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Optimization of Fuel Consumption for Municipal Solid Waste Collection in Al Ain City, UAE

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OPTIMIZATION OF FUEL CONSUMPTION FOR MUNICIPAL SOLID WASTE COLLECTION IN AL AIN CITY, UAE

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This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Sciences

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Declaration of Original Work

I, Elkhalifa Mohamed Zeyada Swar Aldahab, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Optimization of Fuel Consumption for Municipal Solid Waste Collection in Al Ain City, UAE*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Munjed Maraqa, in the College of Engineering at the UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to research, data collection, authorship, presentation and/or publication of this thesis.

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Copy 6 of 6

Abstract

Collection and transportation of municipal solid waste (MSW) often account for a significant amount of the total budget allocated for waste management. A major portion of that is attributed to fuel consumption. Meanwhile, vehicles involved with waste collection can emit significant levels of atmospheric pollutants. Hence, optimization of waste collection yields both financial and environmental benefits. No work has been done to optimize fuel consumption during MSW collection in Al Ain city. In this study, several cases were developed using ArcGIS Network Analyst tool in order to establish optimum conditions for MSW collection in Um Gafa district in Al Ain city, with an objective function of minimization of fuel consumption. A geographic information system was created based on data collection and GPS tracking of collection route and bins position. The study revealed that waste collection at Um Gafa at the current time does not strictly follow U-turn and curb approach policies. When route optimization is applied for similar traffic conditions as the current ones, a saving of 14.3% in fuel consumption is gained. In addition, emitted CO_2 is reduced by 7.2%. However, by strictly following the U-turn and curb approach policy of the traffic department, the relative saving in fuel consumption was much less (5%) as compared to the current practice of vehicle maneuvering for waste collection. Two new models were proposed for optimal number and location of bins. One model was based on a 40-m service zone while the other was based on population density and landuse. By adopting the first model, the number of bins was reduced by 12%, while in the second model the number of bins was reduced by 20%. In both models, more efficient routes in terms of fuel consumption and reduction in emissions have resulted, with second model showing superiority compared to the first model.

Keywords: Geographic Information system (GIS), Municipal Solid waste (MSW), Route Optimization, Waste Collection, Al Ain city.

Title and Abstract (in Arabic)

تحديد استهلاك الوقود الأمثل لعملية جمع ونقل النفايات الصلبة في مدينة العين، الامارات العربية المتحدة

الملخص

ان عملية جمع ونقل النفايات البلدية الصلبة (النفايات الصلبة) تأخذ حيزيا كبيرا من الميزانية الإجمالية المخصصة لادارة النفايات. وجزء كبير من ذلك يرجع الى استهلاك الوقود. وفي الوقت نفسه، فان المركبات المستخدمة في جمع النفايات تنبعث منها ملوثات غازية مختلفة، وبالتالي، فان عملية تحسين جمع ونقل النفايات ينتج عنها فوائد مالية و بيئية. لم يتم إنجاز أي عمل مسبق لتحسين استهلاك الوقود خلال جمع ونقل النفايات الصلبة في مدينة العين. لذلك في هذه الدراسة، تم استخدام نظم المعلومات الجغرافية (ArcGIS) لانشاء المسار الأمثل لجمع النفايات بمنطقة أم غافا بمدينة العين، وذلك بهدف التقليل من استهلاك الوقود. وكشفت الدراسة أن جمع النفايات في منطقة ام غافا في الوقت الحالي لا يتبع بدقة القواعد المرورية للأنعطاف والوصول الى حاويات النفايات. وعند تطبيق المسار الأمثل للمسار الحالي المتبع و بنفس الظروف المرورية، يتم توفير 3 ..1% من الوقود المستهلك. بالإضافة إلى ذلك، يتم تقليل غاز ثاني أكسيد الكربون (CO_2) المنبعث بنسبة 7.2٪. ولكن من خلال الالتزام بقواعد المرور، فان التوفير النسبي في استهلاك الوقود سيبلغ نحو 5٪ مقارنة بالوضع الحالي المتبع في جمع النفايات. وتم اقتراح نموذجين جديدين بالأعداد اللازمة والمواقع الصحيحة للحاويات. واعتمد النموذج الأول على توفير منطقة خدمة في حدود 40م بينما اعتمد النموذج الثاني على التوزيع السكاني والنشاطات المرتبطة بذلك. ومن خلال اعتماد النموذجين تم تقليل عدد الحاويات في النموذج الاول بنسبة 12% وفي النموذج الثاني بنسبة 20% ، مما ساهم في مسارين أكثر كفاءة من حيث استهلاك الوقود والتقليل من الانبعاثاث الغازية. وأظهرت النتائج كفاءة النموذج الثاني مقارنة بالنموذج الأول.

مفاهيم البحث الرئيسية: نظم المعلومات الجغرافية (GIS)، النفايات البلدية الصلبة، المسار الأمثل، جمع النفايات، مدينة العين.

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Dedication

I dedicate this thesis work to my family, to my loving parents who never stopped short on giving me encouragement and pushed me to do the best I can. I also dedicate this work to all siblings who supported me every time I encounter some difficulty during the course of my work

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Management of municipal solid waste (MSW) is one of the most challenging issues concerning protection of the environment and conservation of natural resources faced by developing countries. The purpose of MSW management is to ensure solid waste is managed in such a way that it protects both public health and the environment. MSW management is characterized by various kinds of objectives, constraints and a multidisciplinary activity that includes collection, transportation, treatment and disposal of the waste to find solutions that are economically and environmentally sustainable.

Unsustainable and inadequate collection, recycling or treatment and uncontrolled disposal of waste in dumps are sensitive issues that could lead to severe hazards, such as health risks and environmental pollution in today's world which can contribute to pollution of water, land, and air as well as putting people at risk. Direct dumping of waste without proper inspection and separation, usually occurs in low- and mid-income countries, leads to a serious environmental impact which causes a tremendous growth in health-related problems. "Domestic, industrial, and other wastes, whether they are of low or medium level, are causing environmental pollution and have become perennial problems for mankind" (Ramasamy et al., 2003).

In response to waste management challenges (i.e., low collection coverage, unavailable transport services, and a lack of suitable treatment and disposal facilities), some municipalities often privatize waste management services. However, the consumption levels of people around the world are not the same. Thus, the amount of waste generated is often linked directly to income level and lifestyle. In rapidly growing cities of developing world and a high rate of population growth, thousands of tons of MSW are generated and must be managed daily. The problem is also faced by industrialized economies, which have to find ways to minimize or recycle generated waste. Thus, MSW management industry is affected by multiple factors including changes in population, waste generation rates, technology, consumer behavior, and the state of the economy.

Most of municipal bodies are unable to provide a 100% efficient MSW management system and even are not able to reach to an efficiency of 60%. Solid waste management frequently suffers more than other municipal service when budget allocations and cuts are made. Management of solid waste refers to the handling of waste material from generation at the source through the recovery processes to disposal. Improving solid waste management in developing countries requires efforts to increase funding raise, public awareness, and build expertise.

Newly industrialized countries like the UAE is confronted with enormous solid waste management problems that will severely strain municipal financial resources and the handling of the ever increasing waste volumes. There has been a significant increase in MSW generation in the UAE in the last few decades. This is largely because of rapid population growth, economic development in the country, and high-consuming society. Solid waste management has become a major environmental issue in the UAE. The per capita MSW generated daily in the country ranges from 1.8 to 2.4 kg in large towns, with an average collection efficiency of about 82.5% (CWM-AD, 2015).

Nonetheless, the UAE government is working hard to reduce the per capita waste generation rate, which is one of the highest in the world, and started privatizing solid waste management in order to meet the collection and disposal demand of the enormous waste being generated. Few local bodies in the country have prepared long term plans for effective solid waste management in their respective cities. For obtaining a long-term economic solution, planning of the system on long term sustainable basis is very essential.

Waste collection is the most fuel intensive step in waste management. It accounts for 40 to 60% of the total MSW management budget (Bueno, 2011). Many problems are encountered during collection such as variation of waste production over time, large extension of area to be served, traffic and viability conditions, labor costs and lack of logistic planning. Most of the waste collection fleet is composed of diesel fueled vehicles which contribute to significant atmospheric emissions, including greenhouse gases (GHGs). Thus, the waste collection industry has a significant carbon footprint. More stringent emission standards, national energy security policies, and pollution concerns have led to the investigation and testing of fuel consumption, reductions in road time, and optimization of equipment. However, collection and disposal services for MSW are not perceived as deserving higher priority. Therefore, little effort has been directed towards assessing the cost of waste services and increases their cost effectiveness in the country. Particularly, no work has been done to optimize fuel consumption during MSW collection and transportation. Also, it is not clear if the currently adopted practice of waste collection and transportation results in an optimum solution in terms of fuel consumption.

1.2 Objectives of Study

The main objective of this project is to develop a GIS-based model to calculate fuel consumption of vehicles that collect and transport MSW in Um Gafa area in the city of Al Ain. Based on the developed model, it will be possible to establish optimum conditions for waste collection and transportation for the studied area. The optimum condition is defined as the one that minimizes fuel consumption. Results of this study can be used to improve the efficiency of waste management system in the city and thereby reduces the cost of waste collection and transportation and could ultimately results in environmental benefits.

Constraints such as truck speed, and time needed to lift collection bins, and bins location will be considered. The scale of the network will include Um Gafa area in the city of Al Ain from which solid waste is currently being collected. Different alternative scenarios for waste collection will be explored. Specifically, the study intends to:

1. Determine fuel consumption for solid waste collection in Um Gafa area in Al Ain city under the current conditions.
2. Explore different alternative scenarios to reduce fuel consumption associated with solid waste collection.
3. Determine fuel consumption with the explored scenarios. It should be indicated that reducing fuel consumption may not necessarily reduce the cost as newer vehicles could be suggested that results in lesser fuel consumption but could increase the cost.
4. Compare the amount of emitted greenhouse gases of the explored scenarios with those emitted under current conditions.

1.3 Scope of Work

The scope of work comprises mainly the following:

1. Study of Network Analyst extension of Arc View GIS.
2. Review of existing practices of solid waste management in Um Gafa district in Al Ain city.
3. Apply Network Analyst extension to arrive at the optimal route waste collection at Um Gafa area.
4. Calculate fuel consumption and emitted greenhouse gases under the current conditions and for different explored scenarios using SIDRA TRIP software.

1.4 General Approach

This study involves the following tasks:

Task 1: Study solid waste collection in Um Gafa district in Al Ain city under current conditions.

Task 2: Develop a GIS-based model to explore different alternative scenarios to arrive at the optimal route for waste collection in Um Gafa district.

Task 3: Calculate fuel consumption under the current conditions and for the explored different scenarios.

Task 4: Calculate emitted greenhouse gases under the current conditions and for the explored different scenarios.

Task 5: Investigate the adequacy of the number and positions of existing collection bins in Um Gafa district and Conduct route optimization.

Chapter 2: Literature Review

2.1 Introduction

In a wider term, waste can be said as, the items which are no more in use and are not expected to be used in future either. The only solution to these items is to destroy them. Waste is also defined as any unwanted or discarded material intentionally thrown away for disposal which has no marketable value (Shekdar, 1999). Waste is resources consumed by inefficient or non-essential activities. However, certain wastes may eventually become resources valuable to others. In other words, somebody’s waste is often someday else’s raw material when they are removed from our ways of life and they are generated at every stage of process of production and development. It is essential to know about the types and sources of waste in an area in order to design and operate an appropriate solid waste management system.

Solid waste is used to describe the unwanted or useless waste material that is not a liquid or gas generated from domestic, trade, commercial and public services. It comprises of countless different materials such as dust, food wastes, packaging in form of paper, metal, plastics or glass, discarded clothing, garden wastes, pathological waste, hazardous waste and radioactive waste. There are also some technical descriptions to the term solid waste. "Solid waste is the term used to describe non-liquid waste materials arising from domestic, trade, commercial, agricultural, industrial activities and from public services" (Palnitkar, 2002). Domestic waste consists of the organic (combustible material) and inorganic (noncombustible material) household waste. It has different characteristics such as density, moisture content, ash content, and constituents which vary from country to country according to the level of industrial development.

MSW includes waste generated from residential, commercial, industrial, institutional, construction and demolition process, and municipal services. Waste characterization consists of collecting waste at its source and directly sorting it out into types of materials. Weighing and sorting of wastes at source makes the identification of waste materials easy and eliminate any uncertainty as to their origins (Bhide and Shekdar, 1998). MSW includes commercial and residential wastes generated in municipal or notified areas in either solid or semi-solid form excluding industrial hazardous wastes but including treated bio-medical wastes. Though the definition of the term will remain the same in all times, but it changes its features in different times.

