main research question that was derived from the *primary aim* was the following:

1. *To which extent can full GPS tracks be replaced by just O-D points and shortest paths (length, time)?*

To begin with, in order to answer the research questions, the city of Tilburg has been used as a case study for the implementation of the methodological framework. The road network of the city and secondary GPS data from the B-Riders program were used for the analysis. In this study, the analysis was based on three types of routes: observed, shortest path based on distance, and shortest path based on time. The main hypothesis that has been tested is that car drivers opt to minimize either the travel time or distance. Shortest paths were generated using TransCAD (GIS). Travel times were based on posted speed limits considering the influence of the urban design on drivers' speed choice as well. Observed routes were manually reconstructed from the GPS tracks in TransCAD (GIS) and compared to their shortest alternatives routes. Through the comparison information about the common traveled distance between observed and shortest routes was obtained. In addition, the total travel distance and time, as well as the distance traveled by road type was also calculated based on network calculations. Based on this information, a paired samples t-test was conducted in SPSS to examine whether there are significant differences between observed and shortest alternative routes.

The results of the paired samples t-test suggest that there are significant statistical differences for both variables (average travel time and distance) when compared to the observed routes. Therefore, it can be concluded that the observed routes are not optimized once they appear to be longer both in terms of travel time and distance than their shortest alternatives. In particular, observed routes significantly exceed the shortest alternative routes based on time and distance by 13.4% and 16.2% respectively. Thus, it seems that shortest paths do not fully represent observed routes, but to some extent though. Remarkably, on average, the shortest path based on time correctly estimates the 75% of the observed routes' total travel distance. However, the shortest path based on distance correctly estimates only 52% of the observed routes' total travel distance. Therefore the findings of this research suggest that drivers consider travel time as their selection path criterion more than travel distance. It is also implied that the shortest path algorithm do not fully capture the real world route choice decisions as these can be observed from the GPS data.

The comparison of the observed routes to shortest time routes based on the road type composition revealed that the use of the external ring-road is almost equal. In addition, the use of the main roads is slightly overestimated by the shortest time routes. Finally, the local roads are significantly underestimated due to the fact that this type of road provides lower speeds; therefore, local roads are selected by the shortest path algorithm based on time. The comparison of the observed routes to the shortest distance routes revealed that the use of the external ring-road and the local roads are significantly underestimated and overestimated respectively. The reason is that local roads are usually selected as shortcuts to minimize the total travel distance, therefore, they are overestimated. On the other hand, the ring-road provide higher speeds but no shortcuts, therefore, it is underestimated.

Finally, considering the shortest path based on time, which has been found to be closer to the observed routes than the shortest path based on distance, a possible practical application was presented through a traffic assignment model in TransCAD (GIS). More specifically, using as an example the parking facility of Pieter Vreedeplein, as it has the highest trip frequency with 15 car trips, the occupancy rate of the parking facility on a specific day was used for the application of the traffic assignment. Traffic was assigned on the network by allocating traffic between each origin and destination point (parking facility). The outcome was the traffic flow which provides an estimation of the parkers' route choice as well as the most congested links occurred from cars traveling towards the parking facility. The comparison of the actual traffic flow to the estimated traffic flow revealed that the use of some streets is missed by the shortest path algorithm. This causes the misrepresentation of the traffic volume on other streets. This is related to the 25% overall inaccuracy of the shortest path method based on time. Definitely, the magnitude of the consequences occurred from this inaccuracy should be tested using more data in order to provide more solid evidence of the overall performance of this method.

At the same time, without neglecting the promising capabilities of the GPS technology, the *additional aim* was to provide insight into the parking-related traffic with the use of GPS data and GIS and highlight the valuable information this promising technology offers.

The additional research question that was derived from the *additional aim* was the following:

2. *How GPS technology and GIS can be utilized to provide insight into the parking-related traffic and what kind of information can be obtained?*

Focusing on the GPS tracks, the car trips were assigned to the parking facilities available in Tilburg. Parking facilities were segregated into on-street, parking lots, and parking garages. In this study, particular attention was paid to the eight main parking garages in and around the city centre. Unfortunately, the frequency of trips assigned to these parking facilities was low. Considering the two parking facilities with the highest frequency, the Pieter Vreedeplein and Schouwburg, with 15 and 12 car trips respectively, traffic was assigned on the road network and the actual traffic flow towards these parking facilities was simulated in TransCAD (GIS). This process was supported by scaled symbol theme maps which illustrate the traffic flow as well as the traffic volume on the network's links. Although the few car trips used in this study, it can be said that tracking people and vehicles with GPS receivers can provide great insights into drivers' route choice by capturing their spatial information in real-time. The observed routes from GPS tracks can reveal valuable information about parkers' route choice decision making, such as spontaneous movements due to the presence of unexpected traffic or in their try to avoid traffic lights, turns etc. It can also reveal any possible drawbacks of the way the road network is organized in terms of the accessibility that provides. Finally, it has been also seen that along with the positional information that a GPS receiver can provide, background information can be obtained as well. For instance, the time and day of each registration can provide insight into many aspects. This can be used to attain knowledge, for instance, how traffic levels on streets or occupancy rates at a specific parking facility differentiate within the day.

For traffic management purposes, municipalities adopt a policy according to which several means (e.g. road signing) are utilized in order to prompt drivers and especially visitors from other cities to use the main roads of the city when approaching main destinations such as the city center, central stations, or big parking facilities. At the same time, the policy indicates that local roads should be mainly used by local traffic, for instance, people who live and work in the city. The findings regarding the road type composition of the observed routes seem to be in line with the aforementioned policy. For instance, the observed routes remarkably tend to follow the external ring road and the main roads (29% and 59% of the total route distance respectively). Also, local roads are used to a lesser extent (12% of the total route distance). Undoubtedly, due to the few car trips available in the analysis, more evidence is required to support this assertion.

6.3. Recommendations and Future work

Undoubtedly, the time constraint to conduct this study was one of the factors that influenced many aspects that could have been further improved. At the same time, there were factors such as the available number of GPS data observations which their effect on the study's outcome was unavoidable. These recommendations can be considered as possible further steps that could be used to improve this thesis's components focusing on the further development of the shortest path approach which can be used to estimate parkers' route choice decision making and its understanding. Besides this, the study's experiences can be considered as a starting point for future research.

6.3.1. General Recommendations

The shortest path approach developed in this study intended to estimate parkers' route choice using O-D pairs testing the hypothesis that drivers opt to minimize either travel time or travel distance. It can be said that the hypothesis tested in this study is an open ended, once it leaves space for further discussion and research. Despite the few GPS observations which were available in this study as well as the time restriction, the performance of the shortest path algorithm considering travel time shows good potential for estimating parkers' route choice. However, there is a need for further development. To all the involved stakeholders that this study concerns, it is recommended that a more extensive data collection should be employed in order to provide more solid evidence of the traffic assignment model's performance and the magnitude of the shortcomings of its application. A recommended aspect which should be taken into account to further improve the shortest path approach is congestion. Finally, if the hypothesis is validated, the traffic assignment model can then be used for estimating the traffic flow on streets and intersections towards parking facilities and also as a tool for monitoring the performance of the network especially if a measure is going to be applied e.g. the construction of a new road or changing the function of a road (e.g. one way). This can provide feedback which can be used by traffic managers to support their decisions.

On the other hand, this study also demonstrated the capabilities of GPS technology in capturing travel information. It can be said that tracking people and vehicles with GPS receivers can provide great insights into drivers' route choice by capturing their spatial information in real-time. In addition to the positional information, also the day, time, and speed information is captured. This can be used to attain knowledge, for instance, how traffic levels on streets or occupancy rates at a specific parking facility differentiate within the day. However, for the time being, if this method is used there are issues that need to be considered. In particular, these issues refer to data accuracy, people recruitment, equipment cost, and the post-processing procedures required for the excessive amount of data that is collected.

6.3.2. Improvement within the scope of this study

The quality of the road network in terms of the links' connectivity and their compatibility with the real road network plays a very significant role for the performance of the shortest path algorithm. Within the time framework of this study, the road network in TransCAD (GIS) has been improved to the best possible extent by implementing two-way roads and identifying the pedestrian and bike roads which are not accessible by car. In addition, the road network has been accordingly adjusted in order to be in line with the way the road network was composed in 2014 when the data has been collected. This was achieved by identifying newly constructed roads which did not exist in that time period or roads that their function or accessibility has been changed. Therefore, a study with recent data and road network could avoid these interventions and thus eliminate the possibilities of an error in the process. At a first place, it would be suggested that this study is supported by more and recent GPS data. This could lead to strengthening the evidence of the shortest path algorithm's performance that will form more solid conclusions. Moreover, a recent overview of the parkers' route choice could be obtained to test the assertions that were determined in this study.

Regarding the shortest path approach based on time and distance, undoubtedly there is plenty of room for further improvements. As aforementioned, in this study posted speed limits have been used and accordingly adjusted to incorporate the effect of urban street characteristics on the average travel speed. This attempt turned out to be effective to provide a more advanced distinction between different roads and travel speed. However, the speed adjustment values which have been used to implement this effect could definitely be reconsidered based on the researcher's perceptions and on recent scientific evidence. In addition, one strongly suggested improvement is the implementation of time delays on the road network which have been neglected due to time constraints. These time delays refer to the delays caused by traffic lights and stops. Moreover, what would be of utmost interest is the implementation of traffic congestion in the form of congested travel times. This can be seen as an attempt to incorporate the possible effects of congestion in choosing a route such as a spontaneous deviation from the shortest path due to the presence of congestion. The overall performance of the shortest path algorithm after the implementation of these proposed improvements should be re-determined.

In addition to the aforementioned improvements, there also might be other ways to express the time effort car drivers. For instance, drivers might value their time effort as a function of the time of the day e.g. when it is morning or afternoon which might affect the drivers' route choice. In addition, the road condition can also be another factor, for instance, bad road conditions might be related to a non-comfort time even if a main road is considered to provide the same maximum speed as a main road with good conditions. The same logic applies to the case of travel distance. In this study, distance has been expressed in terms of the link segments' length. However, there might be other ways to generalize travel distance, for instance, a kind of distinction between the road types.

6.3.3. Future research ideas

The shortest paths algorithms can run considering different path selection criteria. In this study due to the time availability, only the variables of time and distance have been investigated. The results suggest that travel time seems to influence parkers' route choice more than distance. However, time attribute was found to not fully represent the observed routes and the route choice decision-making process of drivers. Consequently, more research is required to reveal if other path selection criteria can better describe the complex process of drivers' route choice decision making such as congestion, minimizing traffic lights, time of the day, road conditions etc.

One interesting factor that is recommended to be investigated is the weather conditions (use external files of weather data on different days). More specifically, weather data could be related to the trips that follow the shortest paths. By examining if there is a relation in these trips with the different weather conditions interesting travel patterns can be derived.

In addition, it would be very interesting to also investigate to which extent the drivers that follow the shortest path might consider the number of traffic lights/signs as a factor to choose their route towards their destination.

Along with the spatial information which is provided by a GPS receiver, also of utmost importance is the temporal component of each registration. To this extent, another interesting topic would be to investigate any possible relation of the trips which follow the shortest path with the variation of the time within the day and in turn the congestion levels on these time slot variations (use of external files of traffic data). In this way, the influence of congestion levels on drivers' route choice decision making can be investigated to examine if drivers mostly deviate due to the presence of congestion.

Chapter 7

Discussion

Finally, in this chapter, a general discussion takes place addressing the limitations and weaknesses of this study which have been identified through the process, the outcome, the tools used, as well as the challenges that were faced.

All in all, in this study, observed routes from GPS data were compared to two variations of the shortest path approach testing the hypothesis that drivers either minimize travel time or distance.

Significant statistical differences were found between the observed and both shortest path routes based on travel time and distance variables. These results are broadly consistent with the findings of a study conducted by Papinski & Scott (2011) based on which GPS data were compared to shortest time and distance paths. This thesis also demonstrates that drivers consider time more than distance as their path selection criterion. These findings concur with other studies which show that one of the most important factors that influence drivers' route choice is travel time (Bekhor et al., 2001; Papinski et al., 2009; Outram & Thompson, 1977).

As the analysis revealed, on average 75 % of the observed routes total traveled distance can be correctly estimated by the shortest time algorithm. To this extent, a traffic assignment was presented in a try to estimate drivers' route choice towards a parking facility considering the shortest path method based on time. However, the shortcomings of this method need to also be considered. The 25% inaccuracy of the shortest path algorithm causes some streets (links and intersections) to be missed, as the comparison of the actual traffic flow to the estimated traffic flow revealed. More specifically, the deviation of this method could lead to missing the use of some streets and intersections. A possible implication of this could be the misrepresentation of the actual traffic on some streets and intersections (traffic lights, stops). Therefore, if traffic lights are re-programmed based on inaccurately estimated traffic patterns as a measure for decongestion (e.g. give more/less time on a green light) this might lead to the improper use of the traffic lights, causing other externalities. Thus, there is a need for further investigation of the drivers' incentives regarding route choice and this study can certainly be used as the basis for a future research.

Moreover, some car trips revealed another limitation of the shortest path approach. This drawback refers to the inability of the algorithm to capture spontaneous movements of drivers who deviate from the shortest path. Interestingly, a few cases revealed that parkers do not drive directly to the parking facility that they eventually have chosen. However a kind of detour was observed which could be related to either the presence of unexpected congestion (drivers deviate to avoid traffic) or to a kind of searching for a free parking spot (mainly on-street) near the activity location and then decide to park their car in the parking garage if they are not succeeded. To this extent, on the one hand, this might imply that other than distance and time criteria need to be evaluated in order to examine the drivers' route choice decision-making process, for instance, minimizing the number of turns, traffic lights, the weather conditions, time of the day etc.

This research also presented the usefulness of the information provided by the GPS data to study parkers' route choice. Due to time restrictions as well as the lack of the necessary equipment, it was not possible to collect recent GPS data. Thankfully, secondary GPS data that was collected in the context of a previous study has been provided by the Eindhoven University of Technology. However, using secondary data hides some challenges as well. This data has been collected in the context of a bike stimulation program in 2014. Therefore, the challenge was to improve the road network considering the way it was organized in 2014 and identifying roads that are not existed now or their function has changed (one-way to two way and the vise-versa). The effort required to derive activity travel diaries from raw GPS data was not the case in this study once the data was already translated into trips and activities in the context of a previous study. Furthermore, the preparation of the GPS data was an important task as well. Organizing and cleaning the data ensured good quality and smooth routes. The inaccuracy issue of the GPS tracks was also something that this study has experienced. In particular, in some cases, poor quality trips did not provide a clear view of the actual path that drivers have traveled. Therefore, this phenomenon did not facilitate the reconstruction of the observed routes and in return, these trips were eliminated. In addition, the issue regarding the coordinate system alignment between GPS data and the road network is a common phenomenon. The GPS data is usually collected based on the WGS 84 (World Geodetic System) coordinate reference system while the network used in this study was projected in the Amersfoort/RD. To this extent, the coordinate reference system of the GPS data needed to be transformed to match the networks coordinate reference system.

One of the most important means for the execution of this study was the use of TransCAD (GIS). One of the main capabilities of a GIS and so TransCAD's is the ability to combine and process data from a variety of sources. In this way, in this study, it was made possible to observe the GPS tracks and relate them to the underline road network. In addition, of utmost importance was the use of the data-analysis technique of the shortest path algorithm that TransCAD (GIS) offers. Among the capabilities and functionalities that this package offers for network analysis, the traffic assignment is one of them. Although the time restrictions of this study, I had the opportunity to get insight into the ways a traffic assignment is conducted in TransCAD (GIS) and the valuable information that can be derived from. Undoubtedly, there are some services that would make this package more powerful. These desired improvements are derived from some difficulties found in this study. These services are derived from some tasks that either another tool was used to conduct them or even in TransCAD (GIS) these tasks were still difficult and time-consuming to accomplish. More specifically, for statistical analysis of the network calculations obtained from TransCAD (GIS) the data needed to be transferred to an Excel file, and therefore, to the SPSS software tool for further analysis. This can cost valuable amount of time to users. In addition, from the best of my knowledge, another important feature that could make TransCAD dominant is the map-matching feature based on which the GPS tracks are matched to the underlying road network in order to reconstruct the observed routes of drivers. This process is very time consuming and labor intensive if this needs to be done manually due to the lack of the necessary means. Although map-matching algorithms still have some inaccuracy issues, it would be very useful if this kind of feature is provided by a GIS tool, even if some interventions by the user are required to correct these issues. In addition, this would save much valuable time to users to spend on other important aspects of their research.

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Appendices

Appendix A. Street characteristics

Table A 1: Profiles based on street characteristics

Profile 1

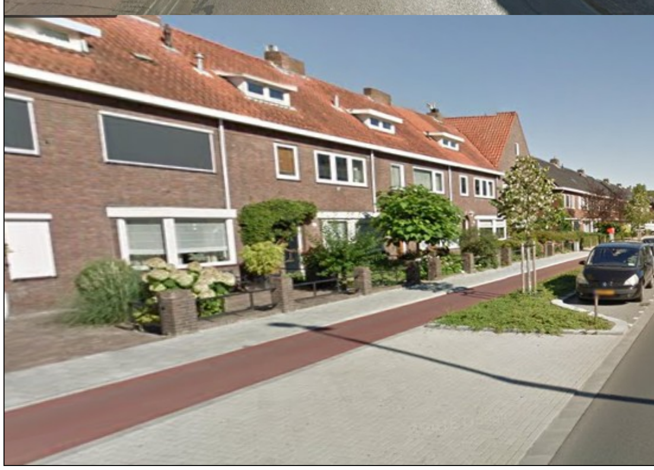
Building setback 0 - 2m

Small building setback increases the driver’s concern of the presence of kids playing, and pedestrians walking very close to passing through vehicles. Thus, inducing them to decrease their speed.

Profile 2

Building setback 2 - 4m

The effect here is similar to the explanation of Profile 1 above. When the building setback is increased the effect on the average travel speed is decreased.



Profile 3

Building setback > 6 m

Here the drivers’ concern is decreased more due to the increase of the feeling of safety. This can cause a small increase in the average travel speed.

Profile 4

Tree-lined street

Optical height > Optical width

Speed reduction is achieved if the above condition is met. Drivers' feeling of safety is decreased due to limited view which is interrupted by trees, thus inducing them to decrease their speed.

Profile 5

Tree-lined street

Optical height < **Optical width**

In contrast to Profile 4, in this case, the level of concern is decreased. This might encourages drivers to increase their speed once the optical width (street width) is greater than the optical height of the driver.

Profile 6

Road surface Brick vs. Asphalt

Cause a feeling of concern due to:

- Appearance of texture
- Vibration
- Tire noise

Thus, inducing drivers' to decrease their speed.

Profile 7

Bike lane separated with marking line

In this case, the pavement width is reduced and the drivers become closer to bikers. This causes the increase of the possibility of an unexpected event with bikers, thus inducing drivers to be more careful and therefore decrease their speed.

Profile 8

Elevated bike lane

In contrast to Profile 7, here, the presence of an elevated bike lane which is separated from the main road reduces the likelihood of an unexpected event with cyclists. Therefore, drivers might be encouraged to increase their speed due to the increase of the feeling of safety

Profile 9

Elevated bike lane separated with vegetation.

The effect on average travel speed is similar to Profile 8 but to a lesser extent. Drivers here might increase their speed but at the same time the presence of vegetation separating bike lane with the main road limiting the view between drivers and bikers.

Profile 10

Bus lane

The presence of a bus lane increases the feeling of concern for the drivers thus inducing them to decrease their speed.

Profile 11

On-street parking on both sides of a one-way narrow street

In this case, drivers feeling of concern is considerably increased once the likelihood of an unexpected event with a parked car or a pedestrian. The narrower the street width the more influence it has on the driving speed.

Profile 12

On-street parking on both sides of a wide street

In this case where the width of the street is considerably bigger than Profile 11 the effect of the on-street parking on the average travel speed is much less and is considered to be negligible.

Profile 13

On-street parking on both sides of the road

-Left side → On-street parking next to the main road
-Right side → On-street separated with bike lane
The feeling of concern, in this case, is increased thus inducing drivers to significantly decrease their speed.

Profile 14

On-street parking next to one-way road

In this case, the effect of on-street parking is less once it is separated from the street by a bike lane. The likelihood of an unexpected event with a parked car or people that might be between these cars is reduced.

Profile 15

On-street parking in a two-way narrow road

In contrast to Profile 14, in this case, the road is two directional and at the same time, the street width is small. This causes the increase of the feeling of concern for the drivers. Therefore, although the on-street parking is separated from the street with a bike lane, the effect on the average speed is still significant.

Appendix B. Comparison of observed and shortest alternative routes based on distance and time

