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Model of Urban Freight Transportation: The Case of Waste Collection

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MODEL OF URBAN FREIGHT TRANSPORTATION IN AGGLOMERATIONS: THE CASE OF WASTE COLLECTION

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Dedication

I would like to dedicate this thesis to the memory of my supervisor

doc. Ing. Ladislav Bina, CSc.

I would also like to dedicate this work to my family and all friends in El Paso.

MODEL OF URBAN FREIGHT TRANSPORTATION IN AGGLOMERATIONS

by

RADIM VEČEŘA, Bc.

THESIS

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Abstract

This thesis introduces the role of urban freight transportation in global economies and its negative environmental impacts. Because the volume of urban freight is continually increasing sustainable measurements have to be implemented during all phases of transportation planning and operation processes.

The thesis is mainly focused on waste collection, as it is an often neglected part of urban freight transportation. Since urban areas are growing the waste collection is starting to be complex problem which is difficult to manage. Therefore different types of optimization software are used to improve the whole process. In this thesis TransCAD software is used to perform an arc routing optimization in the north part of El Paso, Texas, U.S. The results are compared with current waste collection route used by the City of El Paso to see if TransCAD is a suitable software for routing optimization.

Key words: urban freight transportation, externalities, waste production, waste collection, arc routing, TransCAD

Declaration

This thesis is an output of the Transatlantic Dual Masters Degree Program in Transportation Science and Logistics Systems, a joint project between Czech Technical University, Czech Republic, The University of Texas at El Paso, USA and University of Zilina, Slovak Republic.

This thesis is jointly supervised by the following faculty members:

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Chapter 1: Introduction

Freight transportation is a very important part of economies all around the world and its efficiency may serve as an indicator of a country's economic development. In the United States (U.S.), one of the key measures of economic competitiveness and growth is the Gross Domestic Product (GDP). According to the Federal Highway Administration (FHWA) Freight Analysis Framework, there is a strong correlation between GDP and ton-miles of travel (Figure 1.1) or diesel fuel consumption (Mid-America Freight Coalition 2011). Figure 1.2 shows that the same correlation was observed in European Union (EU) as well.

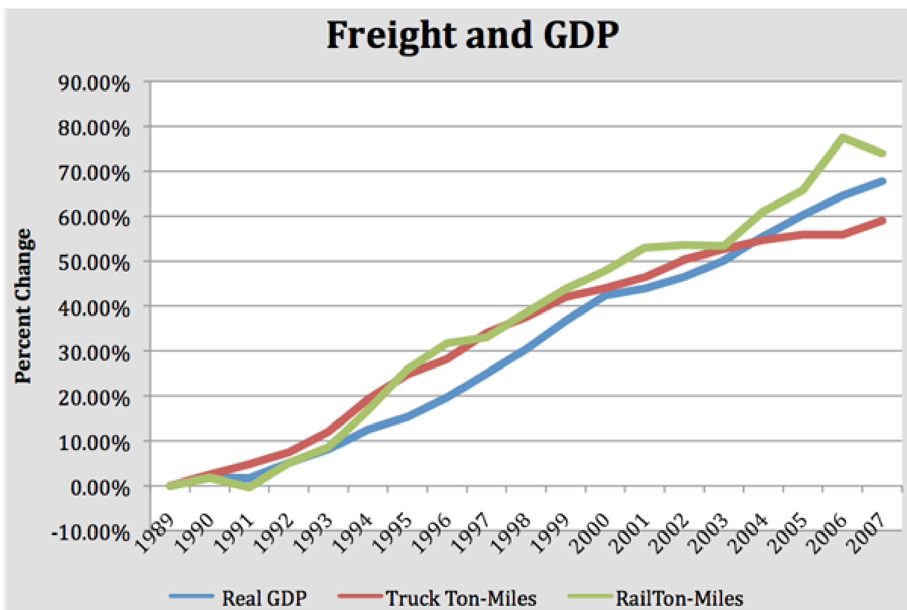

Figure 1.1 Ton-Miles and GDP in U.S.

Source: Mid-America Freight Coalition (2011)

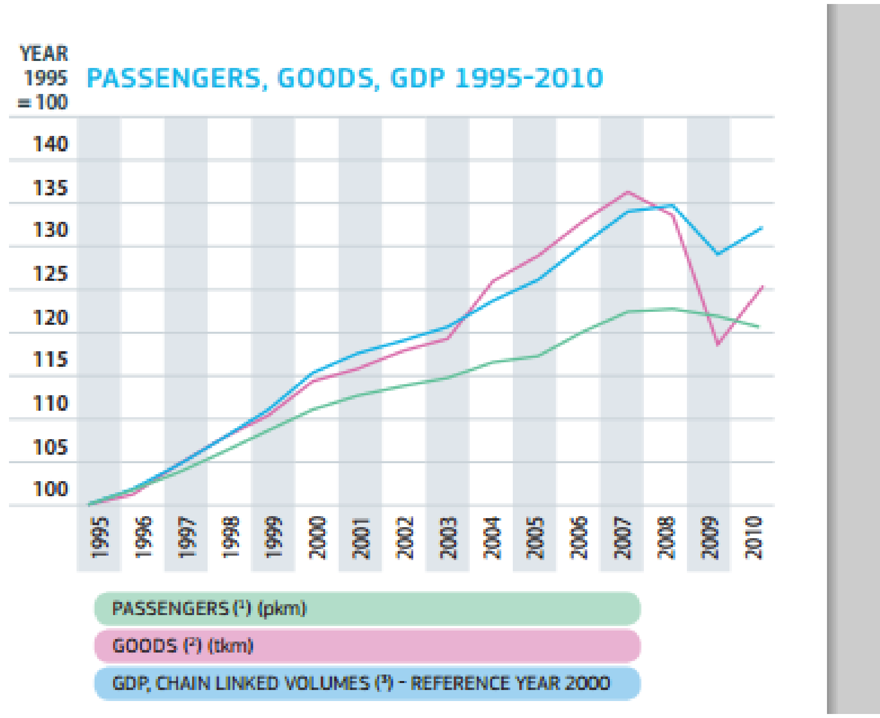

Figure 1.2 Transportation and GDP in EU

Source: European Commission (2012)

Also, transportation (person as well as freight) contributes 9.8% of the GDP in U.S. and more than 10% in EU. (Bureau of Transportation Statistics 2012; European Economic and Social Committee 2010) According Crafts and Leuning (2006), the lack of efficiency and reliability can seriously harm the economic growth. Therefore the European Commission (EC) is trying to develop policies how to ensure that economic growth in EU can continue without necessarily entailing traffic growth with an increase in the negative effects of transportation. (European Commission 2014) The reduction in dependency between of economic growth and transportation demand can be achieved by continuous revision of all parts transportation system and introduction of measurements which will focus on mitigation of the negative impacts.

1.1 BACKGROUND

Due to urbanization process, rural areas are transformed into densely populated urban areas fulfilling heterogeneous functions as result of industrialization and historical, social, economic changes in society (Peng et al. 2000). According the U.S. Census Bureau (2010), an urban area is qualified as the territory with densely settled core along with adjacent territory containing non-residential urban land uses as well as territory with low population density which encompasses at least 2,500 people, at least 1,500 of which reside outside institutional group quarters. The U.S. Census Bureau identifies two types of urban areas:

- *Urbanized Areas* (UAs) of 50,000 or more people;
- *Urban Clusters* (UCs) of at least 2,500 and less than 50,000 people.

The statistic collected by the United Nations (UN) finds that since year 2007, majority of people live in the urban areas and according to Table 1.1, it is 82% in U.S and 76% in EU which makes these countries the most urbanized areas in the world (Organisation for economic co-operation and development 2010).

Table 1.1 World population in year 2010

World population in year 2010					
	EU-27	USA	JAPAN	CHINA	RUSSIA
Population (million)	501.79	310.00	127.59	1 341.41	142.90
Urban population (% of total)	76	82	67	50	73

Source: European Commission (2012)

The European Commission divides urban areas in more detail into four categories: (MDS Transmodal Limited 2012)

- *Metropolises* - the largest urban areas in Europe with over 3 million inhabitants
- *Other Large Urban Zones* - urban areas with more than 500,000 inhabitants (excluding the "metropolises")
- *Smaller Heritage Urban Areas* – smaller urban areas that have "sensitive" environments because of the importance of the town or city in cultural or heritage terms.
- *Other Smaller Urban Areas* – all other urban areas

People living in urban areas do not have available primary sources to fulfill their needs near to their residences and therefore they generate demand for transportation (Quak 2008). It can be assumed that the majority of transportation demand would be generated in big agglomerations where the population density is very high.

Transportation then can be fundamentally divided into two groups:

- *Passenger transportation* – transportation of passengers by their own or by public transportation. In EU, 84% of inland passenger-km are realized by cars and the rest by public transportation. (Eurostat 2013)
- *Freight transportation* – transportation of goods, merchandise and cargo.

This thesis describes the role of freight transportation in urban areas and provides a review of the effects of the Urban Freight Transportation (UFT). It then focuses on waste collection as a neglected part of UFT. A case study, based on a real problem in El Paso, Texas,

U.S., is constructed to show that route optimization of waste collection will help to decrease traveled distance and consequently lower pollution of given area in El Paso.

1.2 Objective and Scope

The main objectives of this thesis are:

1. To show the importance of the urban freight transportation and its negative effects.
2. To evaluate a suitability of TransCAD software for solving waste collection problems.

1.3 ORGANIZATION OF THESIS

Chapter 1 introduces the significance of transportation and motivation for improvement of urban freight transportation systems.

Chapter 2 describes urban freight transportation and focuses on its negative effects, which should be mitigated.

Chapter 3 describes waste production and waste collection in the world.

Chapter 4 introduces the arc routing problem and its solution algorithm as a tool for solving waste collection routing task.

Chapter 5 describes waste collection in region 10 in El Paso, Texas, U.S. and conversion of given data to suitable format for TransCAD 5 software and their processing in this software.

Chapter 6 compares the optimized results obtained from TransCAD 5.0 with the current routing plan.

Chapter 7 summarizes the findings in this thesis and gives some possible directions for future work.

Chapter 2: Urban freight transportation and its negative impacts

Urban freight transportation (UFT) plays a key role in the welfare and the development of a city. According the study “C-Liege” (Lucietti 2012) urban freight transportation is not fixed only carrying goods but it also contains reverse logistics operations. Therefore UFT takes care about replenishing stocks of food and other retail goods in shops, delivering documents, parcels and other supplies to offices, removing household waste from urban areas etc. It is therefore a very complex system using the same transportation infrastructure as passengers travel (Tamagawa et al. 2010).

As oppose to passenger transportation homogeneity, a one of UFT main characteristics is its diversity in the content transported. There are as many transportation and logistics chains as there are different economic sectors (Dablanc 2009). In a single city, vehicles, delivery times, size of shipments may even vary according to each business or customer. Therefore it is difficult task to identify homogeneous freight movements in urban and metropolitan areas and decision-makers. Cities usually put big effort into planning person-trips and improving traffic movements in the city, but little attention is given to freight transportation because the freight transportation is more connected with the private sector than the public sector. However, inefficient freight transport causes a number of problems, among which are traffic congestion, infrastructure deterioration and environmental pollution. Therefore, comprehensive logistics planning in a city is needed to achieve efficient freight transport.

Urban freight transport is essential as a support system for urban economy and industry competitiveness of the city. However the growth of the urban freight transport also carries impacts which negatively influence living in urban areas and could seriously threaten sustainable development of the city. The sustainable development was defined in 1987 by Brundland

Commission (Brundtland 1987) in the UN Assembly as "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.". Jeon and Amekudzi (2005) identified that three recurring considerations are found to be especially important and may be considered as three main pillars of sustainability (Hardy 2011, Paglione 2006, Jeon and Amekudzi 2005). These are:

- Economic development;
- Environmental preservation; and
- Equity- social development.

According to Richardson (2005), the main indicators of sustainability of a transportation system are safety, congestion, fuel consumption and vehicle emissions. Figure 2.1 shows which factors affect these indicators and how these factors are related to each other.

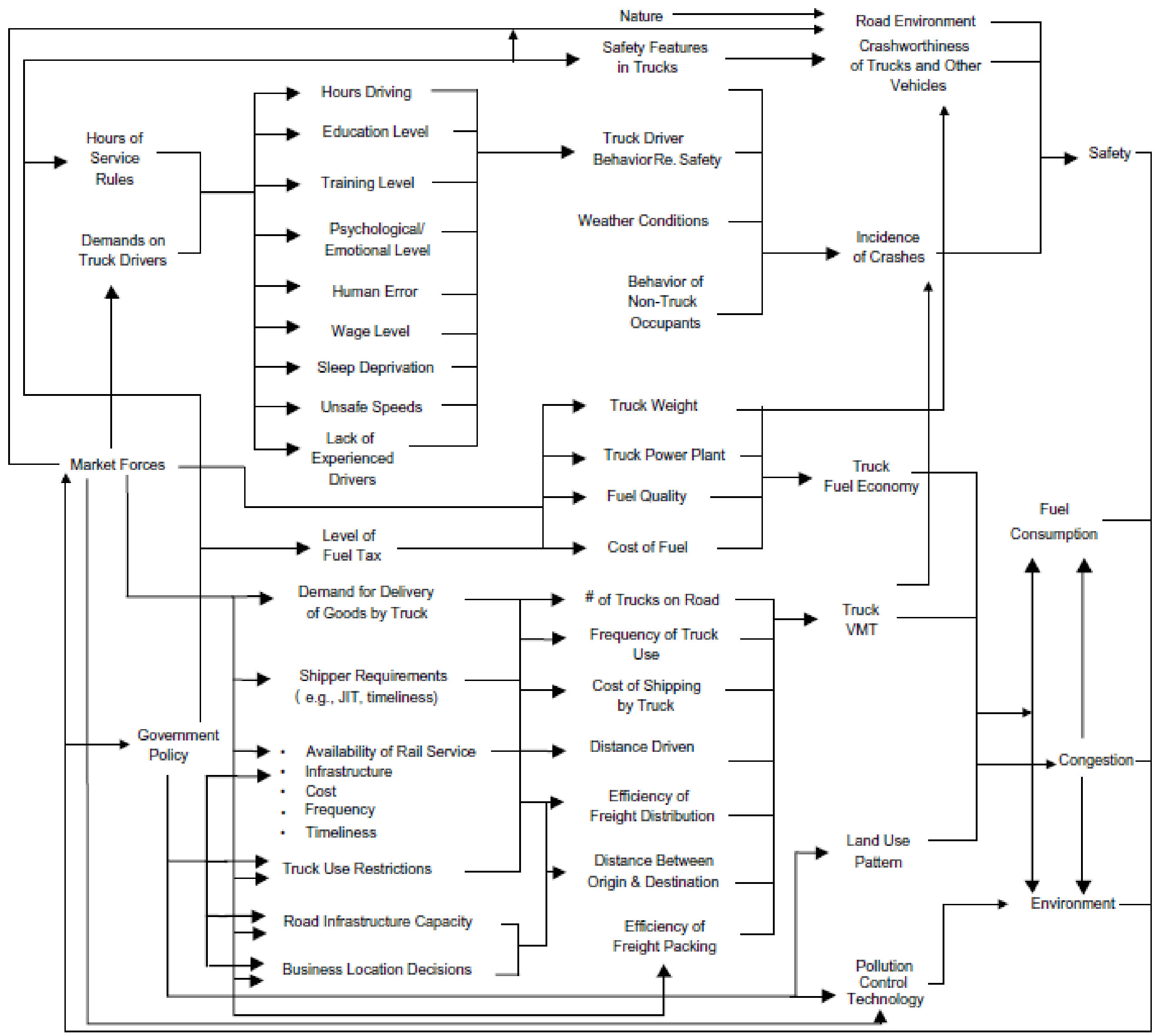

Figure 2.1 Freight factors affecting sustainability of the transportation system

Source: Richardson (2005)

2.1 NEGATIVE EXTERNALITIES OF URBAN FREIGHT TRANSPORTATION

Urban freight transportation does not bring only positive effects and welfare to the cities, but also many negative impacts which lead to negative externalities. Negative externalities are costs generated outside the economic process which affect that process or if the costs are

generated inside the economic process but affect its environment (Datz 2011). That means that externalities are a kind of economic process failure when actors of this process do not bear the full costs for the impact they made by their economic decision and these costs are transferred to someone other than the originator. The following text describes the major negative impacts of UFT and they are divided to three main groups. These groups are based on three pillars of sustainability and impacts (Nakul et al. 2006).