2.2 Solid Waste Management

Solid waste management is all the activities and actions required to manage waste, and offer solutions, including control of generation, storage, collection, transport or transfer, processing and disposal in a way that best addresses the range of public health, conservation, economics, aesthetic, engineering and other environmental considerations. It also encompasses the legal and regulatory framework that relates to waste management. Solid waste management is an intensive service that includes planning, administrative, financial, engineering and legal functions in the process of solving problems arising from waste materials. The solutions might include complex inter-disciplinary relations among fields such as public health, city and regional planning, political science, geography, sociology, economics, communication and conservation, demography, engineering and material sciences.

Solid waste management practices can be very different between developed and developing nations and for residential and industrial producers, for urban and rural areas. Management of non-hazardous waste, residential and institutional waste in metropolitan areas is usually the responsibility of local government authorities. On the other hand, management of hazardous waste materials is typically the job of the generator, subject to local, national and even international authorities. Nonetheless, the primary goal of solid waste management is to implement integrated solid waste management by reducing and eliminating adverse impacts of waste materials on human health and environment to support economic development and superior quality of life.

2.2.1 Solid Waste Classification

Solid waste could be classified into different types depending on their source as commercial, institutional, residential, agricultural, and industrial. Solid waste could also originate from hospitals and medical centers. Other types of solid waste include construction and demolition waste. The different types of solid waste along with their description are listed in Table 2.1.

It should be noted that solid waste can also be classified according to its properties as biodegradable and non-biodegradable waste. Biodegradable waste may be degraded by living organisms such as papers, wood and fruits. Non-biodegradable waste, on the other hand, cannot be broken down by living organisms, such as plastics, bottles and machines.

2.2.2 Solid Waste Collection

Collection of MSW has important impacts on public health and the appearance of towns and cities. Waste collection is the collection of solid waste from point of production (residential, industrial commercial, institutional) to the point of treatment and disposal. Waste collection service can often be divided into primary and secondary collection services. In primary collection, waste is collected from its source and is transported to a transfer station. Secondary collection is related to waste collected from a transfer station to a treatment facility or a disposal site.

Municipal solid waste is collected house to house or by placing larger bins on the curb that serve a group of users. In the house to house collection, refuse generated and stored in individual premises is collected by several methods or services including curb, alley, setout, setout setback and backyard service.

Table 2.1: Types of solid waste (Bhide and Sundersan, 1983)

Solid waste type	Description
Commercial	All types of solid wastes generated by stores, offices, restaurants, warehouses, and other non-manufacturing activities, excluding residential and industrial waste
Institutional	Solid wastes generated by educational, health care, correctional and other institutional facilities.
Residential	Wastes generated by the normal activities of households including, but not limited to, food wastes, rubbish, ashes, and bulky wastes.
Agricultural	Solid waste that is generated by the rearing of animals, and the producing and harvesting of crops or trees.
Industrial	Solid waste generated by industrial processes and manufacturing.
Construction and Demolition	Waste building materials, packaging, and rubble resulting from construction, remodeling, repair, and demolition operations on pavements, houses, commercial buildings, and other structures.
Hazardous	A waste or combination of wastes of a solid, liquid, contained gaseous, or semisolid form which may cause, or contribute to, an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness, taking into account the toxicity of such waste, its persistence and degradability in nature, its potential for accumulation or concentration in tissue, and other factors that may otherwise cause or contribute to adverse acute or chronic effects on the health of persons or other organisms.
Infectious	Equipment, instruments, utensils, and formites of a disposable nature from the rooms of patients who are suspected to have or have been diagnosed as having a communicable disease and must, therefore, be isolated as required by public health agent. Laboratory wastes, such as pathological specimens (e.g., all tissues, specimens of blood elements, excreta and secretions obtained from patients or laboratory animals) and disposable formites (any substance that may harbor or transmit pathogenic organisms) attendant thereto. Surgical operating room pathologic specimens and disposable formites attendant thereto.

In the curb service the house owner is responsible for placing the refuse containers at the curb on the schedule day, when the work man from solid waste collection vehicles collect and empty the containers in the collection vehicle and place them back at the curb. The house owner is required to take the empty containers to the house. In the alley service, the container is placed at the alley line from where they are picked up by workmen from solid waste collection vehicles who deposit back the empty containers.

In the set-out set-back service, collection crew go to individual houses, collect the containers and empty them in the solid waste collection vehicle. Another collection crew returns them to house owner yard. However, in the set-out service, solid waste workers collect the containers from individual houses and empty them in the collection vehicles, but the house owner is required to take back the empty containers. As for backyard service, solid waste workers carry a bin handcart sack or cloth to the yard and empty the solid waste container in it. The hand cart or bin is subsequently taken to solid waste collection vehicles where it is emptied. Table 2.2 compares the various method of house to house waste collection.

In communal collection service, people are responsible for bringing their waste to one or a number of communal collection points. Communal bin storage placed in street corners, several locations on densely populated streets, or at the edge of neighborhoods or villages accessible to generators and collection vehicles. Vehicles collect and return the containers from their point of origin. Communal systems are common in many industrialized countries like the UAE.

Collected MSW can be separated or mixed, depending on local regulations. Many communities instituted regulations for separation of solid waste at the source by generators such as; food waste, organic matter and recyclables. While other regulations instituted for separation of solid waste at the sorting facility.

Table 2.2: Comparison of various methods of house to house collection (Bhide and Shekdar, 1998)

Description	Curb	Alley	Setout setback	Setout	Backyard
House owner corporation is required to carry full can	Yes	Optional	No	No	No
House owner corporation is required to carry empty can	Yes	Optional	No	No	No
Schedule service is necessary for obtaining owner cooperation	Yes	No	No	Yes	No
Average crew size	1-3	1-3	3-7	1-5	3-5
Services evaluation with reference to service to citizens	Poor	Low	Fair	Low	Good
Services evaluation with reference to crew cost	High	Fair	Medium	Good	Medium

Segregation of MSW is the process by which waste is separated into dry and wet dry waste including metals, glass and wood. MSW also can be segregated on basis of biodegradable or non-biodegradable waste. The degree of separation can vary over time and by city. ‘Separation’ can be a misnomer as waste is not actually separated but rather is placed out for collection in separate containers without first being ‘mixed’ together. Often, especially in developing countries, MSW is not separated or sorted before it is taken for disposal, but recyclables are removed by waste pickers prior to collection, during the collection process, and at disposal sites.

Collected MSW percentage depends on national income. Countries with high income which have relatively good roads collection rates tend to be mechanized, efficient, and frequent, although less of the solid waste management budget goes towards collection and collection costs can represent less than 10% of municipality`s budget. In low-income countries, collection rates tend to be much lower, leading to lower collection frequency and efficiency, although collection services make up the bulk of a municipality's MSW management budget (as high as 80 to 90% in many cases) (Bhide and Shekdar, 1998).

2.2.3 Community Waste Storage

Community waste containers, act as temporary storage for MSW, filled either directly by residents or from primary collection vehicles such as tricycles or handcarts. The stage of waste containers is the point where waste leaves the house and enters a waste management system. Community waste containers are particularly appropriate in densely populated residential areas, such as low-income to medium-income areas with single family dwellings, or multi-story housing in all income groups.

Community waste storage facilities may be either stationary (fixed) or portable and portable containers may be emptied in-situ or replaced with empty containers. The capacity or volume required for a community container depends on the following factors (Rahman, 2008):

1. The quantity of waste arising from households and commercial premises that are expected to use the container, which is usually estimated by dividing the generation rate on a weight basis by the density of waste at the community storage stage. Much depends on how and where the density is measured. It is better to measure the density of the waste as it is found in the container just

before collection rather than to try to estimate the density based on measurements made at the household.

2. The number of people expected to use the container. It may be difficult to know how many people will use any particular container. Residents usually use the container nearest to their dwellings, but sometimes they use containers in the direction that they usually go (to school, work or shops). Numbers using the storage will increase if new housing is built in the area.

3. The type of container. A taller container may provide more compaction of the lower layers of waste caused by the waste above, but tall containers may be difficult for children to use, so that more waste is dumped outside the container. Covered containers that are filled through relatively small openings in the cover may not be filled completely because the waste may form a mound inside the container to block the opening while there is still empty space beside this mound inside the container.

4. Other types of waste that are expected to be put in the container, such as street sweepings, garden waste, construction and demolition waste and commercial waste. If street sweepings are added, this will be on a regular basis and so should be allowed for, but amounts may vary with days of the week and after events. On the other hand, garden waste is usually generated in large quantities at only certain times of the year, and so it may not be reasonable to allow for this when estimating the capacity needed for community containers. Small quantities of construction and demolition debris resulting from minor construction and renovation of dwellings may also be put into community containers. Although the containers may be intended

only for household waste, shops and offices in the area may use these containers because they are more convenient or to avoid making payments for commercial waste collections.

5. The collection method, frequency and time. If the waste is collected six days a week there is an interval of two days over the rest day. For example, if Friday is the rest day and the waste is collected early in the morning from Saturday to Thursday, the waste of Thursday and Friday must be collected early on Saturday morning. In the same way if collection is three times a week, the longest interval between collections is three days, the other intervals being two days each.
6. Seasonal, weekly and random variations in the quantities of household waste should be allowed for. Random variations tend to become less significant when more households are involved as quantities get "averaged out".
7. If the container will be supervised by a municipal employee, it may be possible to allow a lower storage capacity because the employee can distribute and compact the waste in community containers to make space for additional loads. It is very unlikely that residents using a community container will try to rearrange or compact the waste if the container is full; instead they will simply dump their waste on the ground nearby.

2.2.4 Vehicle for Collection and Transfer

The designation and operation of the waste collection system must be conducted in an integrated way. This can be achieved by taking into consideration all of the links in the waste management chain, so that all system components are compatible. There is a wide range of vehicle combinations that are used for collecting waste. This section describes the main factors which should be considered before selecting the preferred type of waste collection vehicle, bearing in mind that the objective of any waste collection system is to collect and transport wastes from specific locations at regular intervals to a disposal site at minimum cost (UNDP, 2010).

2.2.4.1 Frequency of Collection

Frequency of waste collection is defined as the number of times in a week or a month that waste is collected. Frequency of collection is an important parameter of any waste collection system. From health perspective, high frequency of waste collection is needed to avoid accumulation of waste. Frequency of collection is influenced by many factors including the size of the bin, volume of waste generated, cost, climate, public expectations, fly breeding and decomposition. In general, the frequency must be acceptable to the residents; otherwise waste may be dumped in the streets. Residents expect that their waste will be collected every day. If the wastes are allowed to accumulate in the street in large quantities, local people may set fire to the waste, causing harmful and unpleasant local air pollution.

It may be that the freshness of biodegradable waste is a factor to consider if the waste is used to feed animals and to reduce odors at the input end of a compost plant. In hot and humid climates, waste such as food decomposes rapidly, posing an aesthetic and health risk. Decomposing waste will attract disease carrying insects and animals such as flies and rats. Meanwhile, leaving waste in steel containers for longer periods may result in faster corrosion of the containers because the initial decomposition of organic materials produces acids which attack metals.

A further point related to frequency is the issue of reliability. It is very desirable that the frequency does not vary, so that householders and shopkeepers know when their waste will be collected. Small adjustments to collection frequency may be needed because of public holidays, and it is important that generators are informed of these changes in advance. Unexpected fluctuations in frequency undermine confidence in the waste collection service and in municipal management (Amar, 2012).

Cost is another factor that influences frequency of collection. Generally, it is more expensive to collect smaller quantities of waste on more occasions, though the extra cost may not be so high in the case of primary collection with simple equipment where wage levels are low. More frequent collection allows the use of smaller containers, which could be a significant benefit if waste generators are required to carry their waste to a collection point at a particular frequency.

2.2.4.2 Time of Day

Normally waste collection is carried out during the hours of daylight in urban areas. Although collection of the waste at night increases work time and reduces productivity, in some of large congested cities the collection operations may be carried out at night in order to avoid traffic congestion that blocks many roads during daylight hours. Waste collection vehicles themselves cause congestion, particularly if they must stop in narrow streets. There may also be regulations that prevent trucks from using city streets during business hours, to reduce congestion.