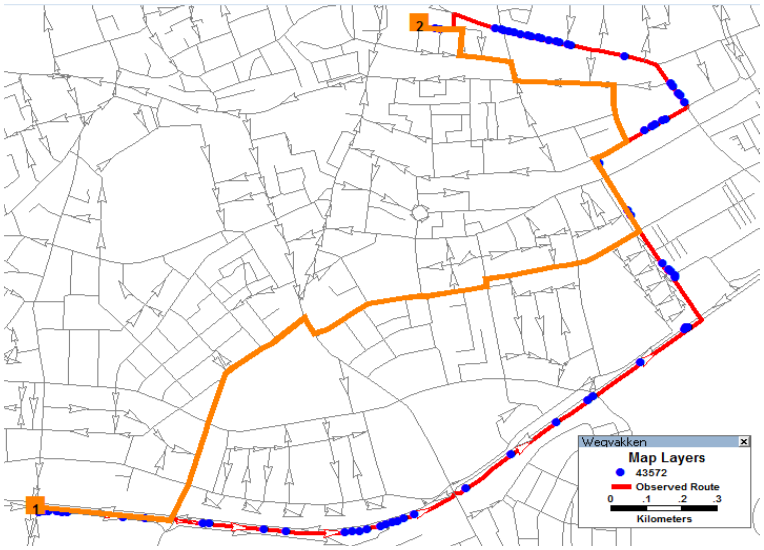


Figure B 1: Trip ID: 43572 Observed vs. Shortest Distance Route

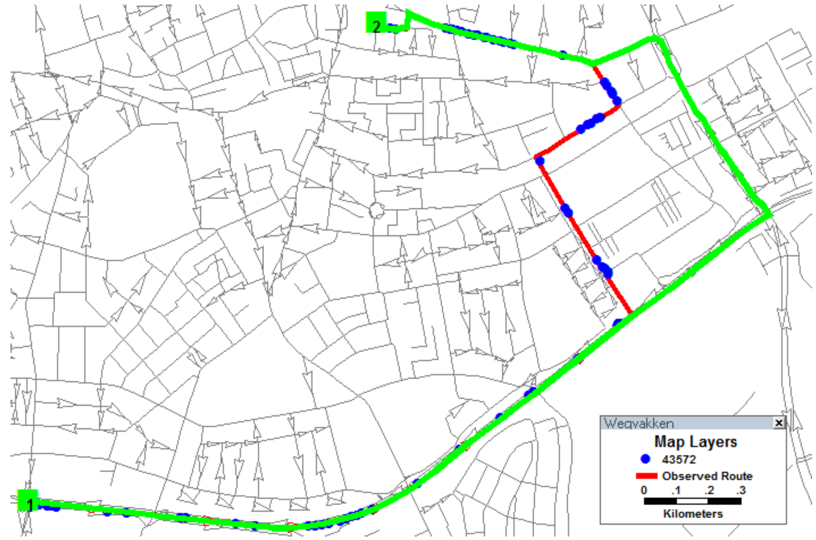


Figure B 2: Trip ID: 43572 Observed vs. Shortest Time Route

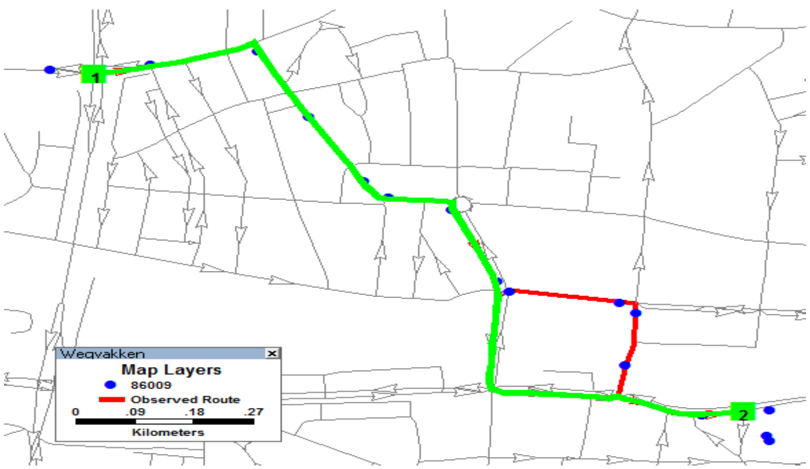


Figure B 3: Trip ID: 86009 Observed vs. Shortest Distance Route

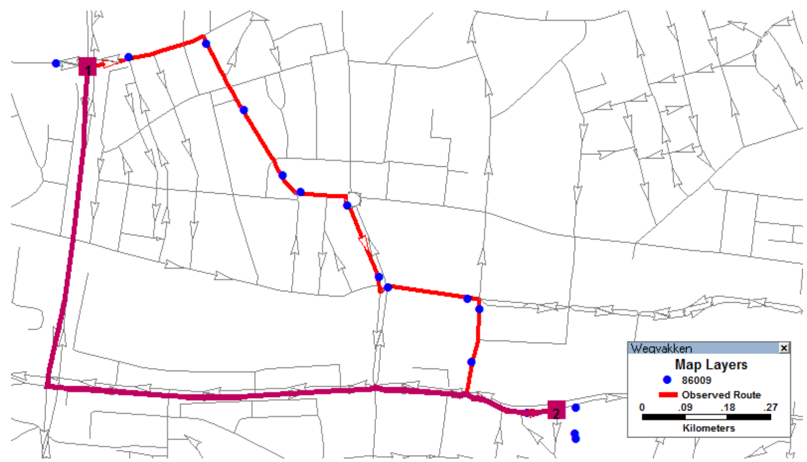


Figure B 4: Trip ID: 86009 Observed vs. Shortest Time Route

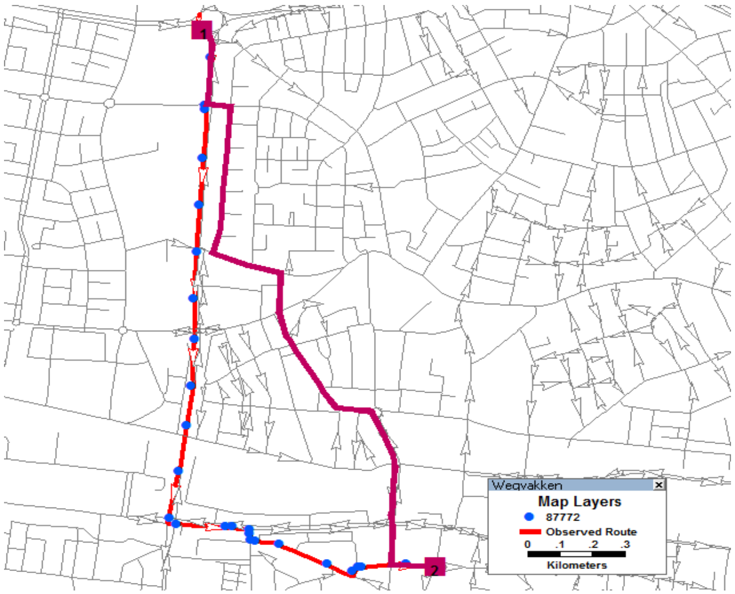


Figure B 5: Trip ID: 87772 Observed vs. Shortest Distance Route

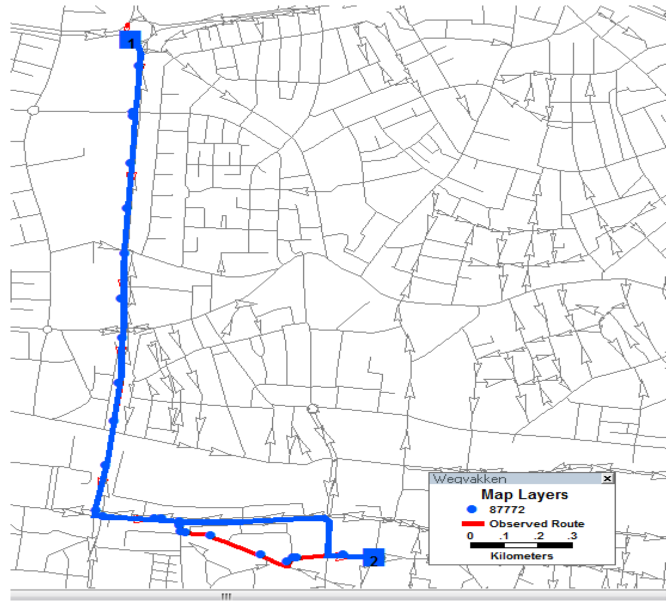


Figure B 6: Trip ID: 87772 Observed vs. Shortest Time Route

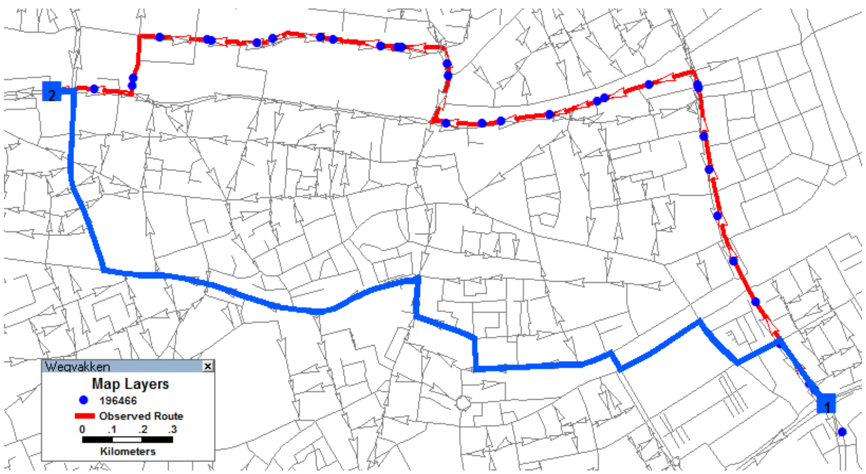


Figure B 7: Trip ID: 196466 Observed vs. Shortest Distance Route

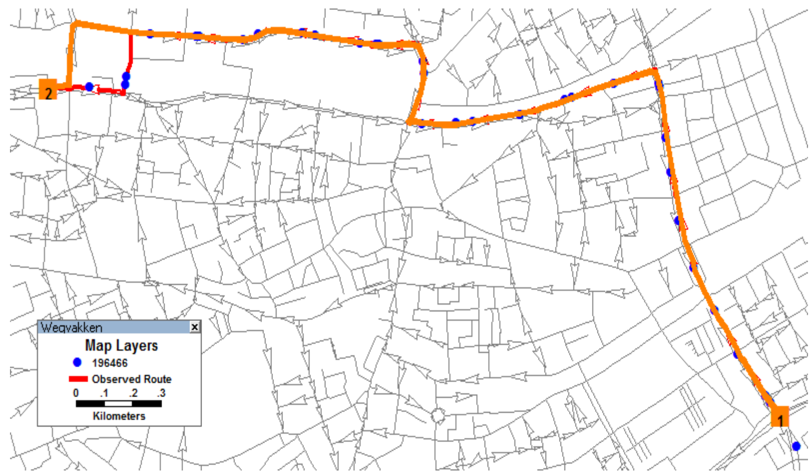


Figure B 8: Trip ID: 196466 Observed vs. Shortest Time Route

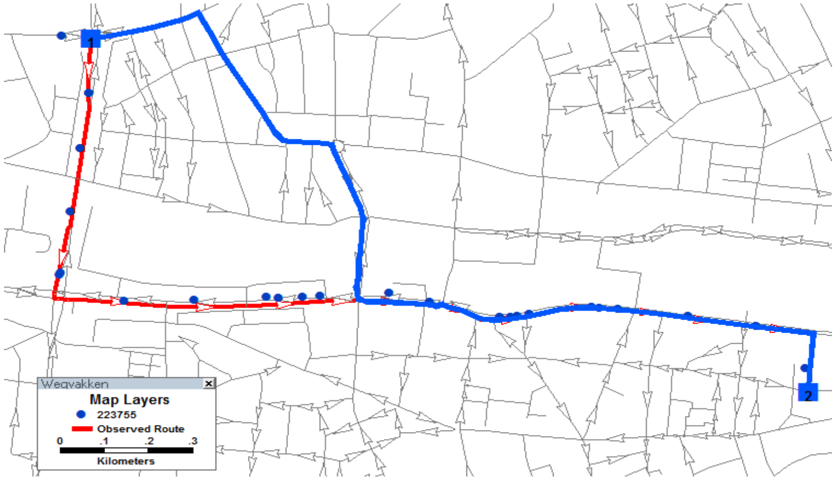


Figure B 9: Trip ID: 223755 Observed vs. Shortest Distance Route

Figure B 10: Trip ID: 223755 Observed vs. Shortest Time Route

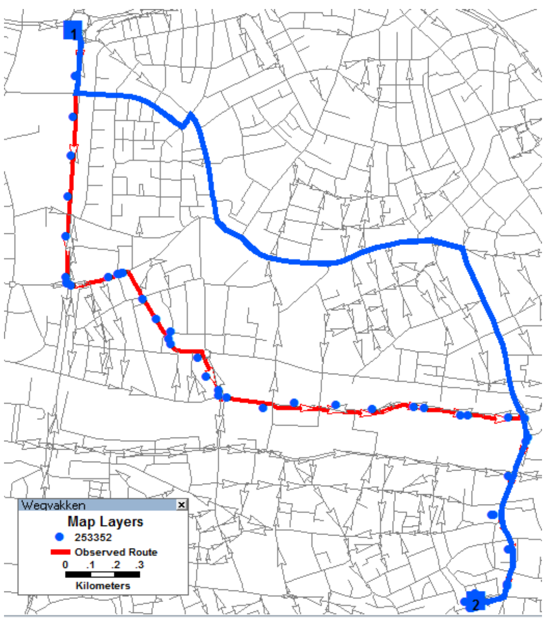


Figure B 11: Trip ID: 253352 Observed vs. Shortest Distance Route

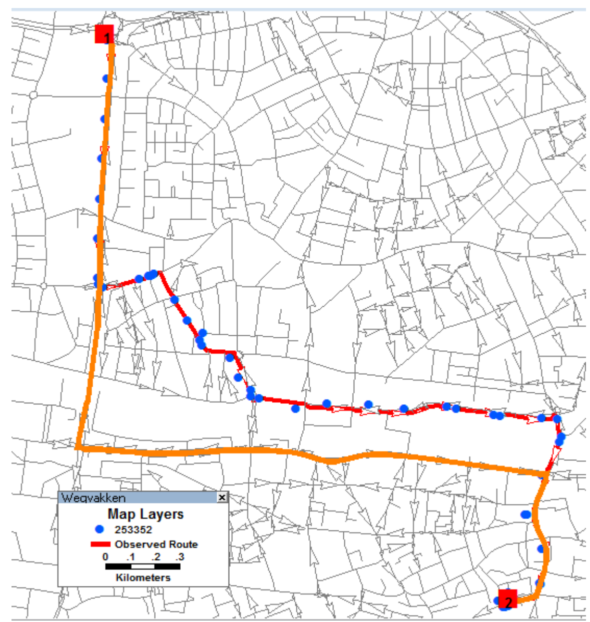


Figure B 12: Trip ID: 253352 Observed vs. Shortest Time Route

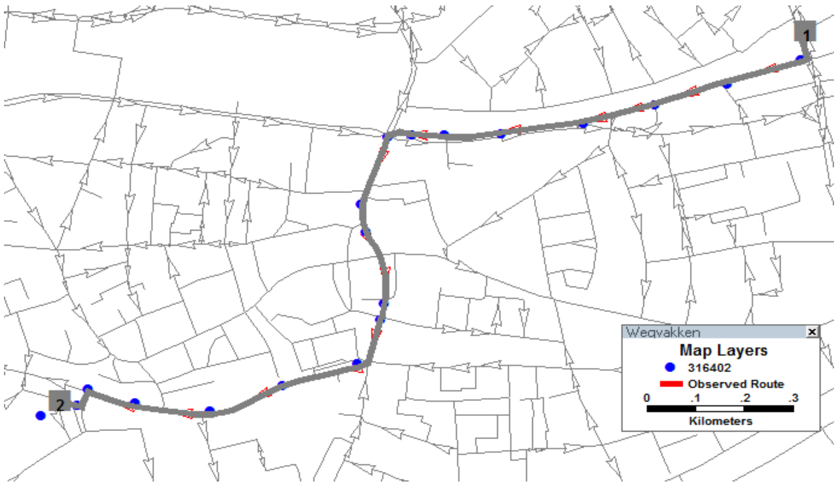


Figure B 13: Trip ID: 316402 Observed vs. Shortest Distance Route

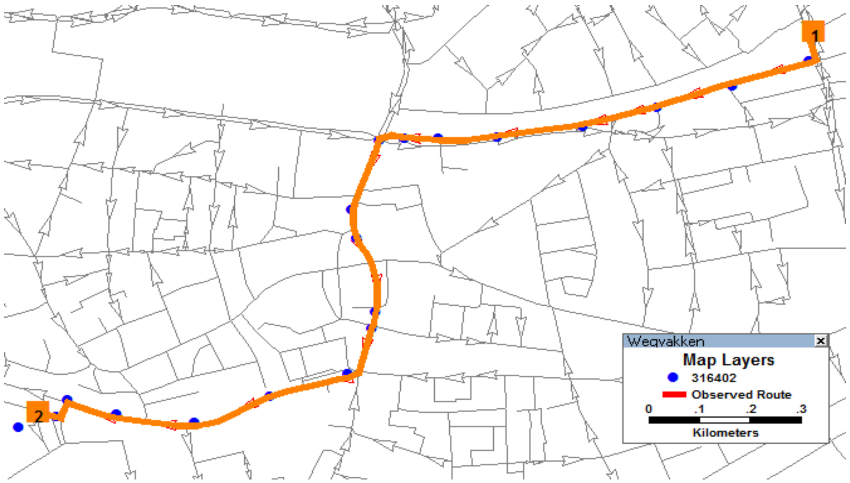


Figure B 14: Trip ID: 316402 Observed vs. Shortest Time Route

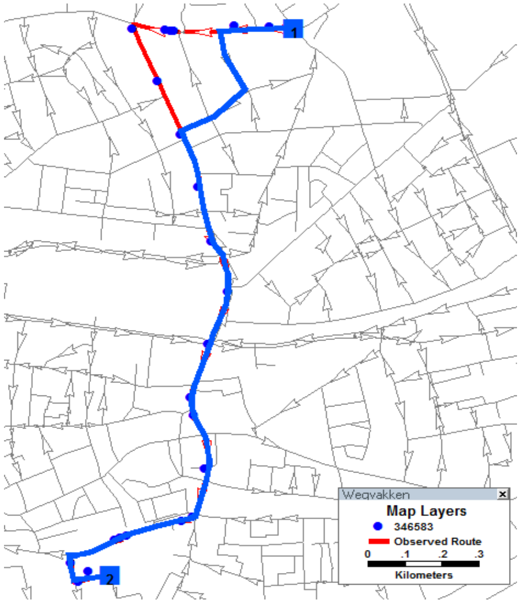


Figure B 15: Trip ID: 346583 Observed vs. Shortest Distance Route

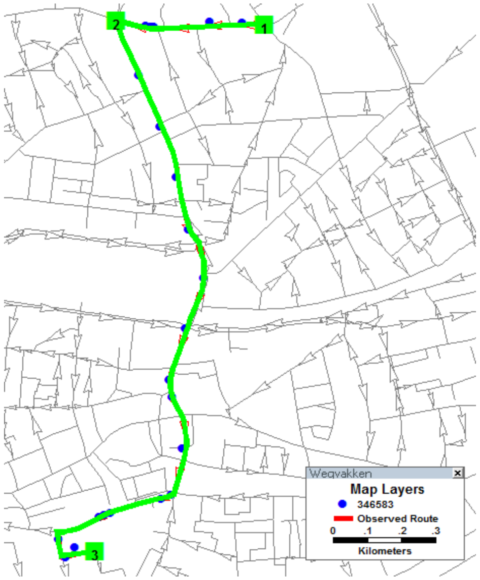


Figure B 16: Trip ID: 346583 Observed vs. Shortest Time Route

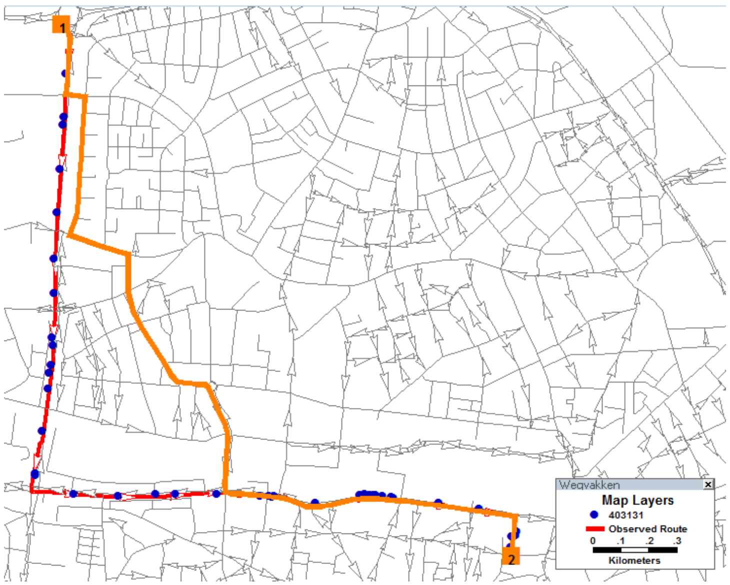


Figure B 17: Trip ID: 403131 Observed vs. Shortest Distance Route

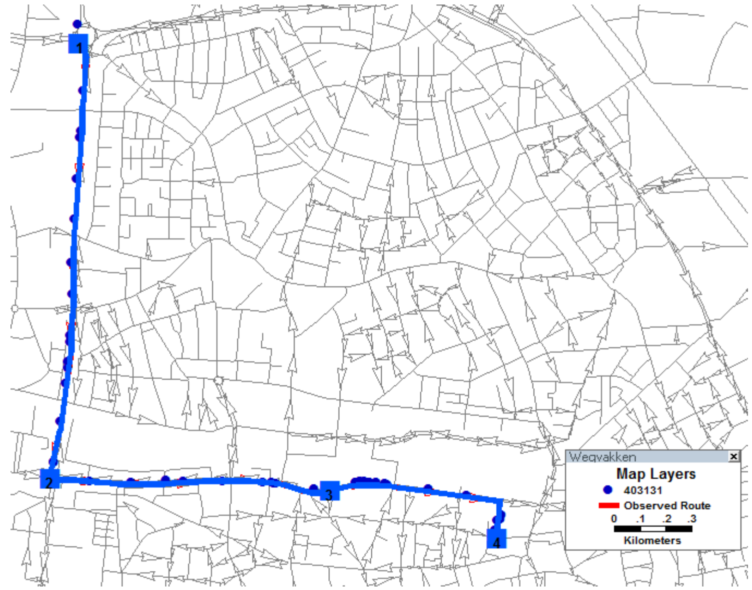


Figure B 18: Trip ID: 403131 Observed vs. Shortest Time Route

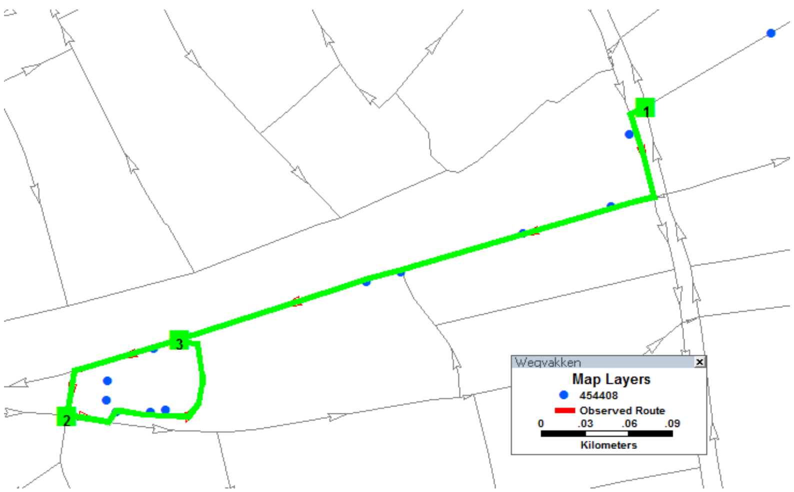


Figure B 19: Trip ID: 454408 Observed vs. Shortest Distance Route