1. Economic impacts
    - Congestions
    - Resource waste
2. Ecological impacts
    - Air pollution
    - Vibrations
    - Use of non-renewable natural resources, such as fossil-fuel.
    - Waste products, such as tyres, oil and other materials.
    - Loss of wildlife habitats and the associated threat to wild species
3. Social impacts
    - Injuries or death as results of accidents caused by freight vehicles
    - Loading/unloading issues
    - Discrepancy between supply chains agent's interest
    - Disrupted health as a consequence of negative ecological impacts
    - Noise disturbance, visual intrusion, stench, and vibration
    - Reduction in quality of life elements
    - Damage to buildings and infrastructure.

2.1.1 Congestions

"Congestion is the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity" (Essen & Grinsven 2011). It means that the speed of traffic is decreasing with the increasing density of vehicles. The graphical representation of this relation is shown in Figure 2.2.

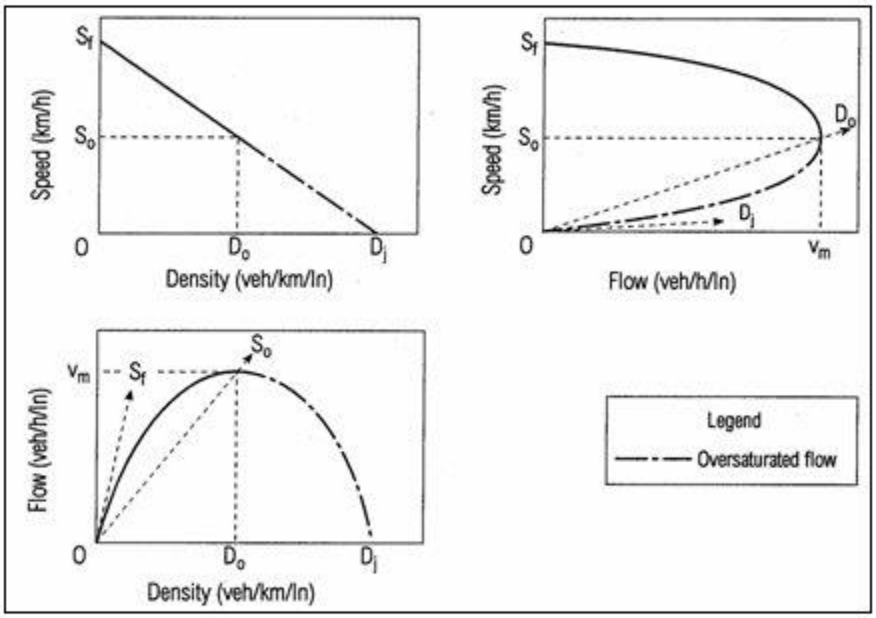

Figure 2.2 Generalized relationships among speed, density, and flow rate on uninterrupted-flow facilities
Source : U.S Department of Transportation (2013)

Congestion level continually changes with time. Roadway congestion certainly impacts both commuters and goods movement, and may occur because of different reasons (Rosen 2013):

- Too many private cars for the roadway due to inadequate public transprotation options or other reasons.

- Obstacles in the road causing a blockage and merger. These can be any of the following:
    - Double parking;
    - Road work;
    - Lane closure due to utility work;
    - Road narrowing down;
    - Accident;
- Traffic signals out of synchronization many times on purpose or occasionally when the computers are malfunctioning;
- Inadequate green time;
- Too many trucks on the road due to inadequate rail freight opportunities;
- Overdevelopment in areas where the mass transit system is already overcrowded and the road system is inadequate.

Congestion causes also problems in U.S. According to the Texas A&M Transportation Institute (2011), Americans traveled 4.8 billion hours more which increased the total fuel consumption by 1.9 billion gallons and the extra cost was evaluated at $101 billion.

In EU (plus Norway and Switzerland) the annual congestion cost of road transport amount to between €146 and €243 billion, if one take into account the cost of delays. This is 1% to 2% of the GDP. When we consider that total external costs of transport in EU which is approximately €500 billion per year, or 4% of the total GDP, than congestions contributes to the traffic external costs by nearly 50% (Schroten et al. 2011).

2.1.2 Air pollution

Freight transport in cities represents only relatively small amount of all vehicles, from 10% to 18%. However, freight transportation's share on air pollution and noise is more than 40%. (Winisee 2011)

Freight transportation depends 97% on fossil fuels which produce global pollutants, such as carbon dioxide (CO_2), and local pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM10) and volatile organic compounds (VOC). All these emissions contribute to the global climate change (especially CO_2 emissions). (Nakul et al. 2006) Road transportation contributes 16,3% of CO_2 in the air in EU. The combination of NO_x with volatile organic compounds (VOC) and sunlight can cause the formation of photochemical smog, which affects the air quality of many urban areas. In addition nitric acid (HNO_3) can cause paint deterioration, corrosion, degradation of buildings, and damage to agricultural crops. (Maroudas – Tsakyrellis 2011)

2.1.3 Noise

Noise is defined as unwanted or undesirable sound. (Washington State Department of Transportation 2014) Traffic noise is not constant and the level of traffic noise depends on three factors: (U.S. Department of Transportation 2011)

- Traffic volumes - Roads with more vehicles are generally louder;
- Traffic speeds - Traffic is louder at higher speeds; and
- Percent of heavy trucks on the road.

Millions of people in U.S. and in the EU are affected by traffic noise. In fact, traffic noise impacts more people than any other environmental noise sources. Traffic noise annoys people

and cause stress, decreased ability to work, learn, rest or sleep and can lead to illness or serious mental or physical health problems (Acoustics.com 2003). Figure 2.3 illustrates how noise affects health.

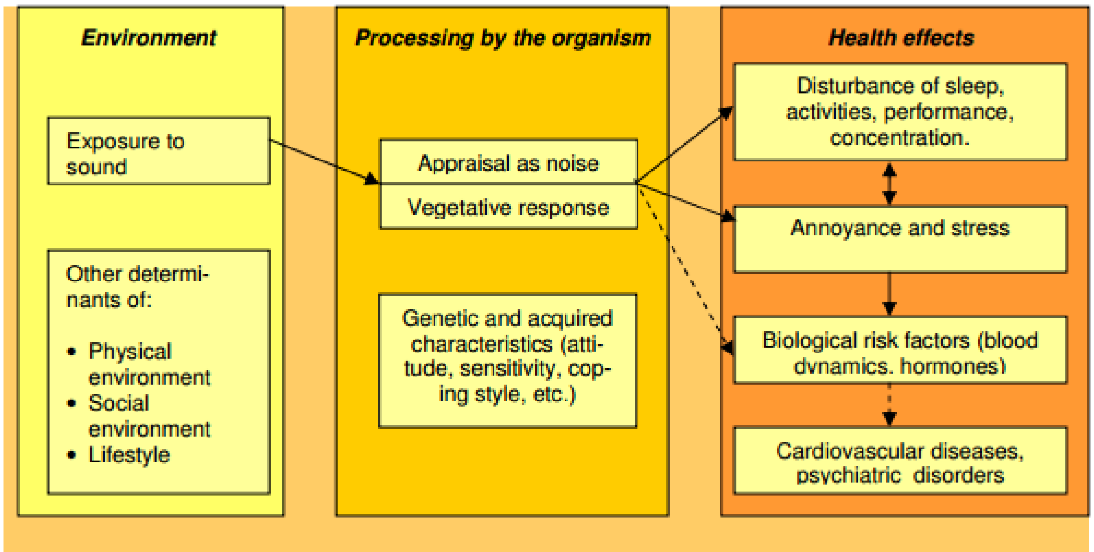

Figure 2.3 The mechanisms of noise-induced health effects

Source: Boer & Schroten (2007)

More than 44% of EU's population (about 210 million people) is exposed to over 55 dB of road traffic noise, a level potentially dangerous to health (Boer and Schroten 2007).

Chapter 3: Waste Collection

3.1 INTRODUCTION

Waste is defined by UN as "materials that are not prime products (i.e. products produced for the market) for which the generator has no further use for his own purpose of production, transformation or consumption, and which he discards, or intends or is required to discard. It excludes residuals directly recycled or reused at the place of generation and waste materials that are directly discharged into ambient water or air" (Shah 2008).

Figure 3.1 shows driving forces and subsequences of waste production and links between them.

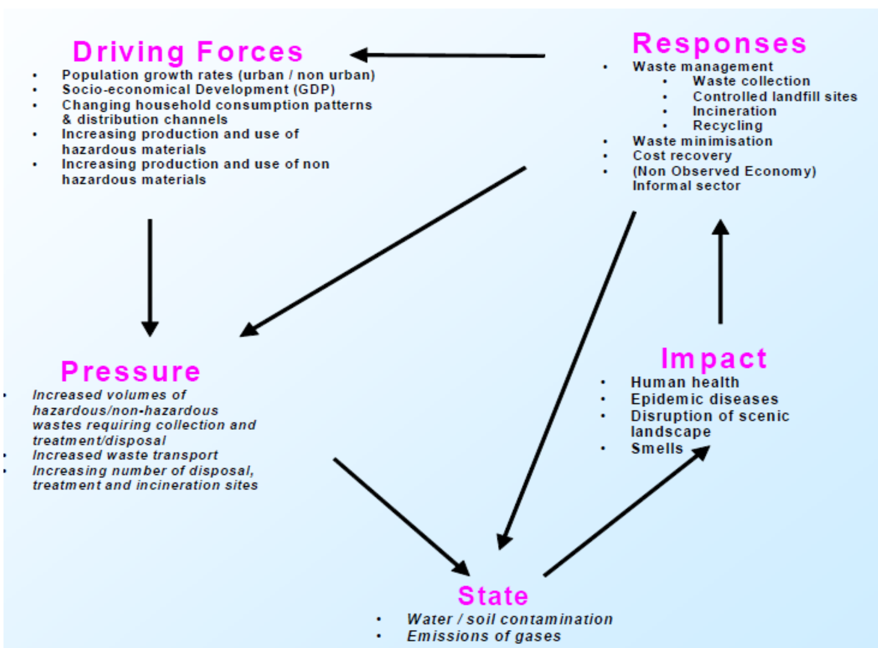

Figure 3.1 Enviromental impact of waste

Source: Shah (2008)

3.1.1 Driving Forces

One of the driving force of waste production is a change of household consumption patterns as a result of a today‘s lifestyle. The waste generation correlates with consumption and production and it increases and varies more with economic development. In developed countries people’s consumption is driven by seasonal trends. They throw away needless things easily. Also, redundant number of single-use packing is often used. (Santibañez-Aguilar 2013) Table 3.1 shows the composition of municipal waste in countries around the world. It can be seen that in developed countries the majority of municipal waste is formed by packaging materials such as plastic and paper.

Table 3.1 Composition of municipal solid waste fot several countries

Type of waste	USA[a] 2010	Mexico[b] 2009	France[b] 2009	Colombia[b] 2009	American[c] Samoa 2009	China[c] 1993
Paper and cardboard	28.5	14.2	35	22	26.4	3.1
Plastic	12.4	5.8	7	5	12.8	4.9
Metals	9	3.1	5	1	7.9	0.7
Textiles	5.3	1.2	5	4	4.2	2.1
Glass	4.6	6.6	12	2	3.4	2.2
Food wastes	13.9	31.6	21	56	3.78	46.9
Yard trimmings	13.4	9.8	–	10	11.30	–
Others	12.9	27.7	15	–	30.22	40.1

Source: Santibañez-Aguilar (2013)

Another driving force of the waste production is a population growth in urban areas. Currently, about 1.3 billion tonnes of municipal solid waste (MSW) per year is generated in cities around the world and this number should increase to 2.2 billion tonnes by 2025. Annual expenses of waste removal are currently \$205.4 billion and this figure should rise to \$375.5 billion in 2025 (Hoornweg and Bhada-Tata 2012).

The U.S. generated about 250 million tons of waste in year 2010 (United States Environmental Protection Agency 2010). Figure 3.2 shows that there is a strong correlation between generated MSW and population growth. The correlation between generated MSW and GDP is weaker but both curves follow rising trends.

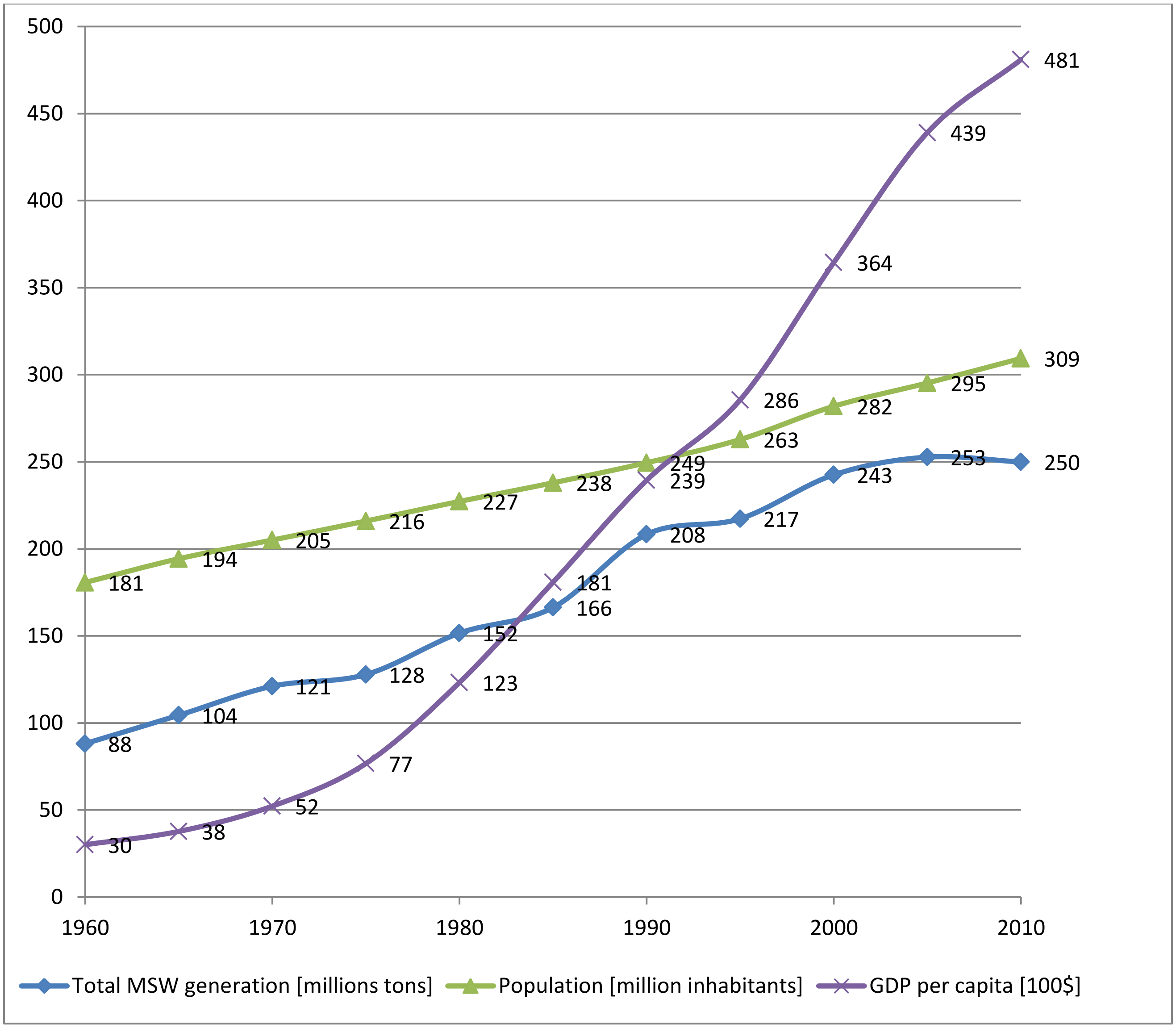

Figure 3.2 Municipal generation rates, population and GDP per capita 1960 to 2010 in the U.S.

Source: author (2014), United States Environmental Protection Agency (2010), Multpl (2014a, 2014b)

3.1.2 Responses

The main response to waste generation is waste collection and its management. Waste collection is usually a required service for residents provided by the city government. Because the environmental impacts, costs and level of service are strongly dependent on the waste type, waste collection is distinguished by the three major waste generation sources according to land use type (Sahoo et al. 2005):

- Commercial;
- Industrial; and
- Residential.

All of them produce municipal solid waste as well as recyclable waste. Commercial waste collection includes mainly waste from restaurants, grocery shops, malls and office buildings. According to a study in New York City (Ahmed et al. 2011) commercial waste forms around 23% of the total volume (see Figure 3.3). Collection routes should significantly differ and one route may serve 60 to 400 customers. However after setting up they are relatively constant because customers waste generation patterns seldom change (Sahoo et al. 2005).