In some small cities and towns waste has been collected, and perhaps is still being collected, at night, for reasons that are not clear. Bhide and Shekdar (1998) highlighted possible reasons that influence the decision to collect waste at night including:

1. Due to traffic congestion, waste is collected in the big cities at night, and the smaller cities and towns do the same because of national policy.
2. Most of shopkeepers and residents put their waste out for collection in the evening, after the close of business and after the last meal has been prepared, and therefore the waste is collected at night so that no waste is left for the next morning.
3. When daytime temperatures are very high and the sun is very strong, Collection at night may be preferred by collection crews.
4. Waste collection is considered to be an unpleasant occupation that should not be seen, or waste workers wish to remain anonymous.

Collection at night suffers, however, from several disadvantages, including (Tavares et al., 2009):

1. Residents may object to collection operations at night, when they are trying to sleep as a result of collection vehicles noise, especially compactor trucks.
2. Difficultly of loading waste and sweeping streets at night, especially in places where there is inadequate lighting and female workers may be reluctant to work at night because of fears of harassment.
3. Operation of landfills at night may be difficult if there is inadequate lighting at the landfill site, which can cause accidents especially if pickers are sorting through the freshly dumped waste.
4. Supervision may be less effective.

2.2.4.3 Shift Working

Normally waste collection is carried out during the morning shift (typically 7:00 am to 3:00 pm), while in some of large congested cities the collection operations may be carried out during the night shift (typically 11:00 pm to 7:00 am). Sometimes waste collection agencies provide additional services to business districts and/or to finish work that was not completed during the morning shift. Some workshop managers are reluctant to deploy their vehicles on more than one shift each day, arguing that the vehicles need to be rested or maintained during the other shifts. However, in many situations it may be more economical to use expensive vehicles more intensively and maintain adequate levels of availability by spending more on maintenance, having one or more extra backup vehicles and expecting a shorter economic life from vehicles that are regularly used for two shifts. Decisions on such matters should, however, be based on operational data and calculations, in cases where managers have the opportunity to consider alternatives.

2.2.4.4 Days of the Week

Daily collection of waste may mean collection for seven days a week or for six days a week (i.e., with no work on the weekend rest day). Collection of waste seven days a week requires a larger workforce to allow employees to have one day off each week and may cause problems for supervision. Also, collection on daily basis for 7 days a week may require provision of sufficient storage capacity for the waste of two days if services are suspended on holidays or festivals. Alternate collection days generally mean three days between collections over the weekend, and a greater load of waste to collect after the weekend. In the same way, collection twice a week means collection once after three days and once after four days.

2.2.4.5 Factors Affecting Selection of Vehicle Types

Selecting particular types of vehicles and equipment are mostly concerned with the technical and rational reasons. The task of choosing waste collection vehicles that are supplied are often made by executives who have good knowledge of technical issues. The choice of waste collection vehicle is based on factors including, the stage of collection (primary or secondary), the nature of the waste, topography of the city, the method of waste collection adopted, the budget available for collection, and distance to disposal site. In selecting optimum waste collection vehicle, several decisions should be made related to the characteristics of the machinery required; this includes power source (human or machine powered vehicle), vehicle body, and speed of loading.

The gross vehicle weight (GVW) is defined as the maximum permitted total weight for any fully loaded vehicle (Figure 2.1). GVW should never be exceeded to comply with the regulations and for reliable performance. The total weight available for the body and the load can be estimated by subtracting the weight of the cab and chassis from the GVW. From this must be deducted the body weight to arrive at the payload (i.e., the maximum weight of the load that may be carried). For economic operation, the load actually carried should be as close as possible to the payload, and the payload should be as large as possible. The lighter the body, the heavier the payload, and, if the load carried is equal to the payload, the lower the cost of collection (UNDP, 2010).

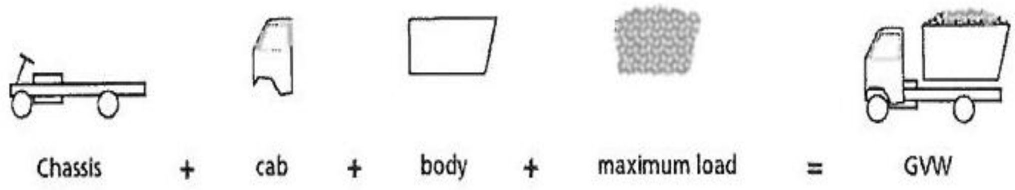


Figure 2.1: Components of the gross vehicle weight (UNDP, 2010)

In many cases the vehicle type, worker productivity and storage system are interrelated. In general, small vehicles can be more productive than large vehicles, where small quantities of waste are collected. Available vehicle types for waste collection include non-dedicated vehicles (handcarts, tractor trailer unit) and purpose-built vehicles (compactor vehicle, drop sided lorries). In high income and industrial countries, compaction vehicles are the standard MSW collection vehicles, while non-compaction vehicles are more efficient and cost effective in small cities where worker costs are low.

2.2.5 Mismanaged Waste

Poor waste management is not an individual county's problem but rather it is increasingly becoming an issue in many cities of the world. The main cause of mismanaged waste is insufficient funds, which mean poor institutional arrangements, poor technologies like modern vehicles used and lack of the capacity to handle wastes. Lack of funds directed towards waste management lead to poor purchase of collecting equipment to clean up huge quantities of waste, leading to insufficient collection methods. It also means lack of dumping sites and treatment facilities, because of poor government attitude toward waste management. This can explain why low income countries uses the easiest way to manage all the waste by opening landfills with unhygienic system. In addition, lack of enough man power to deal with waste collecting machinery, weak laws and weak policies have made the problem of waste management worse. Another issue is lack of environmental awareness that lead to ignorance among the people about the effects of poor waste management. Moreover, low public awareness and attitudes can affect the enthusiasm to participate in programs that might improve waste management. People could lack awareness of their own health and the effect on the environment due probably to lack of information.

Accumulation of waste around the bins is another problem of mismanaged waste, wherever there is an uncovered bin. Accumulated and uncovered garbage becomes an invitation for several problems in the locality. Bad odor is created around the waste bins area which makes unpleasant environment. The situation becomes worse in the rainy season, where waste is directly exposed to the rain. This is a source of pollution and provides breeding ground for mosquitoes, insects and flies (UNDP, 2010).

The major risks associated with poor management of solid waste include the spread of diseases, overall environmental pollution (air, water, soil) including emission of greenhouse gases, and physical, chemical, and fire and explosion hazards. This also affects the economic factor, since the market value of the area decreases if there is a badly maintained waste area nearby as it poses a bad aesthetics.

2.2.6 Fuel Consumption and Emitted Pollutants During Waste Collection

Fuel consumption plays a dominant role in the costs of MSW collection. Approximately, 91% of the waste collection trucks, transfer vehicles and recycling vehicles were diesel-fueled (Gordon et al., 2003).Waste collection vehicles are heavy-duty vehicles (HDV) with gross vehicle weight greater than 12 tons (US EPA, 2007). HDV fuel consumption and emissions are highly dependent on the vehicle class, weight, vehicle age, driving activity, driving speed, terrain traveled, and even the skill of the driver. There are many factors which affect HDV fuel consumption including:

- Engine and accessory design and maintenance
- Vehicle operation (driver operating procedures)
- Tire selection and maintenance
- Environmental conditions including winds, road surface (smooth-textured, coarse-textured) and ambient temperature

Despite the improvement in waste collection vehicles, the industry continues to rely almost completely on diesel fuel; and, in fact, for the last century, diesel-fueled refuse trucks were considered the backbone of the waste management industry (Gordon et al., 2003). Historically, diesel fuel has been inexpensive and, in the US, HDV were not regulated until 2000. US regulations actually did not take effect until 2007 models and later (US EPA, 2007).

HDV can emit significant levels of undesirable atmospheric pollutants, which include carbon dioxide (CO_2) and nitrogen oxides (NOx). These atmospheric contaminants are of major concern due to their contribution to the greenhouse effect and to acid rain. Reducing pollutant outputs through fuel economy therefore yields both environmental and financial benefits.

In vehicle fleet systems, as MSW collection and transportation can be considered, the environmental impact of operation is, to some extent, a controllable function of vehicle routing and scheduling decisions. In spite of that, only a few works have addressed so far the environmental impact in the optimization of vehicle fleet routing and scheduling (Dessouky et al., 2003; Armstrong and Khan, 2004).

Vehicles assigned to collect MSW, e.g. with a self-compactor or with a crane arm, represent considerable operating expenses. While loading and unloading containers, trucks have to keep their engines running, producing constant exhaust emissions. The non-transportation time, including time spent for load/unload operations and other idling times can reach as much as 50% of the total time of waste collection in cities with high population density and high traffic congestion (Faccio et al., 2011). Therefore, it is crucial to devote effort to reduce vehicle emissions by designing efficient collection strategies in terms of the optimized vehicle routing, reducing both the transportation time and the number of load/unload stops.

Several computer programs were used to calculate fuel consumption and emissions. Some of these models usually tend to generalize some values like vehicle specifications as not all vehicles related values can be obtained. The vehicle's structure, engine and parameter scan have a great impact on the outcome, and simple models such as VT-Micro and MOVES use constants for generic types of vehicles, or prompt the user about that information. Some applications such as SIDRA TRIP prompt the user to insert vehicle profiles, which can encompass values like engine displacement, fuel type, tank level and capacity, car size and weight, RPM redline, among others, or even more detailed engine information.

For users not familiar with vehicle specifications, filling that information can be confusing and time-consuming. Furthermore, there are more complex models that not only encompass more detailed vehicle parameters, but are also designed for specific vehicle classes or engines as it is expectable to obtain differences in results between, for example, a gasoline passenger car and a diesel heavy duty truck using just generic models, resulting in low accuracy. There are some models that also use very different approaches, ranging from speed and acceleration to vehicle specific power and some use external sensors, like an emission sensor on the tailpipe.

2.3 Optimization of Waste Collection

It is now widely accepted in the field of MSW management that implementation of vehicle routing techniques is necessary for effective decision making. With route optimization, the objective could be either to optimize travel distance, travel time, fuel consumption, or reduction in emitted greenhouse gases. Generally, two different approaches have been reported to achieve a stated objective including the use of operational research methodologies through which different numerical methods have been used to solve the problem (Lia et al., 2008; Arribas et al., 2010; Solomon, 1987; Chang and Wei, 2002; Teixeira et al., 2004; Nuortio et al., 2006; Goran et al., 2015; Vecchi et al., 2014; Badran and El-Haggar, 2006; Kim et al., 2006; Benjamin and Beasley, 2010; Johansson, 2006; Sonesson, 2000; Faccio et al., 2011; Angelelli and Speranza, 2002) and the use of geographic information systems (GIS) (Lunkapis et al., 2002; Bylinsky, 1989; Ghose et al., 2006; Ericsson et al., 2006; Chalkias and Lasarid, 2009; Kallel et al., 2016; Anwar, 2009; Sumedh et al., 2015; Tavares et al., 2009; Bhambulkar, 2011).

Several investigators used different software to solve the vehicle routing problem. Moustafa et al. (2012) developed the solutions to the problem of collection/transport of solid waste in Alexandria, Egypt using TransCAD®. While Apaydin and Gonullu (2007) used RouteViewPro™ for route optimization for the city of Trabzon, Turkey; showing that 24.7% benefits in the total expenses could be granted. Thanh et al. (2009) used MapInfo for optimizing the route in the city of Can Tho, Vietnam. The authors showed that distance and travel time can be reduced by 19% and 12%, respectively, and could save 20% of fuel consumption. Crick and Holtgis (2008) used RouteSmartTM and helped to reduce the traveled distance by 12 to 20% and the working time by 8% in Northamptonshire, UK. Furthermore, 10% reduction in the number of solid waste collection trips was achieved by Sahoo et al. (2005) using the WasteRoute software in the area of Elgin, Illinois, USA.

2.3.1 Operational Research Approach

Several investigators used operational research approach for MSW optimization. Lia et al. (2008), for example, used the approach for allocating trucks to existing collection routes and balancing trip assignment to recycling facilities in Porto Alegre, Brazil. The authors modeled the case as a minimum-cost network flow problem by assigning vehicles to a set of predetermined trips with fixed starting and ending times. The authors showed a significant savings in cost by adopting the solution. On the other hand, Solomon (1987) proposed algorithms for vehicle routing and scheduling problems with time windows constraints, after describing a variety of heuristics, and conducting an extensive computational study of their performance.