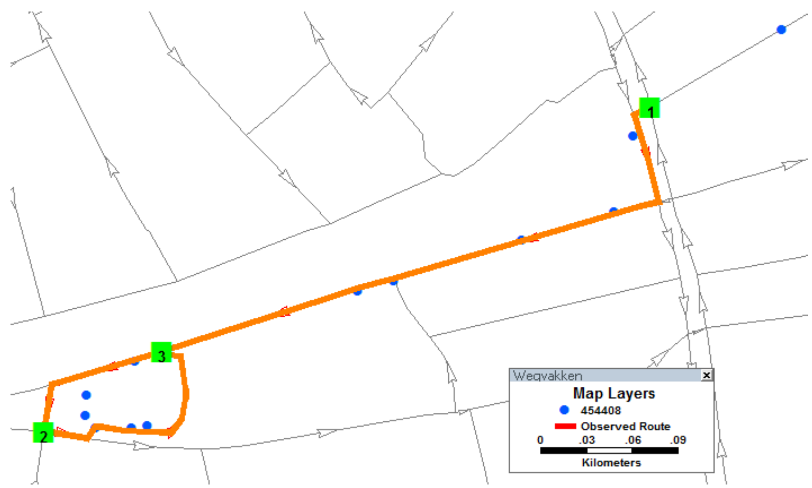


Figure B 20: Trip ID: 454408 Observed vs. Shortest Time Route

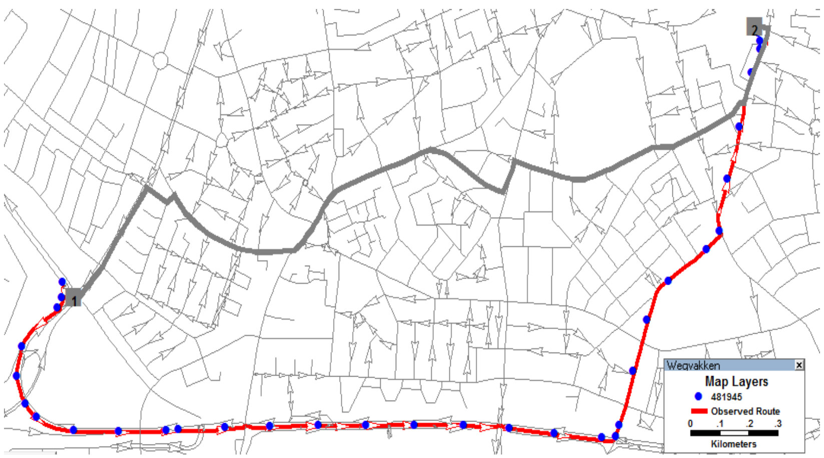


Figure B 21: Trip ID: 481945 Observed vs. Shortest Distance Route

Figure B 22: Trip ID: 481945 Observed vs. Shortest Time Route

Figure B 23: Trip ID: 510835 Observed vs. Shortest Distance Route

Figure B 24: Trip ID: 510835 Observed vs. Shortest Time Route

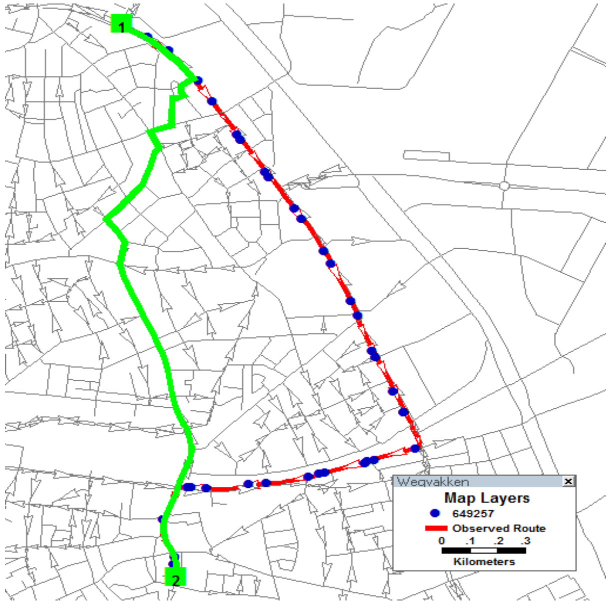


Figure B 25: Trip ID: 649257 Observed vs. Shortest Distance Route

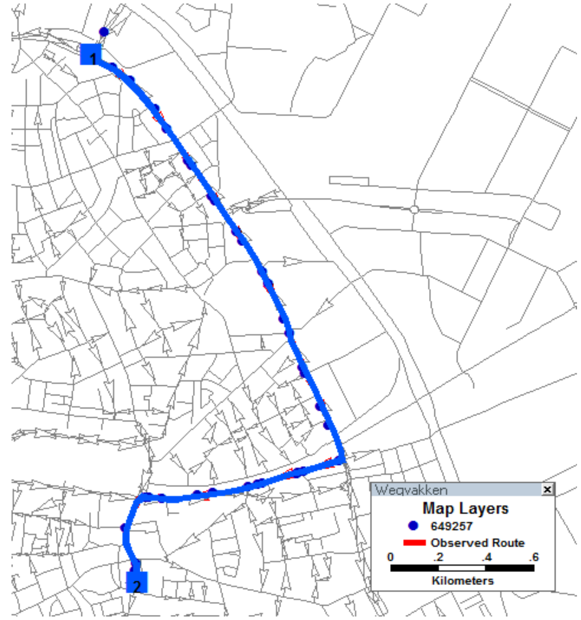


Figure B 26: Trip ID: 649257 Observed vs. Shortest Time Route

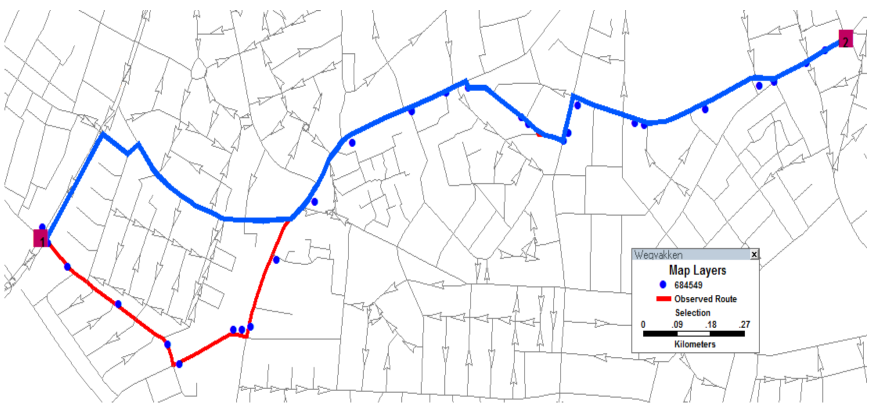


Figure B 27: Trip ID: 684549 Observed vs. Shortest Distance Route

Figure B 28: Trip ID: 684549 Observed vs. Shortest Time Route

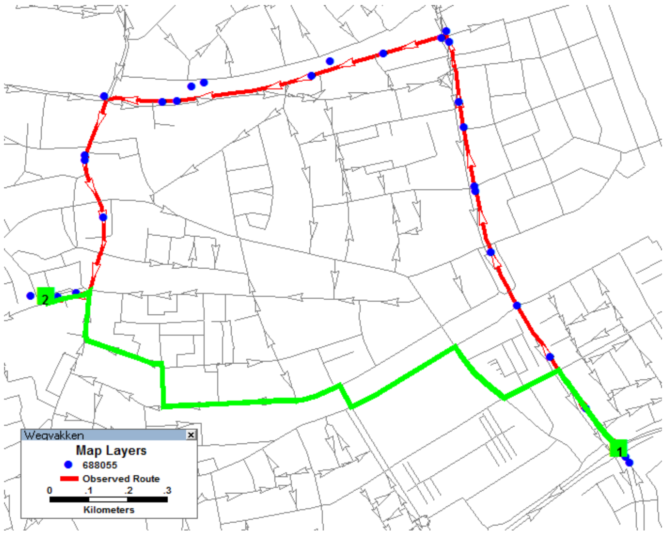


Figure B 29: Trip ID: 688055 Observed vs. Shortest Distance Route

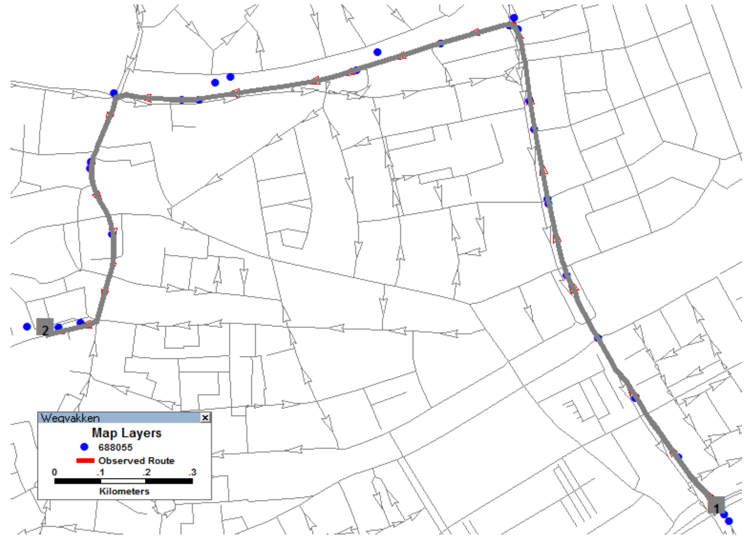


Figure B 30: Trip ID: 688055 Observed vs. Shortest Time Route

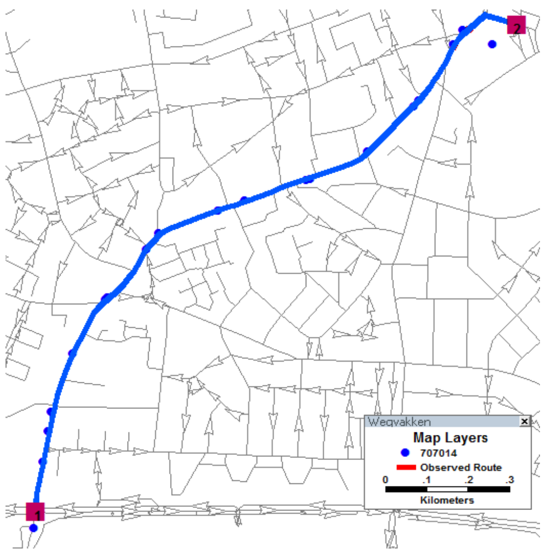


Figure B 31: Trip ID: 707014 Observed vs. Shortest Distance Route

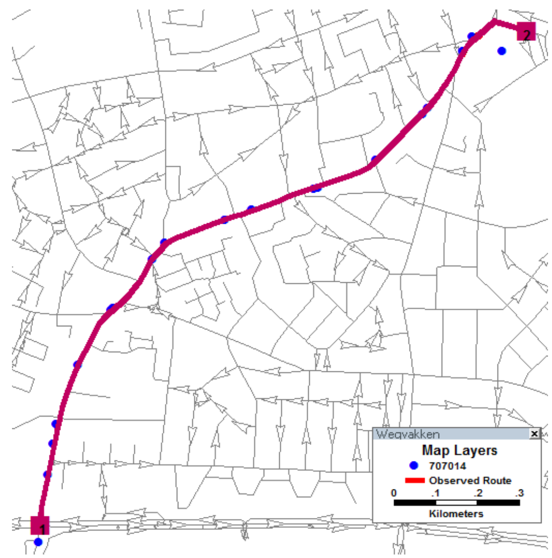


Figure B 32: Trip ID: 707014 Observed vs. Shortest Time Route

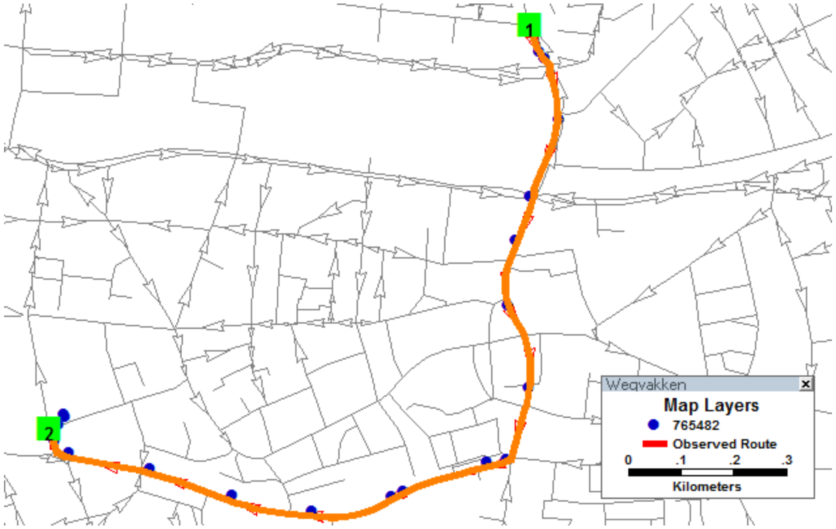


Figure B 33: Trip ID: 765482 Observed vs. Shortest Distance Route

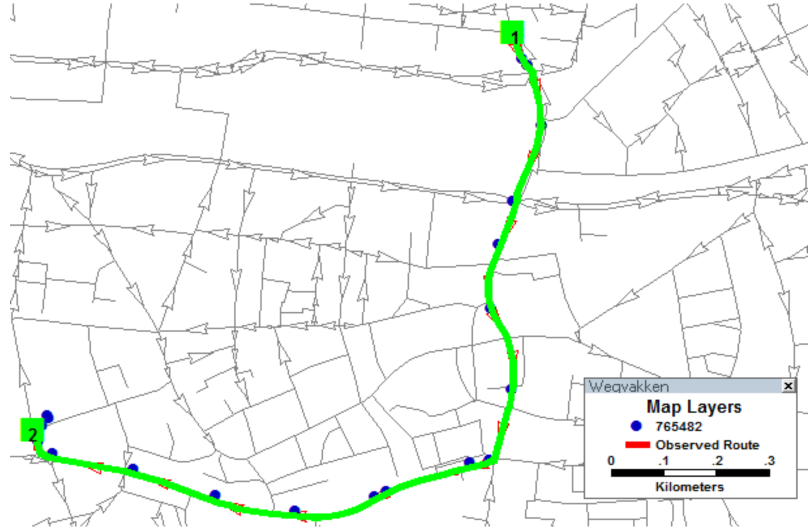


Figure B 34: Trip ID: 765482 Observed vs. Shortest Time Route

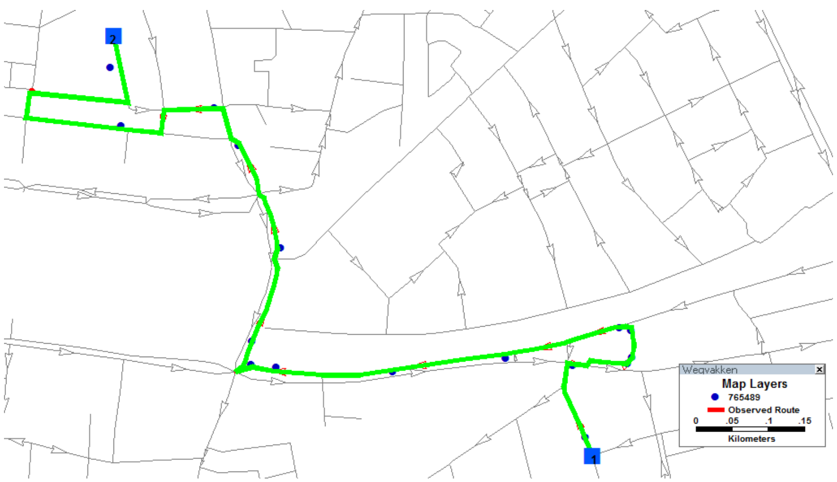


Figure B 35: Trip ID: 765489 Observed vs. Shortest Distance Route

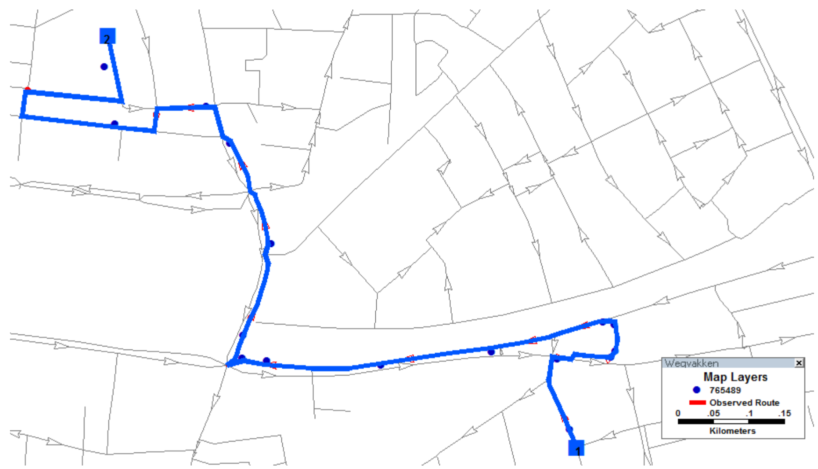


Figure B 36: Trip ID: 765489 Observed vs. Shortest Time Route

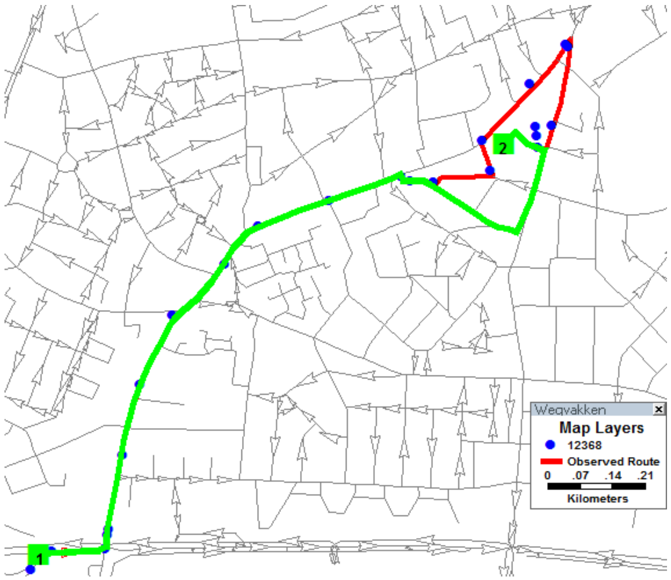


Figure B 37: Trip ID: 12368 Observed vs. Shortest Distance Route

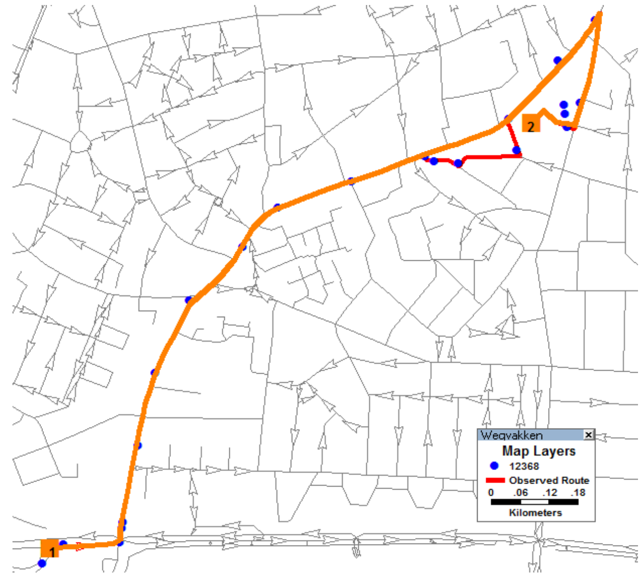
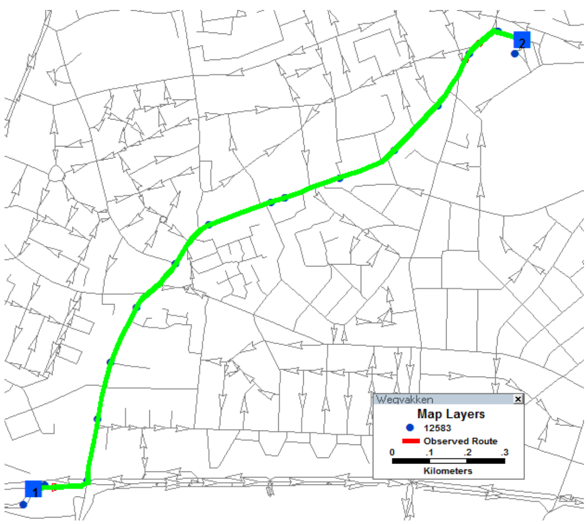


Figure B 38: Trip ID: 12368 Observed vs. Shortest Time Route



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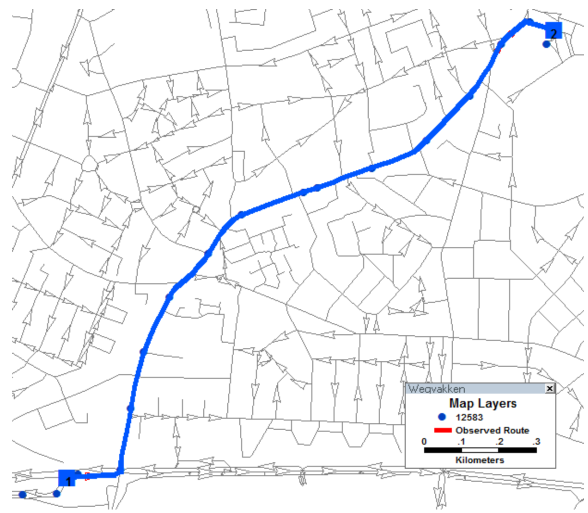