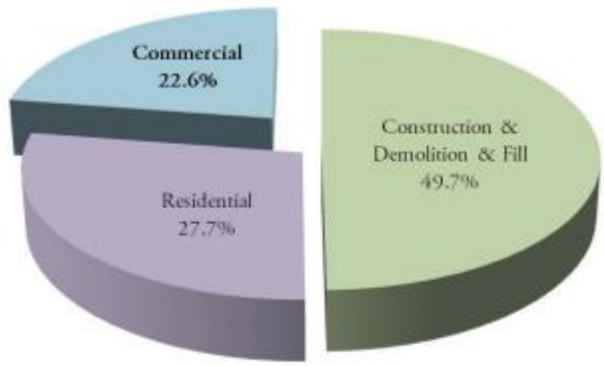

Figure 3.3 Types of waste in New York City, the U.S.

Source: Ahmed et al. (2011)

Industrial area usually covers construction or demolition waste and waste from manufacturing plants. The industrial dumpsters are bigger than the ones used in commercial areas. A typical commercial container is eight cubic yards, while an industrial container may range from 20 to 40 cubic yards (Sahoo et al. 2005). Therefore, collecting trucks can handle only one industrial container at a time and they have to go straight to a landfill. Drivers then operate only few pick-ups and drop-offs during a shift.

Residential Waste Collection (RWC) usually serves residents of a city who live in private homes. Waste collection is usually provided by a city department but it could be outsourced to a private company as well. RWC routes varied, because length, number of stops and weekly frequency of collections strongly depend on a city's geography, climate, population density, average waste generation during week, and etc. Normally, routes operate through 130 to 1300 homes per day (Sahoo et al. 2005).

The most significant difference of residential waste collection routes beside commercial or industrial ones is the fact that the trucks has to travel along one side of a street and they cannot

perform point-to-point collection in opposite direction of traffic flow. A graphical interpretation is shown on Figure 3.4.

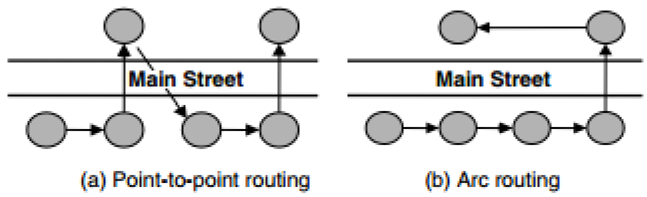

Figure 3.4 Comparison of arc and point-to-point routing

Source: Sahoo et al. (2005)

3.2 RECYCLING

Recycling is an important part of waste management and waste collection. Nearly 70 million tons among the 250 million tons of MSW in the U.S were recycled or composted in year 2010. In EU, more than 40% MSW was recycled which is significantly higher. Figure 3.5 shows that paper, auto batteries and steel cans are the most often recycled products.

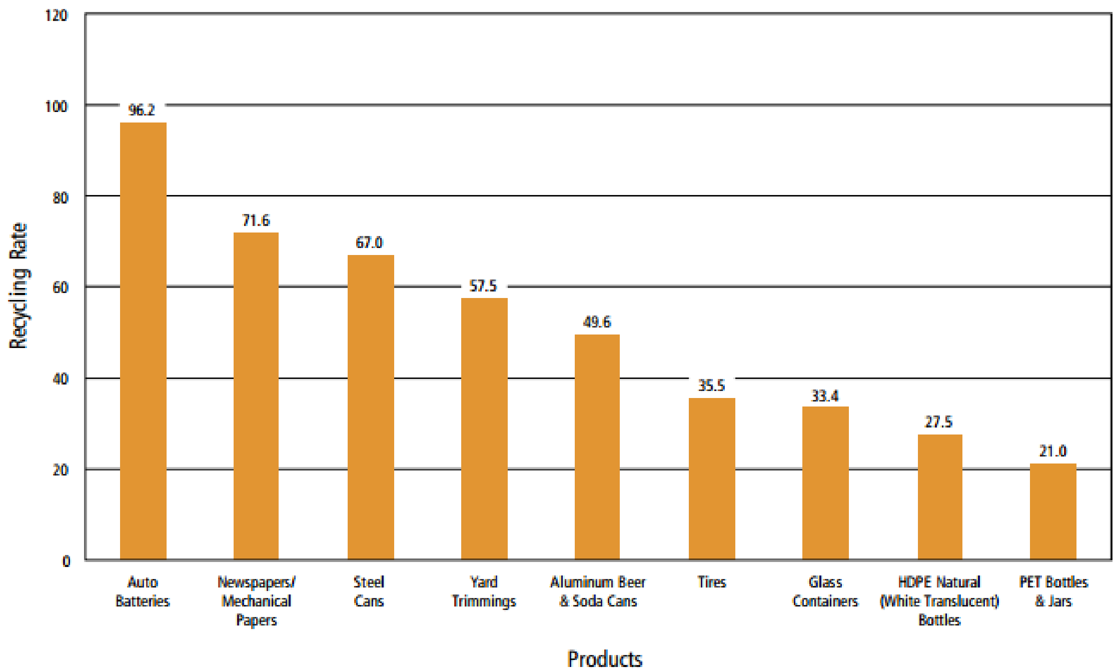

Figure 3.5 Recycling rates for selected products

Source: United States Environmental Protection Agency (2010)

If recycled waste is collected separately from MSW, special trucks are used and routes usually have fewer stops than residential ones, normally between 100 and 900.

3.3 Waste management

Good waste management should enforce minimization of waste generation in the first instance, because increasing volume of MSW is an important issue in large urban areas with insufficient landfill capacities and inefficient waste management systems (Santibañez-Aguilar et al. 2013).

Figure 3.6 shows the decision pyramid on how to reduce waste generation. Actions respecting this pyramid should bring positive economic, social and environmental benefits in processes of companies or households. Companies may for example start using a philosophy of

lean manufacturing, which focuses on continuous improvement of processes to eliminate of waste. Usually companies gain a competitive advantage by using lean manufacturing (McGivern and Stiber 2006).

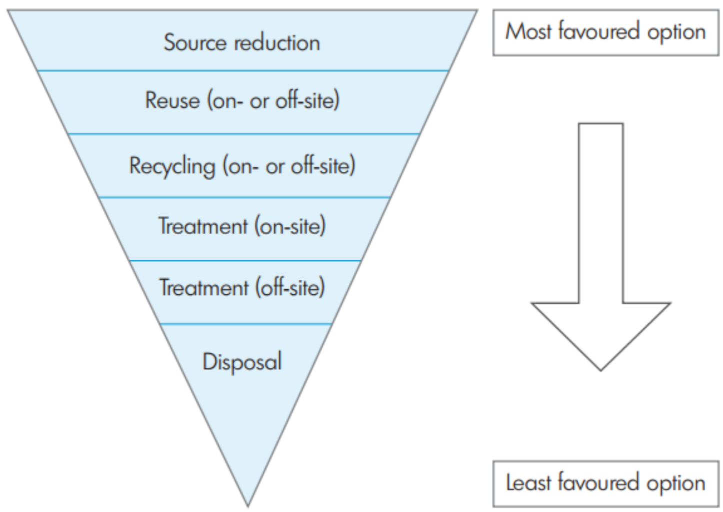

Figure 3.6 Waste management hierarchy

Source: Department of Environmental Affairs Republica of South Africa (2011)

Residential homes should be supported in recycling efforts or in minimizing redundant use of one-use-only products. The support can be provided at educational and informative level for example by television spots, articles in newspapers, public discussions etc. Also facilities which collect to recycle should be easily accessible.

Figure 3.7 shows costs which are related to waste collection. The act of collection itself creates half of the total costs. Therefore a priority should be set on optimizing waste collection.

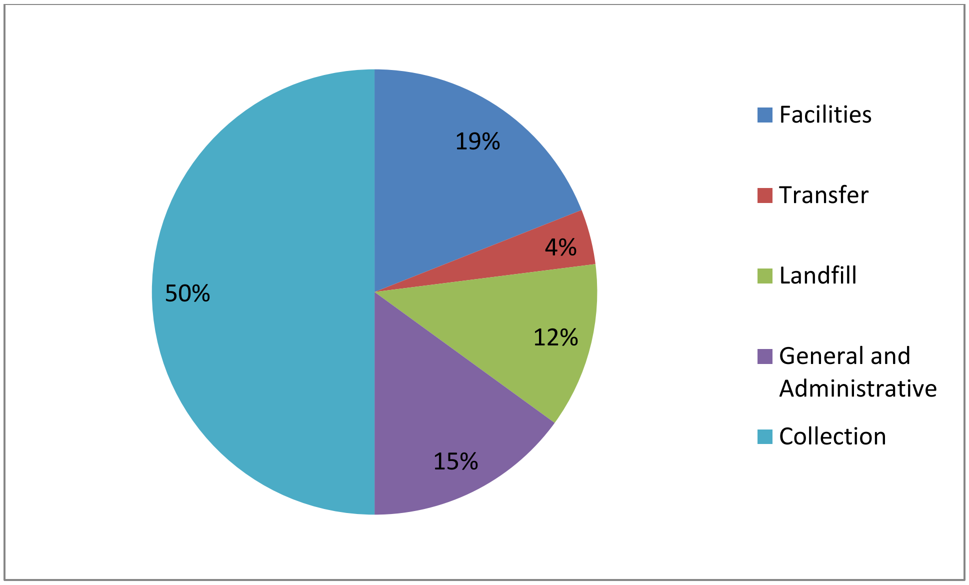

Figure 3.7 Solid waste collection – Management system costs

Source: National Renewable Energy Laboratory (1995)

There are numerous strategies to control or cut solid waste or recyclables collection costs, but technical, economic, environmental and social aspects must be considered. (Santibañez-Aguilar et al. 2013)

Four widely used strategies focus on: (United States Environmental Protection Agency 1999)

- Changing collection frequency;
- Using automated collection equipment;
- Implementing a dual collection system (i.e., collecting RSW and recyclables in separate compartments on one vehicle); and
- Improve routing.

Changing collection frequency enables waste collection managers to reduce a number of MSW collections to one collection per week. In some parts of U.S. there are two collections per week which should ensure that odor and pest will not occur. However, the second collection is usually under-utilized and collection costs per ton of waste are significantly higher. Also, cities where a service was switched from twice to only once a week did not recorded any increase of odor or pest (United States Environmental Protection Agency 1999).

Automation of waste collection is starting to be used in U.S more and more often. The main reasons for using automatic equipment are decrease of labor requirements and reduction the number of vehicles required to serve a collection territory. For the same reasons, automated collection is usually implemented as a dual collection system, which collects two separated waste streams with single vehicle by a single pass. (United States Environmental Protection Agency 1999)

Another strategy which should bring positive results is an improvement of collection routes. Many managers believe that drivers are able to identify best route from their experience. However increasing complexity and growth of cities makes finding the optimal waste collection route a complicated task. There are two approaches to optimize collection routes (United States Environmental Protection Agency 1999):

- Manual routing
- Computer based routing

For manual planning of routes, there are existing guidelines with best practices. One of these guidelines is Heuristic Routing for Solid Waste Collection Vehicles produced by U.S. Environmental Protection Agency (EPA) in year 1974 (United States Environmental Protection Agency 1999).

Computer based routing allows to use the Geographical Information System (GIS) for visualization and for applying optimization algorithms to obtain the best results. The use of computers also saves labor costs and time. A study conducted by Avinashilingam University for Women showed that route optimization by GIS software can lead to distance savings higher than 45%, and running and maintenance cost reduction by 86% (Velumani 2013).

Chapter 4: Arc Routing Problem

4.1 ROUTING PROBLEMS

Routing problems are problems which design routes on a transportation networks. The main objective is to visit desired locations and to minimize or maximize a certain objective. The networks are represented by graphs containing arcs (or links) and nodes. The locations to be visited can be placed either in nodes or on arcs. When the locations are in nodes then the problems are called a Node Routing Problems. An example of this type of problem is the well-known Travelling Salesman Problem. Problems where target locations are along arcs (and therefore it is necessary to traverse whole arc) are called Arc Routing Problems(ARP) (Keenan 2001). Figure 4.1 visualizes initial inputs needed to construct routing problems and Figure 4.2 shows the relationships between the different types of routing problems. The meanings of the acronyms is explained in Table 4.1.

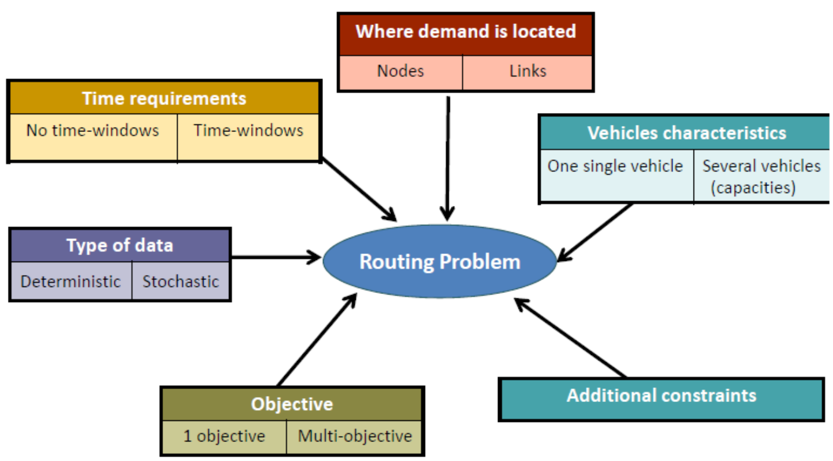

Figure 4.1 Characteristics of routing problems

Source: Fernández (2013)

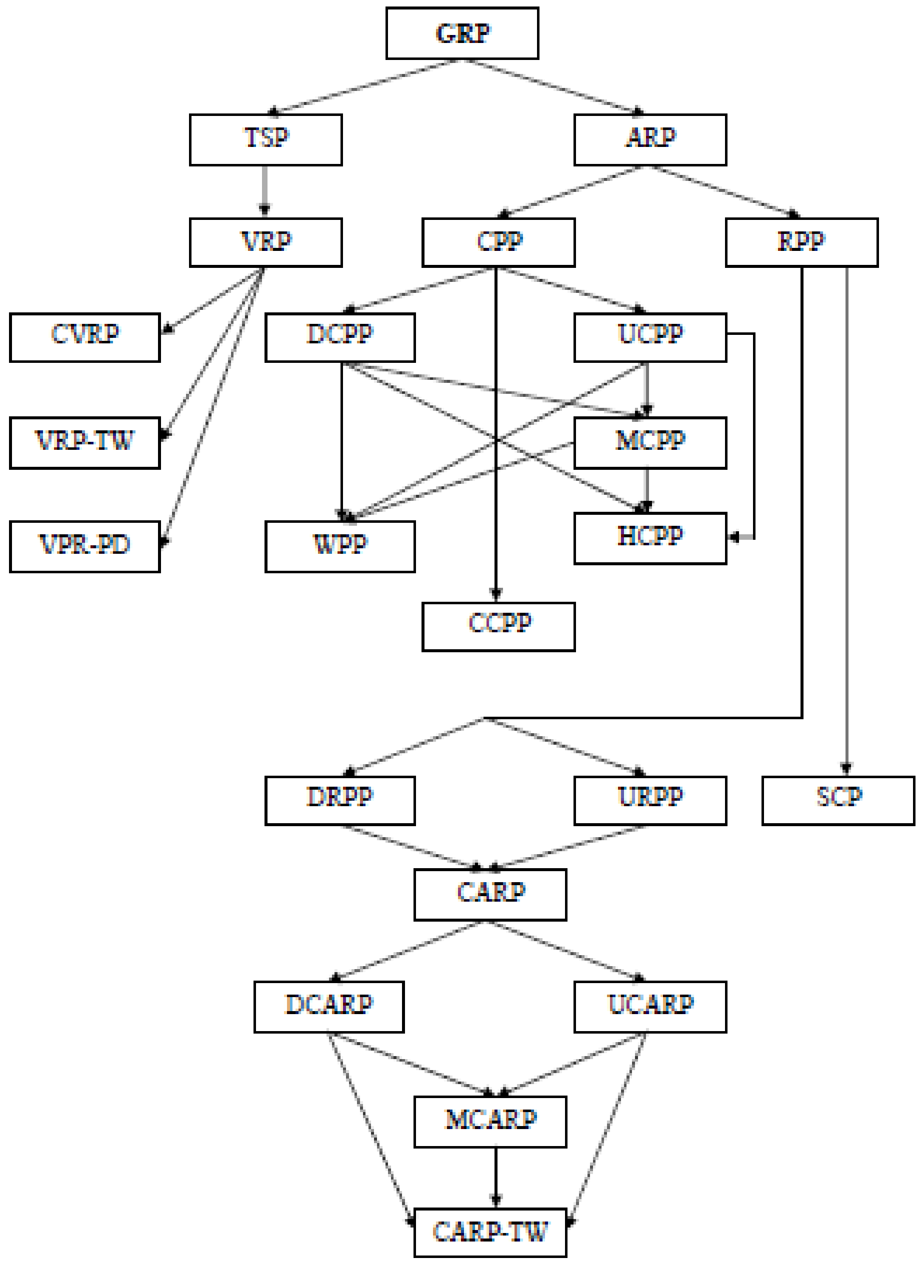

Figure 4.2 Relations between routing problems

Source: Vízner (2011)

Table 4.1 Table of acronyms

Acronym	**Full meaning**
GRP	General Routing Problem
TSP	Travelling Salesman Problem
ARP	Arc Routing Problem
VRP	Vehicle Routing Problem
CPP	Chinese Postman Problem
RPP	Rural Postman Problem
CVRP	Capacited Vehicle Routing Problem
DCPP	Directed Capacited Arc Routing Problem
UCPP	Undirected Capacited Arc Routing Problem
VRP-TW	Vehicle Routing Problem with Time windows
MCPP	Mixed Chinese Postman Problem
VPR-PD	Vehicle Routing Problem with Pick-Up and Delivery
WPP	Windy Postman Problem
HCPP	Hierarchical Chinese Postman Problem
CCPP	Capacited Chinese Postman Problem
DRPP	Directed Rural Postman Problem
URPP	Undirected Rural Postman Problem
SCP	Stacker Crane Problem
CARP	Capacited Arc Routing Problem
DCARP	Directed Capacited Arc Routing Problem
UCARP	Undirected Capacited Arc Routing Problem
MCARP	Mixed Capacited Arc routing Problem
CARP-TW	Capacited Arc Routing Problem with TimeWindows

Source: Vízner (2011)

In real world application there are usually two stages of route planning:

- macro routing; and
- micro routing.