Chang and Wei (2002) used integer programming model to improve vehicle routing efficiency with a variant of the minimum spanning tree in combination. Teixeira et al. (2004) used a three-phase heuristic that aims to create collection routes for every day of the planning horizon. Nuortio et al. (2006) used a node routing approach through guided variable neighborhood search to cope with the highly variable amount of waste in the containers. Arribas et al. (2010) determined fleet size by using integer programming which minimizes the total number of vehicles given fixed travel time and clusters derived using heuristic approach to yield a 50% cost savings for the city of Santiago.

Goran et al. (2015) developed integrated system of sustainable waste management that aim to identify and analyze the elements, criteria and data relevant to the development of optimization models of transport routes. Vecchi et al. (2014) developed mathematical model for solving the planning of collection and transportation of solid waste in medium sized cities in Brazil that formulate a problem of linear programming with mixed integer variables and transcribed into software general algebraic modeling system. Badran and El-Haggar (2006) proposed a mixed integer programming-based model for selecting the best location for collection station in Port Said – Egypt, considering cost minimization of the MSW management system as the main objective.

Kim et al. (2006) addressed a real life waste collection vehicle routing problem with time windows (VRPTW) assuming multiple disposal trips and drivers' lunch breaks. They assumed a weekly predetermined schedule and presented a route construction algorithm that was an extension of Solomon's insertion algorithm (Solomon, 1987). Benjamin and Beasley (2010) considered exactly the same waste collection problem as in Kim et al. (2006) involving multiple disposal facilities, drivers rest period and customer/depot/disposal facility time windows.

Johansson (2006) carried on route optimization for waste collection by introducing a dynamic scheduling based on the real-time information provided by a level sensor placed inside the containers. Sonesson (2000) extended the aforementioned research and also took into consideration the energy and fuel consumed during haulage and waste compaction. Faccio et al. (2011) implemented the modern traceability devices in waste collection (e.g. volumetric sensors, RFID, GPRS and GPS) and presented a multi-objective routing model for waste collection based on the integration of real-time traceability data inputs, including real-time bin level status and real time vehicle position.

Most of the models based on operation research methodology do not provide the flexibility and responsiveness needed in real time logistic problem and are difficult to apply in practice. Moreover, most of these models do not account for heterogeneous vehicle fleets or maximum loading capacity of trucks. Kulcar (1996) developed a model to minimize transportation cost by studying different means of transportation rather than the use of trucks only and deciding on optimal locations for transfer station. Angelelli and Speranza (2002) developed a model for estimating the operational costs of waste collection strictly related to distance travelled to collect the waste without consideration of the time required to deliver it to the disposal site.

2.3.2 GIS Approach

Geographic information systems (GIS) could help in dealing with several factors simultaneously which needs to be considered while planning waste management. GIS is computer system for capturing, storing, displaying data related to positions on earth’s surface. GIS is designed to allow users to collect, manage, analyze and retrieve large volume of spatially referenced data and associated attribute data collected from a variety of sources" (Upasna and Natwat, 2003). Given that many planning aspects are involved in waste management, a good planning would support proper management policies. There are several problems which need to be treated with decisions taken considering all the related factors. Often the order and the amount of preferences given to these factors, decides the decision's credibility. Manual methods adopted for analysis of many factors would be a lengthy and tedious work. Also, there are possibilities of errors while merging the spatial and non-spatial data. But in GIS, as the work is carried in layers, there are least chances of confusion or error and the system is capable enough to coordinate between spatial and non-spatial data. As indicated by Lunkapis et al. (2004), the spatial operation is normally performed in conjunction with GIS functionality found in most GIS software.

Since routing models make extensive use of spatial data, it is possible to take advantage of new technologies such as GIS. GIS has multifunctional feature of the GIS, the information can be related spatially with a very good flexibility to exchange, compare, evaluate, analyze and process it. For example, Lunkapis et al. (2004) used GIS as a tool to aid the decision-making process and to test its effectiveness for landfill site selection in Malaysia subject to some established government guidelines. On the other hand, Zamorano et al. (2009) developed a GIS model for the optimal siting of landfills as it has the potential to assist planners, decision makers and other agents involved in the process of selecting suitable sites for municipal landfills.

In many countries, GIS has demonstrated the ability to strengthen the functioning of infrastructure service delivery and to enhance sustainable development in the cities. Experiences may be obtained from both developed and developing countries. This technology works for spatial and attributes data acquisition, storage, analysis and visualization. It has proved success in assisting planners to give suitable location for transfer stations for solid waste storage, designing short routes for waste collection, creating databases for households that pay and those who have not paid for the services, arranging time tables for trucks to collect waste, etc (Bylinsky, 1989).

Poor spatial and non-spatial data linkage in developing countries is the main cause for almost all problems in solid waste management. Issues such as waste piles on streets, inadequate waste collection, high operational costs, long routes, scattered location of collection points and failure to pay for service due to high cost, etc., are pronounced to be applicable under poor linkage of spatial and non-spatial data in solid waste management. Route optimization application is very new in waste management. Route optimization would help to reduce expenditure for collection by monitoring container emptying process, identifying truck mileage and capacity, identifying containers types and locations, and estimating solid waste production amounts.

The GIS approach is capable of effective handling, display and manipulation of geographic and spatial information. Ghose et al. (2006), for example, developed a GIS model for MSW collection that includes load balancing of vehicles, distribution of collection bins, and generation of optimal routes. On the other hand, Ericsson et al. (2006) proposed a model to estimate possible fuel savings and reductions in CO_2 emissions utilizing the GIS approach. Bhambulkar (2011) used ArcGIS Network Analyst to carry on route optimization of MSW for the city of Nagpur. A similar approach was used by Chalkias and Lasarid (2009) for replacement of the large number of small bins in Athens, Greece with a smaller number of large bins and their reallocation. This followed finding optimal routes, using proposed bins as stops.

Kallel et al. (2016) used ArcGIS Network Analyst in order to improve the efficiency of waste collection and transportation in Sfax city, Tunisia. Anwar (2009) applied GIS to model how much area is covered by a waste bin at varying walking distances. Sumedh et al. (2015) discussed the role of GIS in solid waste management and its use in waste bin allocation strategies in Sri Lanka. Tavares et al. (2009) applied 3D ArcGIS to optimize fuel consumption during MSW collection through which road slope and vehicle weight have been considered as additional factors. Nithya et al. (2012) developed a GIS-based model to investigate the adequate number and positions of collection bins in the Sidhapudur ward of Coimbatore, India. Khan and Samadder (2014) addressed the use of GIS in optimizing routes for collection of solid wastes from transfer stations to disposal sites to reduce the overall cost of solid waste management.

Chapter 3: Methodology

3.1 Introduction

GIS provides an effective means to import, manage, and analyze spatial data. The methodology followed in this work consists mainly of three main steps. First, develop a GIS-based model to explore different alternative scenarios to arrive at the optimal route for waste collection in Um Gafa district in Al Ain city. Second, calculate fuel consumption and emitted greenhouse gases under the current conditions and for the explored different scenarios using SIDRA TRIP software. Third, investigate the adequacy of the number and positions of existing collection bins and conduct route optimization of the proposed bins location. Figure 3.1 shows the design of the geodatabase and analysis of the results.

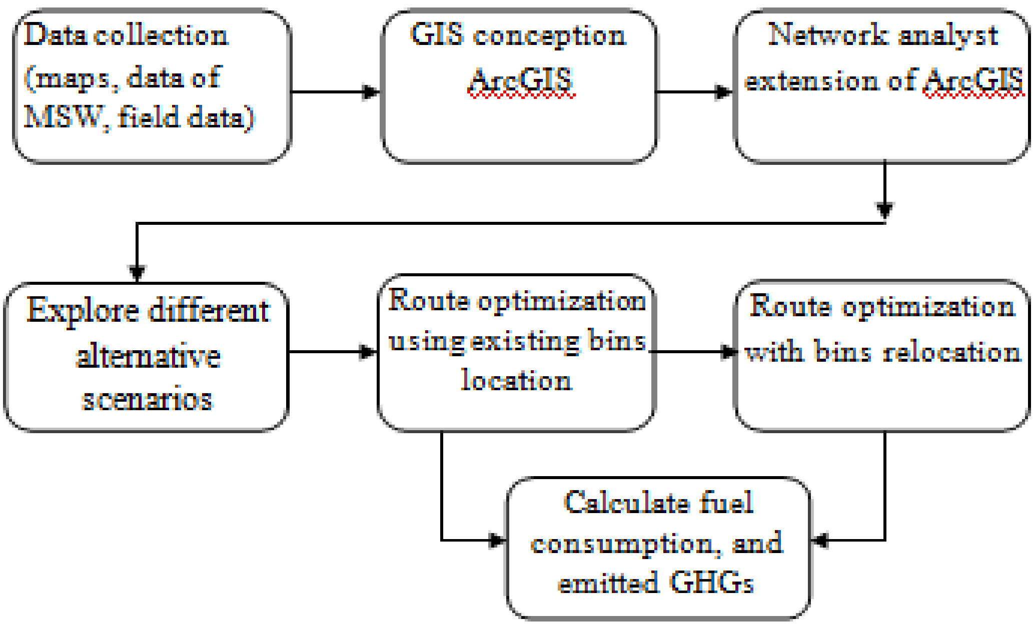


Figure 3.1: Flow of work and analysis steps

3.2 About GIS

GIS integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. GIS allows us to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. A GIS helps answer questions and solve problems by looking at data in a way that is quickly understood and easily shared. GIS technology can be integrated into any enterprise information system framework (ESRI, 2015).

ArcGIS is a complete and integrated system for the creation, management, integration, and analysis of geographic data. It consists of a gee-referenced spatial database, which includes all required parameters for MSW management. These parameters involve sanitary wards, collection points, transportation road network, as well as the location and capacity of disposal sites and its connection with different wards. ArcGIS has the capability to input and store the geographic (coordinate) and tabular (attribute) data, to find specific features based on location or attribute value, to answer questions regarding the interaction between multiple datasets, to visualize geographic features using a variety of symbols and to display the results in a variety of formats, such as maps and graphs.

The ArcGIS Desktop includes three integrated applications, i.e., ArcMap, ArcCatalog and ArcToolbox as shown in Figure 3.2 and 3.3. ArcMap is the primary GIS application for performing analysis and making maps. It is used for displaying, querying, editing, creating and analyzing GIS data. ArcCatalog application helps to organize and manage all GIS data. It includes tools for browsing and finding geographic information, recording and viewing metadata, quickly viewing any dataset and defining the schema structure for geographic data layers. ArcToolbox application provides tools for data conversion, managing coordinate systems, and changing map projections (ESRI, 2015).

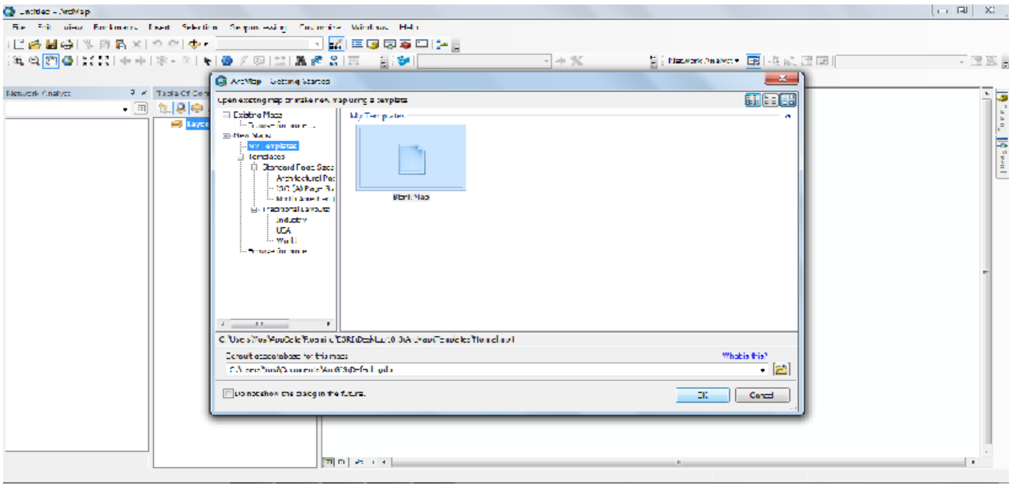


Figure 3.2**:** Window of ArcMap 10.3 (ESRI, 2015)

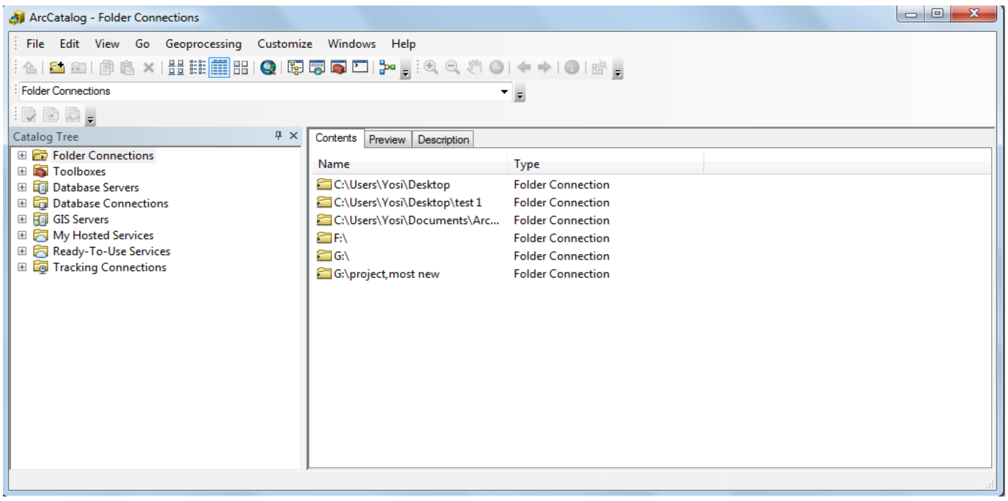


Figure 3.3: Window of ArcCatalog 9 (ESRI, 2015)

3.2.1 Attribute

A characteristic of a geographic feature described by numbers or characters, typically stored in tabular format, and linked to the feature. For example, attributes of a well, represented by a point, might include depth, pump type, location and flow rate.