Figure B 40: Trip ID: 12583 Observed vs. Shortest Time Route

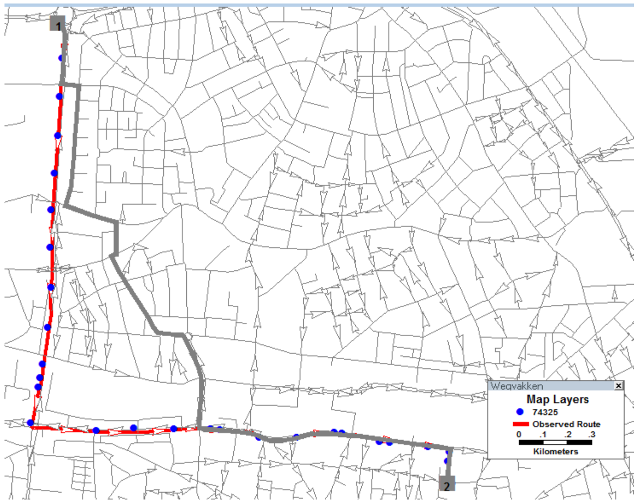

Figure B 41: Trip ID: 74325 Observed vs. Shortest Distance Route

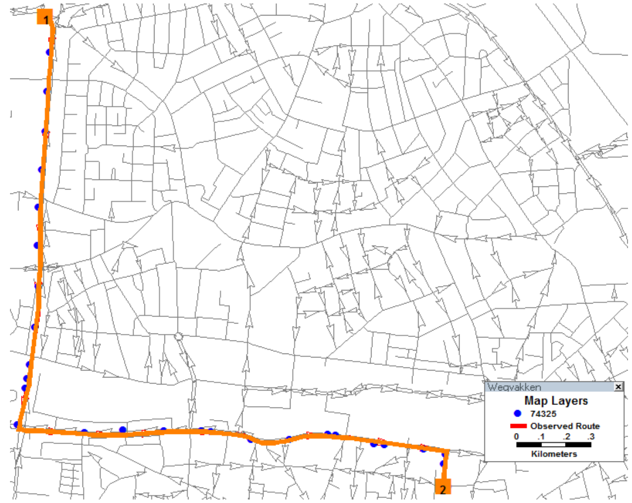

Figure B 42: Trip ID: 74325 Observed vs. Shortest Time Route

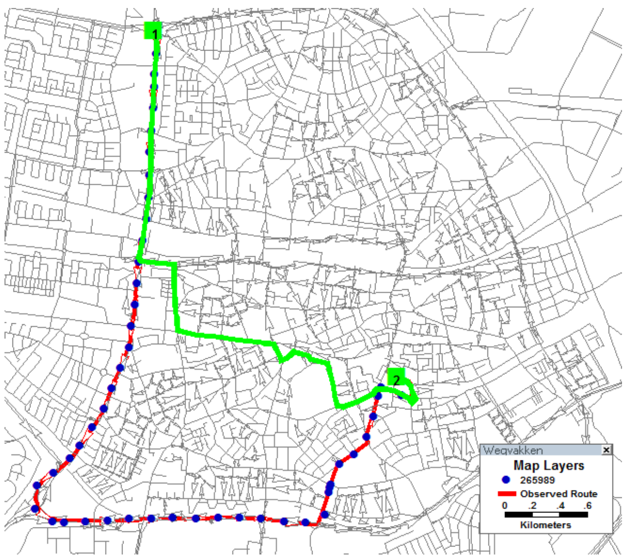

Figure B 43: Trip ID: 265989 Observed vs. Shortest Distance Route

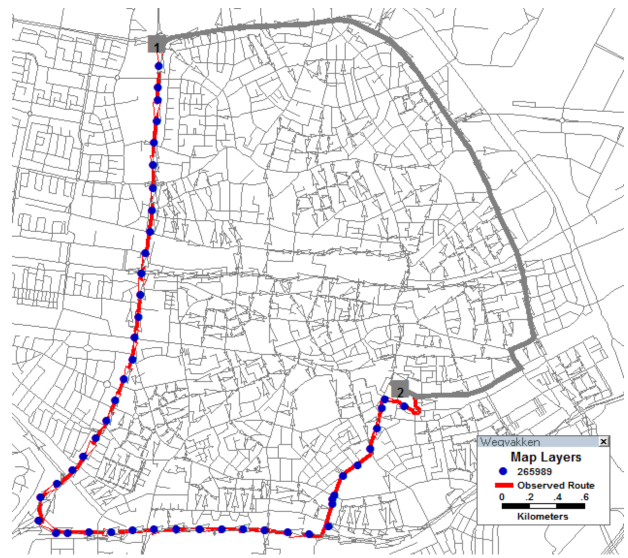

Figure B 44: Trip ID: 265989 Observed vs. Shortest Time Route

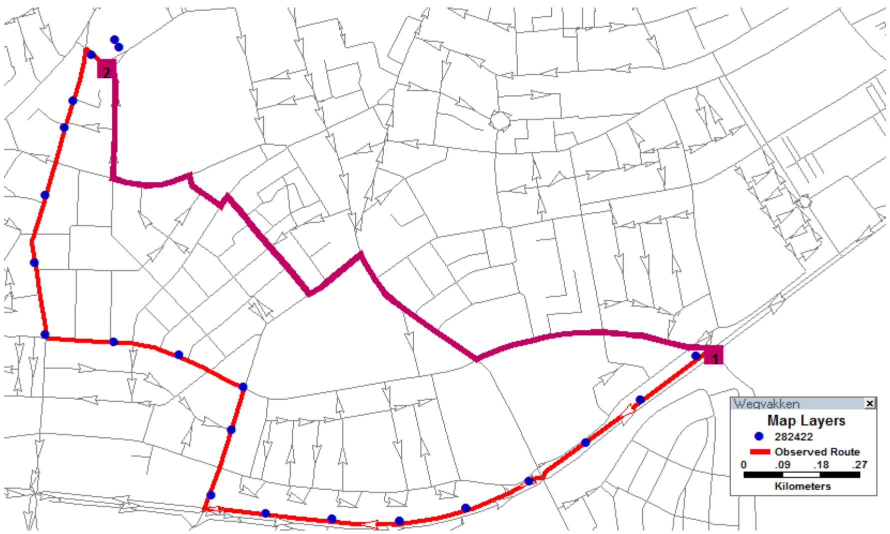

Figure B 45: Trip ID: 282422 Observed vs. Shortest Distance Route

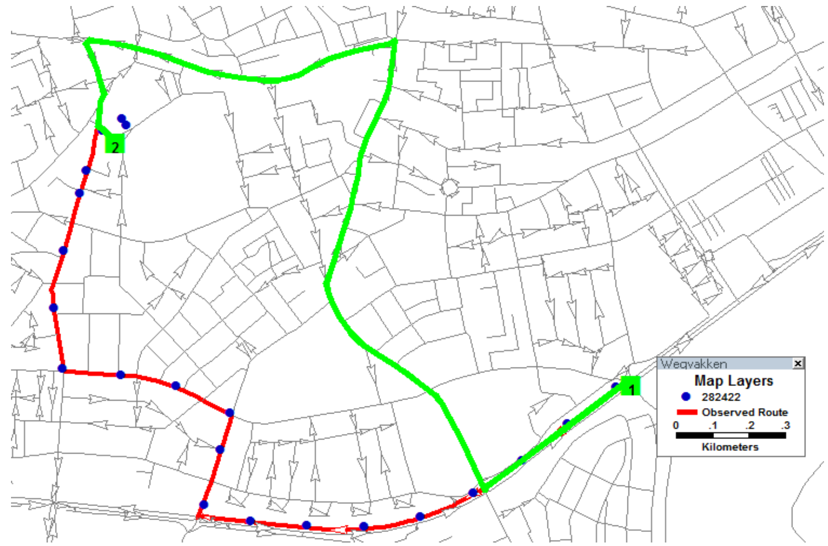

Figure B 46: Trip ID: 282422 Observed vs. Shortest Time Route

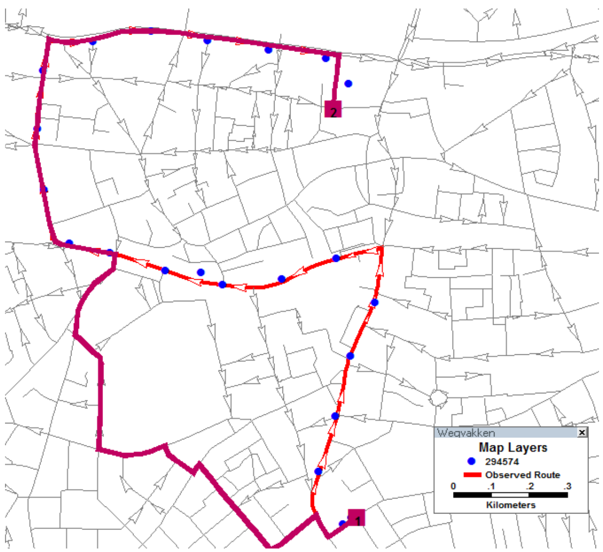

Figure B 47: Trip ID: 294574 Observed vs. Shortest Distance Route

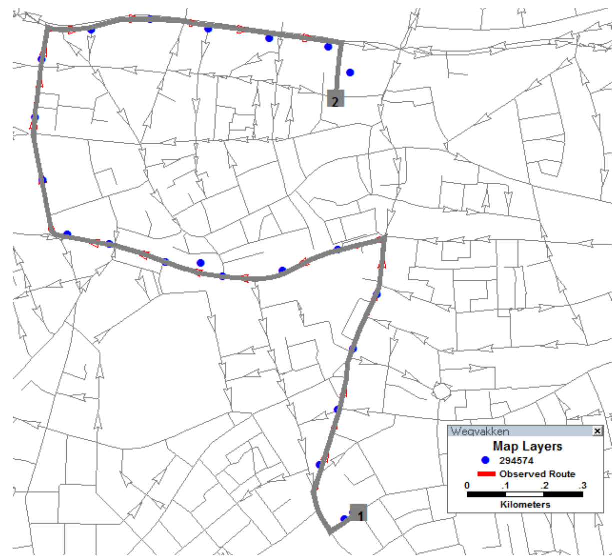

Figure B 48: Trip ID: 294574 Observed vs. Shortest Time Route

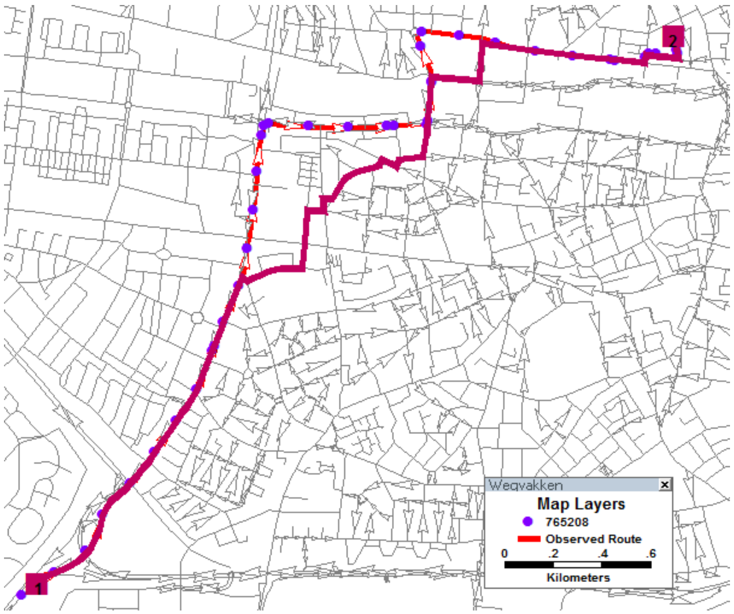

Figure B 49: Trip ID: 765208 Observed vs. Shortest Distance Route

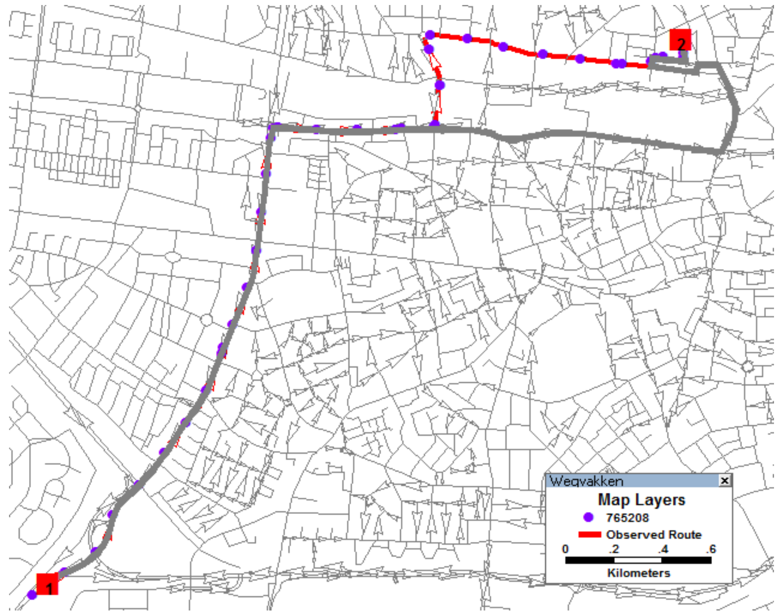

Figure B 50: Trip ID: 765208 Observed vs. Shortest Time Route

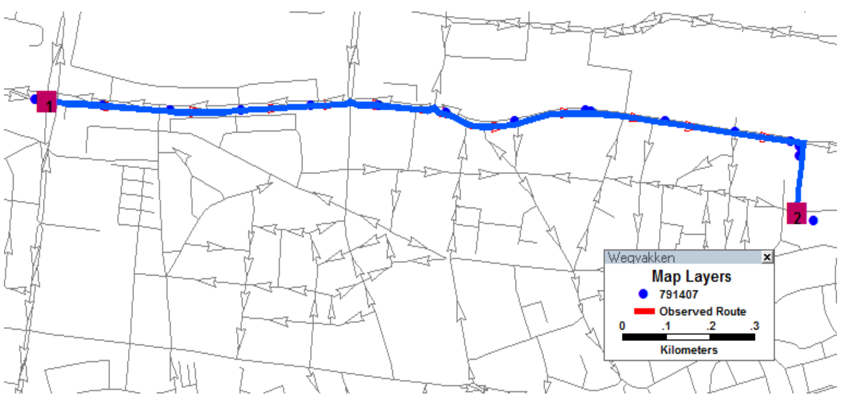

Figure B 51: Trip ID: 791407 Observed vs. Shortest Distance Route

Figure B 52: Trip ID: 791407 Observed vs. Shortest Time Route

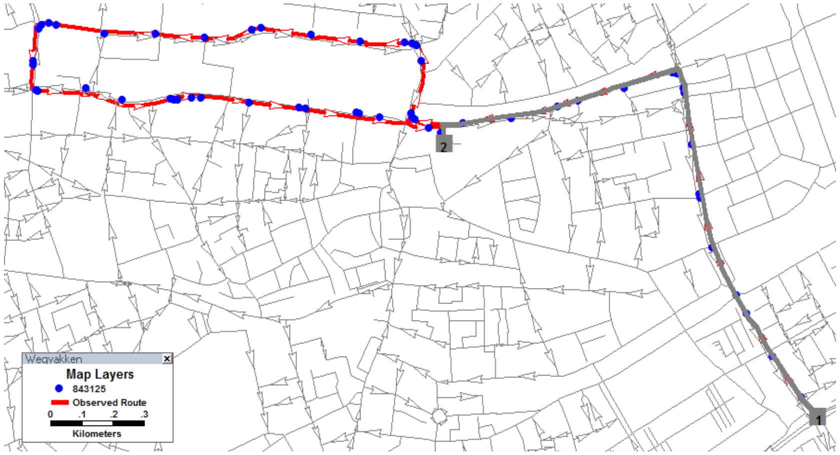

Figure B 53: Trip ID: 843125 Observed vs. Shortest Distance Route

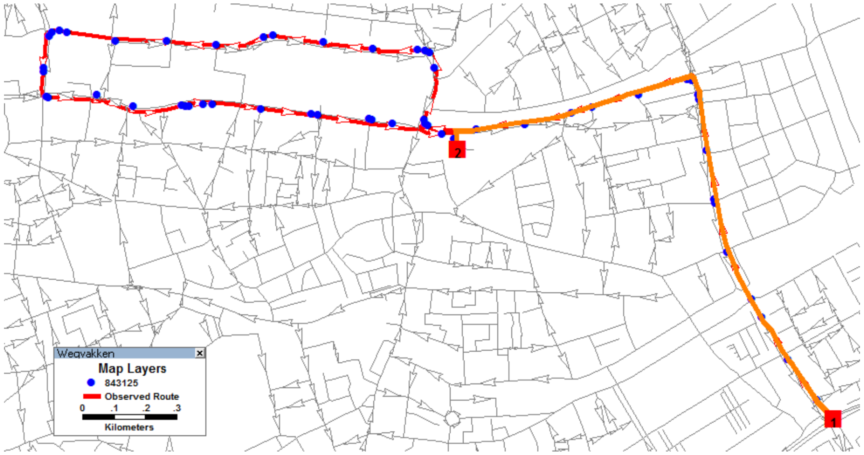

Figure B 54: Trip ID: 843125 Observed vs. Shortest Time Route

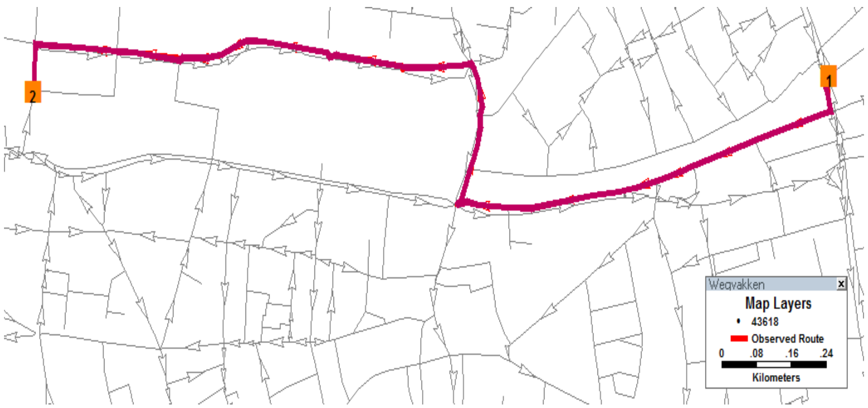

Figure B 55: Trip ID: 40216 Observed vs. Shortest Distance Route

Figure B 56: Trip ID: 40216 Observed vs. Shortest Time Route

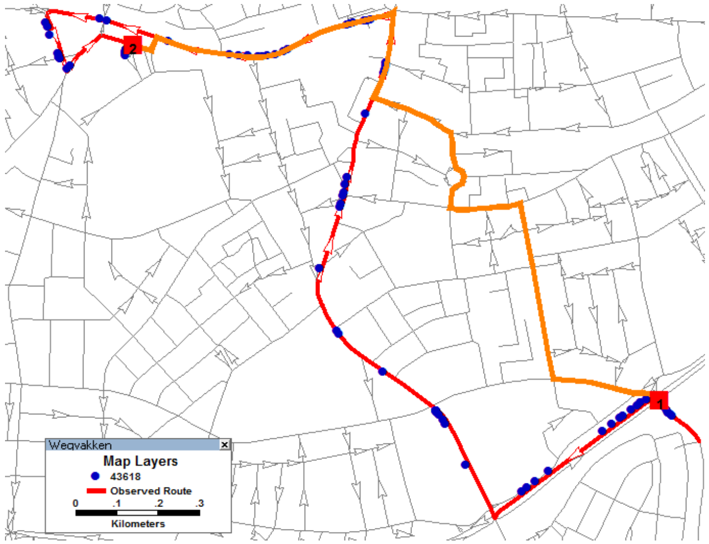

Figure B 57: Trip ID: 43618 Observed vs. Shortest Distance Route

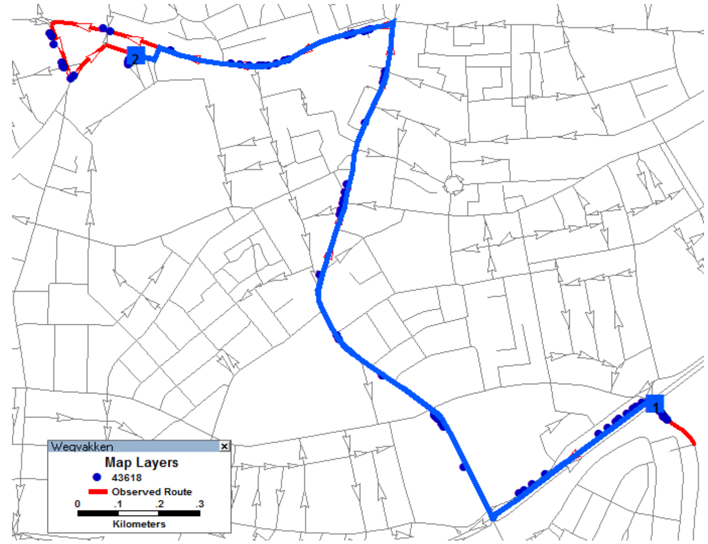

Figure B 58: Trip ID: 43618 Observed vs. Shortest Time Route

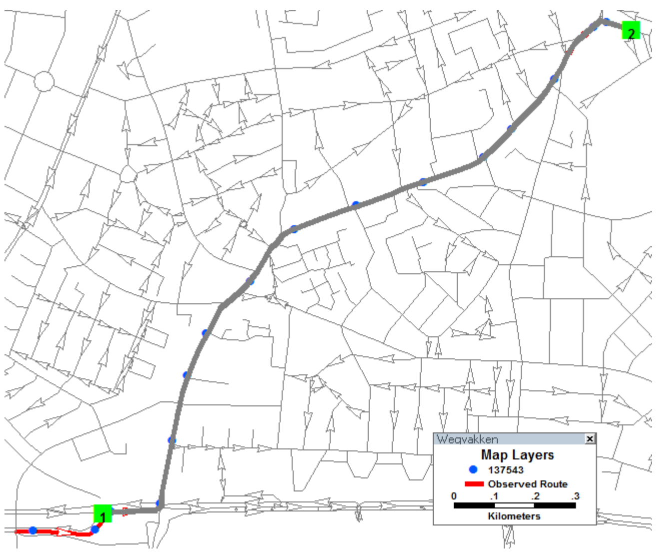

Figure B 59: Trip ID: 137543 Observed vs. Shortest Distance Route

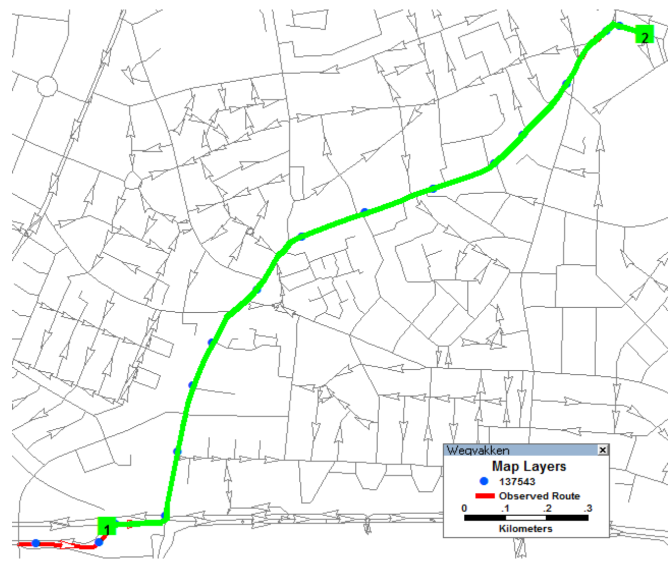

Figure B 60: Trip ID: 137543 Observed vs. Shortest Time Route

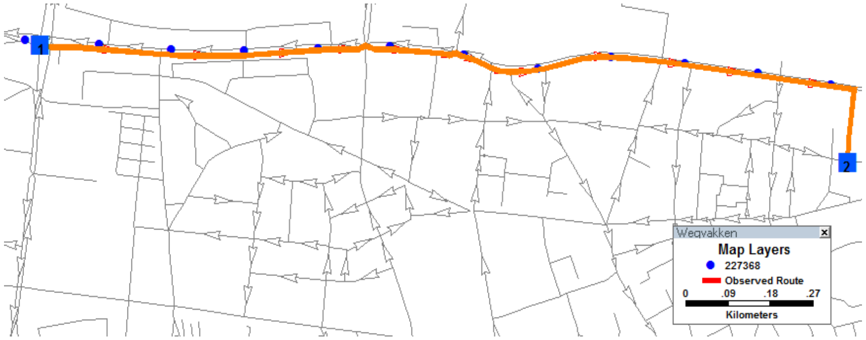

Figure B 61: Trip ID: 227368 Observed vs. Shortest Distance Route

Figure B 62: Trip ID: 227368 Observed vs. Shortest Time Route

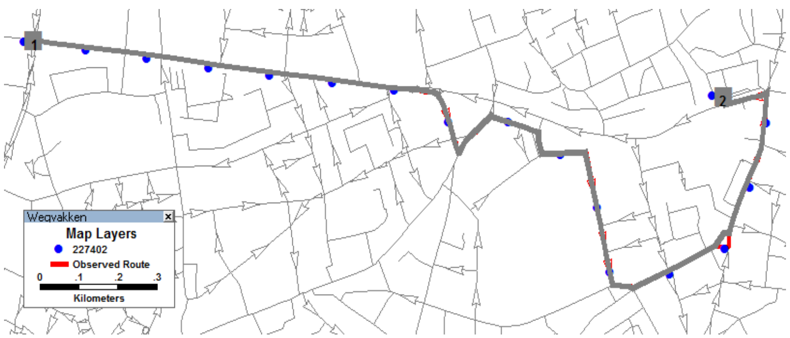

Figure B 63: Trip ID: 227402 Observed vs. Shortest Distance Route

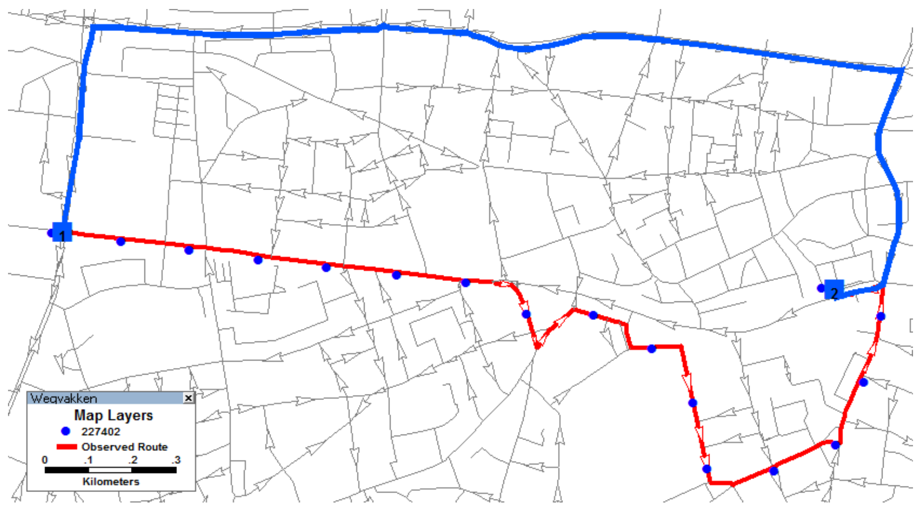

Figure B 64: Trip ID: 227402 Observed vs. Shortest Time Route

Figure B 65: Trip ID: 235779 Observed vs. Shortest Distance Route

Figure B 66: Trip ID: 235779 Observed vs. Shortest Time Route