Macro routing deals with dividing a given area (network) into total smaller parts (sub-networks) which represent areas served in one collection day or areas to be served by a single route.

Micro routing then designs the specific path that each individual vehicle will follow which is the subject of the route optimization (within a sub-network). The size of each route will depend on a wide variety of factors, including geographic features of the territory, demographic considerations, vehicle design and loading features, set-out requirements, staffing patterns, types of service being provided, frequency of collection, and institutional considerations, shift hours as discussed below. (United States Environmental Protection Agency 1999)

4.2 ARC ROUTING PROBLEM

The Arc Routing Problem is an optimization routing problem where the points of interest and resource constrains are located on the arcs. The objective is to determine how to traverse through all arcs with nonzero service demand while a desired objective is minimized or maximized. ARP is considered to be Non-Polynomial (NP) hard problem. NP hard problem means that an algorithm for solving the problem (in this case ARP) can be translated into one for solving any NP-problem. NP-problems are problems which should be solved in nondeterministic polynomial time. NP-hard therefore means "at least as hard as any NP-problem," although it might, in fact, be harder. (Mathworld 2014) ARP is used for instance in (Corberán and Prins 2010):

- collection or delivery of goods;
- mail distribution;
- snow plowing;

- network maintenance; and
- garbage collection.

Study of ARP started in year 1735 when Leonhard Euler solved well known Könisberg bridge problem (Wøhlk 2008). The most fundamental problem is named the Chinese Postman Problem and its usage in the real world is very limited due to the many limiting assumptions. The problem is defined on undirected graph with one depot and constructs one route for one postman. One of the first real life problems which used ARP were the Street Sweeping Problem and the Electric Meter Reading Problem (Wøhlk 2008).

4.2.1 Capacitated Arc Routing Problem

Consider a strongly connected oriented graph $G= (N, A)$, where N is the nod set and A is the arc set. The arcs represent streets and roads and nodes represent depot, intersections, dead-end streets. We assume that A is divided into two disjunctive subsets A_1 and A_2. The subset A_1 represents arcs which must be serviced and the subset A_2 refers to arcs without demand for service. Every arc e is defined by a pair of nodes (i_i, i_j) at the end of the arc and if the arc is a part of the subset A_1 then it is associated with demand for service d_e, length l_e, travel time t_e, service time st_e, and in special cases it could be associated with travel cost tc_e or time-dependent service cost function $sc_e(T_e)$ where T_e is the time of beginning of service on arc e. The rest of the arcs in subset A_2 have only length l_e, travel time t_e and travel cost tc_e. The service time st_e can be equal to travel time t_e, but it is usually larger because it takes more time to serve an arc than just travel along it. The arc are served by a set $K = \{1, . . . ,m\}$ of identical vehicles each with capacity Q. The vehicles start and end their round trips at a depot node D and they are not allowed to wait along their route and must be back at the depot by a given deadline. The

objective of this problem is to serve all arcs from subset A_1 with minimal value of a target variable which should be minimal service time, minimal service cost or minimal length of the route (Tagmouti et al. 2006; Constantinoa et al. 2013). For each route $p=1,\ldots,P$ let:

- x_e^p is 1 if arc $e \in A$ is served by route *p,* and 0 otherwise:
- y_e^p is a number of times that arc $e \in A$ is deadheaded by route *p:*

$$\min \qquad \sum_{p=1}^{P} \left(\sum_{e \in A_1} st_e x_e^p + \sum_{e \in A} t_e x_e^p \right) \tag{1}$$

s.t.

$$t_e > 0 \tag{2}$$

$$\forall e \in A_1, d_e > 0 \tag{3}$$

$$t_e \leq st_e \tag{4}$$

$$\sum_{p=1}^{P} x_e^p = 1 \quad \forall e \in A_1 \tag{5}$$

$$\sum_{p=1}^{P} (x_{e(i,j)}^p + x_{e(j,i)}^p) = 1 \quad \forall e \in A_1 \tag{6}$$

$$\sum_{e \in A_1} d_e^p \leq Q \quad \forall p \tag{7}$$

In above formulation, (1) is the objective function which minimizes the total time needed to serve all the required arc; (2) implies that travel time on every arc is larger than zero and (3) ensures that all arcs from the subset A_1 have non-zero demand on an arc. (4) ensures that arc service time is greater than or equal to the arc travel time; (5) - (7) prevent routes from

overlapping and ensure that arc will be served just once without exceeding the capacity of the service vehicles (Gouveia 2010).

Chapter 5: Waste Collection in El Paso

El Paso is located in west Texas, U.S. directly on the borders with Mexico. It is important entry point and exit for international trade between U.S. and Mexico. Nowadays El Paso has around 649,000 inhabitants and it is the 22nd largest city in U.S. (The City of El Paso 2014).

Solid waste collection from residential areas in El Paso is provided by The City of El Paso Environmental Services Department (ESD). Garbage is collected once a week between Tuesday and Friday from more than 163 000 homes. For effective management, 84 waste collecting routes in El Paso are clustered into 9 regions which are coordinated by assigned supervisors. These regions are then divided into areas according the day of service as shown in Figure 5.1.

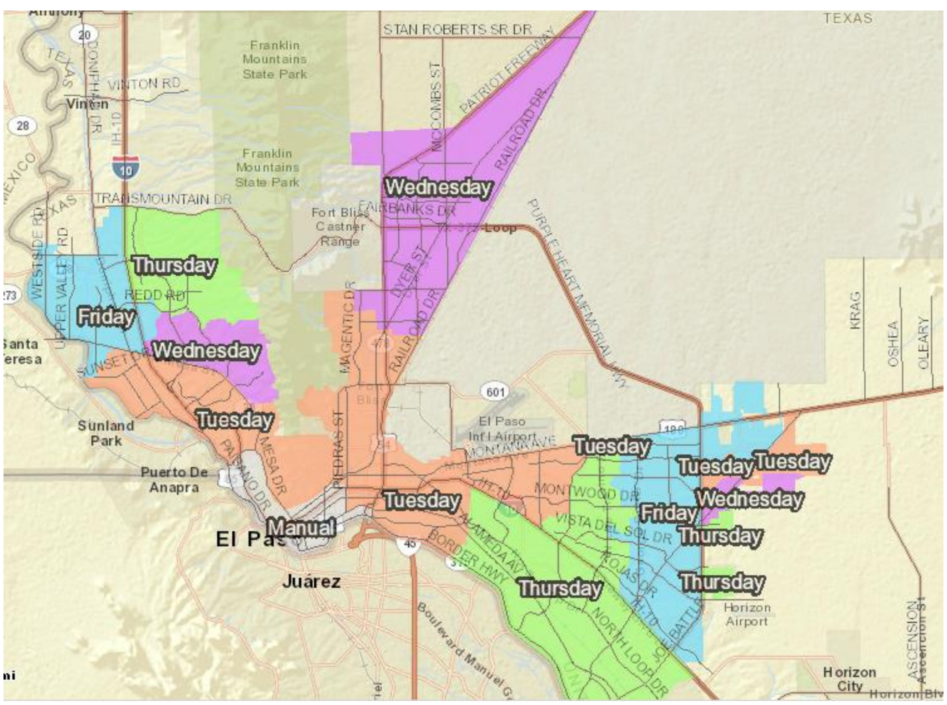

Figure 5.1 Service areas in particular days

Source: City of El Paso Environmental Services (2014)

Drivers work in two shifts (in the morning and in the afternoon) and are able to operate one route during these two shifts. They begin their shifts in a depot which is next to the headquarter of ESD at 7968 San Paulo Drive. At the end of a route, collected waste is disposed at one of the two landfills: Camino Real and Greater El Paso. Internal restrictions of Camino landfill allow dumping only a total of 15,000 tons in a given quarter. Figure 5.2 shows the map of El Paso with highlighted landfills and depot.

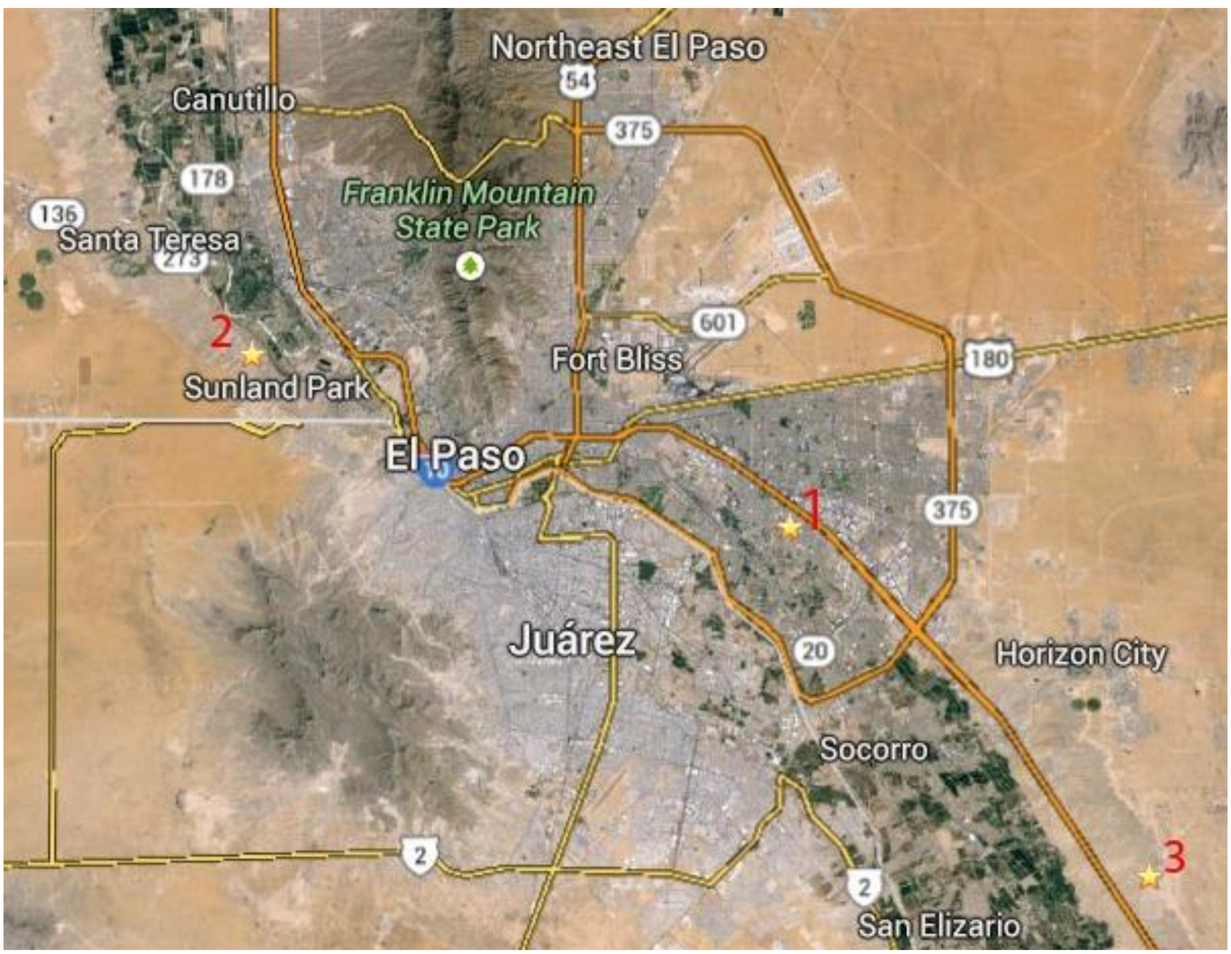

Figure 5.2 [1] Environmental Services Department headquarter, [2] Camino landfill, [3] Greater el Paso landfill

For a waste collection ESD uses trucks with automatic side loading. These trucks can carry a maximum of 10 tons of waste to be able to legally Texas use state highways. ESD set up the maximum weight of 9.5 tons per truck and they use this limit during waste collection route planning. The capacity of these trucks is 31 compacted cubic yards what is 5380.66 gallons.

5.1 Case Study: Waste collection routing in El Paso

The main purpose of this case study is to implement routing tools of TransCAD Version 5.0 software on selected region in El Paso and evaluate results with the currently used routes. ESD uses a specialized software eRoute Logistics Waste developed by Institute of Information Technology for dividing a set of pick up points into separate clusters (sub-networks), which represent areas served by a one route. The actual routes are then planned manually by planners on paper maps.

ESD saves all data about waste container in eRoute Logistics Waste and for further use. It is possible to export these data to a Microsoft Excel Spreadsheet.

For the purpose of this thesis one region containing eight routes (ET-1 to ET-8) was selected. The area covered by these routes lays in the northeast of El Paso at the foothill of Franklin Mountains. The exact position of the area is shown in Figure 5.3.

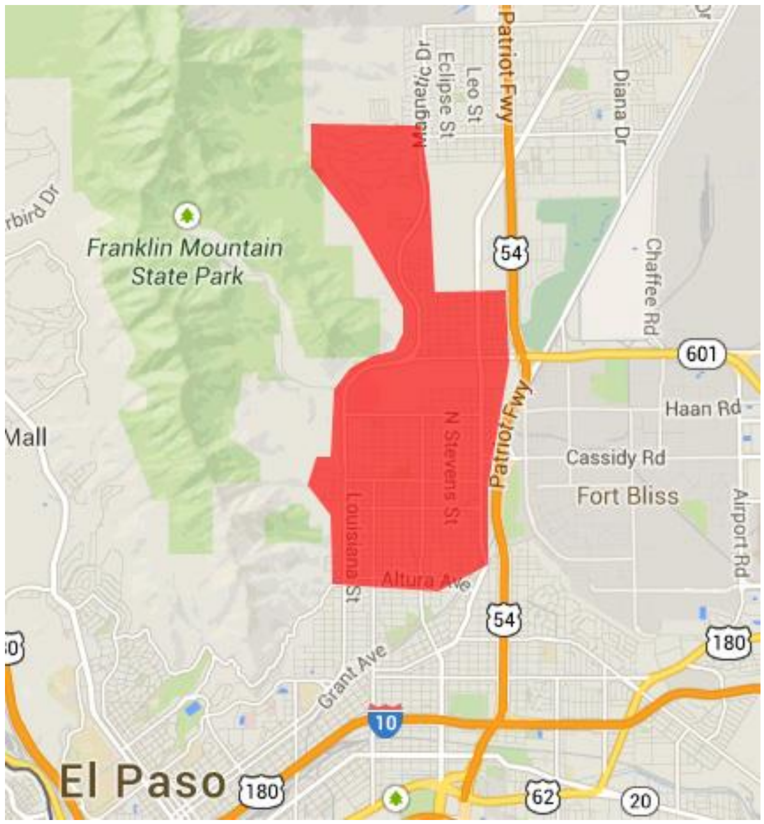

Figure 5.3 Area of the given region

These eight routes cover 7,801 houses and 10,208 waste containers. They are part of Tuesday's waste collection. For the case study, routing optimization was performed for route ET-3 (see Figure 5.4).