3.2.2 Coordinate

An x,y location in a Cartesian coordinate system. Coordinates are used to represent locations on the Earth's surface relative to other locations. Planar coordinates describe a two-dimensional x,y location in terms of distance from a fixed reference.

3.2.3 Database

A logical collection of interrelated information managed and stored as a unit, usually on some form of mass-storage system such as magnetic tape or disk. A GIS database includes data about the spatial location and shape of geographic features recorded as points, lines, areas, pixels, grid cells or tins as well as their attributes.

3.2.4 Database Management System (DBMS)

A set of computer programs for organizing the information in a database. A DBMS supports the structuring of the database in a standard format and provides tools for data input, verification, storage, retrieval, query and manipulation.

3.2.5 Digitizer Extension

ArcView extension provides support for digitizing tablets. Digitizing tablets are used to create and edit shapefiles, and are used as a general input device for using ArcView (instead of a mouse). The Digitizer extension is loaded by making the ArcView Project window active and then choosing Extensions from the File menu. The Digitizer extension is not available on UNIX platforms (ESRI, 2015).

3.2.6 Digitizing

Digitizing is a process of encoding geographic features in digital form as x, y coordinates. It is carried out in order to create spatial data from existing hardcopy maps and documents. Manual digitizing involves placing the map or document on a digitizing table and tracing over the features that are required for the dataset. Automatic digitizing involves placing the map or document in a scanner. Automatic digitizing is generally faster but the equipment is often more expensive and more time is usually needed to clean up and edit the scanned data. Some manual and automatic digitizing is carried out on-screen using aerial photographs and other images as guides.

3.2.7 Network Analyst Extension

This ArcView extension enables users to solve problems to do with street, highway, and other geographic networks, such as finding the most efficient travel route, generating travel directions, finding the closest facility, finding service areas based on travel time, etc. The Network Analyst extension is loaded by making the ArcView Project window active and then choosing Extensions from the File menu (ESRI, 2015).

3.2.8 Network Analyst

ArcGIS Network Analyst is a powerful extension that provides network-based spatial analysis including routing, travel directions, closest facility, and service area analysis. ArcGIS Network Analyst enables users to dynamically model realistic network conditions, including turn restrictions, speed limits, height restrictions, and traffic conditions at different times of the day. Users with Network Analyst extension are able to find efficient travel routes, determine which facility or vehicle is closest, generate travel directions, and find a service area around a site (Karadimas et al., 2008).

In the current work, using Network Analyst, an optimum route for the waste collection of large items is generated in the area under study. Network Analyst uses the Dijkstra's Algorithm (Karadimas et al., 2008) in order to solve the routing problem and it can be generated based on either distance or time criterion. Using the distance criterion, the route is generated taking only into consideration the location of the waste large items. The volume of traffic in the roads is not considered in this case. On the other hand, using the time criterion, the total travel time in each road segment should be considered as the sum of runtime of the vehicle plus the time for waste collection of large items. The runtime of the vehicle is calculated by considering the length of the road and the speed of the vehicle in each road. The time of the waste large items collection would be the total time consumed by the vehicle to collect these objects from all the loading spots. In the second criterion, the length, width and the volume of traffic are taken into account in each road segment. Using the second criterion, several routes could be generated during a random day in order to compare the total travel time between these predefined time intervals. Hence, routes could be generated during the day time or during the night time in order to compare the total travel time in these different time intervals during the day.

The Network Analyst extension allows the user to perform "Find Best Route", which solves a network problem by finding the least cost impedance path on the network from one stop to one or more stops. Network modeling gives the opportunity to the user to include the rules relating to the objects, arcs and events in association with solving transportation problems (Karadimas et al., 2007).

3.2.9 The Path Finding Algorithm

Network Analyst software determines the best route by using an algorithm which finds the shortest path, developed by Edgar Dijkstra. Dijkstra's algorithm is the simplest path finding algorithm, even though these days a lot of other algorithms have been developed. Dijkstra's algorithm reduces the amount of computational time and power needed to find the optimal path. The algorithm strikes a balance by calculating a path which is close to the optimal path that is computationally manageable. The algorithm breaks the network into nodes (where lines join, start or end) and the paths between such nodes are represented by lines.

In addition, each line has an associated cost representing the cost (length) of each line in order to reach a node. There are many possible paths between the origin and destination, but the path calculated depends on which nodes are visited and in which order. The idea is that, each time the node, to be visited next, is selected after a sequence of comparative iterations, during which, each candidate-node is compared with others in terms of cost. The following example, which is an application of the algorithm on a case of 6 nodes connected by directed lines with assigned costs, explains the steps between each iteration of the algorithm (Figure 3.4). The shortest path from node 1 to the other nodes can be found by tracing back predecessors (bold arrows), while the path's cost is noted above the node.

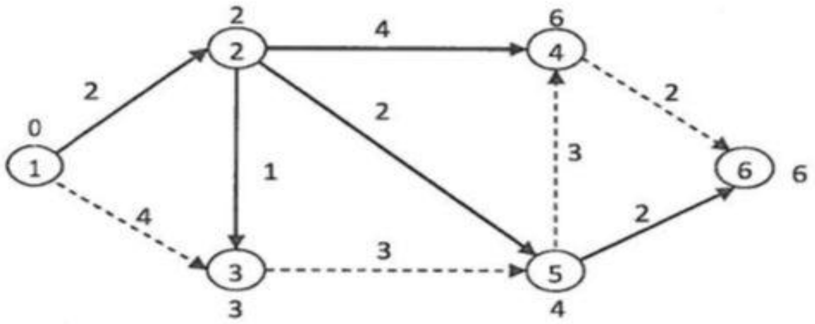


Figure 3.4: An example of Dijkstra's algorithm (Karadimas et al., 2007)

Each node is processed exactly once according to an order that is being specified below. Node l (i.e., origin node) is processed first. A record of the nodes that were processed is kept; call it Queue (Table 3.1). So initially Queue= l. When node k is processed the following task is performed: If the path's cost from the origin node to j could be improved including the vertex kj in the path then, an update follows both of distance j with the new cost and predecessors j with k, where j is any of the unprocessed nodes and distance is the path's cost from the origin node to j. The next node to be processed is the one with the minimum distance. In other words, the distance is the nearest to the origin node among all the nodes that are yet to be processed. The shortest route is found by tracing back predecessors.

Table 3.1: Example of Dijkstra's algorithm (Karadimas et al., 2007)

Queue	Next node	Distance						Predecessors				
		1	2	3	4	5	6	2	3	4	5	6
1	2	-	2	4	∞	∞	∞					
1,2	3	-	-	3	6	4	∞		2	2	2	
1,2,3	5	-	-	-	6	4	∞					
1,2,3,5	4	-	-	-	6	-	6					5
1,2,3,5,4	6	-	-	-	-	-	6					
1,2,3,5,4,6	-	-	-	-	-	-	-					

Network analyst can be very useful in a variety of sectors in our daily life, such as:

1. Business: Scheduling deliveries and installations while including time window restrictions, or calculating drive time to determine customer base, taking into account rush hour versus midday traffic volumes.
2. Education: Generating school bus routes honoring curb approach and no U-turn rules.
3. Environmental health: Determining effective routes for county health inspectors.
4. Public safety: Routing emergency response crews to incidents, or calculating drive time for first responder planning.
5. Public works: Determining the optimal route for point-to-point pickups of massive trash items or routing of repair crews.
6. Retail: Finding the closest store based on a customer's location including the ability to return the closest ranked by distance.
7. Transportation: Calculating accessibility for mass transit systems by using a complex network dataset.

3.3 Site Description

Al Ain city, also known as the Garden City due to its greenery, is the second largest city in the Emirate of Abu Dhabi and the fourth largest city in the UAE. It covers an area of approximately 13,100 km², with a population of 650,221 as of 2015 (SCAD, 2015). It is located approximately 160 km east of the capital Abu Dhabi and about 120 km south of Dubai. Al Ain is located in Abu Dhabi, inland on the border with Oman. The topography of Al Ain is unique and varies as travelling to the east. Jebel Hafeet (Hafeet Mountain) is considered one of the monuments of Al Ain, lying just to the southeast and rising to 1,300 m in elevation. In Al Ain, the mean annual rainfall is 96 mm and the average relative humidity is 60%. Low humidity in Al Ain, particularly during the summers, makes it a popular destination for many people at that time of year. Boer (1997) classified the UAE climate as hyper-arid and divided it into four climatic regions: the coastal zone along the Arabian Gulf, the mountain areas northeast of UAE, the gravel plains around Al Ain area, and the central and southern sand desert. More rainfall and lower temperatures occur in the northeast than in the southern and western regions.

The dry desert air makes Al Ain a welcome retreat from the coastal humidity of the larger cities. Many Emirati nationals in Abu Dhabi have holiday houses in the city making it a popular weekend destination for families from the capital city. Its attractions include the Al Ain National Museum, the Al Ain Palace Museum, several restored forts and the Hili Archaeological Park site, dating back to the Bronze Age. Industry is growing in Al Ain, but is still on a small scale, and includes the Coca Cola bottling plant and the Al Ain Portland Cement Works. Service industries such as car sales, mechanics and other artisans are located in the area known as Sanaiya. Social and governmental infrastructure includes United Arab Emirates University, Higher Colleges of Technology, Abu Dhabi University (Al Ain campus), well-equipped medical facilities including the teaching hospital at Tawam, military training areas and Al Ain International Airport.

Management of MSW in Al Ain is currently under the control of the CWM-AD. From a waste collection perspective, the city is divided into two zones: the north and south zones. Collection of waste from each zone is carried out by two private companies (MBM Dalla and Lavajet) through a contractual agreement with the CWM-AD. Collected MSW from Al Ain city is sent to a sorting station at Seeh Al Hemmah, nearby the compost plant (Figure 3.5). The station also receives wastes from the transfer stations in the peripheral townships (Sweihan, Al-Hayer, Ramah, and Al-Wagen). Laborers stationed in the station sort the waste into different categories. Organic-rich materials are diverted to the compost plant, recyclable wastes are collected and stored for further marketing, and the remaining unwanted materials such as construction and demolition waste are transported to a central single-lined landfill located in Suwaifi (about 18 km west of the transfer station).

Figure 3.5: Satellite image of Al Ain, with waste collection zones and waste processing facilities

3.4 Solid Waste Generation in Al Ain City

Studies by the CWM-AD (2015) estimated that Al Ain City produced between 1.4 to 1.7 kg of solid waste per person per day between 2011 and 2015 (Figure 3.6). The total amount of waste produced in the city was about 2.5 million tons in 2015 (Table 3.2). Local experts believe these figures are representative of the whole country. Non-hazardous waste formed 99.6% of the total produced waste, while hazardous waste accounted for a small proportion of about 0.4% as shown in Table 3.2.