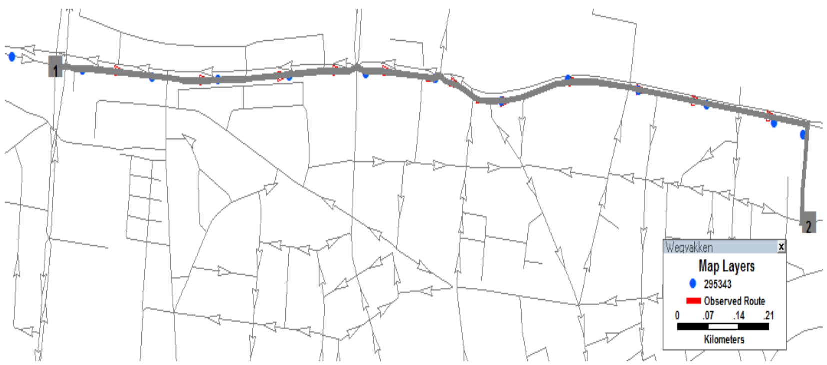

Figure B 67: Trip ID: 295343 Observed vs. Shortest Distance Route

Figure B 68: Trip ID: 295343 Observed vs. Shortest Time Route

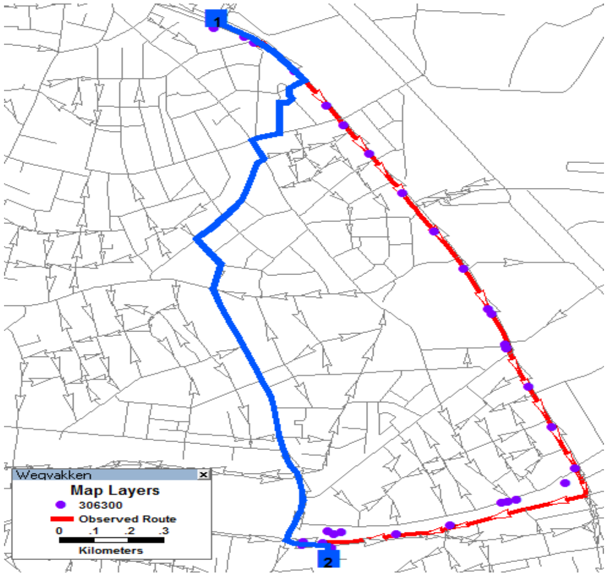

Figure B 69: Trip ID: 306300 Observed vs. Shortest Distance Route

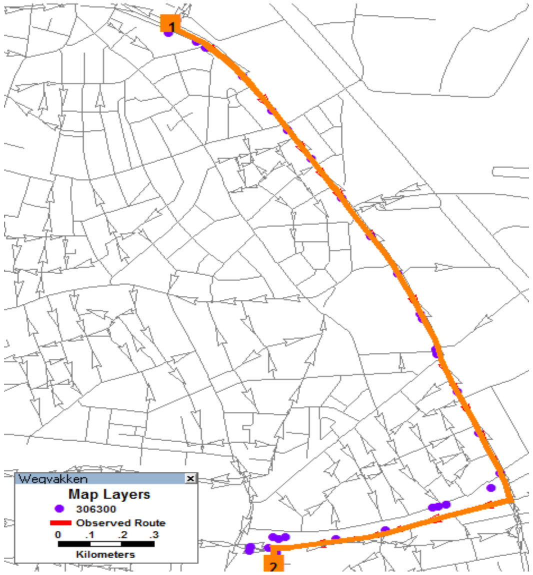

Figure B 70: Trip ID: 306300 Observed vs. Shortest Time Route

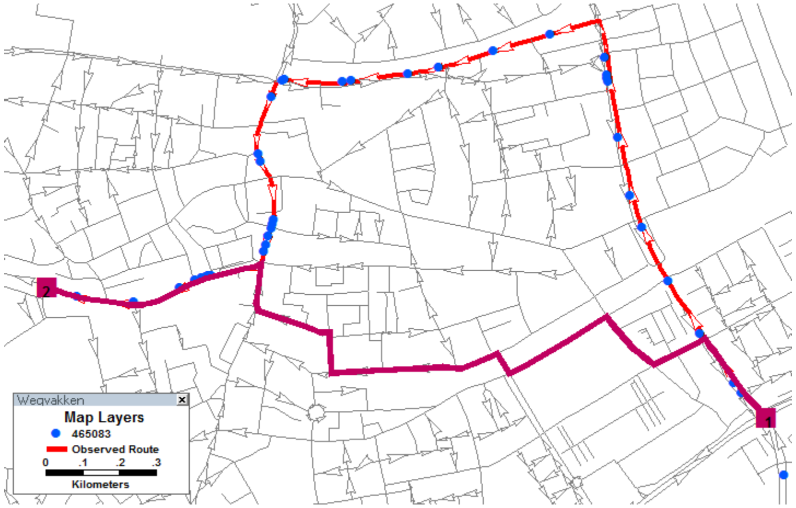

Figure B 71: Trip ID: 465083 Observed vs. Shortest Distance Route

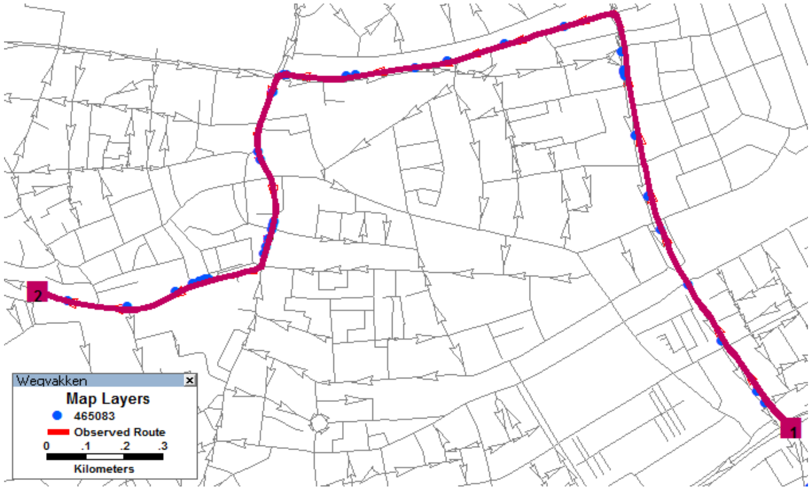

Figure B 72: Trip ID: 465083 Observed vs. Shortest Time Route

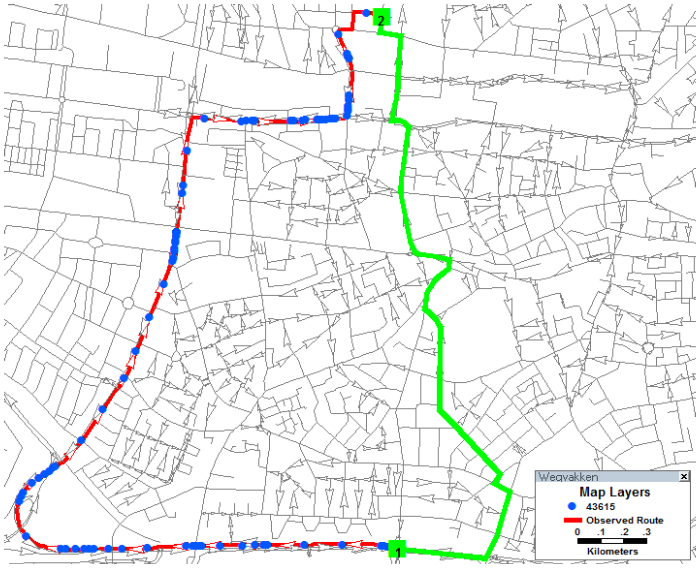

Figure B 73: Trip ID: 43615 Observed vs. Shortest Distance Route

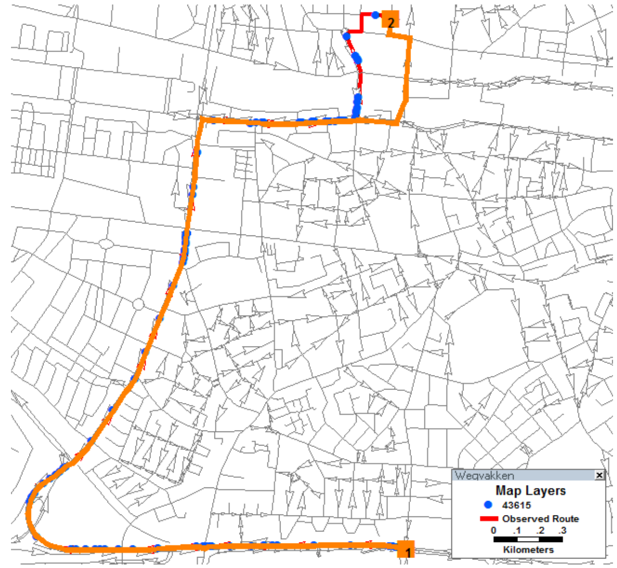

Figure B 74: Trip ID: 43615 Observed vs. Shortest Time Route

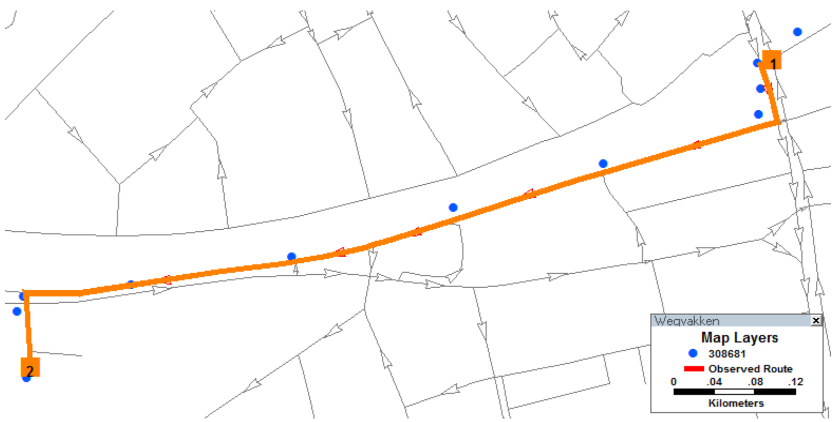

Figure B 75: Trip ID: 308681 Observed vs. Shortest Distance Route

Figure B 76: Trip ID: 308681 Observed vs. Shortest Time Route

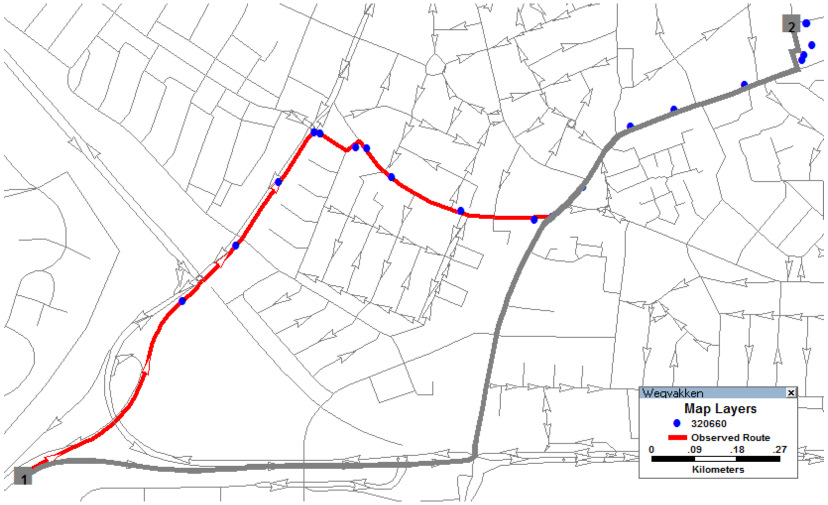

Figure B 77: Trip ID: 320660 Observed vs. Shortest Distance Route

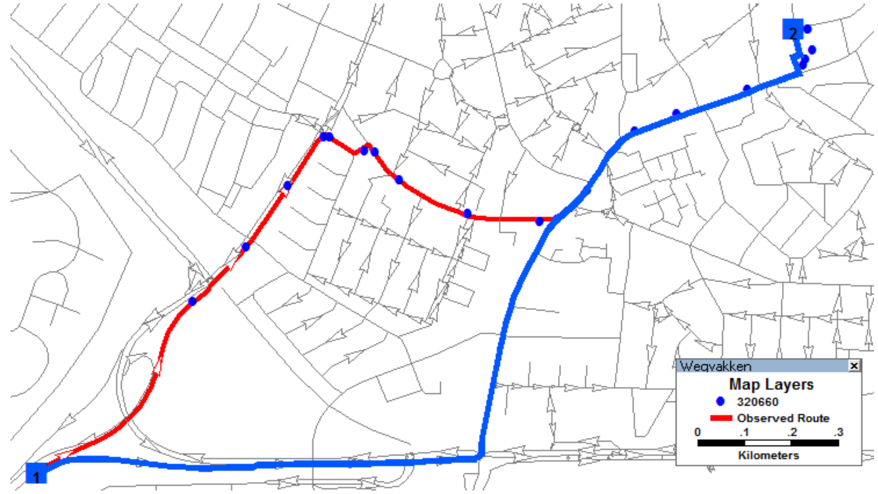

Figure B 78: Trip ID: 320660 Observed vs. Shortest Time Route

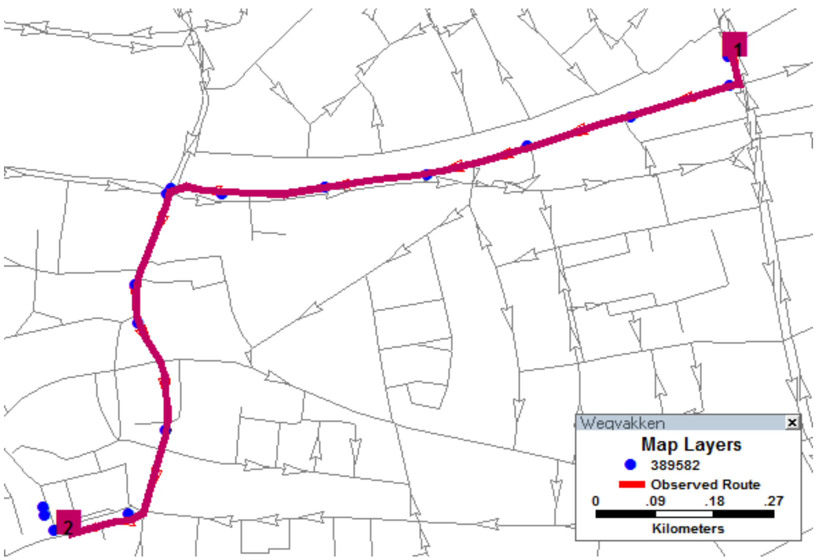

Figure B 79: Trip ID: 389582 Observed vs. Shortest Distance Route

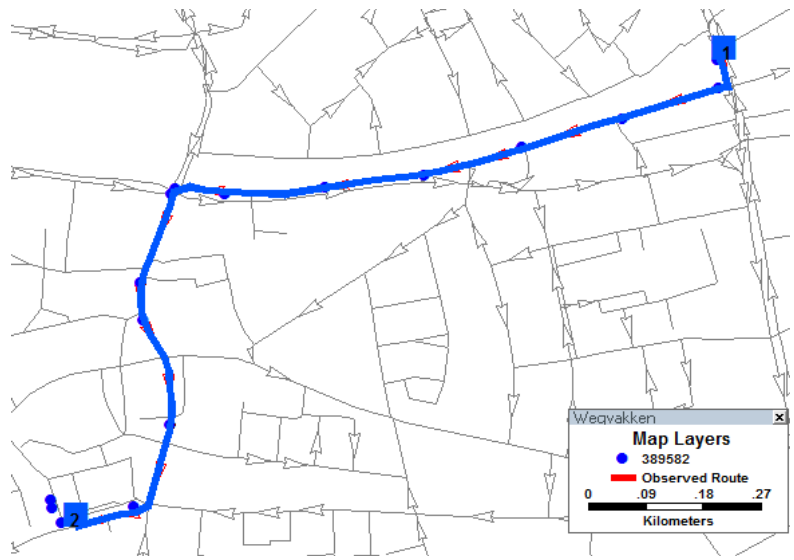

Figure B 80: Trip ID: 389582 Observed vs. Shortest Time Route

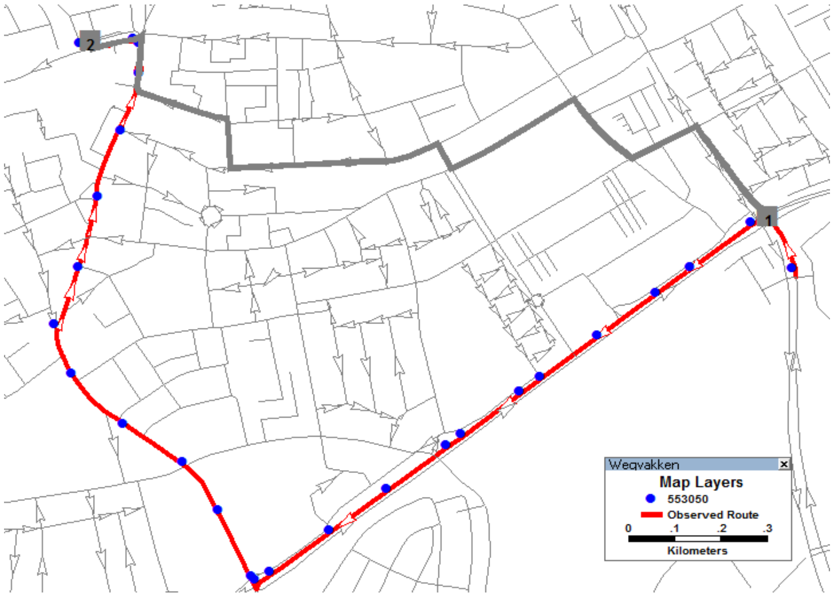

Figure B 81: Trip ID: 553050 Observed vs. Shortest Distance Route

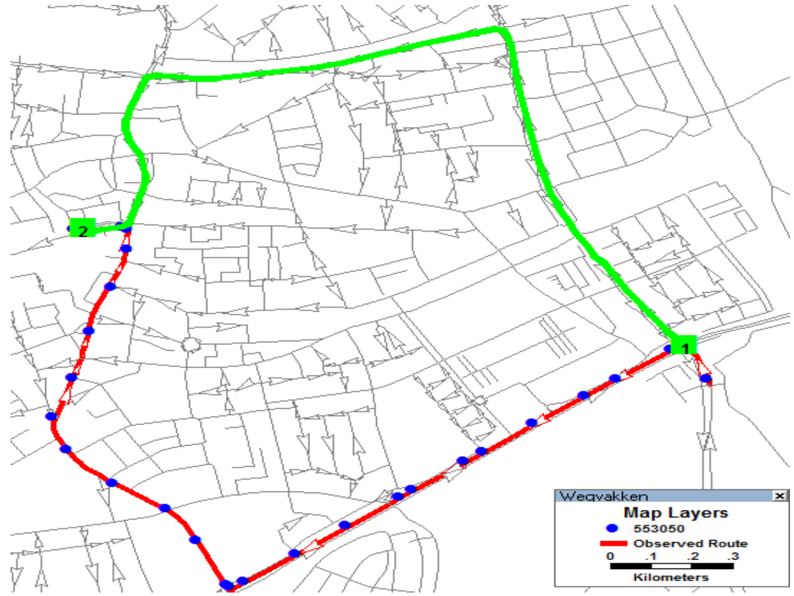

Figure B 82: Trip ID: 553050 Observed vs. Shortest Time Route

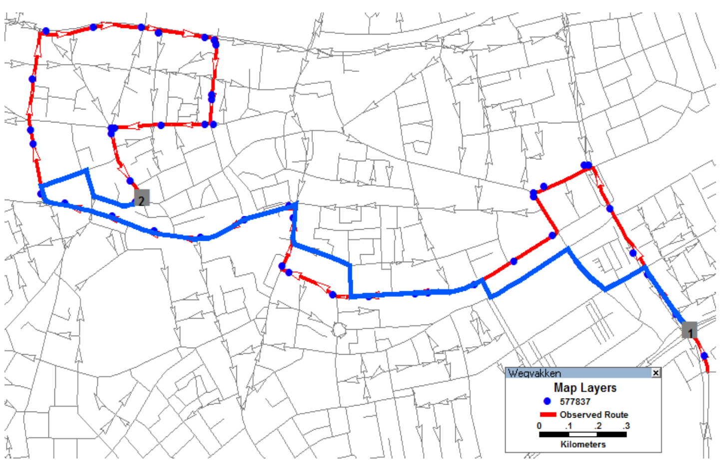

Figure B 83: Trip ID: 577837 Observed vs. Shortest Distance Route

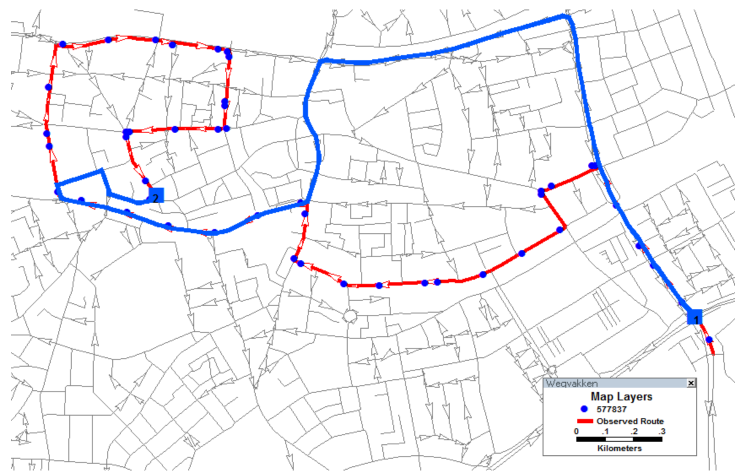

Figure B 84: Trip ID: 577837 Observed vs. Shortest Time Route

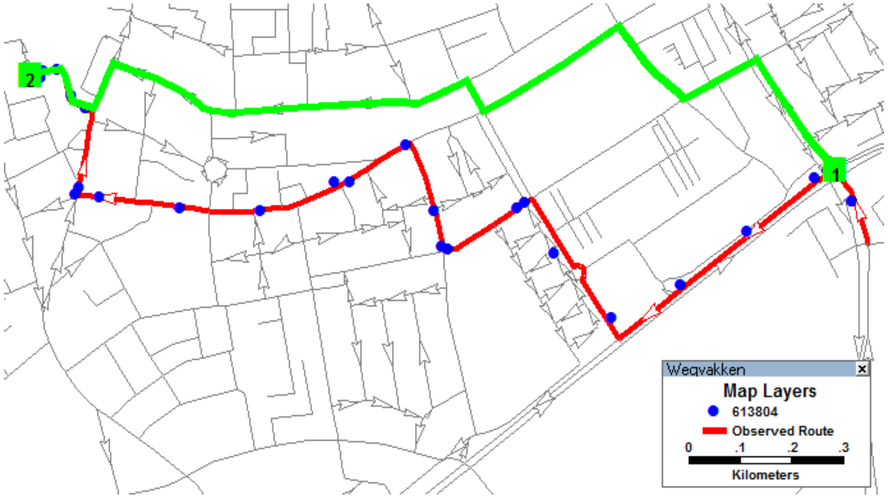

Figure B 85: Trip ID: 613804 Observed vs. Shortest Distance Route

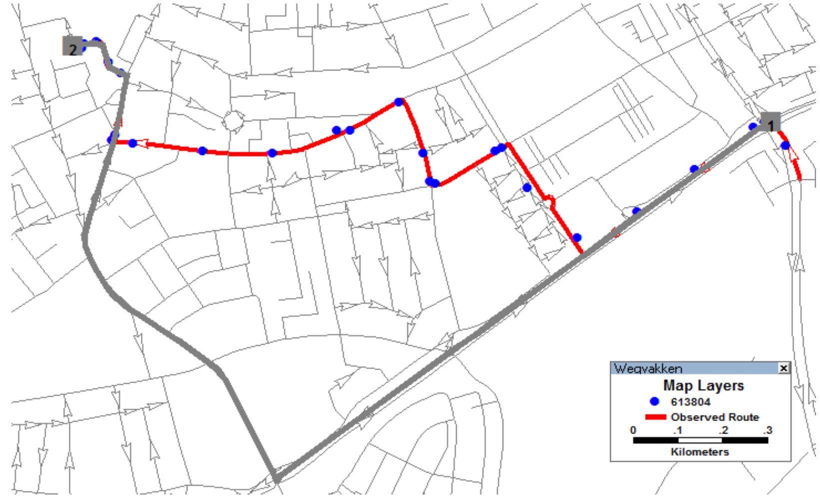

Figure B 86: Trip ID: 613804 Observed vs. Shortest Time Route

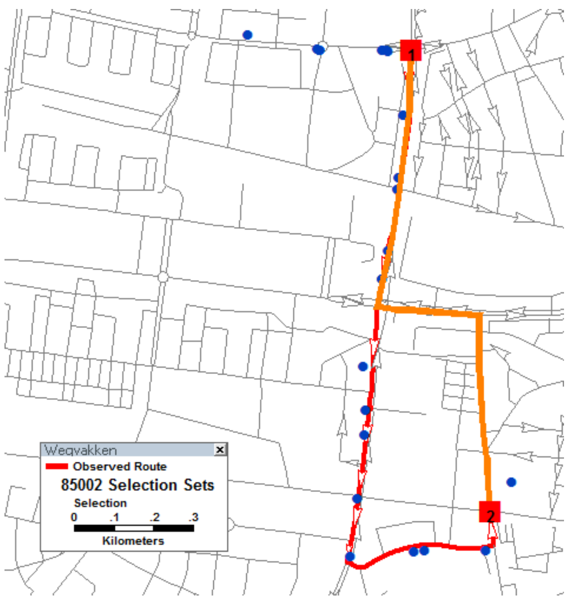

Figure B 87: Trip ID: 85002 Observed vs. Shortest Distance Route

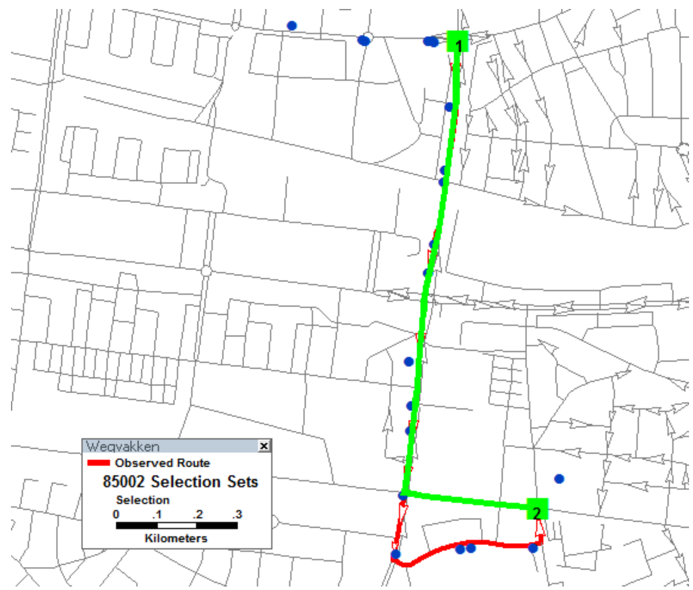

Figure B 88: Trip ID: 85002 Observed vs. Shortest Time Route

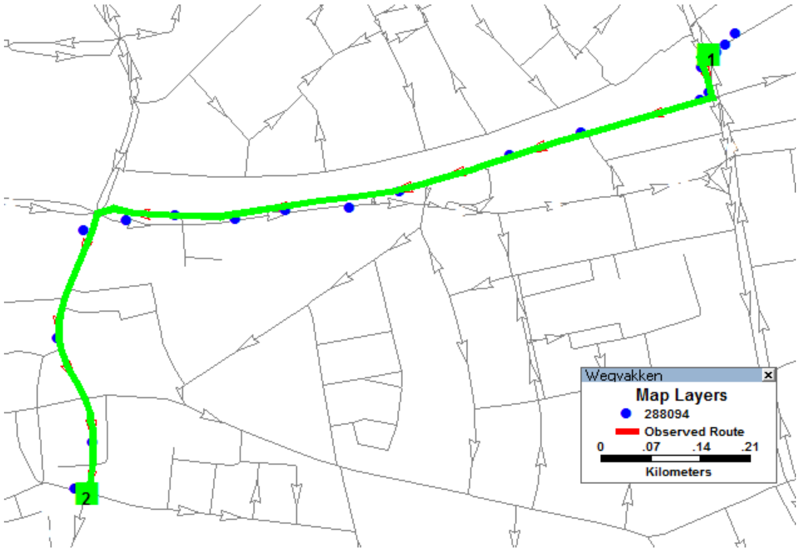

Figure B 89: Trip ID: 288094 Observed vs. Shortest Distance Route

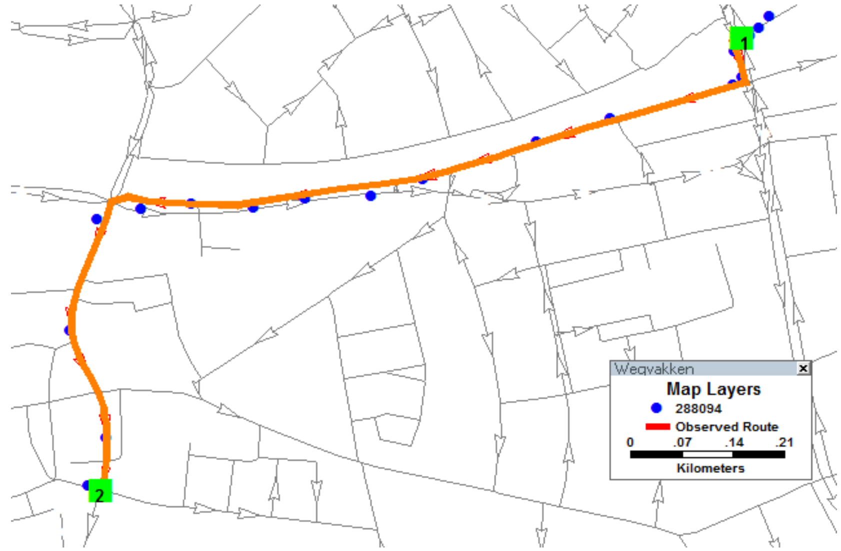

Figure B 90: Trip ID: 288094 Observed vs. Shortest Time Route

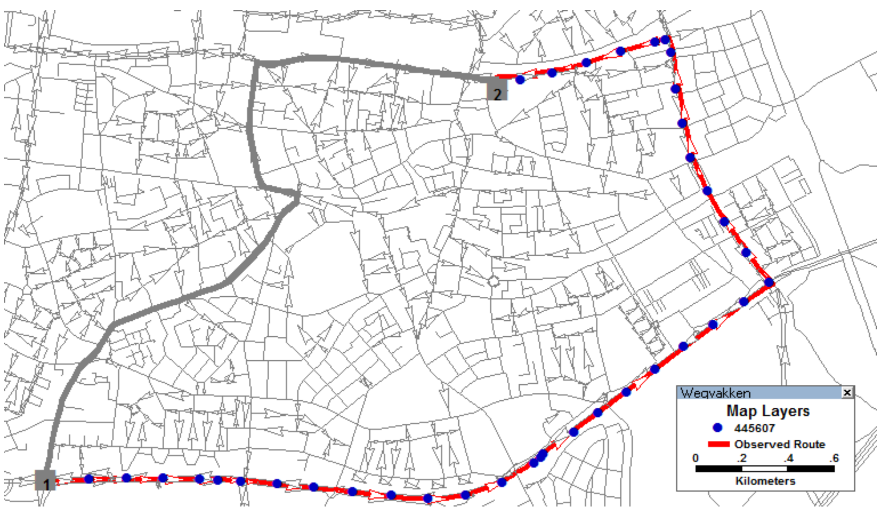

Figure B 91: Trip ID: 445607 Observed vs. Shortest Distance Route

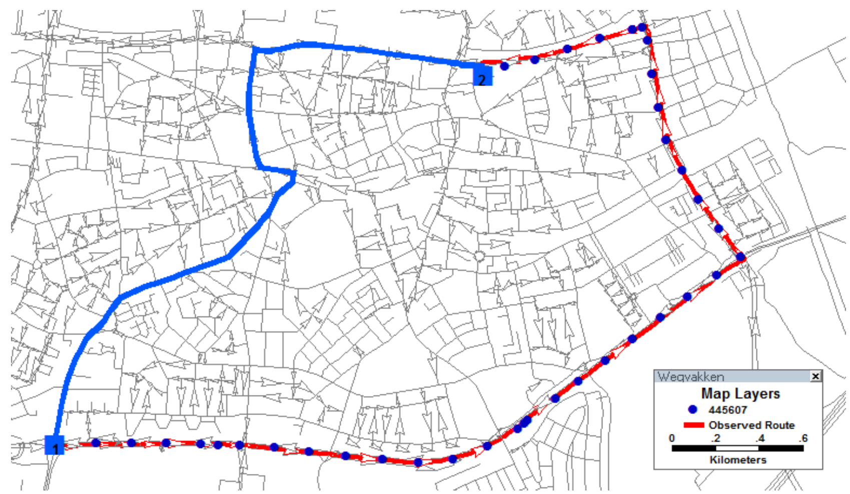