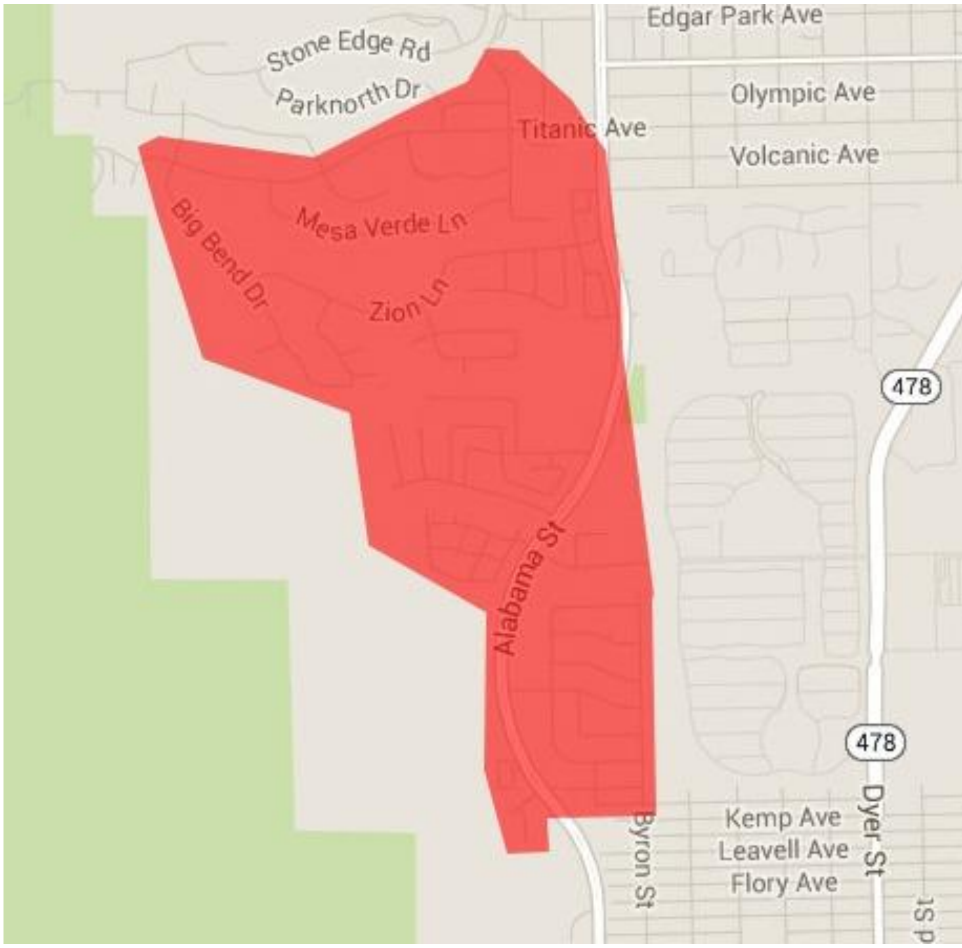

Figure 5.4 Area of the route ET-3

It lies at the north of the given region and streets do not follow a grid pattern. There are also many dead-end streets (cul-de-sac). The area is not compact but formed by smaller neighborhoods connected together by Alabama Street. The route consists of 844 pick-up points and 948 containers.

5.1.1 Data Processing

The data provided by ESD were processed and sorted into columns. The Table 5.1 shows initial and adjusted structure of data columns. Only the container count, latitude and longitude are necessary for the implementation of ARP algorithm.

Table 5.1 Initial and adjusted data

Initial Data	**Process Data**
Route Number	Container Count
Container Count	Longtitude
House Number	Latitude
Street Name	
City	
State	
Zip	
Day of Week	
Operation Area	
Route Type	
X	
Y	
Longtitude	
Latitude	
Container Size	
Service Frequency	

The processed data can be visualized in a map. Using the GPS Visualizer (2014), the GPS coordinates were converted into the KMZ format developed by Google for Google Earth. The visualization allows one to distinguish on which a side of street is the containers are located. Figure 5.5 shows an example of few pick-up points on a route. The numbers next to squares represent container counts.

Figure 5.5 Visualization of pick up points in Google Earth

After visualization it is necessary to prepare a map in TransCAD 5. The map used for this thesis was downloaded from the website Paso Del Norte Mapa (2014). The one with complete street and road network is called “El Paso County Street Centerline” (see Figure 5.6).

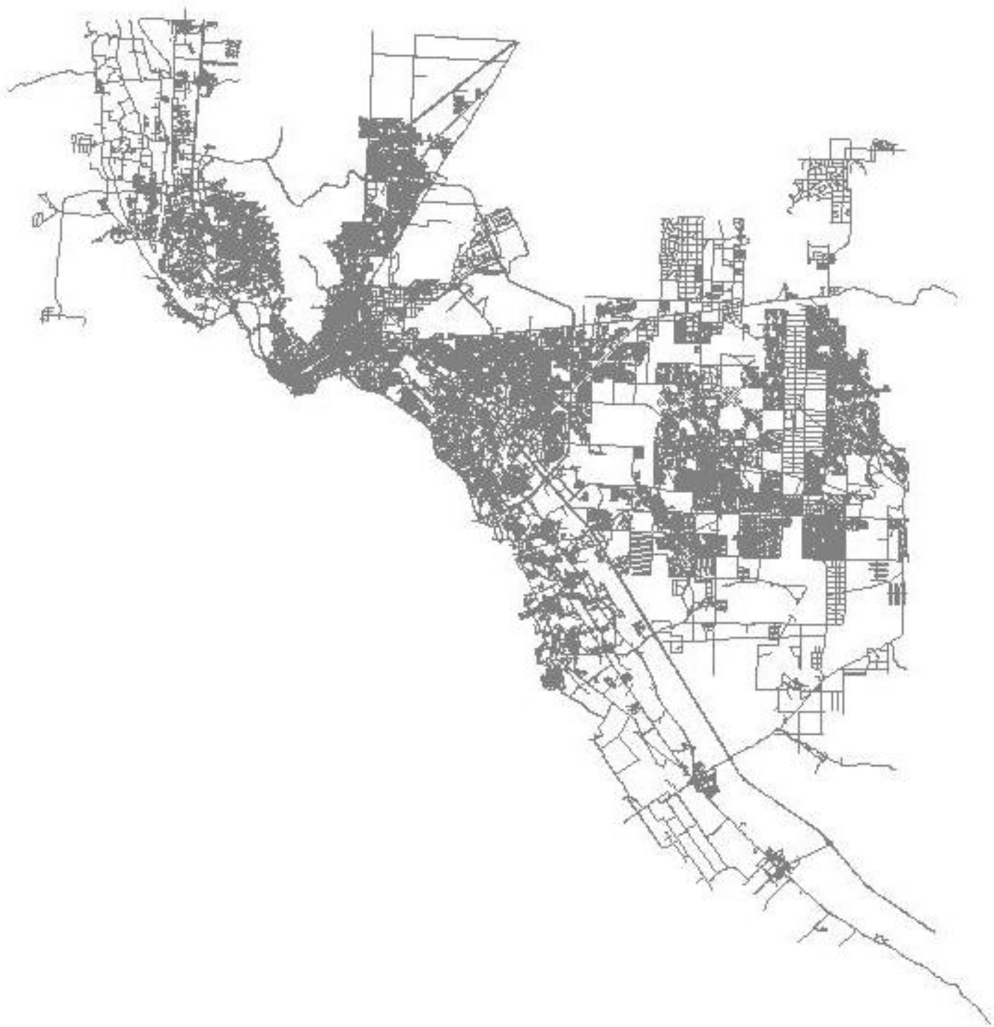

Figure 5.6 El Paso County Street Centerline

Source: Paso Del Norte Mapa (2014)

Figure 5.6 shows the whole El Paso road network. Figure 5.7 is the selected route ET-3 area.

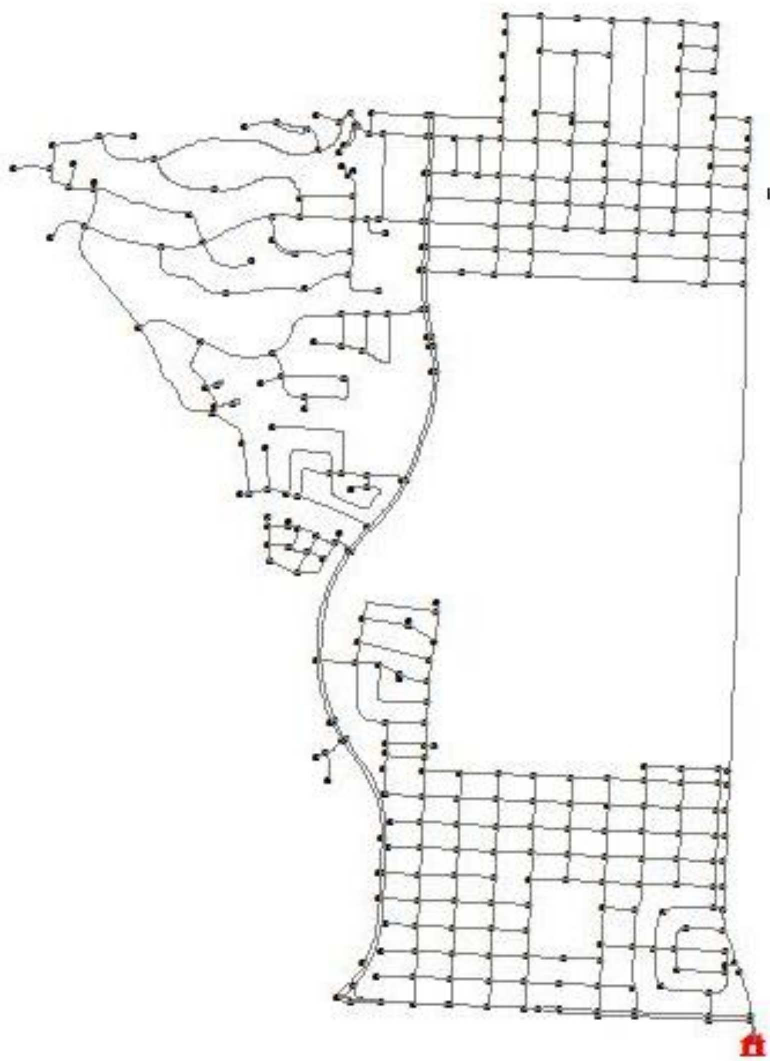

Figure 5.7 Area of the route ET-3 and surroundings

This selected map is a GIS shape file consisting of two layers. The first one comprises links and the second consists of endpoints (nods). Data of the endpoint layer are separated into four columns as shown on Figure 5.8. The most important one is the column with depot selection. A field of a nod where a depot should be located contains value one which serves as an indicator. In this case the depot is the dummy depot and when calculating the total traveled time

or total traveled distance. Later, it is necessary to add to the value obtained by TransCAD the distance or time which take to get from the real depot or the landfill to this dummy depot.

ID	Longitude	Latitude	Depot
19115	-111094444	84108545	--
30894	-111095156	84109680	--
39562	-111216426	84089797	--
39553	-111249872	84088683	--
39559	-111216294	84089364	--
39557	-111228729	84088740	--
39561	-111217264	84087053	--
39543	-111054038	84071939	--
38315	-111053447	84071707	--
23819	-111067544	84074253	--
23820	-111063155	84074345	--
35356	-111072315	84077888	--
23255	-111073876	84080310	--
25302	-111073156	84079102	--
33246	-111071823	84076853	--
35357	-111061429	84073983	--
39549	-111050778	84070742	1
39560	-111216174	84087884	--
35355	-111075783	84083404	--
39554	-111250138	84087517	--

Figure 5.8 Endpoint layer with selected depot

The map is joined in the dataview which provide more information about individual links. The fields included in the dataview are summarized in Table 5.2.

Table 5.2 Fields in the TransCAD dataview

Field Name	Type	Field Name	Type
ID	Integer (4 bytes)	ONW	Character
Length	Real (8 bytes)	COL	Character
Dir	Integer (2 bytes)	COR	Character
ORIG_ID	Integer (4 bytes)	SOD	Character
DIR:1	Character	DLU	Character
STREETNAME	Character	AREAL	Character
STYPE	Character	AREAR	Character
FROMLEFT	Real (8 bytes)	C1_EXCEPTI	Real (8 bytes)
FROMRIGHT	Real (8 bytes)	NO_MSAG	Real (8 bytes)
TORIGHT	Real (8 bytes)	ESNL	Character
TOLEFT	Real (8 bytes)	ESNR	Character
CLASS	Character	STL	Integer (4 bytes)
ZIPR	Real (8 bytes)	STR	Character
ZIPL	Real (8 bytes)	STATUS	Character
MUNR	Character	PRD_ALIAS1	Character
MUNL	Character	STS_ALIAS1	Character
ALIAS1	Character	ADDTYP	Real (8 bytes)
ALIAS2	Character	PRD_ALIAS2	Character
ALIAS3	Character	STS_ALIAS2	Character
PLANAREA	Character	PRD_ALIAS3	Character
EDIT_DATE	Character	STS_ALIAS3	Character
EDITOR_NAM	Character	PRD_ALIAS4	Character
TMPARTERIA	Character	STN_ALIAS4	Character
SPEED	Integer (4 bytes)	STS_ALIAS4	Character
P_LLO	Real (8 bytes)	POD_ALIAS1	Character
P_LHI	Real (8 bytes)	POD_ALIAS2	Character
P_RLO	Real (8 bytes)	POD_ALIAS3	Character
P_RHI	Real (8 bytes)	POD_ALIAS4	Character
STS	Character	SEG_ID	Real (8 bytes)
POD	Character	RoadLevel	Character
		Shape_len	Real (8 bytes)

The above table includes a lot of redundant information which are not needed for Arc Routing Procedure. Therefore it is necessary to completely modify the structure of the dataview

table according to Table 5.3. This table shows which fields are mandatory and have to be added to the data table.

Table 5.3 Dataview prepared for arc routing procedure

Field Name	Type	Width	Decimals	
ID	Integer (4 bytes)	10	0	Mandatory
LENGTH	Real (8 bytes)	10	2	
DIR	Integer (2 bytes)	2	0	Mandatory
STREETNAME	Character	50	0	
AB_SPEED	Real (8 bytes)	10	2	
BA_SPEED	Real (8 bytes)	10	2	
AB_SERVICE SPEED	Real (8 bytes)	10	2	
BA_SERVICE SPEED	Real (8 bytes)	10	2	
AB_SERVICE FLAG	Integer (4 bytes)	8	0	Mandatory
BA_SERVICE FLAG	Integer (4 bytes)	8	0	Mandatory
AB_STOPS	Integer (4 bytes)	12	0	
BA_STOPS	Integer (4 bytes)	12	0	
AB_CONTAINERS	Integer (4 bytes)	12	0	
BA_CONTAINERS	Integer (4 bytes)	12	0	
AB_SERVICE_TIME	Real (8 bytes)	16	3	
BA_SERVICE_TIME	Real (8 bytes)	16	3	
AB_DEADHEAD_TIME	Real (8 bytes)	16	3	Mandatory
BA_DEADHEAD_TIME	Real (8 bytes)	16	3	Mandatory
AB_VOLUME	Real (8 bytes)	10	4	
BA_VOLUME	Real (8 bytes)	10	4	
AB_WEIGHT	Real (8 bytes)	10	4	
BA_WEIGHT	Real (8 bytes)	10	4	
AB_DEADHEAD_WEIGHT	Real (8 bytes)	10	4	
BA_DEADHEAD_WEIGHT	Real (8 bytes)	10	4	
DISTRICT	Integer (4 bytes)	12	0	

The meaning of the fields in the dataview table are explained below:

- ID – Number of a link assigned by TransCAD.
- LENGTH – Length of a link in miles.
- DIR – Direction of a link. This field indicates if a link represents one-way or two-way street. If it contains a zero then a link is two-way. If the link is one-way, this field contains a 1 or a -1. When the direction of the one-way street corresponds with the direction from which coordinates of the line feature are stored (follows topological direction), then the field contains a 1. In the opposite case when the one-way street is in the opposite direction from which the coordinates of the line feature are stored (in the reverse topological direction), the field contains a -1.
- STREETNAME – Name of a street. A street could be divided into several links.
- AB/BA_SPEED – Maximal allowed speed on a link in miles per hour. Indicators AB and BA represent the directions. Figure 5.9 shows a topological view where arrows indicate a topological direction of a link. Into the column which is indicated by AB are inserted values which correspond to the topological direction of a link (direction of arrow). The BA column contains values for the reverse topological direction.