Table 3.2: Annual non-hazardous and hazardous solid waste generated in Al Ain city (CWM-AD, 2015)

Waste type	2012	2013	2014	2015
Non-hazardous (ton)	1,764,649	2,021,166	2,138,867	2,526,616
Hazardous (ton)	35,421	63,077	40,385	43,424
Total (ton)	1,800,070	2,084,243	2,179,252	2,570,040

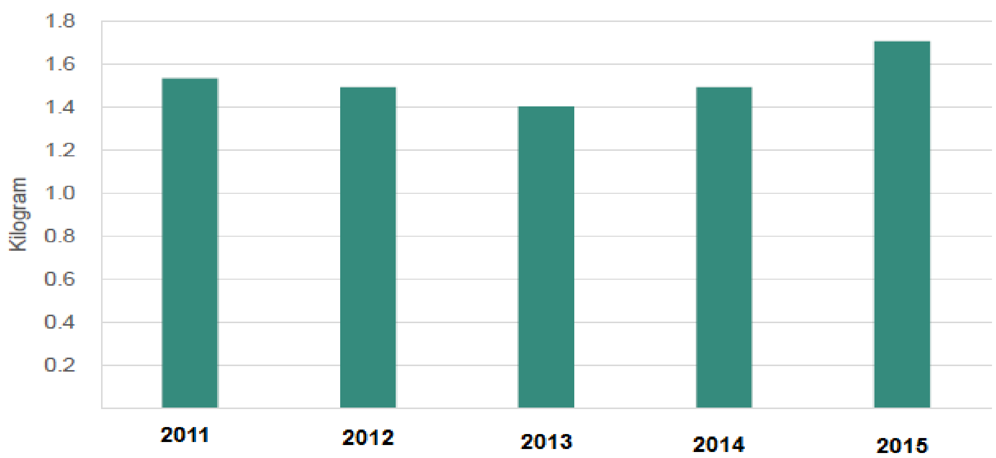


Figure 3.6: Per capita waste generation rate in Al Ain City (kg/cap/day)

Al Ain city is the second largest city in the Emirate of Abu Dhabi. The Emirate is divided into three main regions: Abu Dhabi city, the eastern region which is mainly Al Ain city, and the western region (referred to as Al Gharbia). Al Ain region generates different types of wastes with different quantities, including household waste, commercial waste, industrial waste, agricultural waste, medical waste and others. Table 3.3 shows the quantities of non-hazardous waste produced in different regions of Abu Dhabi Emirate in 2015.

Table 3.3: Non-hazardous solid waste generation (in tons) by region and source activity in the Emirate of Abu Dhabi (CWM-AD, 2015)

Source	Total	Abu Dhabi	Al Ain	Al Gharbia
Total	**11,856,076**	**6,850,287**	**2,605,633**	**2,400,156**
Daily average	**32,482**	**18,768**	**7,139**	**6,576**
Construction and demolition waste	**7,692,921**	**4,662,356**	**1,386,252**	**1,644,313**
C & D waste	2,767,342	1,721,818	474,346	571,178
C & D mixed waste	4,925,578	2,940,538	911,905	1,073,135
Industrial and commercial waste	**1,305,556**	**550,250**	**380,000**	**375,306**
Agriculture waste	**999,239**	**370,979**	**459,696**	**168,564**
General agriculture waste	339,078	120,000	142,078	77,000
Agriculture mixed waste	488,474	190,107	237,279	61,088
Animal waste	171,687	60,872	80,339	30,476
Municipal waste	**1,528,093**	**991,105**	**327,627**	**209,361**
Households, streets, and public gardens waste	1,234,336	857,831	232,430	144,075
Bulky waste	293,757	133,274	95,197	65,286
Sludge	**93,474**	**56,834**	**36,062**	**578**
Other *	**236,793**	**218,763**	**15,996**	**2,034**

Municipal solid waste in Al Ain city totaled 327,627 tons in 2015, of which 59% was disposed in a sanitary landfill while 17% was composted to be used for agricultural purposes, 16% was recycled, and 8% was disposed in dumpsites as shown in Table (3.4).

Table 3.4: Municipal solid waste in Al Ain by method of disposal (CWM-AD, 2015)

Method of disposal	Quantity (ton) in 2015	Percent
Recycling	52420.5	16%
Composting	55696.6	17%
Landfill	193,299	59%
Dumpsite and other	26210.5	8%
Total	327,627	100%

3.5 Study Area

The study area is located in the south zone of Al Ain city as shown in Figure 3.7. The area is called Um Gafa, which is located near to Mazyad area. Um Gafa covers an area of approximately 44.6 km², with a population of about 6,772 in 2015 (SCAD, 2015). Collection of waste in the area is carried out by a private company (MBM Dalla) through a contractual agreement with the Waste Management Center-Abu Dhabi (CWM-AD). It must be mentioned that, Um Gafa district has been selected as a case study as it is one of largest districts in Al Ain city with a high number of bins. During data collection, it has been found that Um Gafa has the least detected map errors among other areas in Al Ain.

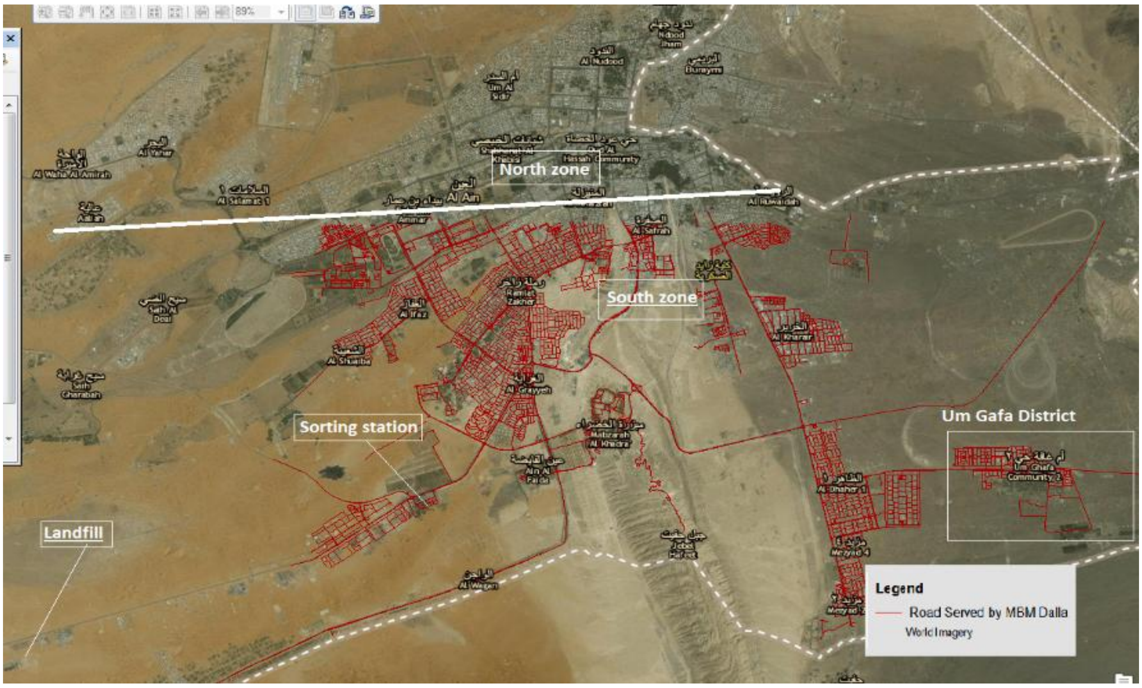


Figure 3.7: Satellite image of Al Ain, showing the location of Um Gafa area and the south zone carried out by MBM Dalla

Municipal solid waste generated in Um Gafa is characterized by a high level of organic matter (68%) and thus a high rate of water content ranging between 65% and

70% (CWM-AD, 2015). Besides individual citizens, potential producers of waste are schools (4), clinics and fuel stations (1), public gardens (1), cafes, restaurants, bakeries, and other businesses (17), shopping centers (2), and farms (23).

Um Gafa district includes one main road with a median that is central to the overall district. The main road has a dual 2-lane, each 3.7-m wide with a posted speed of 80 km/hr. Other roads are local streets with single lane (two-way) and a posted speed of 40 km/hr. Most of Um Gafa streets are not congested with traffic. In addition, Um Gafa district includes six round-abouts and has no traffic signals.

Waste collection service in Um Gafa follows a communal collection system, with waste is carried out manually and/or mechanically. The vehicles available by MBM Dalla for waste collection include 157 units (Table 3.5). MBM Dalla road sweeping staff and vehicle loaders report daily at the work cabin where their attendance is taken by the concerned sanitary inspector. Their normal working hours are 3 am to 11 am and 3 pm to 10 pm without holidays. Every sweeper is assigned a specific area. Handcarts are normally used by male sweepers for transporting silt removed from drains. The crew of each collection vehicle consists of a driver and two workers.

Table 3.5: Vehicles available at MBM Dalla in the south zone of Al Ain City

No.	**Type of Vehicles**	**No. of Units**
1	Compactors	27
2	Bob cat	15
3	Shovel	11
4	Crane	6
5	Water tankers	6
6	Sweepers	7
7	Bin washer	4
8	Pick up 3 ton	22

9	Dump truck	16
10	Hook lifter	7
11	Skip carrier	3
12	Light vehicle	16
13	Fuel tanker	1
14	Busses	7
15	Trailers	5
16	Low bed	1
17	Bins transporter	3

The total number of waste bins in Um Gafa is 661 each of 1.3 m^3 (Figure 3.8), with a total capacity of 113.66 ton. The existing bins are not evenly distributed within the area and no previous study has been done to optimize the location of the bins. The amount of waste collected during a trip is around 16.8 tons per day. The Um Gafa area is swept by one of the 18 m^3 loaded compaction trucks. Besides, laborers carrying hand cart ensure the collection of waste from hardly accessible places. The waste is then transferred to the municipal sorting station directly.

Figure 3.8: Waste collection bins at Um Gafa

The garbage compactor truck (Figure 3.9) compacts the waste using a hydraulically powered mechanism that employs a moving plate or shovel to scoop the waste out from the loading hopper and compress it against a moving wall. In most compactor designs, the plate has a pointed edge (hence giving it the industry standard name packer blade) which is designed to apply point pressure to the waste to break down bulky items in the hopper before being drawn into the main body of the truck. It consists of four main parts, sealed garbage compartment, hydraulic system, operating system, and fully-sealed lifting cylinder. It can compact and dump the garbage automatically. The sewage will flow in the compartment completely to avoid re-pollute during transportation. Technical parameters of compactor truck are presented in Table 3.6.

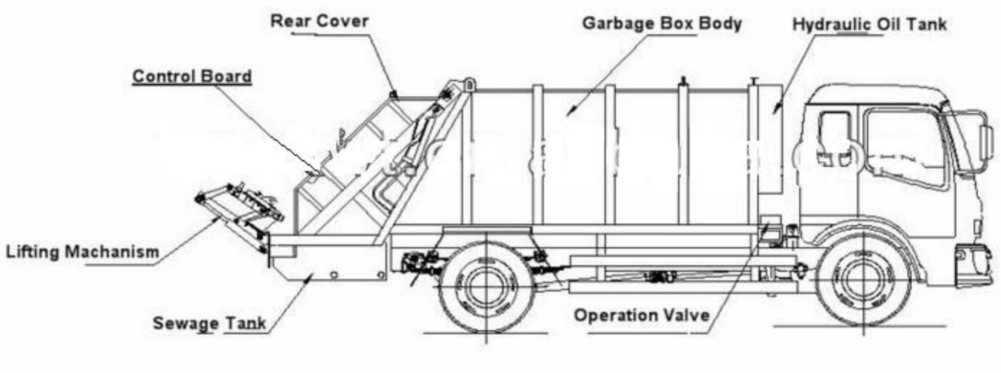


Figure 3.9: Structure of 18-m^3 compactor truck (CWM-AD, 2015)

3.6 Optimization Approach and Data Requirement

3.6.1 Data Required

Data collection is an important work and it is the back bone of the project. Appropriate data is necessary for a proper analysis and this leads to derive accurate results. The data base of the case study area is prepared on the basis of the information collected from different sources. The information of different types and forms has to be transferred into the GIS database. In this thesis, the information was collected from different sources. A shape file of Al Ain map was collected from Al Ain Town Planning Department including attributes data: area boundary, name and type of the roads and their width and traffic volume details. U-turn and curb approach polices have been collected from Al Ain Transportation Police Department.

The existing MSW situation data of Al Ain city was collected from CWM-AD, including waste type, waste generation, collection frequency, vehicles types, shift working, number of storage bins and their capacities. The bins locations have been collected manually using GARMIN eTrexH GPS. The current run route has been tracked by going on trip with waste vehicle’s staff through their duty and then simulated. The average speeds, acceleration, deceleration of the vehicle, and the average service time of the bins have been collected during the trip. The information was integrated to form a database of the case study; the description of the database is presented in Table 3.7.