Figure B 92: Trip ID: 445607 Observed vs. Shortest Time Route

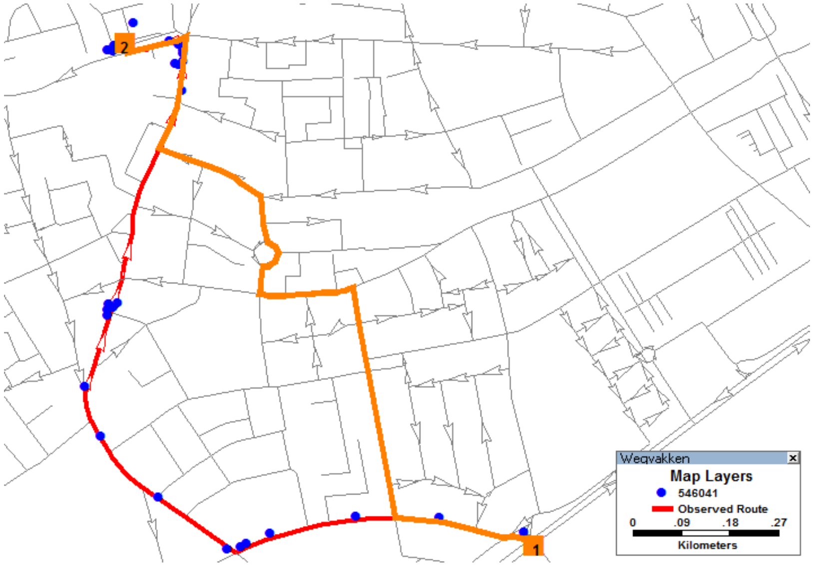

Figure B 93: Trip ID: 546041 Observed vs. Shortest Distance Route

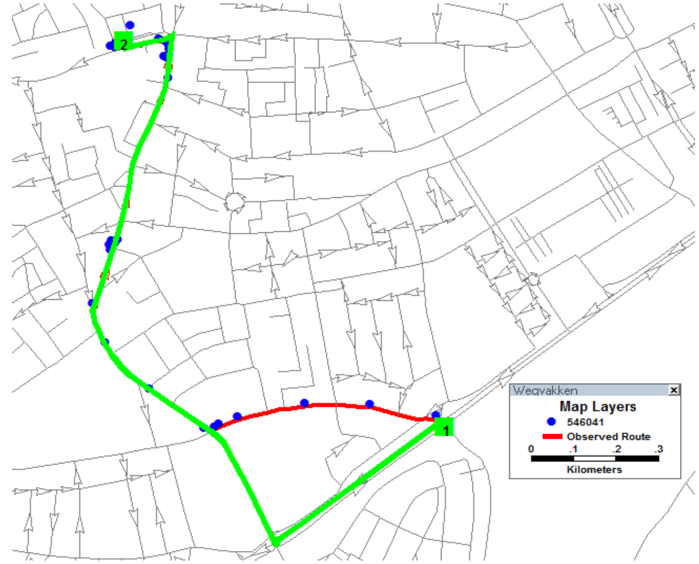

Figure B 94: Trip ID: 546041 Observed vs. Shortest Time Route

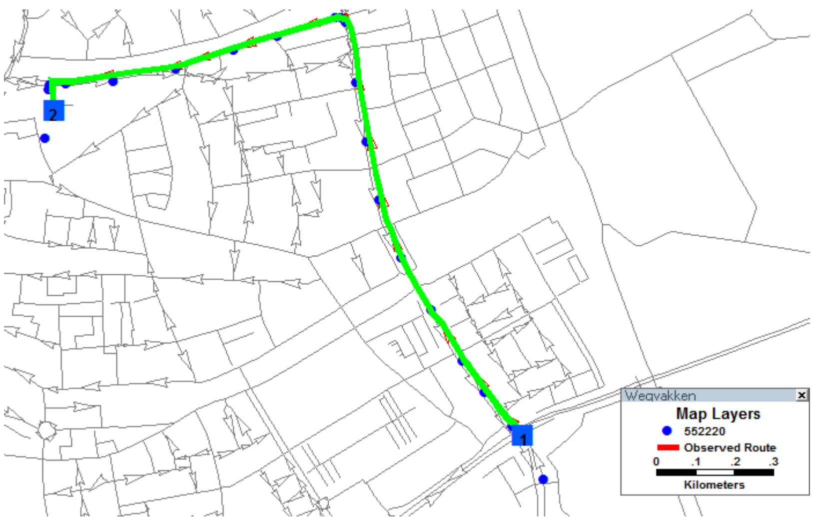

Figure B 95: Trip ID: 552220 Observed vs. Shortest Distance Route

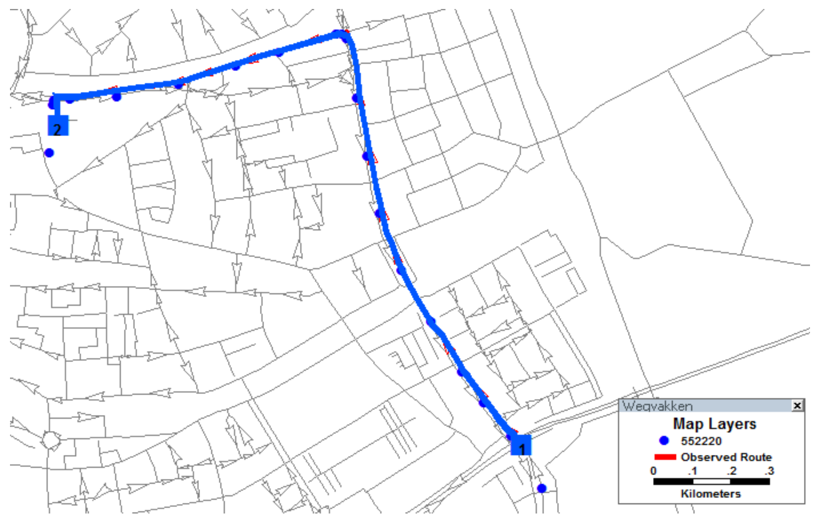

Figure B 96: Trip ID: 552220 Observed vs. Shortest Time Route

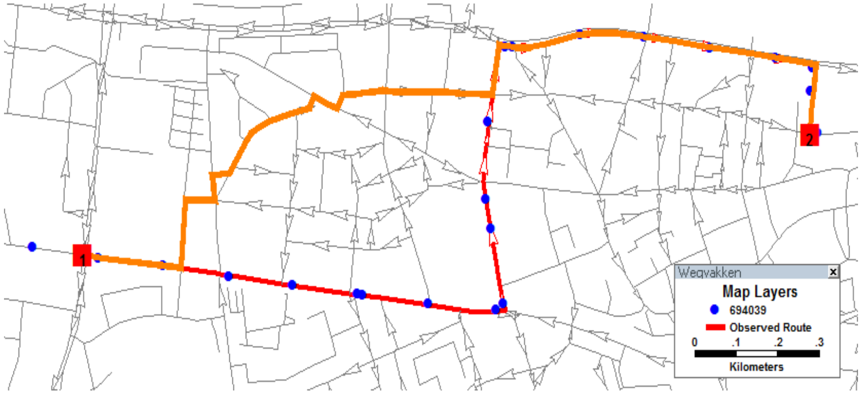

Figure B 97: Trip ID: 694039 Observed vs. Shortest Distance Route

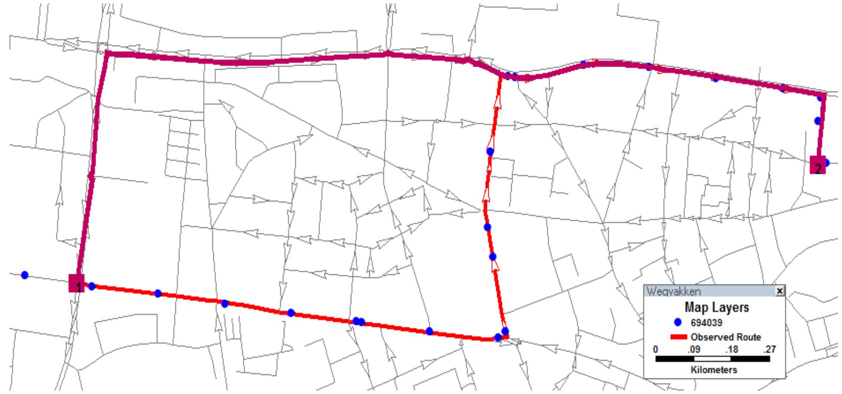

Figure B 98: Trip ID: 694039 Observed vs. Shortest Time Route

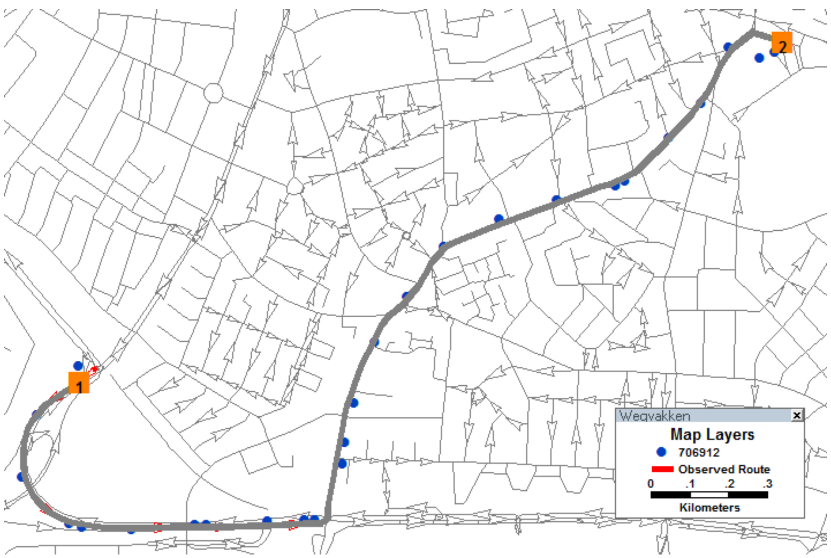

Figure B 99: Trip ID: 706912 Observed vs. Shortest Distance Route

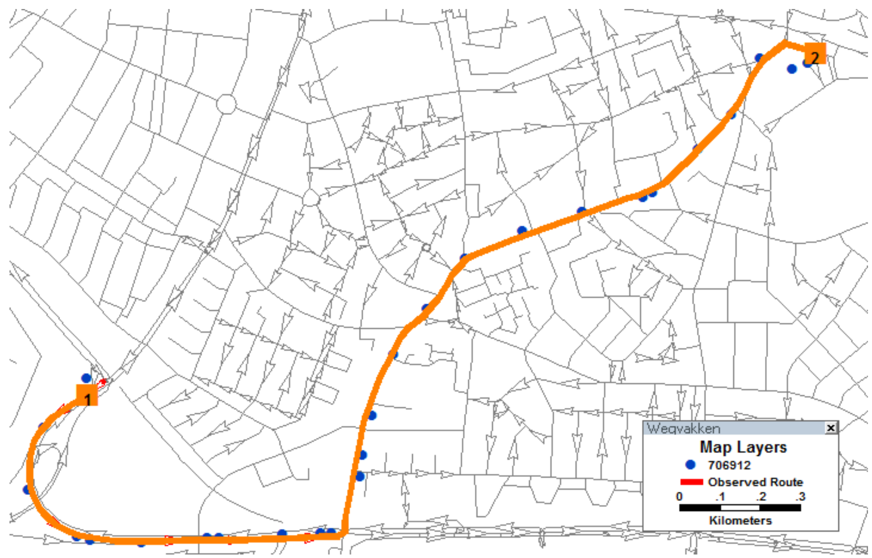

Figure B 100: Trip ID: 706912 Observed vs. Shortest Time Route

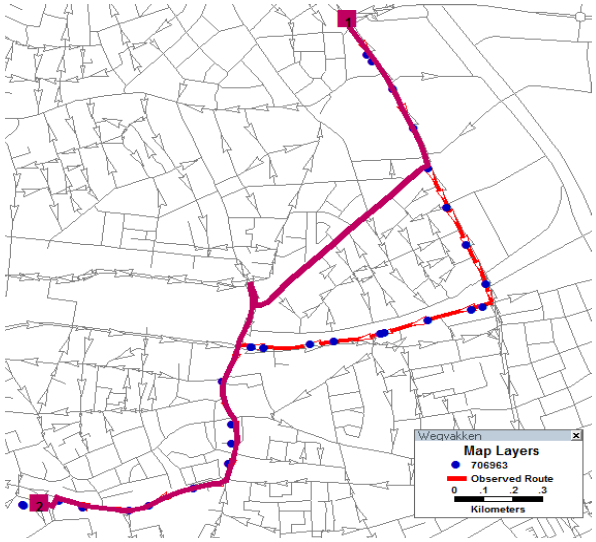

Figure B 101: Trip ID: 706963 Observed vs. Shortest Distance Route

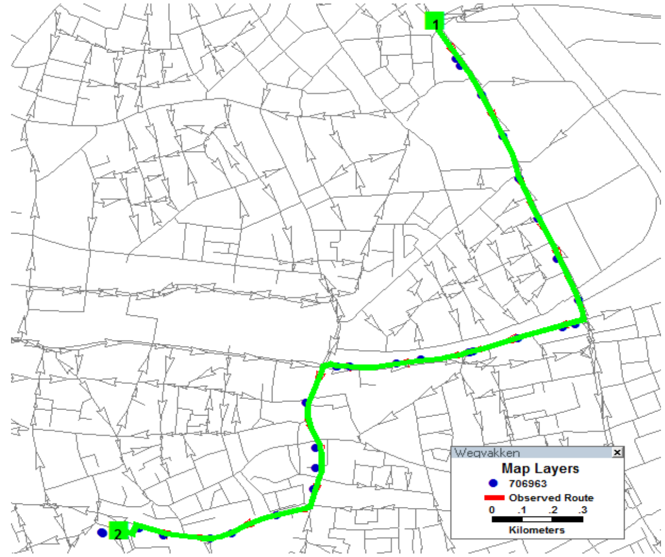

Figure B 102: Trip ID: 706963 Observed vs. Shortest Time Route

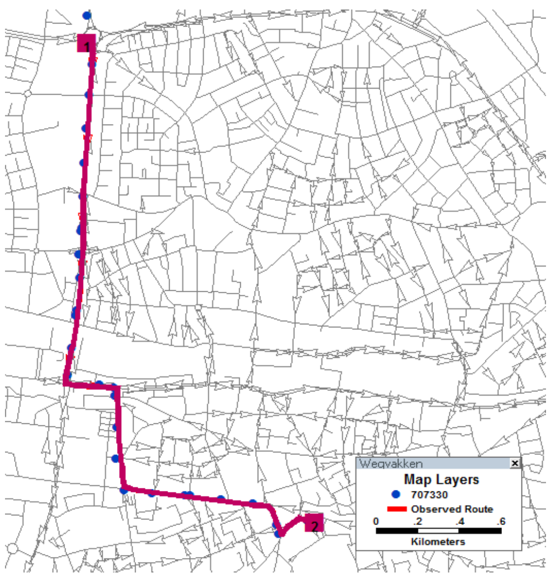

Figure B 103: Trip ID: 707330 Observed vs. Shortest Distance Route

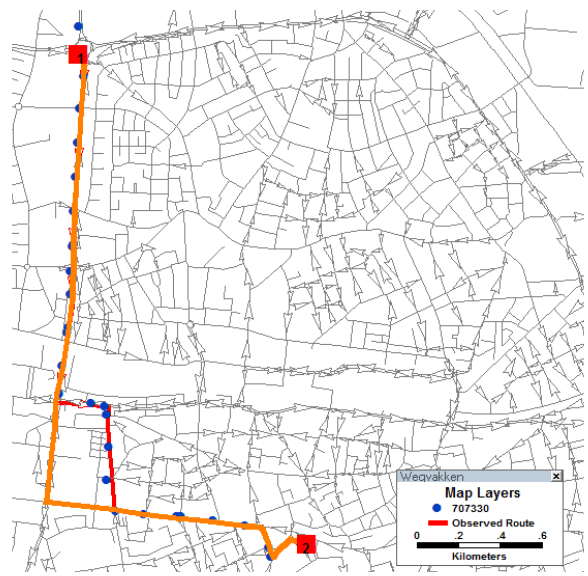

Figure B 104: Trip ID: 707330 Observed vs. Shortest Time Route

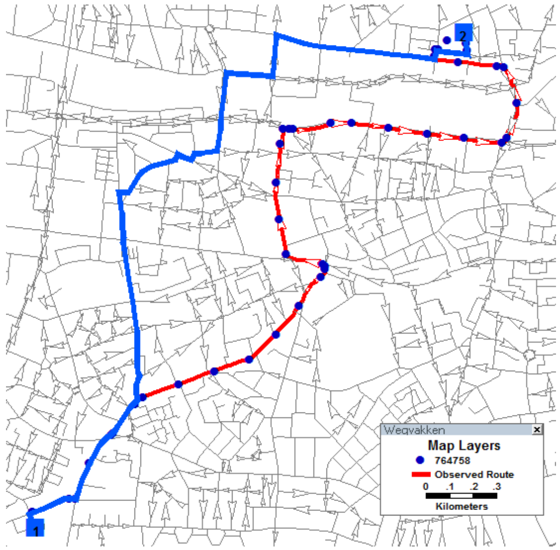

Figure B 105: Trip ID: 764758 Observed vs. Shortest Distance Route

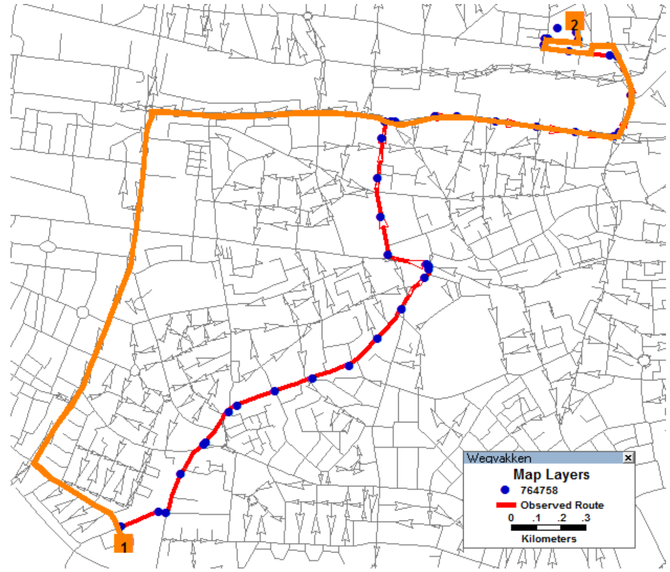

Figure B 106: Trip ID: 764758 Observed vs. Shortest Time Route

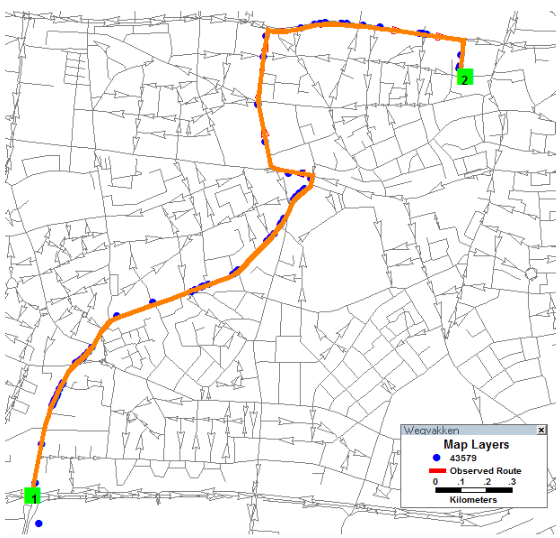

Figure B 107: Trip ID: 43579 Observed vs. Shortest Distance Route

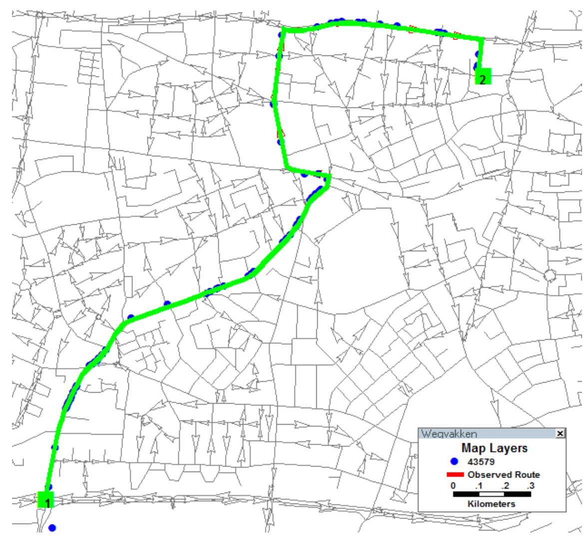

Figure B 108: Trip ID: 43579 Observed vs. Shortest Time Route

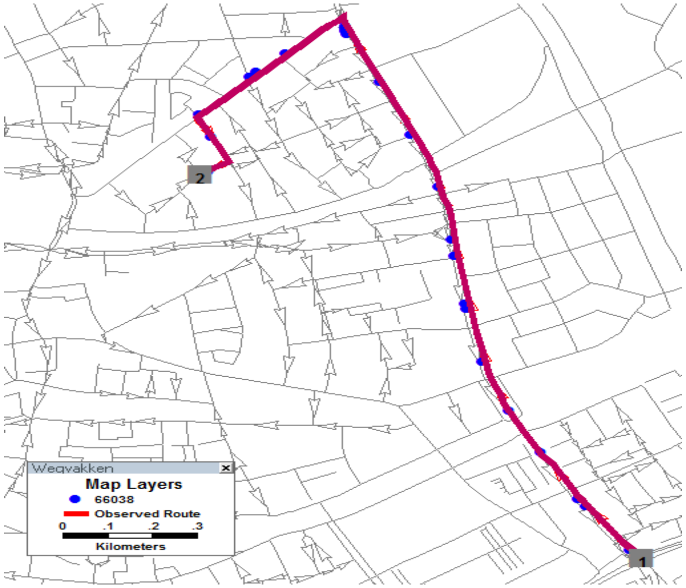

Figure B 109: Trip ID: 66038 Observed vs. Shortest Distance Route

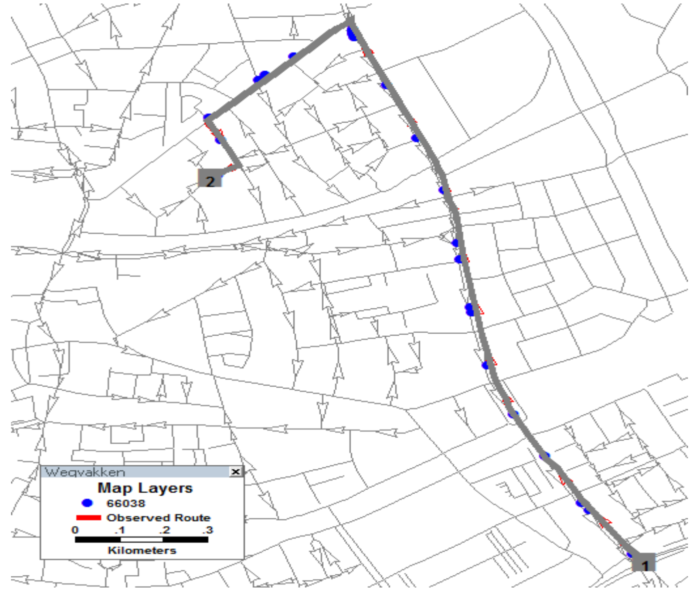

Figure B 110: Trip ID: 66038 Observed vs. Shortest Time Route

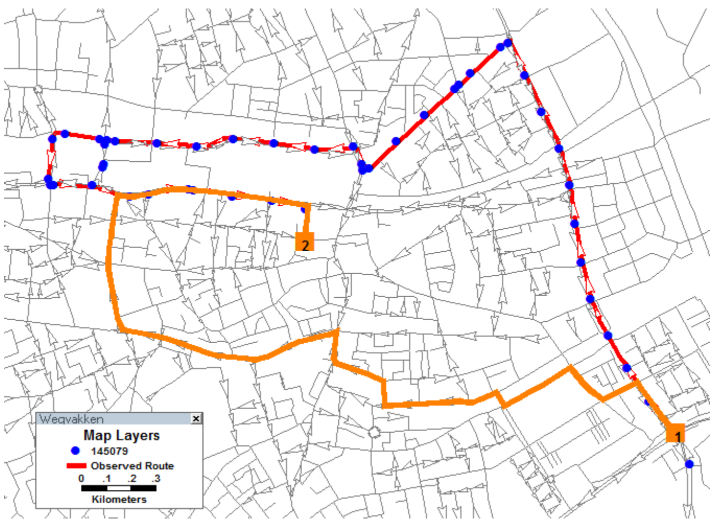

Figure B 111: Trip ID: 145079 Observed vs. Shortest Distance Route

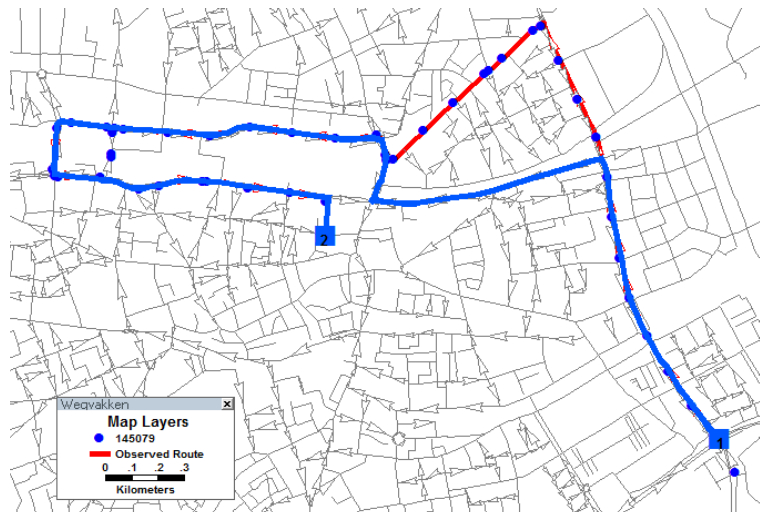

Figure B 112: Trip ID: 145079 Observed vs. Shortest Time Route

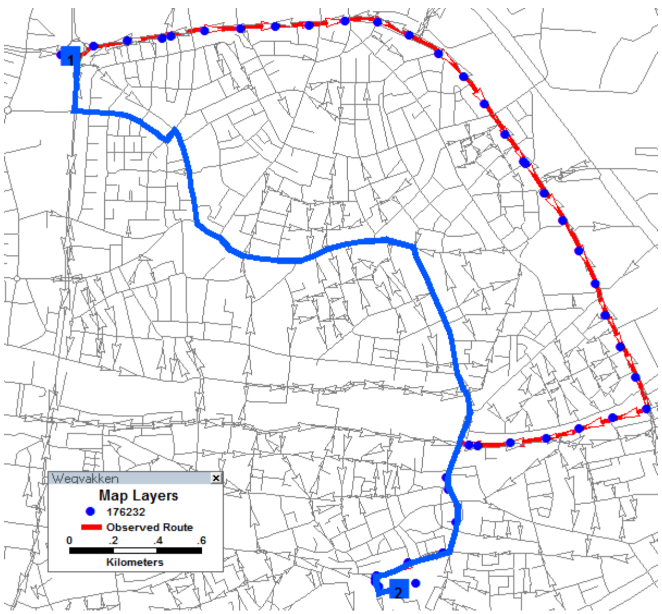

Figure B 113: Trip ID: 176232 Observed vs. Shortest Distance Route

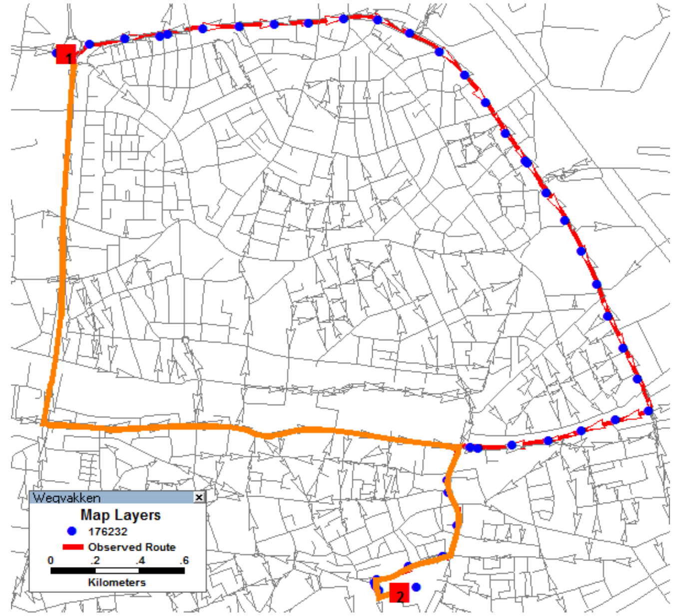

Figure B 114: Trip ID: 176232 Observed vs. Shortest Time Route

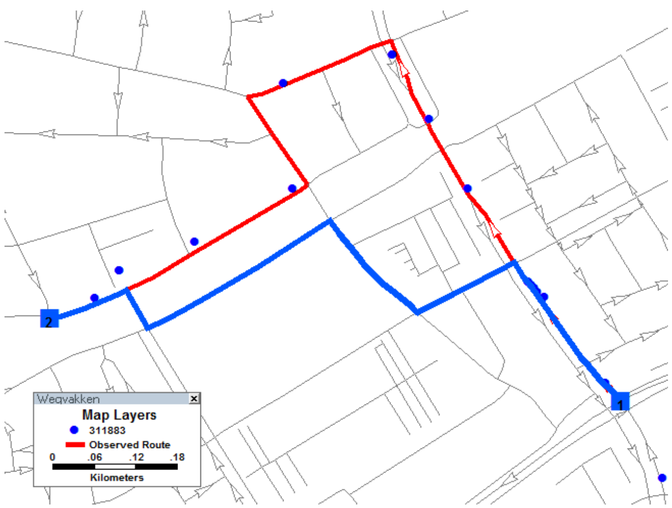

Figure B 115: Trip ID: 311883 Observed vs. Shortest Distance Route

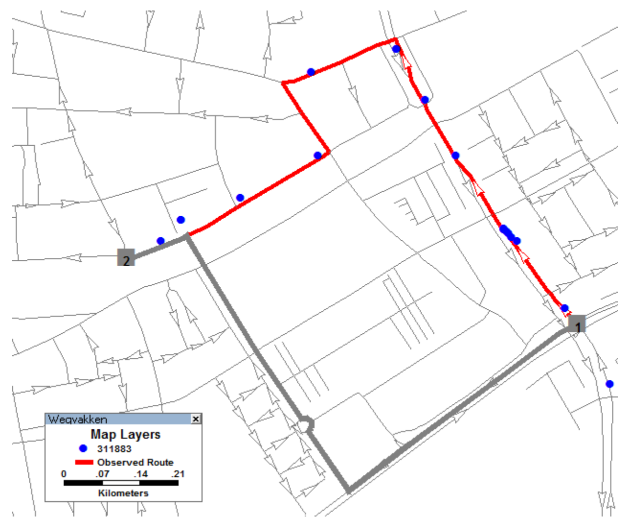

Figure B 116: Trip ID: 311883 Observed vs. Shortest Time Route