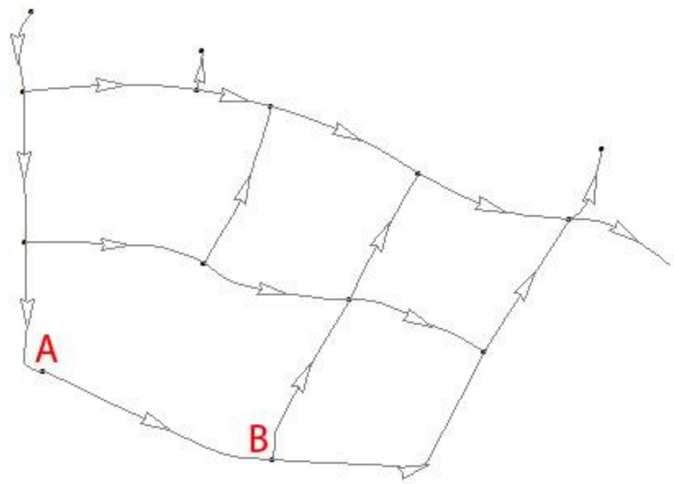

Figure 5.9 Topological style of mapview

Source: author (2014)

- AB/BA_SERVICE SPEED – Speed of a waste collection truck on a link when service is provided. These speeds were calculated from GPS records of trucks servicing the route ET-3 provided by ESD in Microsoft Excel format. Records of two days of operation (April 1. 2014 and April 8. 2014) were provided. The data adjusted into a format which allows filtering and post-processing as illustrated in Figure 5.10.

ID	Asset No.	Date	Time(MDT)	Speed(MPH)	Heading	Log Reason	Distance T	Lat	Lon	Zone	Address
30	Collection	4.1.2014	5:35:30	12,3	West	Motion Start	16,3	31,85298	-106,459		3220 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:35:39	0	West	Motion Stop	16,3	31,853	-106,459		3209 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:36:01	12,6	West	Motion Start	16,3	31,853	-106,459		3205 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:36:12	0	West	Grabber Close, Motion Stop	16,4	31,85299	-106,46		3195 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:36:22	13,2	West	Motion Start	16,4	31,853	-106,46		3193 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:36:27	0	South West West	Grabber Close, Motion Stop	16,4	31,85299	-106,46		3193 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:36:36	12,3	West	Motion Start	16,4	31,85297	-106,46		3191 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:36:43	0	West	Grabber Close, Motion Stop	16,4	31,85298	-106,46		3189 Titanic Ave, El Paso, TX 79904
30	Collection	4.1.2014	5:37:02	12,2	South South West	Motion Start	16,4	31,85288	-106,461		El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:37:14	0	South	Motion Stop	16,4	31,85241	-106,46		3215 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:37:28	15,3	South South East	Motion Start	16,4	31,85226	-106,46		3219 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:37:45	0	South East East	Motion Stop	16,5	31,85162	-106,46		3236 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:38:16	11,3	East	Motion Start	16,5	31,85162	-106,46		3238 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:38:27	0	North East East	Grabber Close, Motion Stop	16,5	31,85167	-106,459		3248 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:38:42	7,6	East	Motion Start	16,5	31,85172	-106,459		3252 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:38:46	0	East	Motion Stop	16,6	31,85171	-106,459		3252 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:38:58	13,4	East	Motion Start	16,6	31,85174	-106,459		3256 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:39:04	0	East	Motion Stop	16,6	31,85174	-106,459		3260 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:39:17	15,1	East	Motion Start	16,6	31,85175	-106,459		3265 El Morro Rd, El Paso, TX 79904
30	Collection	4.1.2014	5:39:54	0	South South East	Motion Stop	16,8	31,85047	-106,457		8007 Tonto Pl, El Paso, TX 79904
30	Collection	4.1.2014	5:40:06	8,1	East	Motion Start	16,8	31,85041	-106,457		8007 Tonto Pl, El Paso, TX 79904
30	Collection	4.1.2014	5:40:09	0	East	Grabber Close, Motion Stop	16,8	31,85041	-106,457		8007 Tonto Pl, El Paso, TX 79904
30	Collection	4.1.2014	5:40:21	14	East	Motion Start	16,8	31,85044	-106,457		8007 Tonto Pl, El Paso, TX 79904
30	Collection	4.1.2014	5:40:31	0	East	Grabber Close, Motion Stop	16,8	31,85047	-106,456		8003 Tonto Pl, El Paso, TX 79904

Figure 5.10 GPS records of route ET-3

The data contains information about the average speed between consequent stops of a truck. The Excel spreadsheet was filtered by “Grabber Close, Motion Stop” in the column Log Reason. Two new columns were added. One represents the speed which follows “Grabber Close, Motion Stop” and second one represents the speed prior to “Grabber Close, Motion Stop”. Parts of a link which each column takes into account are represented by blue line on Figure 5.11.

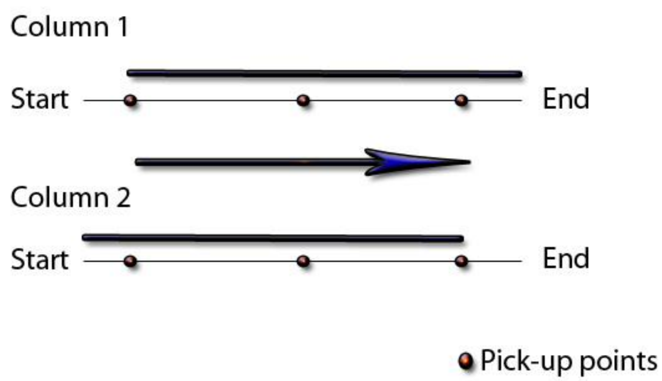

Figure 5.11 Parts of link from which values for speed were taken

Then obtained speed were processed by the Minitab. Basic statistical distribution and graphical visualization of data were found and the results are shown in Figure 5.12 and Figure 5.13.

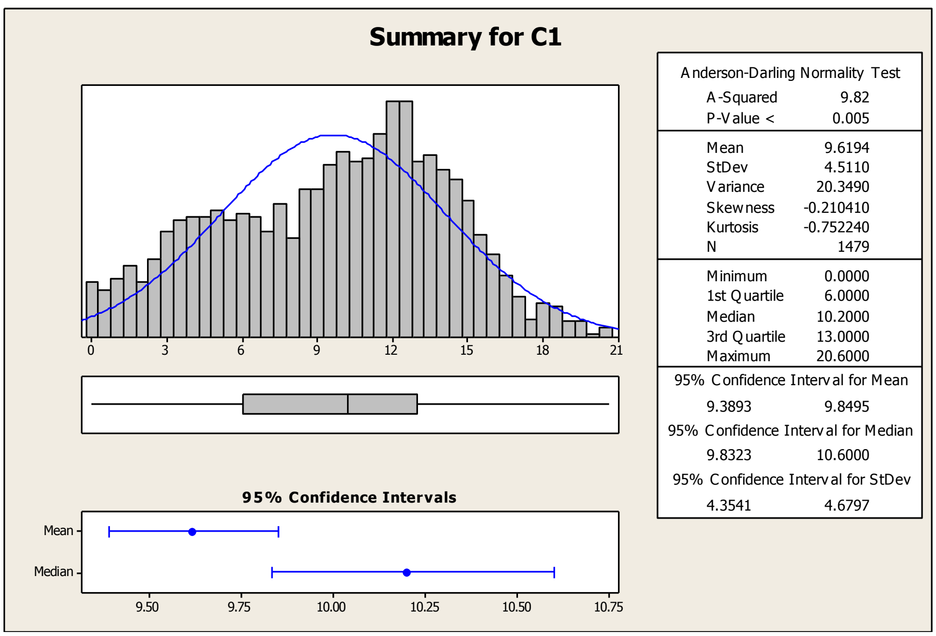

Figure 5.12 Basic statistical analysis for column 1

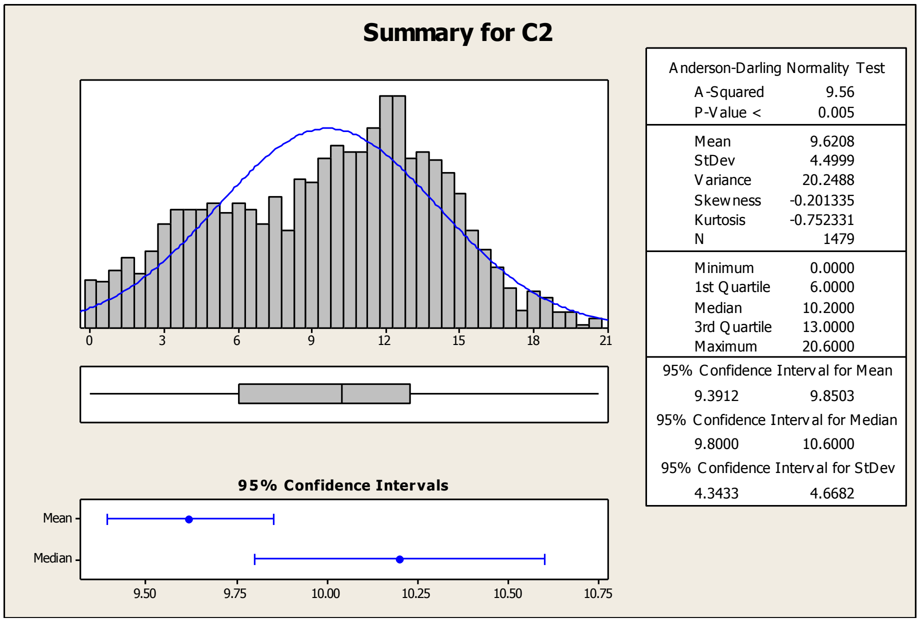

Figure 5.13 Basic statistical analysis for column 2

The median speeds were taken as the AB/BA_SERVICE SPEED. The values for both columns are the same as 10.2 mph.

- AB/BA_SERVICE FLAG – Number that identifies links on which service is required, or that assigns a link to a territory. In this particular case, zero is used for links which do not need to be serviced and 1 for links which require service. AB/BA service flags could also differ because sometimes only one side of a link has to be serviced. Service is required when AB/BA_STOPS > 0.
- AB/BA_STOPS – Number of stops in a link. In this case study a stop is pick-up point with unique GPS coordinates. The numbers in columns were inserted manually by counting pick-up points for particular link represented by grey squares in the Google Earth maps (Figure 5.5). It is necessary to keep in mind that

stops need to be counted for a part of a street which is in accordance with a link in TransCAD.

- AB/BA_CONTAINERS – Number of waste containers on a link. In Google Earth maps containers per pick-up point are represented by numbers next to the grey squares.
- AB/BA _SERVICE_TIME – Time to provide service (in minutes) in a link. The values in this column are calculated according to following equation:

$$\begin{aligned} AB/BA\_SERVICE\_TIME &= \frac{AVG\_STIME \times AB/BA\_STOPS}{60} + \\ &+ \frac{LENGHT}{AB/BA\_SERVICE\ SPEED} \times AB/BA\_SERVICE\ FLAG \times 60\,[\mathrm{min}] \times \\ &\times [AB\_SERVICE\ FLAG] + (1 - [AB\_SERVICE\ FLAG]) \times \\ &\times AB\_DEADHEAD\_TIME \end{aligned} \tag{8}$$

where AVG_STIME in the equations is an average time a truck spent on a pick-up point. The actual value was calculated from data provided by ESD and it is 17 seconds per stop. Given that the data did not distinguish the number of containers at a certain stop, therefore the average time per stop is multiplied by the number of stops on a link. If data about the average handling time of a container were available, the number of stops could be replaced by number of containers.

AB/BA_SERVICE_TIME is the attribute which is minimized by the Arc Routing Procedure in TransCAD. Therefore the equation ensures that links without service will have assigned deadhead time.

- AB/BA_DEADHEAD_TIME – Time of traversing a link without providing service in minutes. The deadhead time for this case study was calculated as:

$$AB/BA\_DEADHEAD\_TIME = \frac{LENGHT}{AB/BA\_SPEED} \times 60 \quad [\mathrm{min}] \qquad (9)$$

  If more detailed data were obtain it would be possible to increase accuracy of this calculation by adding for example a relation for acceleration and deceleration of a truck or by taking into consideration the grade of a link. In that case AB_DEADHEAD_TIME and BA_DEADHEAD_TIME would not have to be equal.

- AB/BA_VOLUME – Volume of waste in gallons collected on a link when service is provided. It is calculated as:

$$AB/B\_VOLUME = AB/BA\_CONTAINERS \times Waste\_volume \qquad (10)$$

  The average city waste container size is according to ESD 96 gallons and the capacity of a waste collection truck is 5380.66 gallons. When the waste volume w set as 96 ft^3 per container the capacity of the truck would be $\frac{5380.66}{96} = 56$ containers. However containers are not usually completely full and in addition the waste collection trucks have waste compression mechanism. Therefore the true waste volume should be set lower. Because ESD did not provided any data about the true waste volume and according their statement waste volume is not a

constrain in route design, this column is created in this case study only for future use. It will not be taken into consideration in this case.

- AB/BA_WEIGHT – Weight of waste in pounds (lbs) collected in a link. The average weight of waste containers varies between 36 and 39 lbs and the allowed capacity of a waste collection truck is 19 000 lbs (9.5 tons). Table 5.4 contains the data about actual weights per load on route ET-3 over eight Tuesdays. The square with red numbers and pink background indicates the shift during which the maximum allowed capacity was exceeded.

Table 5.4 Weights per load on the route ET-3

Tuesday	Weights per Load [tons]							
Route	10.9	17.9	24.9	1.10	8.10	15.10	22.10	29.10
ET-03 Morning	7,775	7,700	8,430	5,140	7,050	7,200	7,380	7,120
ET-03 Afternoon	8,095	4,390	7,420	11,210	5,800	5,890	6,110	5,640

The average weight of container (AW) is calculated according to the following equation>

$$AW = \frac{\sum_{i=1}^{m} (W_{i1} + W_{i2})}{n \times m} \times 2000 [lbs] \qquad (11)$$

where W_{i1} is weight of waste in the morning, W_{i2} is weight of waste in the afternoon, m is number of days which means in this case 8 and n is sum of lifts during morning and afternoon shift. It is equal to 948.

$$AW = \frac{15.87+12.09+15.85+16.35+12.85+13.09+13.49+12.76}{948 \times 8} = 29.63\, lbs$$

The average weight of a waste container in TransCAD was set as 29.63 lbs.

- AB/BA_DEADHEAD WEIGHT – Weight of waste collected in a link without providing service. The value is zero for all entries.
- DISTRICT – ID of depot which serves as a link. The depot could be assigned by a user or by a regional partitioning and clustering procedure. In this case only one depot is used therefore the same district value was assigned to all the nodes manually.

After adjusting data into the correct format and import them into a TransCAD dataview table, a network file is created. A network is a special TransCAD data structure that stores important characteristics of transportation systems and facilities. When creating a network, the line layer is chosen and features are specified. It is important to choose all fields that contain link and node attributes because TransCAD creates a read-only joint file. Figure 5.14 shows how the procedure should look like.

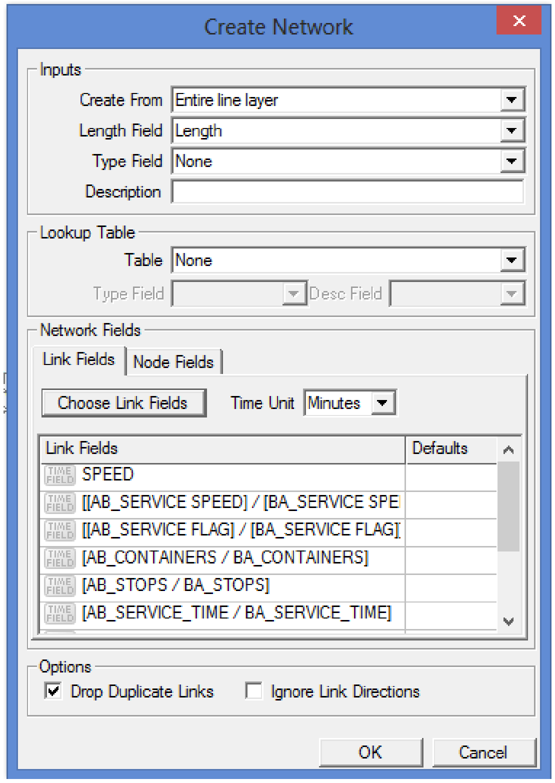

Figure 5.14 Creating a network in TransCAD

To perform the Arc Routing Procedure, a depot has to be selected as separate layer. Therefore a selection tool is used and the depot is selected by condition from a set of nodes according Figure 5.15.