Table 3.6: Technical parameters of compactor truck (CWM-AD, 2015)

Item	**Descriptions**	**Specifications and types**
General	Truck name	Garbage compactor truck
	Truck model	2013
	Drive type	6*4, left hand drive
	Loading capacity	18 m^3 ---(18 ton)
	Curb weight (kg)	14990
	Overall dimensions L*W*H (mm)	10300*2500*3300
Engine	Engine model	YC6A240-46
	Engine brand	Mitsubishi
	Fuel type	Diesel

	Power	177kw/240HP
	Emission standard	Euro IV
	Displacement (ml)	7255
Chassis	Chassis brand	Dongfeng
	Front/rear axle load (kg)	7000/17900
	Tire specification	10.00-20 Nylon tire or 10.00R20 steel tire
	Wheelbase (mm)	3360
	Axle/tire no.	3/10
	Gear box	8 speed forward with 1 reverse, manual
	Brake	Air break
	Radiator	Suitable for tropical climate
	Front/rear suspension(mm)	1250/2900
	Leaf Spring No.	9/10
	Loading device lifting time	≤ 15s
	Compression cycle time	≤ 30s

Table 3.7: Description of geo-spatial database

Spatial Data	Type	Attributes	Geometry
Road Network	Vector	----	Line
Collection bin location	Vector	----	Point
Road network attributes	Tabular	Road Length	----
Collection bin attributes	Tabular	Longitude, latitude, type and size of collection bins	----
Satellite image of the research area	Raster	----	----

The information gathered was quite helpful in the preparation of the needed data. There were also some inadequacies and errors in the information which were not sufficient enough to form a complete database such as errors in the map (duplicate objects, undershoots and zero length objects) that have been corrected manually. Also, some data have been added manually to the map such as one-way and two-way roads, U-turn polices, curb approach polices, driving time, and service time of the bins. Some information such as traffic volume was not sufficient to produce a good data format which was a limitation in the data collection. Some information was confidential such as MSW collection costs and current fuel consumption. The process adopted in information collection and later incorporated into the database is discussed below.

3.6.2 Digitizing and Drawing Cleanup Process

In order to create spatial data from existing maps and documents. Manual digitizing is carried out on-screen using aerial photographs, involves placing the map on a digitizing table and tracing over the features that are required for the dataset as shown in Figure 3.10

Drawing cleanup actions can be used to detect map errors (for example, duplicate objects, undershoots, over shoots or zero length objects), simplify complex 2D maps, and to weed and supplement 3D polylines. Because drawing cleanup can alter data, it is advisable that a backup of the data is made before cleaning up a map. For best results, cleanup actions are run individually or with a minimum of other actions.

Figure 3.10: Digitized map of Um Gafa area

3.6.3 Attribute Addition

The following are the attribute used in the project as shown Figure 3.11:

1. Road name
2. Road lane
3. Road type
4. Road length
5. Travel time
6. Id
7. Speed limit
8. One way
9. Collection frequency

3.6.4 Different Layers of Drawing

3.6.4.1 Route Analysis Layer

The route analysis layer stores all the inputs, parameters, and results of route analysis. Route analysis layer is created from the Network Analyst toolbar by clicking New Route. When a new route analysis layer is created, it shows up in the Network Analyst Window, along with its three categories: stops, barriers, and routes. The route analysis layer also shows up in the table of contents as a composite layer. Each route is composed of three feature layers: stops, barriers, and routes. Each of the three feature layers has default symbols that can be modified on its Layer Properties dialog box (Figure 3.12).

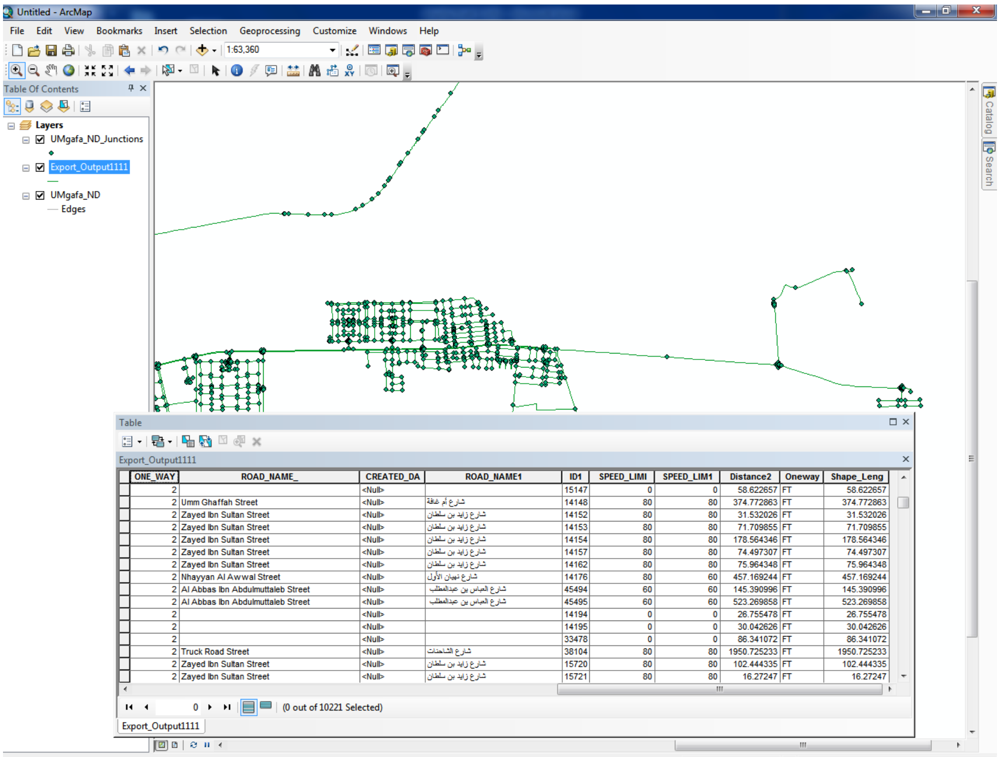


Figure 3.11: Attributes used in the project

Figure 3.12: Road network of Um Gafa area

The route analysis layer properties contain information related to the curb approach, and override parameters as shown in Figure 3.13. These properties are explained below.

The curb approach property specifies the direction a vehicle may arrive at and depart from the network location. There are four choices: either side of vehicle, right side of vehicle, left side of vehicle, and no U-turn. For the “either side of vehicle” setting, the vehicle can approach and depart the network location in either direction. U-turns are allowed. This setting is selected if the vehicle can make a U-turn at the stop or if it can pull into a driveway or parking lot and turn around. The “right side of vehicle” setting is selected if the vehicle approaches and departs the network location with the curb on the right side of the vehicle. A U-turn is prohibited. However, the “left side of vehicle” setting is selected if the vehicle approaches and departs the network location with the curb on the left side of the vehicle. Also, a U-turn is prohibited. The “no U-turn” setting is chosen when the vehicle approaches the network location with the curb being on either side of the vehicle; however, the vehicle must depart without turning around.

The override parameters are defined when adding a travel mode to a network dataset. Override values may differ between travel modes. One has to recognize the following attributes:

1. Impedance: It specifies the cost attribute on which to optimize the analysis. A travel mode modeling cars would need a cost attribute that stores the time it takes a car to traverse an edge or street segment. In contrast, a walking time travel mode would need a cost attribute storing the time it takes to walk along edges or streets.

2. Time attribute: It specifies the time-based cost attribute for reporting directions. The choices for impedance and time attribute are typically the same when modeling time-based travel modes. When modeling distance-based travel modes, however, the time attribute value would need to describe how long it takes the travel mode to travel along network edges. For a walking distance travel mode, for instance, time attribute would be set to a cost attribute storing walking times.

3. Distance attribute: It specifies the distance-based cost attribute for reporting directions and for solving vehicle routing problems.

4. U-turns at junctions: It indicates where the travel mode is allowed to make U-turns. Allowing U-turns implies the solver can turn around at a junction and double back on the same street. Given that junctions represent street intersections and dead ends, different vehicles may be able to turn around at

some junctions but not at others. This depends on whether the junction represents an intersection or dead end. To accommodate that, the U-turn policy parameter is implicitly specified by how many edges, or streets, connect to the junction, which is known as junction valency. The U-turns at junctions are either “allowed”, “not allowed”, “allowed only at dead ends”, or “allowed only at intersections and dead ends”.

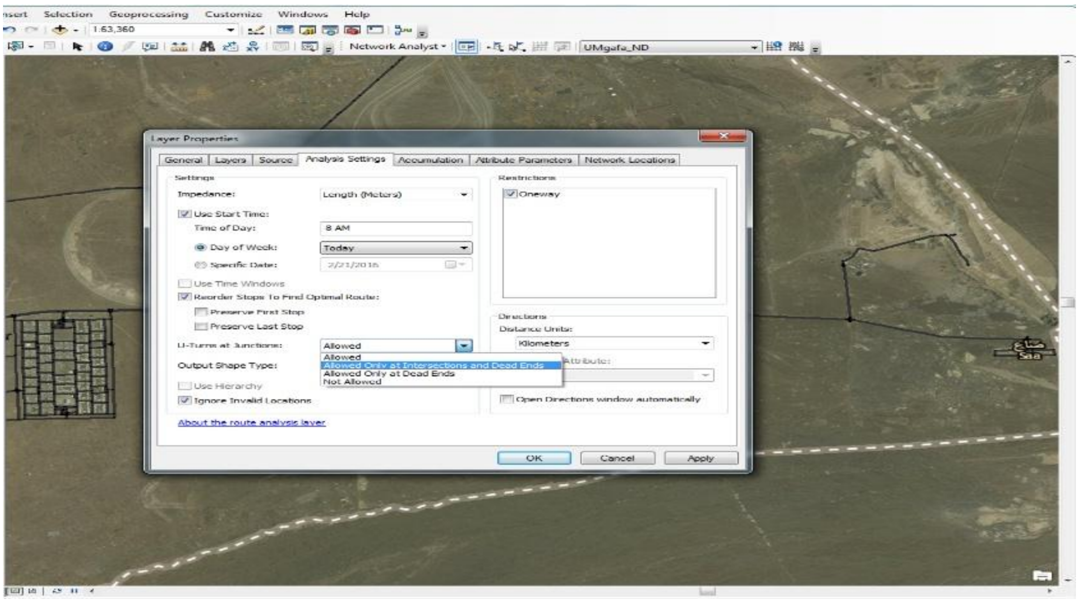


Figure 3.13: Route analysis layer properties

3.6.4.2 Stops Feature Layer

This layer stores the network locations that are used as stops in route analysis. The “stops layer” is symbolized by default in four types: “Located stops”, “unlocated stops”, “error”, and “time violation stop”. The symbology can be modified in the Layer Properties dialog box of Stops. There is a new symbology category, Network Analyst Stops, added for the stops network analysis class. When a new route analysis layer is created, the Stops layer has no features. It is populated only when network locations are added into it.

3.6.4.3 Barriers Feature Layer

Barriers are used in route analysis to denote points where a route can't traverse. The “barriers layer” is classified by default in three types: “Located”, “unlocated”, and “error”. The symbology of each can be modified in the Layer Properties of the “barriers layer”. The “barriers layer” functions as any other feature layer in ArcMap. When a new route analysis layer is created, the “barriers layer” has no features. It is populated only when network locations are added into it.

3.6.4.4 Route Feature Layer

The “route feature layer” stores the resultant route of a route analysis. As with other feature layers, its symbology can be accessed and altered from the Layer Properties dialog box. The “route layer” on the Network Analyst Window is empty until the analysis is complete. Once the best route is found, it is displayed on the Network Analyst Window.

3.6.5 Dijkstra’s Algorithm

The classic Dijkstra’s algorithm solves the single-source, shortest-path problem on a weighted graph. To find a shortest path from a starting location s to a destination location d, Dijkstra's algorithm maintains a set of junctions, S, whose final shortest path from s has already been computed. The algorithm repeatedly finds a junction in the set of junctions that has the minimum shortest-path estimate, adds it to the set of junctions S, and updates the shortest-path estimates of all neighbors of this junction that are not in S. The algorithm continues until the destination junction is added to S.