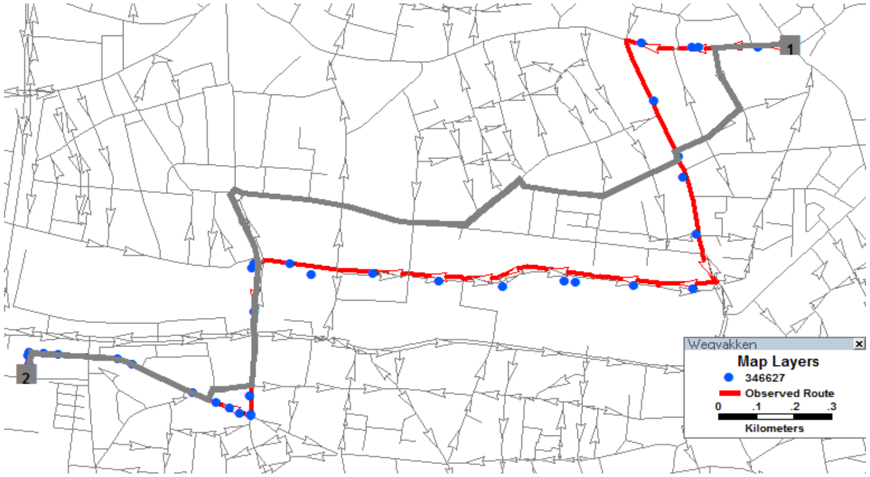

Figure B 117: Trip ID: 346627 Observed vs. Shortest Distance Route

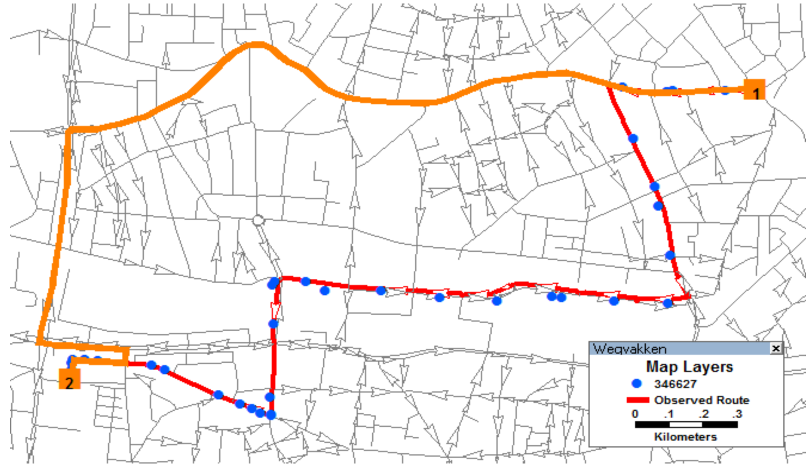

Figure B 118: Trip ID: 346627 Observed vs. Shortest Time Route

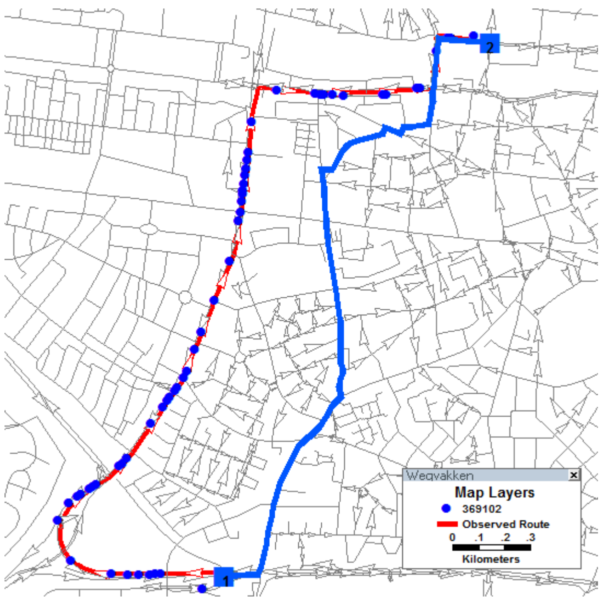

Figure B 119: Trip ID: 369102 Observed vs. Shortest Distance Route

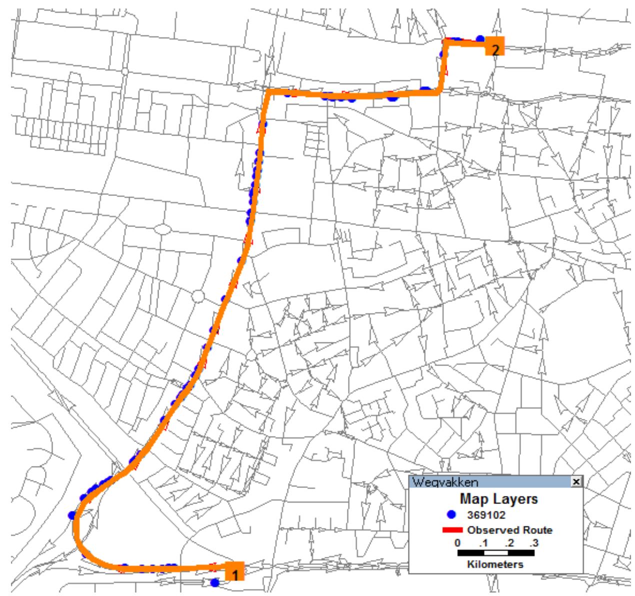

Figure B 120: Trip ID: 369102 Observed vs. Shortest Time Route

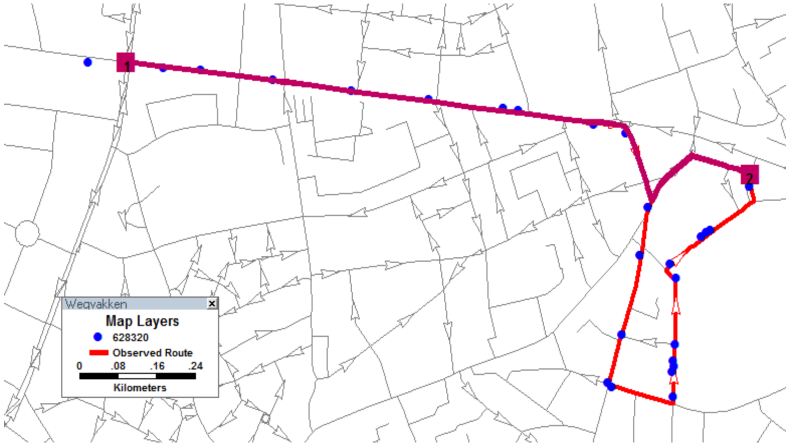

Figure B 121: Trip ID: 628320 Observed vs. Shortest Distance Route

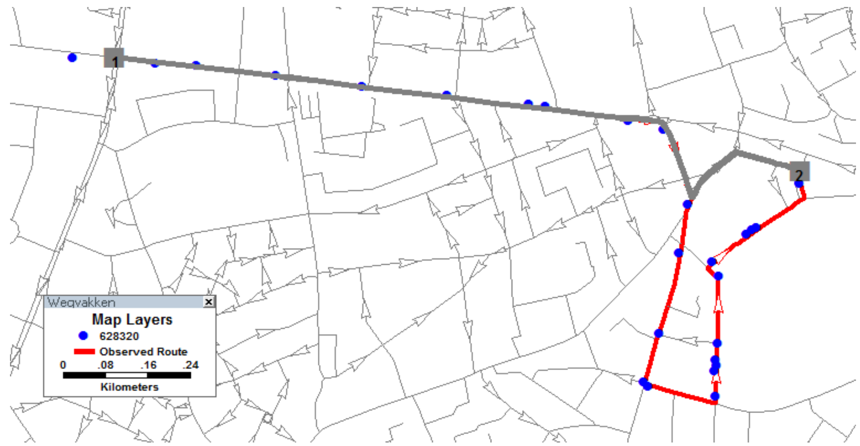

Figure B 122: Trip ID: 628320 Observed vs. Shortest Time Route

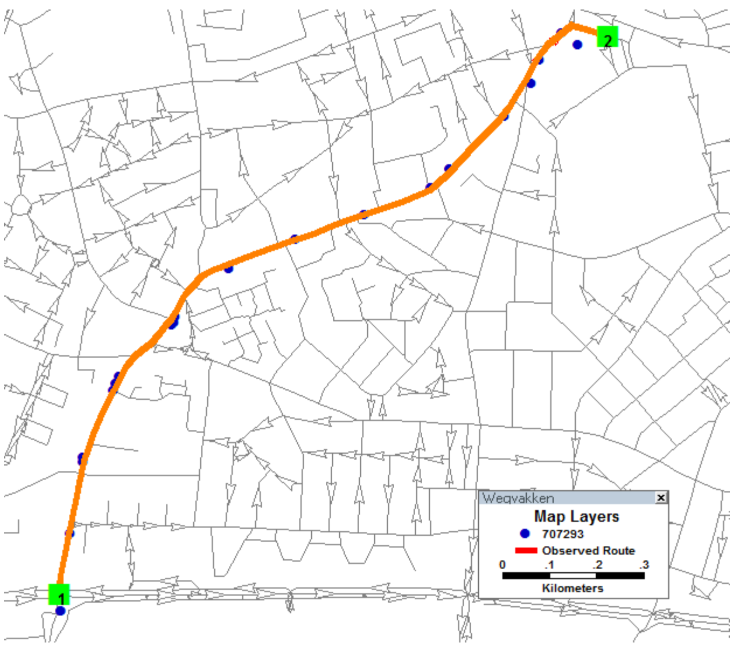

Figure B 123: Trip ID: 707293 Observed vs. Shortest Distance Route

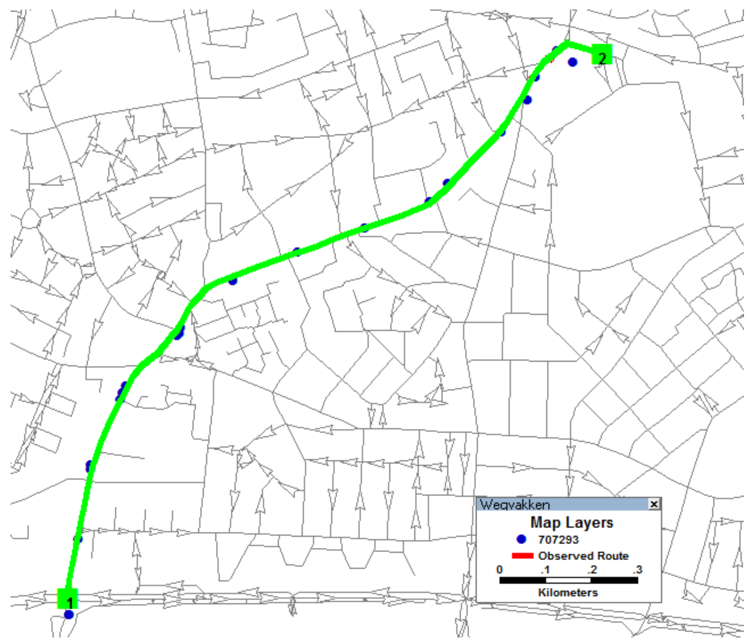

Figure B 124: Trip ID: 707293 Observed vs. Shortest Time Route

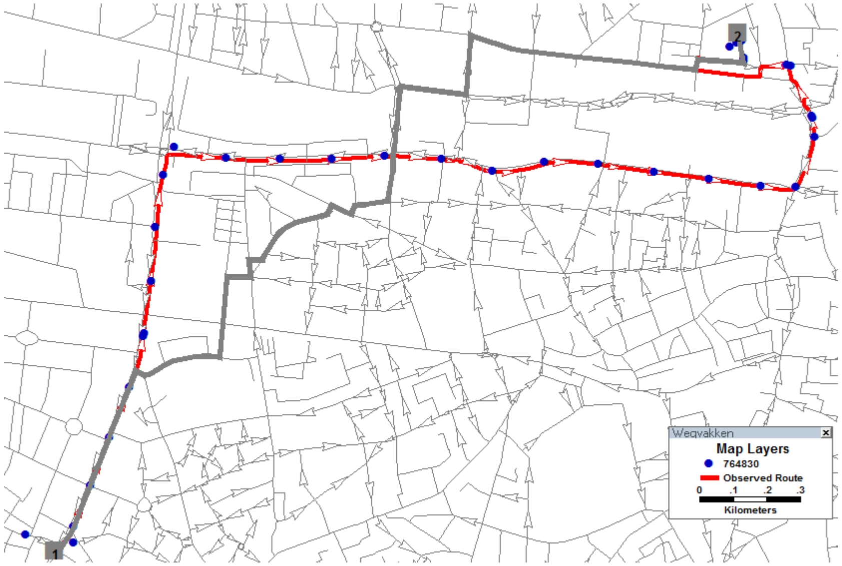

Figure B 125: Trip ID: 764830 Observed vs. Shortest Distance Route

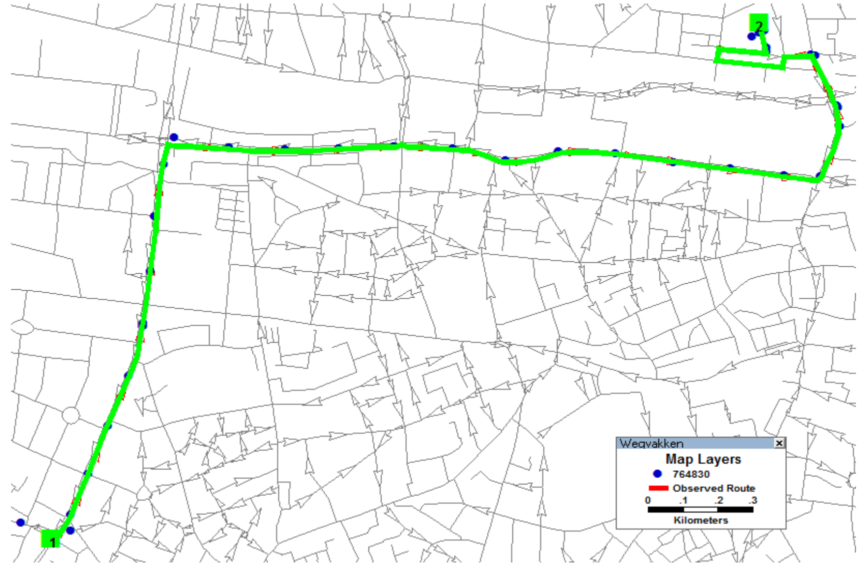

Figure B 126: Trip ID: 764830 Observed vs. Shortest Time Route

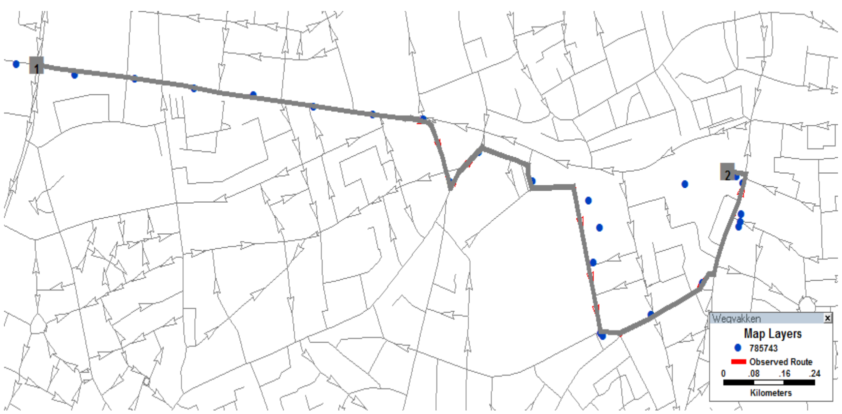

Figure B 127: Trip ID: 785743 Observed vs. Shortest Distance Route

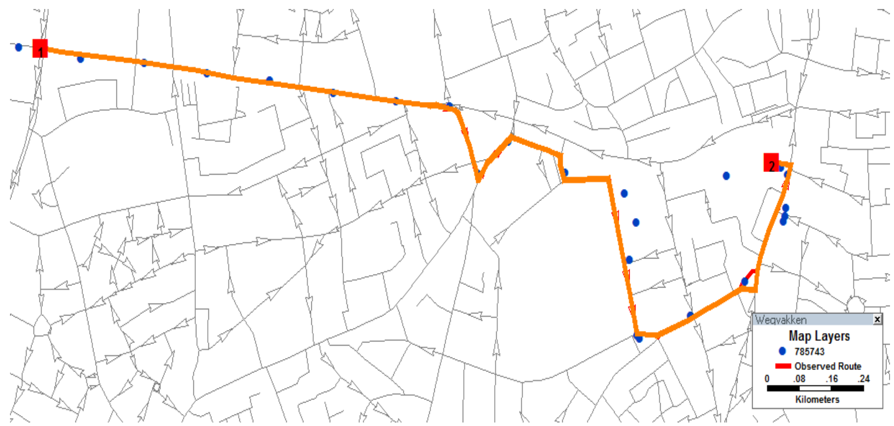

Figure B 128: Trip ID: 785743 Observed vs. Shortest Time Route

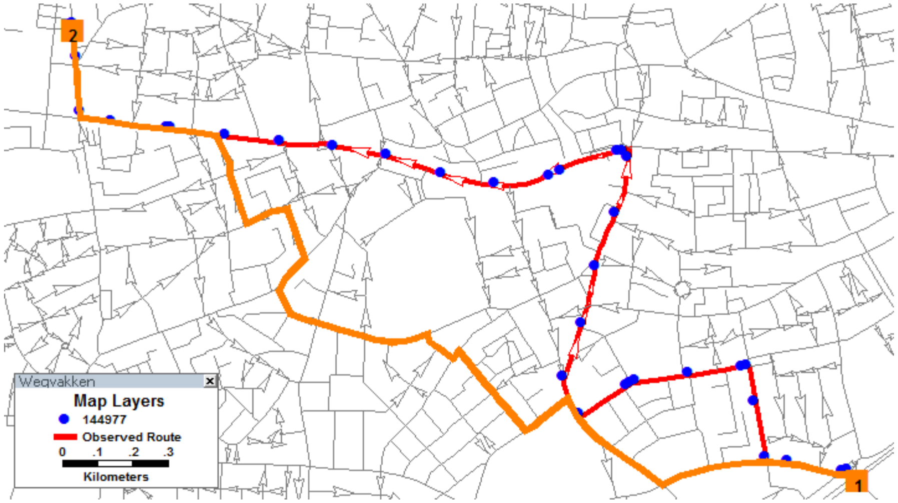

Figure B 129: Trip ID: 144997 Observed vs. Shortest Distance Route

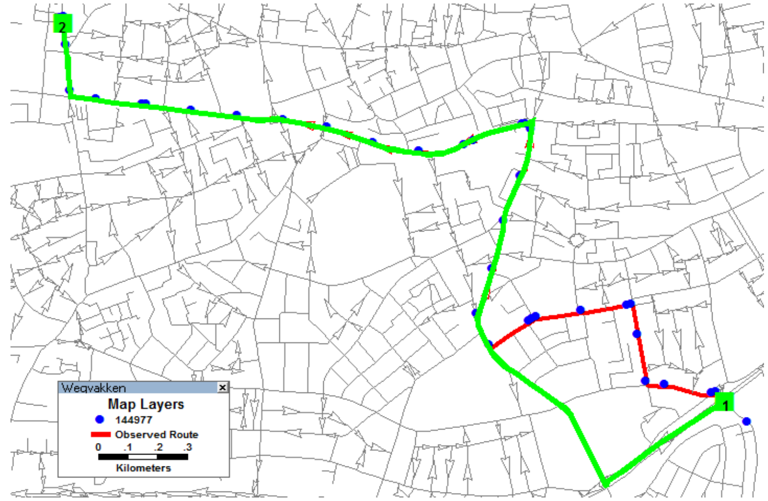

Figure B 130: Trip ID: 144997 Observed vs. Shortest Time Route

Figure B 131: Trip ID: 169286 Observed vs. Shortest Distance Route

Figure B 132: Trip ID: 169286 Observed vs. Shortest Time Route

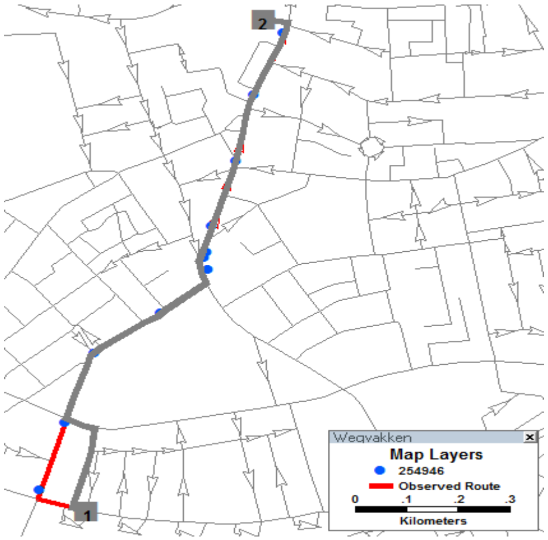

Figure B 133: Trip ID: 254946 Observed vs. Shortest Distance Route

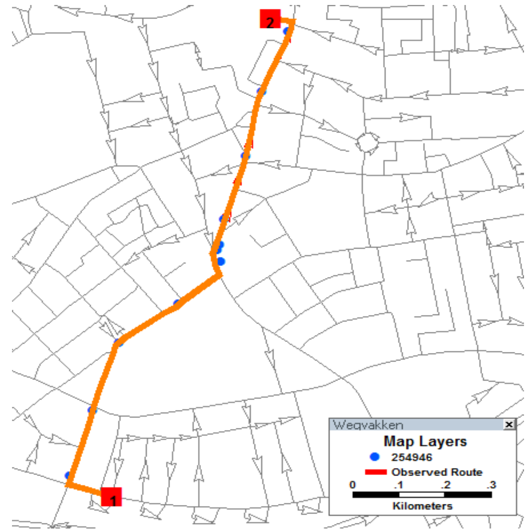

Figure B 134: Trip ID: 254946 Observed vs. Shortest Time Route

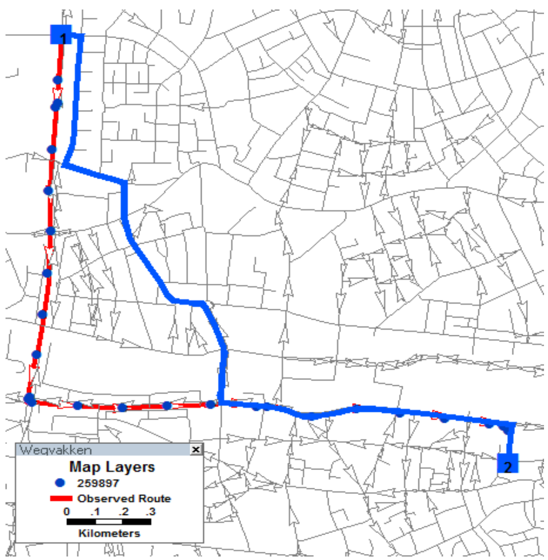

Figure B 135: Trip ID: 259897 Observed vs. Shortest Distance Route

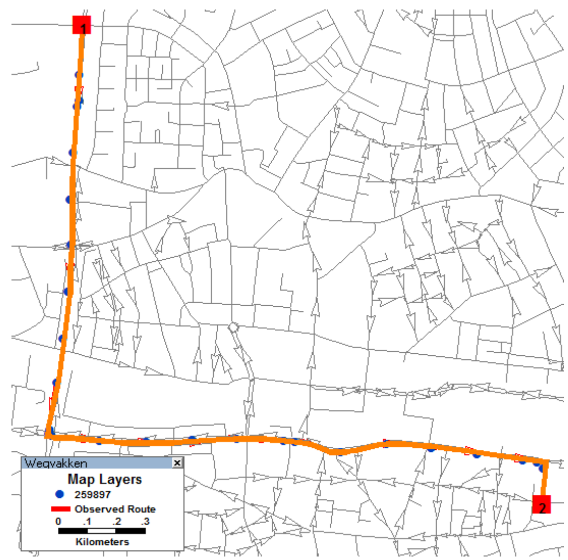

Figure B 136: Trip ID: 259897 Observed vs. Shortest Time Route

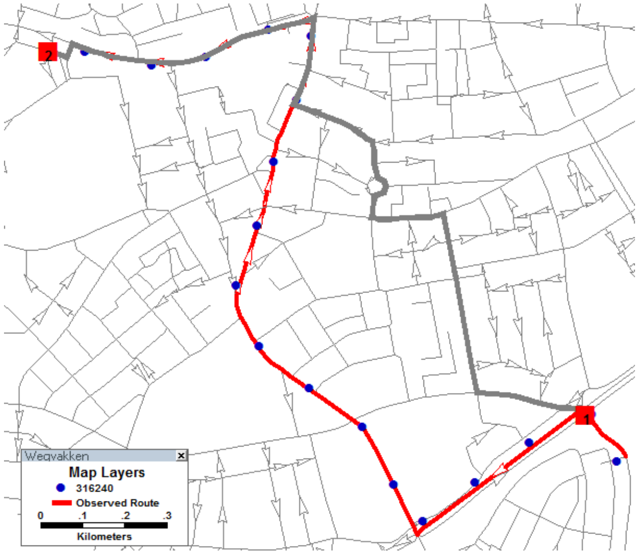

Figure B 137: Trip ID: 316240 Observed vs. Shortest Distance Route

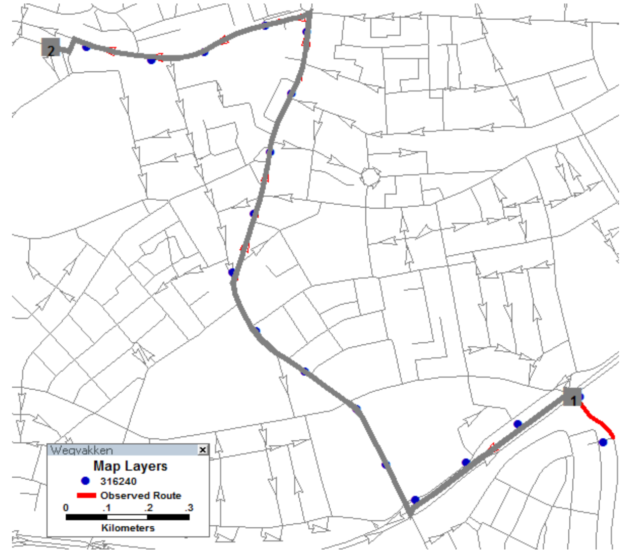

Figure B 138: Trip ID: 316240 Observed vs. Shortest Time Route

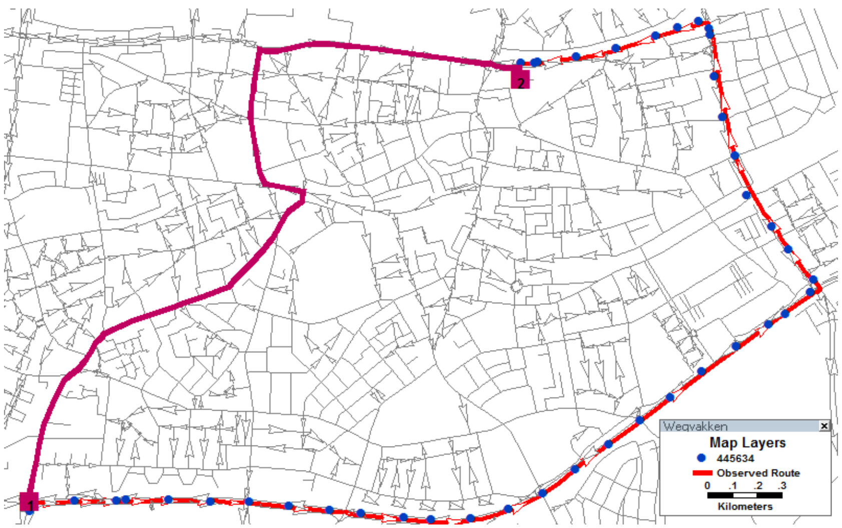

Figure B 139: Trip ID: 445634 Observed vs. Shortest Distance Route

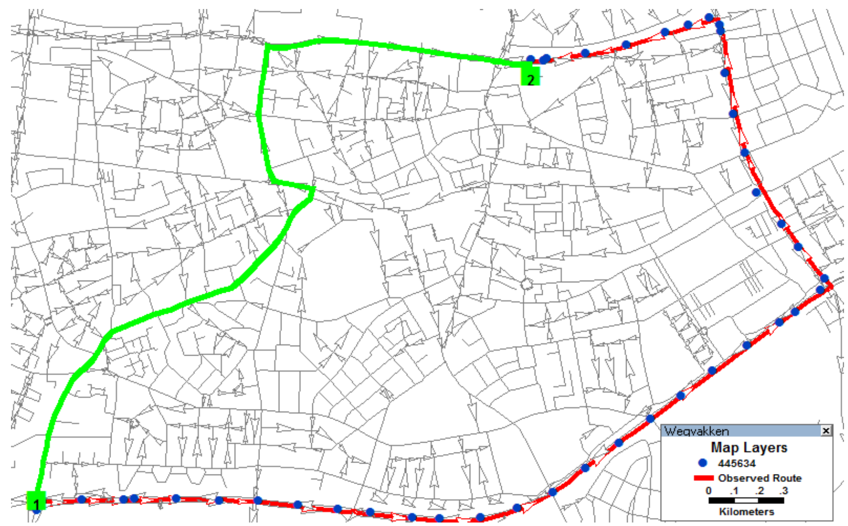

Figure B 140: Trip ID: 445634 Observed vs. Shortest Time Route

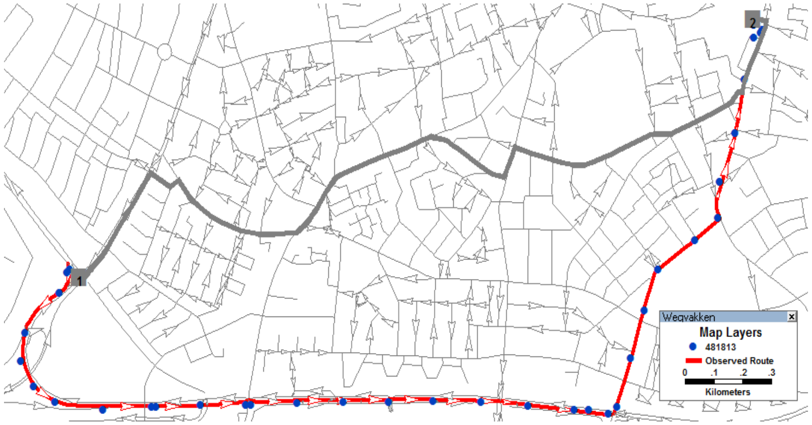

Figure B 141: Trip ID: 481813 Observed vs. Shortest Distance Route