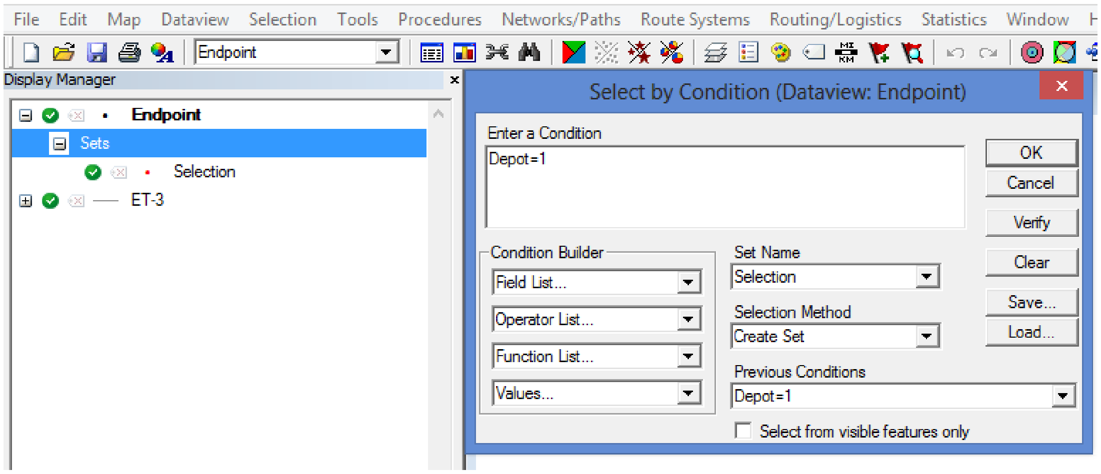

Figure 5.15 Selection of the depot

After this step everything is prepared to run the Arc Routing Procedure. In this procedure a few options have to be chosen to ensure that the optimization will work properly. Figure 5.16 shows the dialog window of the Arc Routing Procedure in TransCAD with all the fields filled correctly.

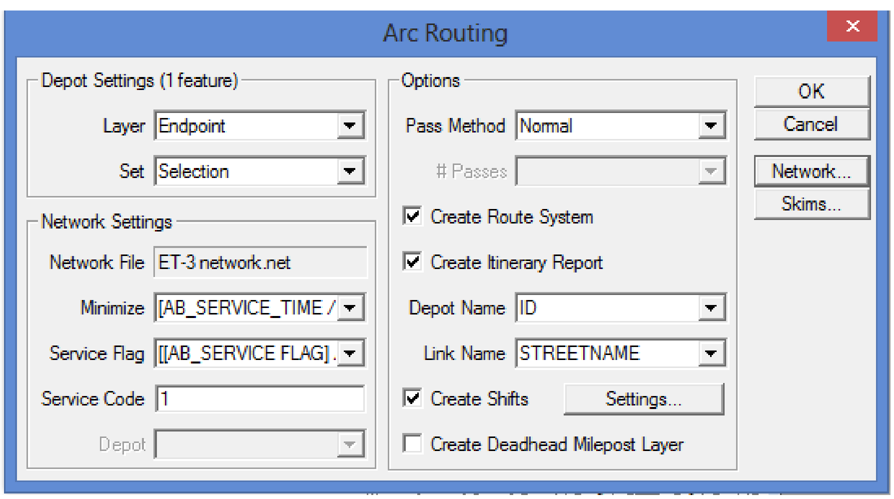

Figure 5.16 Arc Routing Procedure in TransCAD

First the position of the depot is selected from drop-down list. In this case it is the "Endpoint" layer. Then the next field represents the selection of depot or set of depots.

Network Setting defines which attribute will be minimized and how the links which require service are identified. In this particular case routes will be designed to minimize service time. Serviced links are identified by service flag of value 1.

Other options include pass method which has three alternatives. Normal passing means that each link is served once in each direction. Both Curbs means that two-way links are served once in each direction and one-way links are served twice. The last option is User Specified when the user could choose the number of passes of a link.

When route system is created the suggested routes are visualized and added as a new layer into the current map. It is possible to generate an itinerary report with detailed directions for waste collection truck drivers. TransCAD allows the creation of shifts so that the optimized route is divided into shorter routes which suit to certain constrains. There are two options on how to specify the number of shifts. First a user can directly assigned the number of shifts. The dialog window of this procedure is shown on Figure 5.17.

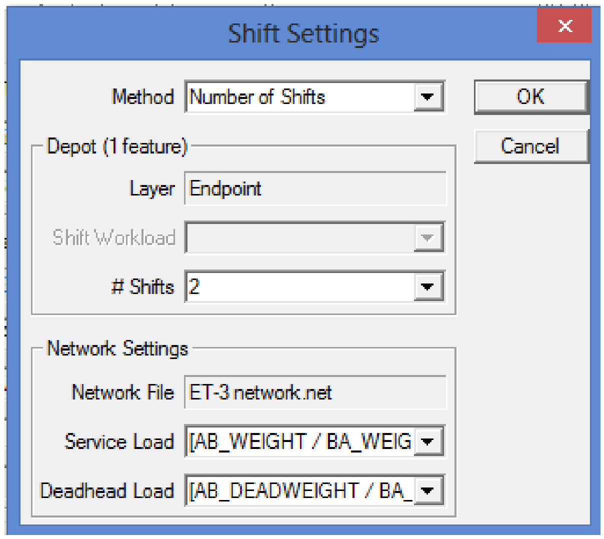

Figure 5.17 Shift Settings dialog window

Another option is to set up the maximum workload for one route (for example, limiting the capacity of truck). TransCAD will ensured that this constrain will not be exceed. It is also necessary to specify which attribute should be considered as the constrain. In this case weight is the limiting factor.

Another constrains that could be added to the procedure is to penalize or prohibit some moves of a truck, such as left turn, U-turn, right turn etc. For this case the turn penalty for left turns were used and it was set to 15 seconds. This penalty reflects the fact that right turns save time. FedEx and UPS introduced the policy of right turn preference and it helped to save them nearly 30 million miles and more than 3 million gallons of gas per year (Arnold 2012). The network setting dialog window is shown on Figure 5.18.

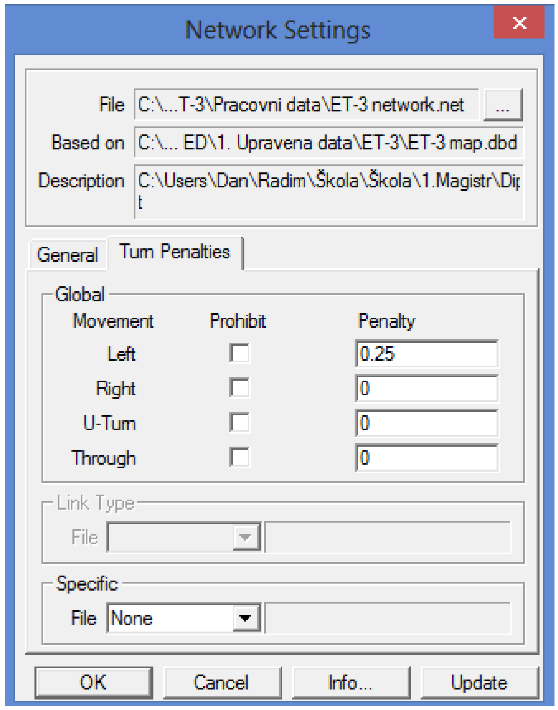

Figure 5.18 Left-turn penalty setting

The Arc Routing Procedure can compute any number of statistics for every created route. These statistics are called skims and they are the sums of various link attributes over portions of the route. They can be computed for the entire route, for the portion of the route spent in-service, and for the deadhead portion of the route. For this case skimming of service time was used as shown in Figure 5.19.

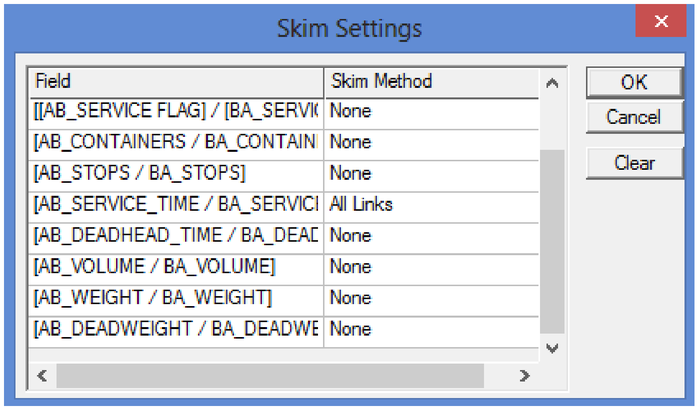

Figure 5.19 Skimming of service time

Outputs of the Arc Routing Procedure are visualized routes in the map and itinerary of the whole route before it is divided into sub-routes. Also new layer with sub-routes containing a dataview table with parameters and statistics were chosen in the Skim Setting.

The itinerary could be divided into sub-itineraries by the procedure Route Service Directions. Dialogue window is in Figure 5.20. Unfortunately the sub-routes does not start and end in the same place (one route starts in the dummy depot and ends somewhere in service area and a second route starts on the place where first route ended and ends in dummy depot). Therefore travel times to starts or ends of these routes from dummy depot have to be calculated.

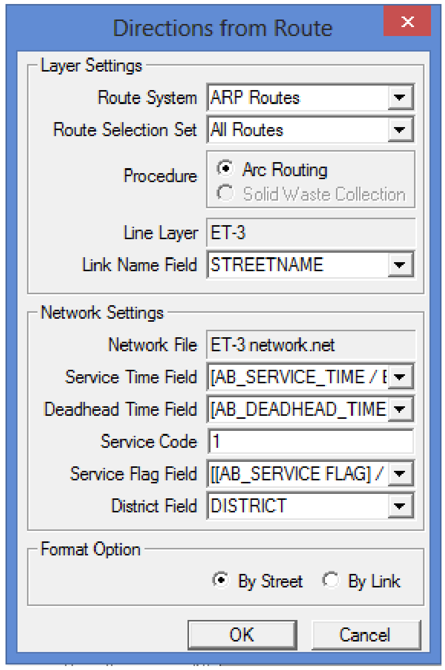

Figure 5.20 Dialogue window for the Route Service Directions procedure

Chapter 6: Evaluation of Results

To compare results of the current routes and routes obtained by TransCAD, an evaluation of current routes has to be done first.

The City of El Paso ESD provided a map with manually planned routes. This map is shown in Figure 6.1.

Figure 6.1 Map of current ET-3 routes

Source: City of El Paso Environmental Services (2014)

The manually drawn ET-3 route consists of two sub-routes. The startings and end points are labeled by green and red marks, respectively. The first route is served early in the morning and the second one early in the afternoon. The total service times were calculated according to the data entred into TransCAD. The service times in each link were displayed (see Figure 6.2) and then the total time was manually calculated following the paths of the current routes.

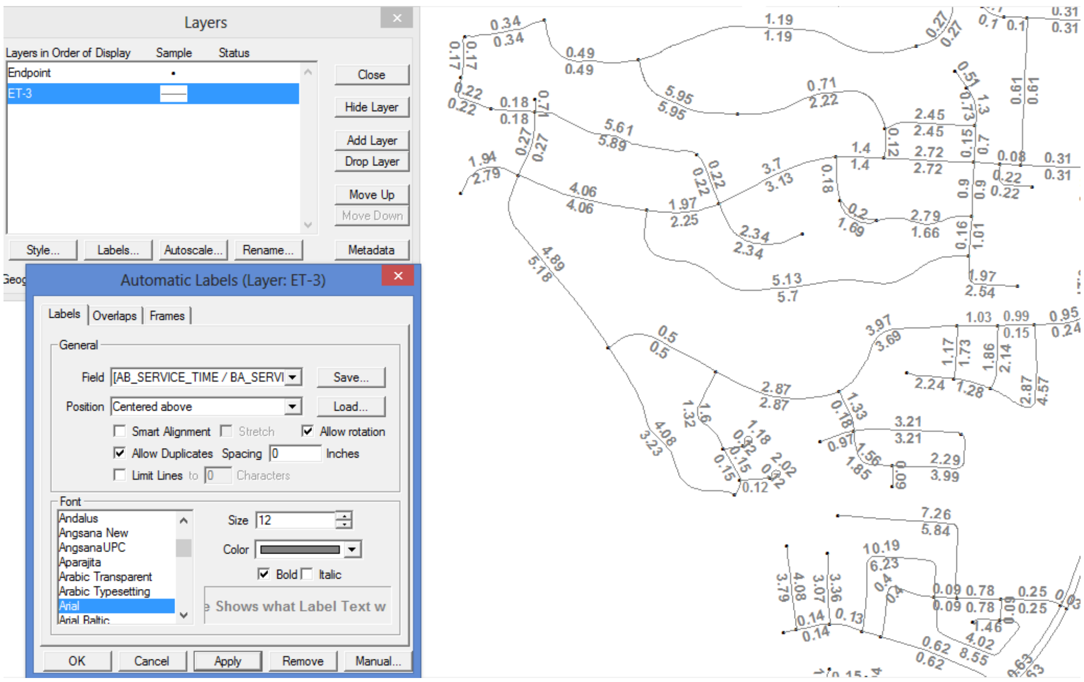

Figure 6.2 Displayed service times on links in TransCAD

During the calculation, left, right and U-turns were counted as well.

Table 6.1 shows the results obtained.

Table 6.1 Statistics of current routes

	West route	**East route**	**Total**
Service time [min.]	196.34	182.465	378.805
Number of right turns	46	36	82
Number of left turns	16	9	25
Number of U-turns	12	15	27

Then the Arc Routing Procedure was run few times in TransCAD with different conditions (which will be explained later) to see how the results will vary.

First, the position of a dummy depot was decided. One depot (Depot 1) was placed at the southeast corner of the network. This point can easily be accessed from the Patriot Freeway (U.S. 54). This depot location allows TransCAD to suggest the best access path to the service area. The node representing the intersection of Alabama Street and Hueco Vista Way was chosen as the second dummy depot (Depot 2). According to the GPS records provided by ESD, truck drivers start their collection routes at the intersection of Hueco Vista Way and Alabama Street. Alabama Street is the main four-lane street providing a good connection to the I-10 Freeway and Patrol Freeway. Routes for these depots were generated and compared. Two shifts (i.e., two sub-routes) and 15 seconds left-turn penalty were used.

The waste collection truck starts its shift in the depot and goes to the dummy depot from where the service begins. After finishing the first sub-route, the truck continues to the landfill, where it unloads all collected waste and then goes back to the service area to the point where the second sub-route starts. After going through the second sub-route the trucks visits the landfill for the second time and from there it goes back to the depot. The total travel time is calculated according the following equation:

$$tt_i = ts_{1i} + ts_{2i} + t_{e_i l} + t_{ls_i} + t_{il} + t_{id} + t_{dl} - p_i \qquad (12)$$

where i distinguishes the depot from which the total travel time is calculated; ts_{1i} is the service time of route one; ts_{2i} is the service time of route two, t_{eil} is the travel time from an end point of a route to a landfill; t_{lsi} is the travel time from a landfill to the start of a route two; t_{il} is the travel time from the dummy depot to the landfill; t_{id} is a travel time from the dummy depot to the real depot; t_{dl} is the travel time from the landfill to the real depot; p_i represents total penalty time if turn penalties are applied. Except the service times and turn penalties which were calculated by TransCAD all other values were calculated by Google Maps.

Table 6.2 Comparison of the routes with different depots

	Time (minutes)	
	Depot 1	**Depot 2**
ts_{1i}	196.56	201.75
ts_{2i}	190.9	177.57
t_{eil}	27	26
t_{lsi}	27	26
t_{il}	21	24
t_{id}	14	17
t_{dl}	25	25
p_i	5.5	3
tt_i	**495.96**	**494.32**

Table 6.2 shows the comparison of result for the two dummy depots. The total travel times are comparable, but using depot 2 has slightly better results. Also, current truck drivers prefer to start their collections from this point. Therefore the position of depot 2 was selected for further comparisons.

In the next step routes without and with left-turn penalty of 15 seconds were compared. This comparison used depot 2 and two shifts (two sub-routes).

Table 6.3 Comparison of the routes with and without left turn penalties

	Time (minutes)	
	No penalties	**Left turn penalty**
ts_{1i}	175.41	201.75
ts_{2i}	203.9	177.57
t_{eil}	27	26
t_{lsi}	27	26
t_{il}	24	24
t_{id}	17	17
t_{dl}	25	25
p_i	0	3
tt_i	**499.31**	**494.32**

Table 6.3 shows that the route with penalized left turns has better results. Even though if 12 left turns (3 minutes) were taken into account the route is still better.