Figure B 142: Trip ID: 481813 Observed vs. Shortest Time Route

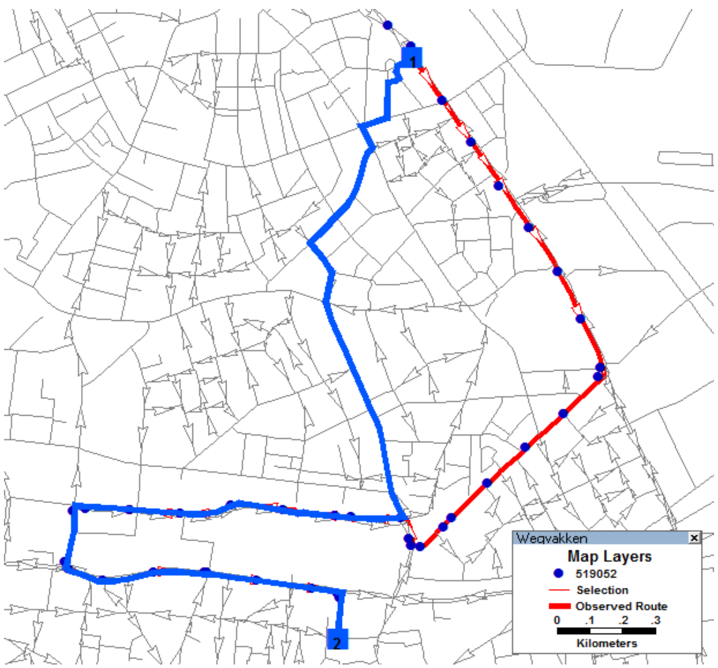

Figure B 143: Trip ID: 519052 Observed vs. Shortest Distance Route

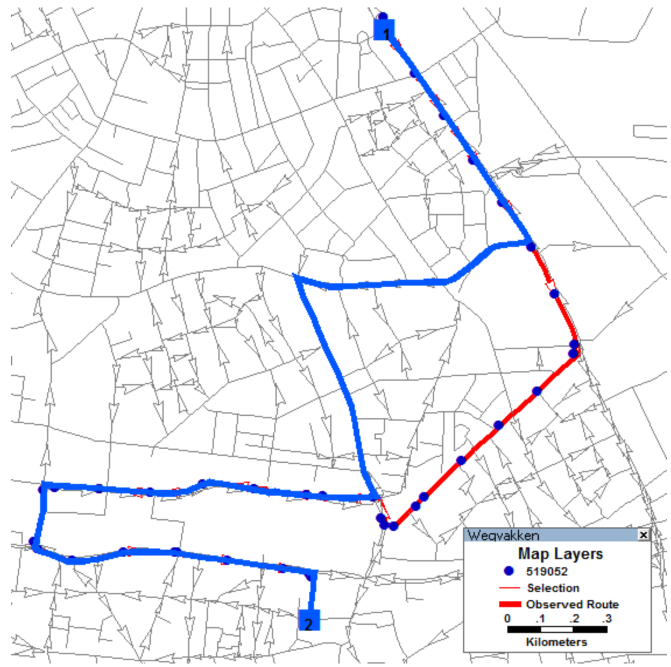

Figure B 144: Trip ID: 519052 Observed vs. Shortest Time Route

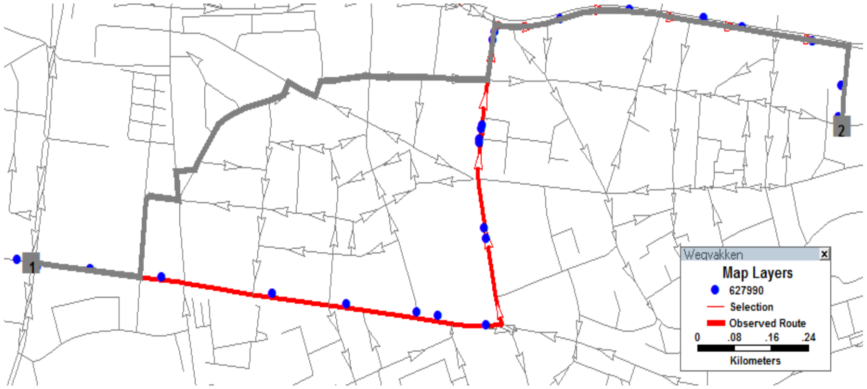

Figure B 145: Trip ID: 627990 Observed vs. Shortest Distance Route

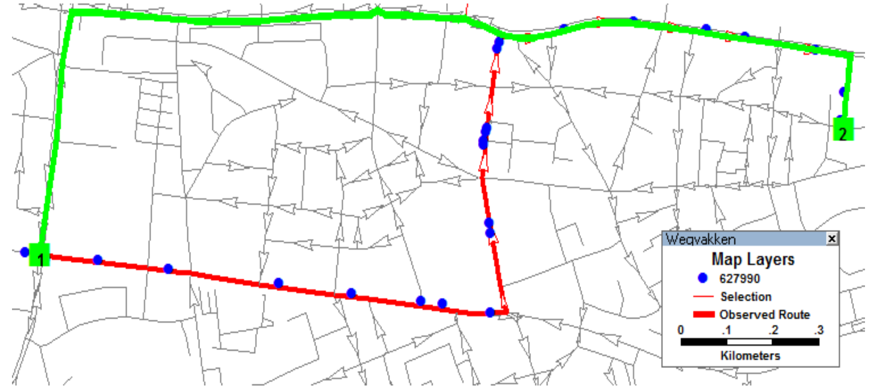

Figure B 146: Trip ID: 627990 Observed vs. Shortest Time Route

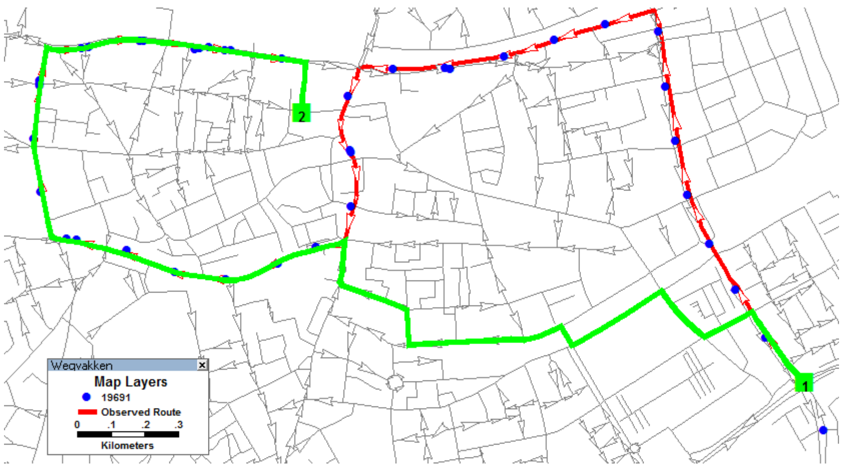

Figure B 147: Trip ID: 19691 Observed vs. Shortest Distance Route

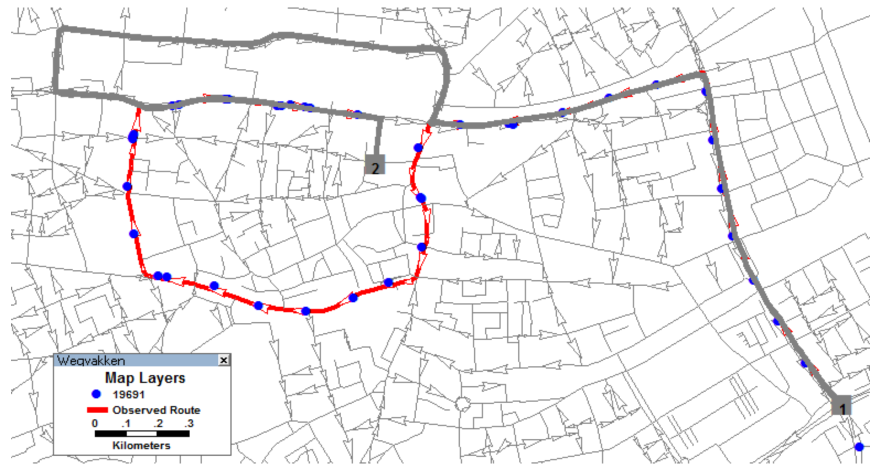

Figure B 148: Trip ID: 19691 Observed vs. Shortest Time Route

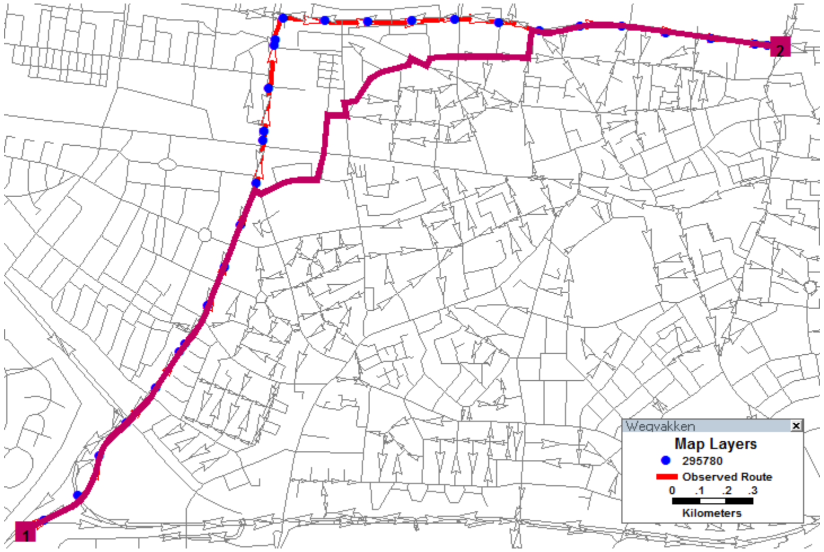

Figure B 149: Trip ID: 295780 Observed vs. Shortest Distance Route

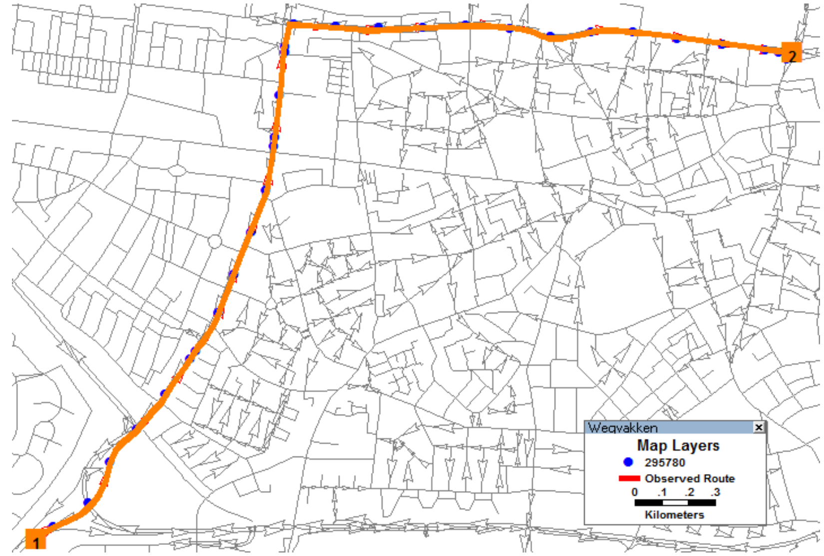

Figure B 150: Trip ID: 295780 Observed vs. Shortest Time Route

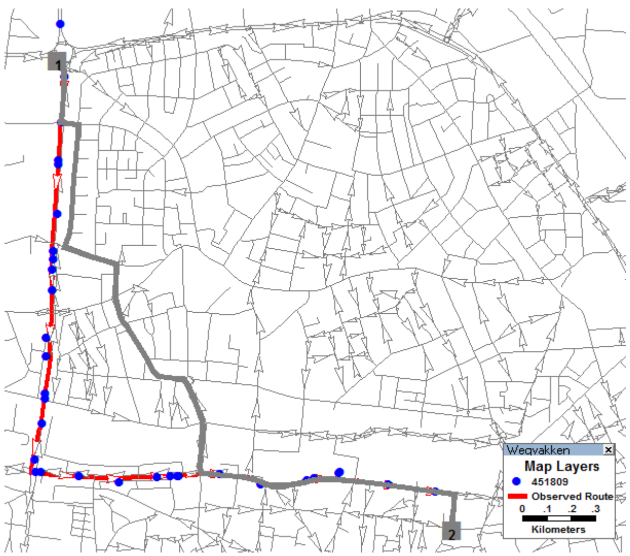

Figure B 151: Trip ID: 451809 Observed vs. Shortest Distance Route

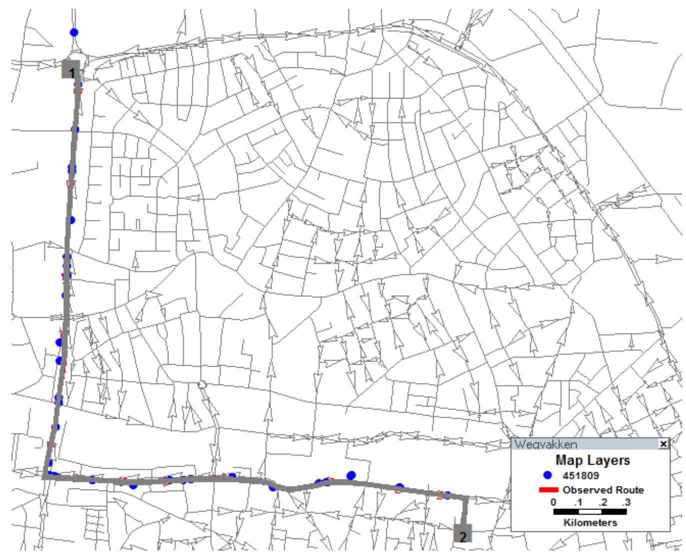

Figure B 152: Trip ID: 451809 Observed vs. Shortest Time Route

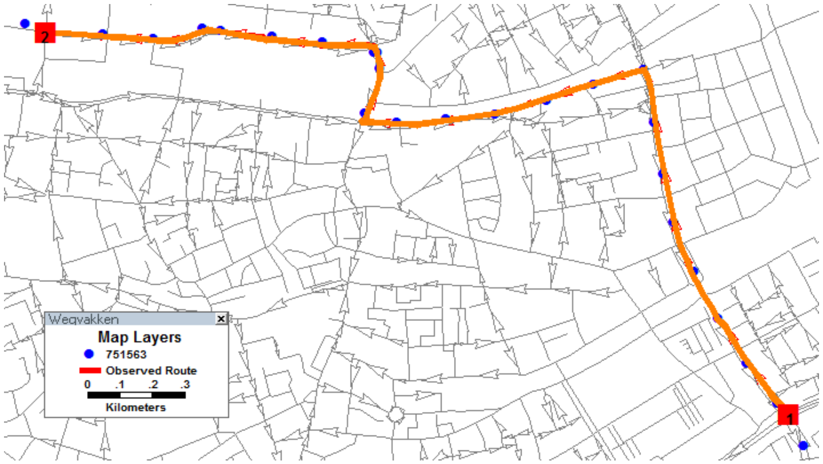

Figure B 153: Trip ID: 751563 Observed vs. Shortest Distance Route

Figure B 154: Trip ID: 751563 Observed vs. Shortest Time Route

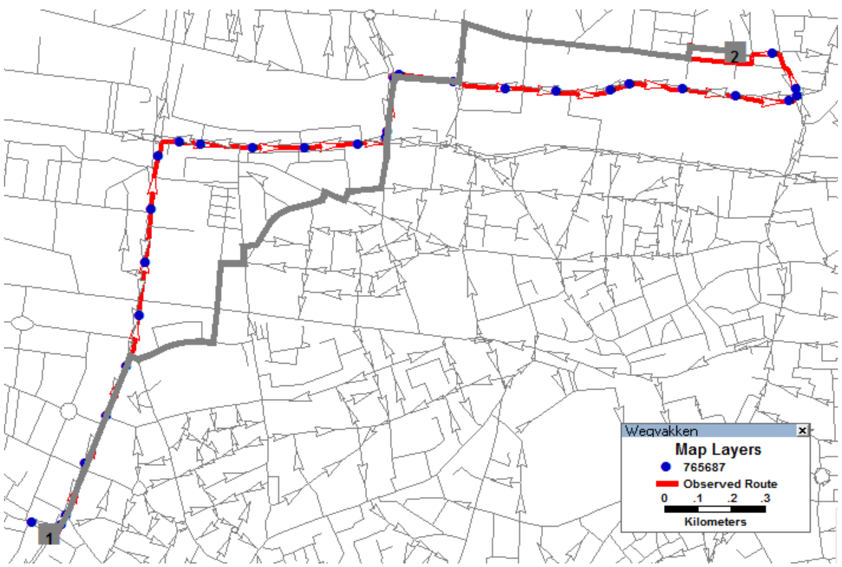

Figure B 155: Trip ID: 765687 Observed vs. Shortest Distance Route

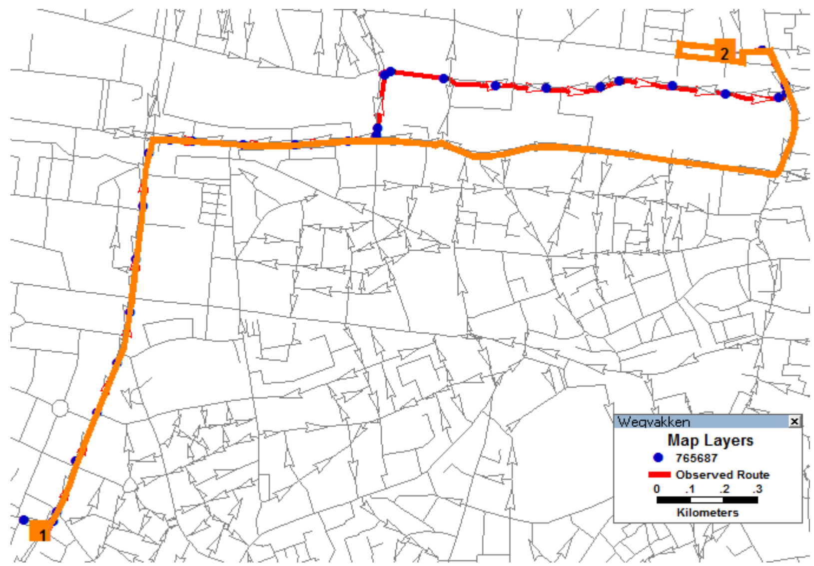

Figure B 156: Trip ID: 765687 Observed vs. Shortest Time Route

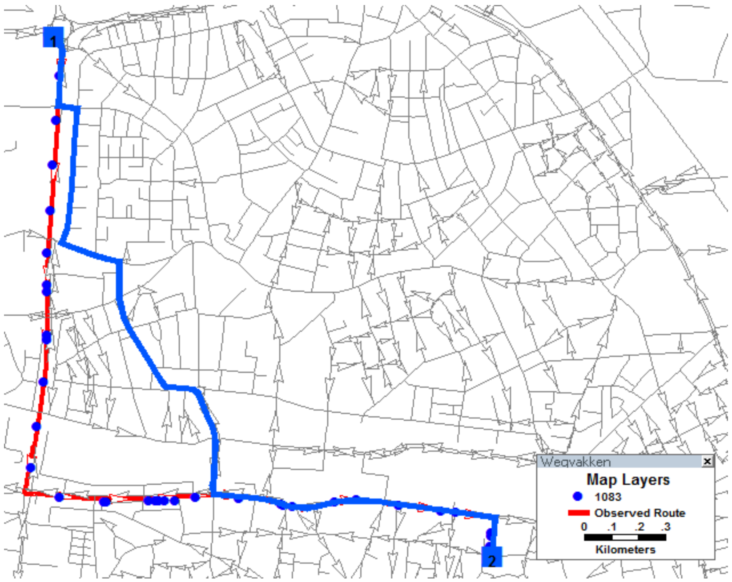

Figure B 157: Trip ID: 1083 Observed vs. Shortest Distance Route

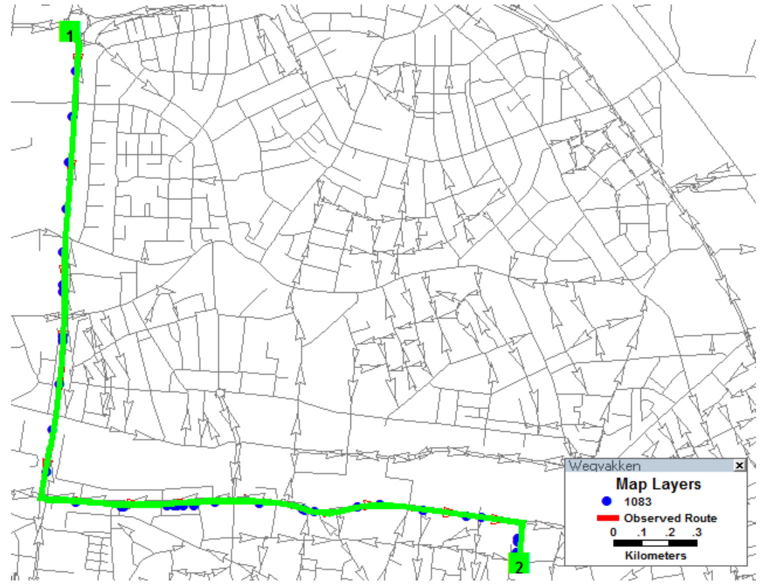

Figure B 158: Trip ID: 1083 Observed vs. Shortest Time Route

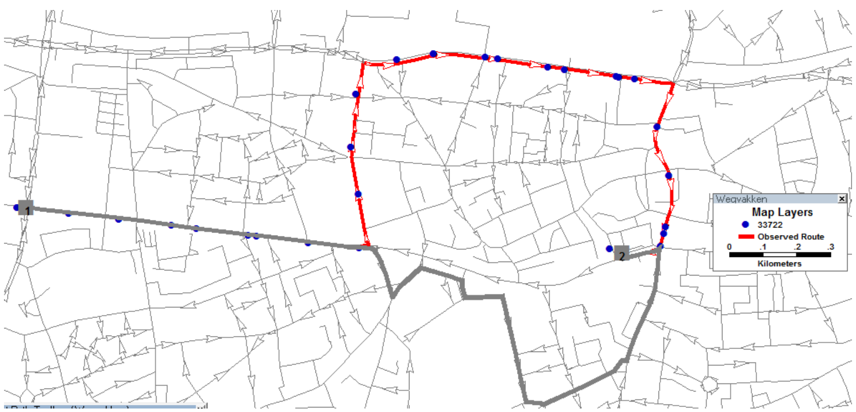

Figure B 159: Trip ID: 33722 Observed vs. Shortest Distance Route

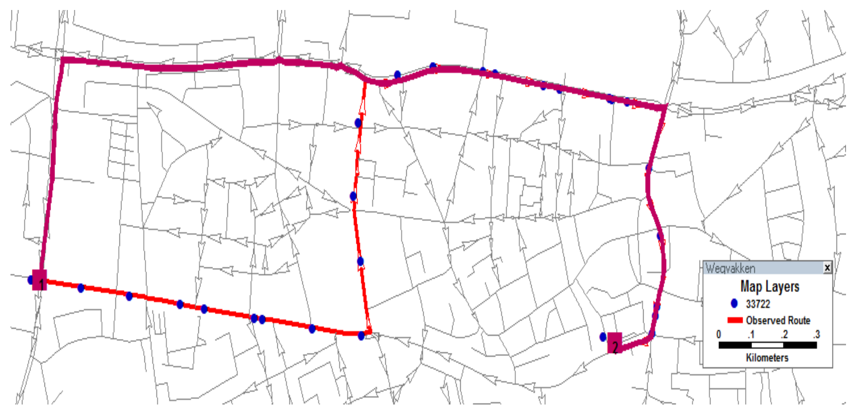

Figure B 160: Trip ID: 33722 Observed vs. Shortest Time Route

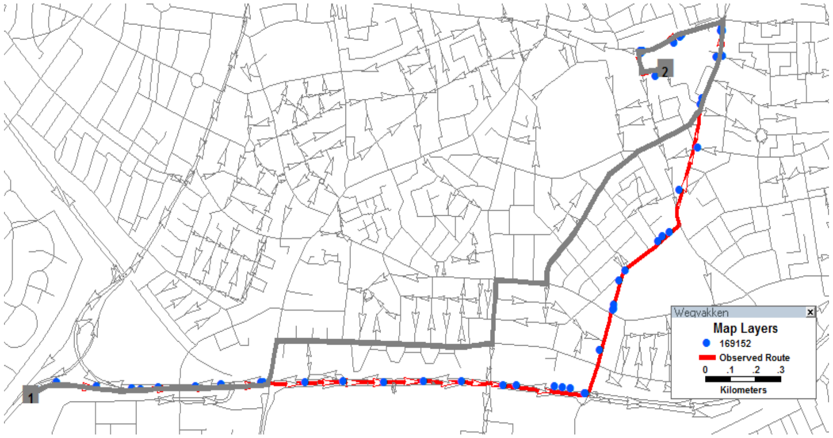

Figure B 161: Trip ID: 169152 Observed vs. Shortest Distance Route

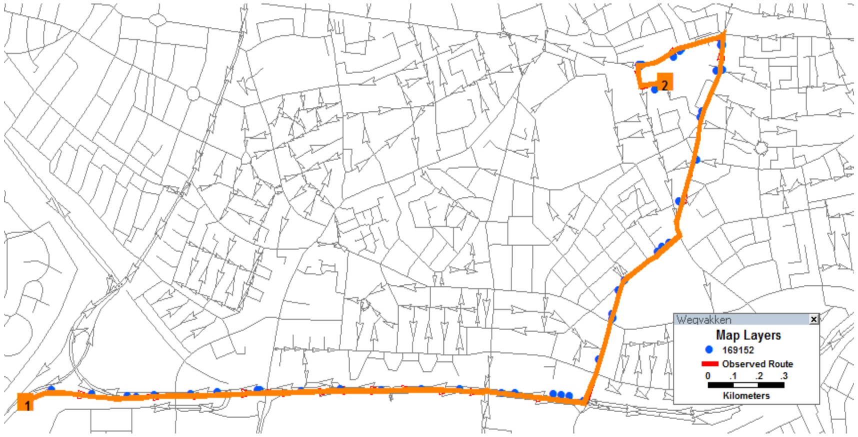

Figure B 162: Trip ID: 169152 Observed vs. Shortest Time Route

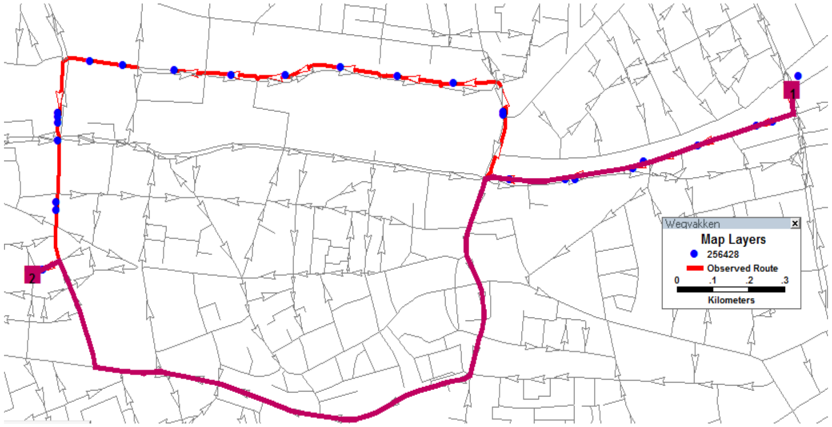

Figure B 162: Trip ID: 256428 Observed vs. Shortest Distance Route

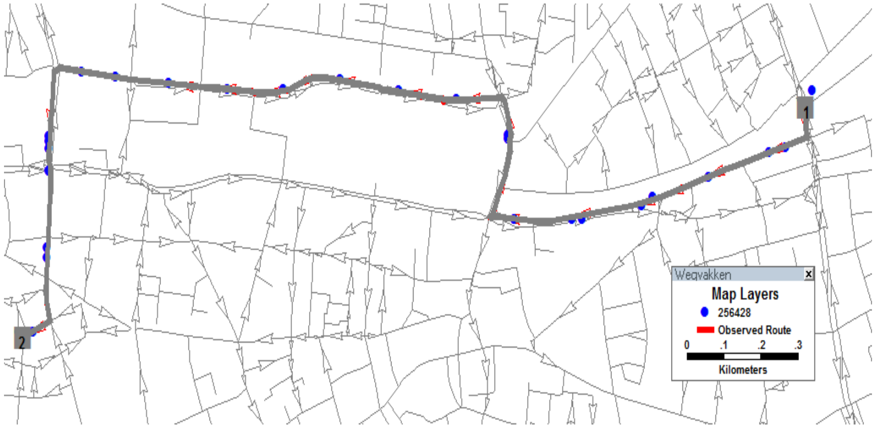

Figure B 164: Trip ID: 256428 Observed vs. Shortest Time Route

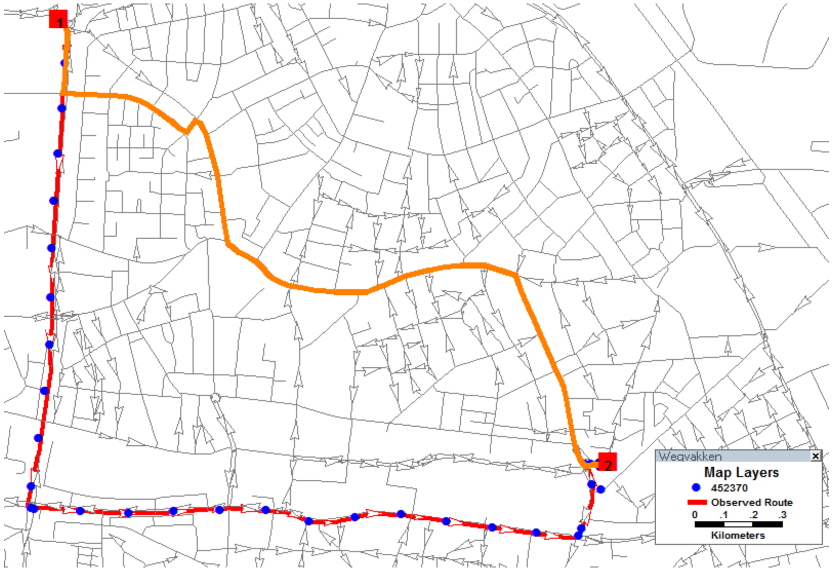

Figure B 165: Trip ID: 542370 Observed vs. Shortest Distance Route

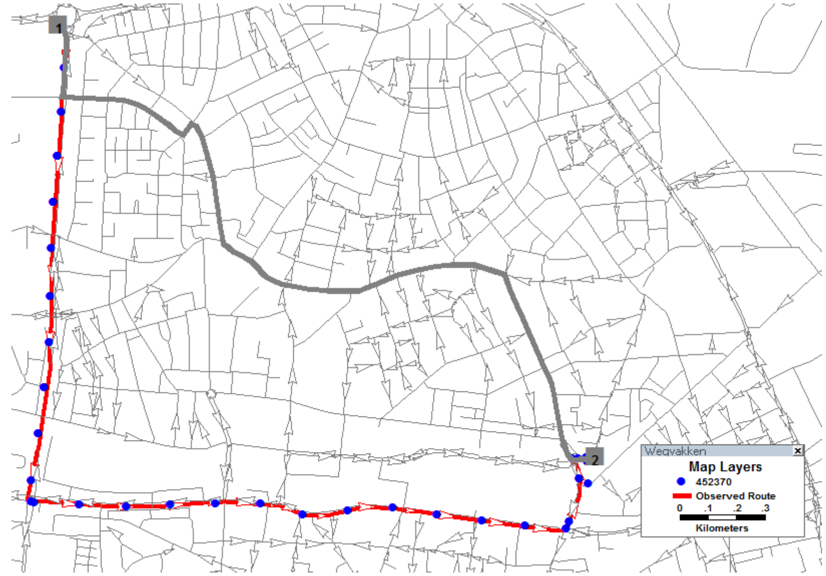

Figure B 166: Trip ID: 452370 Observed vs. Shortest Time Route