The last comparison compares the sub-routes which were divided by different maximal shiftload per route (set to 19,000 lbs; 14,250 lbs and 14,045 in the different runs). The 19,000 lbs limit is the maximum allowed weight per a truck per route. The 14,250 lbs is 75% of the maximum allowed weight per a truck and the 14,045 lbs is half of the total maximum weight which should be collected from all the containers on route ET-3. If the shiftload was under 14,045 lbs TransCAD would design three routes. All routes have the left-turn penalty and use dummy depot 2. No penalty was given for U-turns because most of the U-turns occur at cul-de-sac. They do not incur any delay compared to left turns.

Table 6.4 Comparison of routes with different capacity constrains

	Time (minutes)			
	2 shifts	**max. 19,000 lbs**	**max. 14,250 lbs**	**max. 14,045 lbs**
ts_{1i}	201.75	274.5	203.16	203.16
ts_{2i}	177.57	104.82	176.15	176.15
t_{eil}	26	26	28	28
t_{lsi}	26	26	28	28
t_{il}	24	24	24	24
t_{id}	17	17	17	17
t_{dl}	25	25	25	25
p_i	3	3	2.75	2.75
tt_i	**494.32**	**494.32**	**498.56**	**498.56**

Table 6.4 shows that routes with 19,000 lbs as a capacity constrain and route divided directly into two sub-routes have the same results as earlier runs. However the route constrained by the number of shifts has a more balanced weight load at the end of every sub-route and also service times are more similar (see Table 6.5). Therefore for this route will be compared with the currently used route.

Table 6.5 Weights of collected waste on different routes

	Load at the end of shift (lbs)	
	2 shifts	**max. 19,000 lbs**
Route 1 weight	13659.43	18874.31
Route 2 weight	13303.87	8088.99
Total	26963.3	26963.3

Figure 6.3 shows the best routes from examined variants. Two routes were designed and they are highlighted by the black line with green stripes.

Figure 6.3 Routes with depot 2; 2 shifts and 15 seconds left-turn penalty

The total travel times of the current routes were calculated according to the method introduced above and then results were compared with the best TransCAD routes. The comparisons are in Table 6.6, Table 6.7 and Table 6.8. The lengths of routes represent only lengths of the service routes from dummy depot 2, not the total lengths. They do not include distances to the depot and the landfill and they just serve as additional information. The lengths of the current routes were obtained from GPS records provided by ESD.

Table 6.6 Comparison of the times of the best TransCAD routes with current ones

	Time (minutes)	
	Current route	**Depot 2**
ts_{1i}	196,34	201,75
ts_{2i}	182,47	177,57
t_{eil}	25	26
t_{lsi}	26	26
t_{il}	25	24
t_{id}	18	17
t_{dl}	25	25
p_i	0	3
tt_i	**497,81**	**494,32**

Table 6.7 Comparison of the times of the best TransCAD routes with current ones

	Number of turns	
# of left turns	25	12
# of right turns	82	87
# of U-turns	27	43

Table 6.8 Comparison of the route lengths of the best TransCAD routes with current ones

	Length (miles)	
Length of route 1	16,8	16,96
Length of route 2	12,6	12,49
Total length	**29,4**	**29,45**

6.1 DISCUSSION

Above tables shows that TransCAD is able to provide the comparable solution with the one created by experienced route planners. The time saving is 3.49 minutes and the total travel time on the both routes exceeds eight hours. The number of left turns was reduced by 13, but the number of U-turns is increased by 16 on routes designed by TransCAD (this is because no penalty was assigned to U-turns). All these changes are minor therefore it is not possible to expect be any significant economic or ecological improvement in the overall performance on the routes if ESD decided to use the ones recommended by TransCAD. However TransCAD could be a useful tool for planning waste collection routes, especially in developing areas of the city, because it allows quickly add new pick-up points and to re-design the current route. TransCAD is therefore suitable for solving ARP and the use of TransCAD could lead, in the long- term horizon, to a cost reduction in route planning.

Chapter 7: Conclusion

7.1 Summary Of research

This thesis provides a review of the urban freight transportation. In Chapter 1 the development of overall freight transportation is described. Chapter 2 narrows its focus on urban freight transportation and its negative externalities. Chapter 3 introduces driving forces of waste generation and the main responses including waste collection, waste management and recycling. Chapter 4 gives an overview of vehicle routing problem and basics of the arc routing problem are described, because planning of efficient routes for waste collection belongs to routing problems. In Chapter 5 provides a description of waste management in El Paso is described along with and a methodology on how to process data obtained from ESD into a format suitable for TransCAD. A procedure of processing these data in TransCAD is described in this chapter as well. Then, Chapter 6 performs a case study in an area in El Paso and then compares the results obtained with TransCAD against the current routes solution used by ESD, with the purpose of and evaluating the suitability of TransCAD for solving waste collection problems.

7.2 Contribution

The main contributions of this thesis are:

- Summary of urban freight transportation negative externalities;
- Comparison of different TransCAD outputs with a currently used solution of waste collection in El Paso; and
- Evaluation of TransCAD's suitability for solving of real life waste collection routing problems.

7.3 FUTURE WORK:

The future work could be focused on the improvement of input data, for instance the model could include the grade of a link in the calculation of link service time. Other direction of future research could lead into developing a larger model with higher amount of pick-up points and evaluate TransCAD capability in partitioning a city into different regions.

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Appendix A: Route 1: Depot 1; Number of Shifts: 2; Left Turn Penalty: 0.25

Route_Name	LeftTurns	RightTurns	UTurns	StraightTurns	Length	[_AB_SERVICE_TIME / B]	[_AB_WEIGHT / BA_WEIG]
Route 1 Shift 1	13	44	16	54	18.23	196.56	12859.42
Route 1 Shift 2	9	51	25	56	15.02	190.90	14103.88

Appendix B: Route 2: Depot 2; Number of Shifts: 2; Left Turn Penalty: 0.25

Route_Name	LeftTurns	RightTurns	UTurns	StraightTurns	Length	[_AB_SERVICE_TIME / B]	[_AB_WEIGHT / BA_WEIG]
Route 1 Shift 1	8	39	19	50	16.96	201.75	13659.43
Route 1 Shift 2	4	48	24	34	12.49	177.57	13303.87

Appendix C: Route 2 Service Directions

Route Service Directions

Service Route ID = 1	
Summary	
Route ID	ROUTE ID 1
Depot/District Name	30896
Workload	
Total Time	201.75
Deadhead Time	7.79
# Deadhead Links	33 (out of 117 links)
# Left Turns	8
# Right Turns	39
# U-Turns	19
# Straight Moves	50
Turn Penalty Cost	2.00

Directions (Group by Street)

No.	Movement	Street Name	Service
1	Start West on	HUECO VISTA	No
2	Left on	LLANO	Yes
3	U-turn on	LLANO	Yes
4	Right on	HUECO VISTA	Yes
5	Left on	ALABAMA	Yes

6	Right on	SUNNYSIDE	Yes
7	Right on	MORNINGSIDE	Yes
8	U-turn on	MORNINGSIDE	Yes
9	Continue on	MORNINGSIDE	Yes
10	Right on	SUNNYSIDE	Yes
11	Right on	REGAL	Yes
12	Right on	BYRON	Yes
13	U-turn on	BYRON	Yes
14	Continue on	BYRON	Yes
15	U-turn on	BYRON	Yes
16	Right on	MORNINGSIDE	Yes
17	U-turn on	MORNINGSIDE	Yes
18	Right on	CLEARVIEW	Yes
19	U-turn on	CLEARVIEW	Yes
20	Right on	MORNINGSIDE	Yes
21	Right on	MONTRIDGE	Yes
22	U-turn on	MONTRIDGE	Yes
23	Right on	MONTRIDGE	Yes
24	U-turn on	MONTRIDGE	Yes
25	Right on	MONTRIDGE	Yes
26	Right on	MORNINGSIDE	Yes
27	Right on	BYRON	Yes
28	Right on	REGAL	Yes
29	Right on	SUNNYSIDE	Yes
30	U-turn on	SUNNYSIDE	Yes
31	Right on	SUNNYSIDE	Yes
32	U-turn on	SUNNYSIDE	Yes

33	Continue on	SUNNYSIDE	Yes
34	U-turn on	SUNNYSIDE	Yes
35	U-turn on	SUNNYSIDE	No
36	Right on	ALABAMA	No
37	Left on	MOUNTAIN RIDGE	No
38	Right on	ALABAMA	No
39	Left on	STONEY HILL	No
40	Right on	UMBRIA	Yes
41	Continue on	EILEEN	Yes
42	Right on	EVANS	Yes
43	Right on	MOUNTAIN WALK	No
44	Left on	ALABAMA	No
45	Left on	ZION	Yes
46	Left on	CEDAR BREAKS	Yes
47	Right on	BIG BEND	Yes
48	Right on	TITANIC	Yes
49	Right on	MESA VERDE	Yes
50	Right on	TONTO	Yes
51	U-turn on	TONTO	Yes
52	Continue on	TONTO	Yes
53	U-turn on	TONTO	Yes
54	Right on	TONTO	Yes
55	U-turn on	TONTO	Yes
56	Continue on	TONTO	Yes
57	Right on	MALAPAI	Yes
58	Right on	PARK NORTH	Yes
59	U-turn on	PARK NORTH	Yes
60	Continue on	PARK NORTH	Yes
61	Left on	MALAPAI	Yes
62	Right on	TONTO	Yes
63	Right on	EL MORRO	Yes

64	U-turn on	EL MORRO	Yes
65	Continue on	EL MORRO	Yes
66	Right on	TONTO	Yes
67	Right on	MESA VERDE	Yes
68	Right on	TITANIC	Yes
69	Right on	DEVILS TOWERS	Yes
70	U-turn on	DEVILS TOWERS	Yes
71	Right on	TITANIC	Yes
72	U-turn on	TITANIC	Yes
73	Continue on	TITANIC	Yes
74	Right on	DEVILS TOWER	Yes

Service Route ID = 2

Summary

Route ID	ROUTE ID 2
Depot/District Name	30896
Workload	
Total Time	177.57
Deadhead Time	7.24
# Deadhead Links	39 (out of 111 links)
# Left Turns	4
# Right Turns	48
# U-Turns	24
# Straight Moves	34
Turn Penalty Cost	1.00

Directions (Group by Street)

No.	Movement	Street Name	Service
1	Start North on	BIG BEND	Yes
2	U-turn on	BIG BEND	Yes
3	Left on	DEVILS TOWER	Yes
4	Right on	TITANIC	Yes

5	U-turn on	TITANIC	Yes
6	Right on	BIG BEND	Yes
7	Left on	CEDAR BREAKS	Yes
8	U-turn on	CEDAR BREAKS	No
9	U-turn on	CEDAR BREAKS	No
10	Right on	CEDAR BREAKS	No
11	Right on	ZION	Yes
12	Right on	GRAN QUIVIRA	Yes
13	Right on	PAGOSA	Yes
14	U-turn on	PAGOSA	Yes
15	Right on	GRAN QUIVIRA	Yes
16	U-turn on	GRAN QUIVIRA	Yes
17	Right on	PAGOSA	Yes
18	Continue on	GRAN QUIVIRA	Yes
19	U-turn on	GRAN QUIVIRA	Yes
20	Continue on	PAGOSA	Yes
21	Right on	GRAN QUIVIRA	Yes
22	Right on	ZION	Yes
23	Right on	GRAND CANYON	Yes
24	Right on	OLD SPANISH TRAIL	Yes
25	U-turn on	OLD SPANISH TRAIL	Yes
26	Continue on	OLD SPANISH TRAIL	Yes
27	U-turn on	OLD SPANISH TRAIL	Yes

	28	Continue on	OLD SPANISH TRAIL	Yes
	29	Right on	GRAND CANYON	Yes
	30	Right on	ZION	Yes
	31	Right on	YOSEMITE	Yes
	32	U-turn on	YOSEMITE	Yes
	33	Right on	ZION	Yes
	34	Right on	ALABAMA	No
	35	Right on	MOUNTAIN WALK	No
	36	U-turn on	MOUNTAIN WALK	Yes
	37	Left on	MOUNTAIN WALK	Yes
	38	Right on	EVANS	Yes
	39	Right on	EILEEN	Yes
	40	U-turn on	EILEEN	Yes
	41	Continue on	EILEEN	Yes
	42	Continue on	UMBRIA	Yes
	43	Right on	STONEY HILL	Yes
	44	Right on	EMMETT LARKIN	Yes
	45	U-turn on	EMMETT LARKIN	Yes
	46	Right on	STONEY HILL	Yes
	47	Right on	BIG BEND	Yes
	48	U-turn on	BIG BEND	Yes
	49	Left on	STONEY HILL	Yes
	50	Right on	ALABAMA	No
	51	Right on	MOUNTAIN RIDGE	No
	52	Right on	RIDGE TOP	Yes
	53	U-turn on	RIDGE TOP	Yes
	54	Right on	MOUNTAIN RIDGE	Yes

	55	U-turn on	MOUNTAIN RIDGE	Yes
	56	Right on	MOUNTAIN RIDGE	Yes
	57	Right on	RIDGE TOP	Yes
	58	U-turn on	RIDGE TOP	Yes
	59	Continue on	RIDGE TOP	Yes
	60	U-turn on	RIDGE TOP	Yes
	61	Right on	RIDGLEY	Yes
	62	U-turn on	RIDGLEY	Yes
	63	Right on	RIDGE TOP	Yes
	64	Right on	RIDGE VIEW	Yes
	65	U-turn on	RIDGE VIEW	Yes
	66	Continue on	RIDGE VIEW	Yes
	67	Right on	RIDGE TOP	Yes
	68	Right on	MOUNTAIN RIDGE	Yes
	69	Right on	RIDGLEY	Yes
	70	U-turn on	RIDGLEY	Yes
	71	Right on	MOUNTAIN RIDGE	Yes
	72	Right on	RIDGE TOP	Yes
	73	U-turn on	RIDGE TOP	Yes
	74	Right on	MOUNTAIN RIDGE	Yes
	75	U-turn on	MOUNTAIN RIDGE	No
	76	U-turn on	MOUNTAIN RIDGE	No
	77	Continue on	MOUNTAIN RIDGE	No
	78	Right on	ALABAMA	No
	79	Right on	HUECO VISTA	No

Appendix D: Route 3: Depot 2; Number of Shifts: 2; No Turn Penalties

Route_Name	TurnPenalty	LeftTurns	RightTurns	UTurns	StraightTurns	Length	[_AB_SERVICE_TIME / B]	[_AB_WEIGHT / BA_WEIG]
Route 1 Shift 1	0.00	29	19	19	47	12.80	175.41	12948.31
Route 1 Shift 2	0.00	27	29	19	37	16.65	203.90	14014.99

Appendix E: Route 4: Depot 2; Maximal Shiftload: 19,000 lbs, Left Turn Penalty: 0.25

Route_Name	LeftTurns	RightTurns	UTurns	StraightTurns	Length	[_AB_SERVICE_TIME / B]	[_AB_WEIGHT / BA_WEIG]
Route 1 Shift 1	10	57	28	61	22.37	274.50	18874.31
Route 1 Shift 2	2	30	15	23	7.08	104.82	8088.99

Appendix F: Route 5: Depot 2; Maximal Shiftload 14,250 lbs; Left Turn Penalty: 0.25

Route_Name	TurnPenalty	LeftTurns	RightTurns	UTurns	StraightTurns	Length	[_AB_SERVICE_TIME / B]	[_AB_WEIGHT / BA_WEIG]
Route 1 Shift 1	2.00	8	40	20	50	17.00	203.16	13837.21
Route 1 Shift 2	0.75	3	48	23	34	12.44	176.15	13126.09

Appendix G: Route 6: Depot 2; Maximal Shiftload 14,045 lbs, Left Turn Penalty: 0.25

Route_Name	TurnPenalty	LeftTurns	RightTurns	UTurns	StraightTurns	Length	[_AB_SERVICE_TIME / B]	[_AB_WEIGHT / BA_WEIG]
Route 1 Shift 1	2.00	8	40	20	50	17.00	203.16	13837.21
Route 1 Shift 2	0.75	3	48	23	34	12.44	176.15	13126.09

Curriculum vitae

Radim Večeřa was born in Třebíč, Czech Republic on August 23, 1988. In 2012 He received his Bachelor Degree of Transportation Engineering in Technology in Transportation and Telecommunications - Economics and Management in Transport and Telecommunication from the Czech Technical University in Prague (CTU) in 2012. Afterwards he entered the Transatlantic Dual Master Degree Program in Transportation and Logistics Systems run by the Department of Civil Engineering at the University of Texas at El Paso in cooperation with the Czech Technical University in Prague.

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This thesis was typed by Radim Večeřa