3.6.6 Route Analysis

Creating a route can mean finding the quickest, shortest, or most scenic route, depending on the impedance chosen. If the impedance is time, then the best route is the quickest route. Hence, the best route can be defined as the route that has the lowest impedance, or least cost, where the impedance is chosen by the user. Any cost attribute can be used as the impedance when determining the best route. Accumulated attributes play no role when computing the solution. For example, if ones choose a time cost attribute as the impedance attribute and also wants to accumulate a distance cost attribute, only the time cost attribute is used to optimize the solution. Finding the best route through a series of stops follows the same work flow as other network analyses.

ArcGIS Network Analyst can find the best way to get from one location to another or the best way to visit several locations. The locations can be specified interactively by placing points on the screen, by entering an address, or by using points in an existing feature class or feature layer. The best route can be determined for the order of locations as specified by the user. Alternatively, ArcGIS Network Analyst can determine the best sequence to visit the locations.

3.6.7 Best Route

Whether finding a simple route between two locations or one that visits several locations, people usually try to take the best route. But best route can mean different things in different situations. The best route can be the quickest, shortest, or most scenic route, depending on the impedance chosen. If the impedance is time, then the best route is the quickest route. Hence, the best route can be defined as the route that has the lowest impedance, where the impedance is chosen by the user. Any valid network cost attribute can be used as the impedance when determining the best route.

3.6.8 Directions

Directions can be displayed in ArcMap after the generation of a route in route analysis and closest facility analysis as shown in Figure 3.14. Directions are displayed on the Network Analyst toolbar through the Directions Window button.

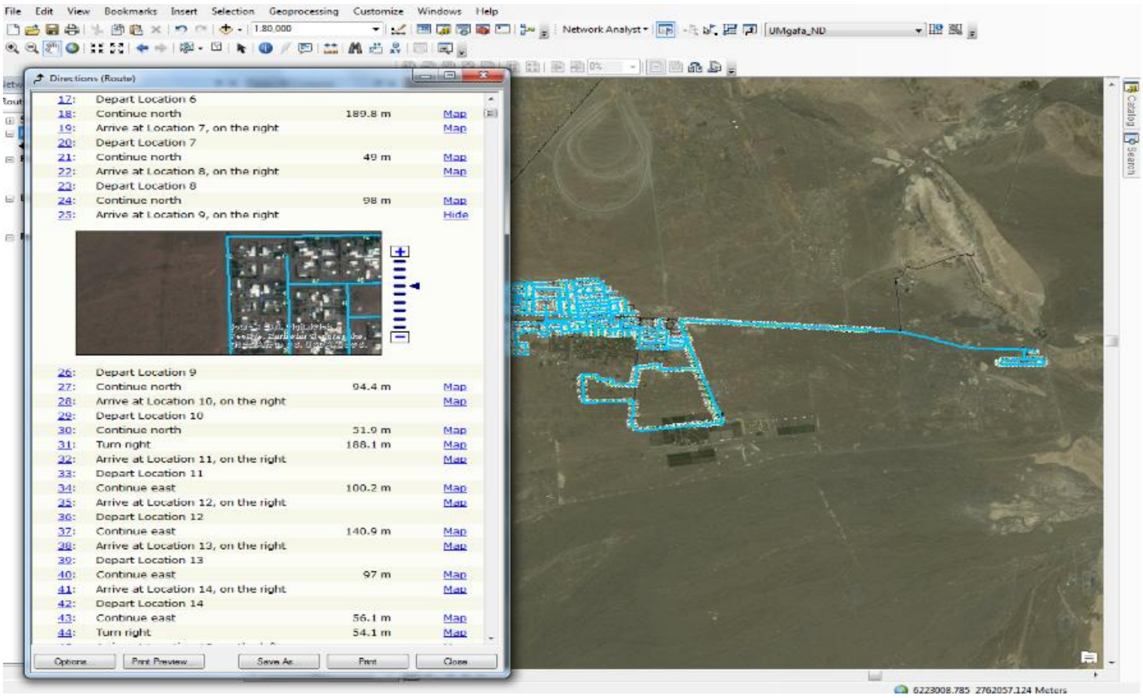


Figure 3.14: Directions window in ArcMap

3.7 Investigated Cases

During the tracking of the current run route (by going on trip with waste vehicle's staff through their duty), some violations of traffic rules have been noticed such as U-turn and curb approach policies. According to Abu Dhabi Traffic Engineering Department (ATED), U-turn policy dictates that the waste collection vehicle is allowed to make U-turns only at junctions (junctions with three or more adjacent edges) and dead ends (junctions with exactly one adjacent edge). The curb approach policy dictates that the waste collection vehicles are allowed to collect bins only on the right-hand side of the vehicle, U-turns at the bins location is prohibited. Therefore, four cases have been investigated. These cases are:

- Case 1: Route optimization with the implementation of traffic rules (U-turn and curb approach policies).
- Case 2: Route optimization without implementing traffic rules (U-turn and curb approach policies).
- Case 3: Route optimization with implementing only U-turn policy.
- Case 4: Route optimizations with implementing only curb approach policy.

3.8 Fuel Consumption and Emissions

Fuel consumption during waste collection and transportation is influenced by the travelled distance and by the actual operating conditions of a given vehicle. In order to evaluate these effects, the method proposed in SIDRA TRIP (Ntziachristos and Samaras, 2000) was used. SIDRA TRIP is a computer program that calculates road vehicle fuel consumption and emissions. Besides considering specific vehicle parameters, SIDRA TRIP also takes into account different driving conditions such as types of the driving situation, vehicle load, etc. The model uses microscopic GPS or trip data representing a standard driving cycle and produces vehicle trip assessment data like distance, speed, operating costs, emissions, noise and fuel consumption. If using a GPS, data is easily gathered. However, it depends on various vehicle variables like engine, traffic and road parameters. It is also possible to input fuel prices, for cost assessment. SIDRA TRIP provides default vehicle profiles that can be configured or created, generalizing vehicle classes to facilitate user input, as some parameters can be complex for normal users.

SIDRA TRIP uses power based model with default vehicle parameters for fuel consumption and carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx) emission rates as summarized in Table 3.8 for heavy vehicles. CO_2 is estimated directly from fuel consumption by applying a CO_2 emission factor to the fuel consumption rate.

In the present study, quick scenario analysis has been used due to lack of microscopic GPS data. Default vehicle profile for heavy vehicles is used. This was done by specifying the vehicle type, travel distance, travel time, road grade (slope of the road) and event data for each investigated scenario. The data used is available in SIDRA TRIP for the category of diesel heavy duty vehicles (from 7.5 to 18 ton) and the EURO III legislation class.

Data that have been input in SIDRA TRIP for each investigated scenario include:

- Vehicle type
- Total travel distance
- Total travel time
- Number of stops
- Stop duration
- Average speed (during collecting bins)
- Average acceleration (from 0 to 80 km/h)
- Average deceleration (from 0 to 80 km/h)

- grade (slope of the road)
- Driving side

Table 3.8: Default vehicle parameters for estimating fuel consumption and various emission rates for heavy vehicles (Akcelik and Associates, 2007)

Parameter	Unit for fuel	Unit for emission	Fuel	CO	HC	NO_x
f_i	mL/h	g/h	2000	50	8	2
A	mL/km	g/km	100	1	0	0
B	$(ml/km)/(km/h)^2$	$(g/km)/(km/h)^2$	0.01800	0.0000	0.00002	0.00006
b_1	kN	kN	1.2500	0.0667	0.0000	0.0000
b_2	$kN/(m/s)^2$	$kN/(m/s)^2$	0.00292	0.0000	0.0000	0.00078
c_1	mL/m	g/m	0.100	0.001	0.000	0.000
c_2	$(mL/m)/(m/s)^2$	$(g/m)/(m/s)^2$	0.0002333	0.000	0.000	0.00000078
β_1	mL/kJ	g/kJ	0.0800	0.0150	0.000	0.0010
β_2	$mL/(kJ.m/s^2)$	$g/(kJ.m/s^2)$	0.0200	0.0250	0.0004	0.0002

3.8.1 Fuel Consumption Model

The SIDRA TRIP fuel consumption model can be expressed in terms of the energy, power or tractive force required by the vehicle. The following function is used to estimate the value of the fuel consumed or emission produced, during a simulation interval (Akcelik et al., 2012):

$$f_t = \alpha + \beta_1 P_T + [\beta_2 a P_I]_{a>0} \quad (1) \quad \text{for } P_T > 0$$

$$= \alpha \quad \text{for } P_T < 0$$

$$P_T = \mathit{min}\,(P_{max}, P_C + P_I + P_G) \quad (2)$$

$$P_C = b_1 v + b_2 v^3 \quad (3)$$

$$P_I = M_v a v / 1000 \quad (4)$$

$$P_G = 9.81 M_v (G/100) v / 1000 \quad (5)$$

Where, f_t is the instantaneous fuel consumption rate (mL/s), P_T is the total tractive power (kW), P_{max} is the maximum engine power (kW), P_C is the cruise component of total power (kW), P_I is the inertia component of total power (kW), P_G is the grade component of total power (kW), R_T is the total tractive force (kN) required to drive the vehicle, G is road grade (per cent), M_v is vehicle mass (kg) including occupants and any other load, v is instantaneous speed (m/s), a is instantaneous acceleration rate (m/s^2), α is constant idle fuel consumption rate (mL/s), which applies during all modes of driving (as an estimate of fuel used to maintain engine operation), b_1 is vehicle parameter related mainly to the rolling resistance (kN), b_2 is vehicle parameter related mainly to the aerodynamic drag (kN/(m/s) ^{2}), β_1 is efficiency parameter which relates fuel consumed to the total power provided by the engine (i.e., fuel consumption per unit of energy (ml/kJ), and β_2 is efficiency parameter which relates fuel consumed during positive acceleration to the product of acceleration rate and inertia power when n = 1.0 (mL/(kJ.m/s^2) or g/(kJ.m/s^2)).

The instantaneous cruise fuel consumption rate (a = 0, P_I = 0) on a level road (G = 0, P_G = 0) is given by:

$$f_{ct} = \alpha + \beta_1 \; P_C \qquad (6a)$$

$$f_{ct} = \alpha + \beta_1 \; (b_1 v + b_2 v^3) \qquad (6b)$$

$$f_{ct} = \alpha + c_1 v + c_2 v^3 \qquad (6c)$$

Where

$$c_1 = b_1 \beta_1 \qquad (7a)$$

$$c_2 = b_2 \beta_1 \qquad (7b)$$

Where the parameter units are mL/m for c_1 and (mL/m)/(m/s)^2 for c_2.

Equation (6c) is used for model calibration of fuel consumption. After parameters c_1, c_2 and β_1 are determined through calibration, the following model parameters are calculated.

Parameters A and B specified as input for software are calculated from:

$$A=1000c_1 \qquad (8a)$$

$$B=c_2/0.01296 \qquad (8b)$$

Where the parameter units are mL/km for A and (mL/km)/(km/h)^2 for B. Parameters b_1 and b_2 are determined indirectly from:

$$b_1 = c_1 / \beta_1 \qquad \textit{if} \quad \beta_1 > 0 \qquad (9a)$$

$$= 0 \qquad \textit{if} \quad \beta_1 = 0$$

$$b_2 = c_2 / \beta_1 \qquad \textit{if} \quad \beta_1 > 0 \qquad (9b)$$

$$= 0 \qquad \textit{if} \quad \beta_1 = 0$$

Parameters b_1 and b_2 are determined from Eq. (9a) and (9b) using c_1 and c_2 values determined for fuel consumption in order to obtain a reasonable representation of drag (cruise) power to be provided by the engine so that the model application for fuel consumption is based on a realistic definition of R_C, P_C, R_T and P_T. Parameters b_1 and b_2 also reflect some component of drag associated with the engine.

The following simpler model is obtained as an alternative model by dropping the (a P_I) term of Eq. (1):

$$f_t = \alpha + \beta P_T \qquad \text{for } P_T > 0 \qquad (10)$$

$$= \alpha \qquad \text{for } P_T \leq 0$$

The values of instantaneous CO_2 emission rate (g/s as a value per unit time) are estimated directly from the instantaneous fuel consumption rate:

$$f_t(CO_2)=f_{CO2}f_t(fuel) \quad (11)$$

Where, $f_t(fuel)$ is the fuel consumption rate (mL/s) and f_{CO2} is CO_2 to fuel consumption rate (g/mL of fuel). The model for estimating the instantaneous CO, HC and NOx emission rates (mg/s), representing the emission production rate at any instant during the trip determined as a value per unit time, has the same structure as the instantaneous fuel consumption model with different parameters.

3.9 Optimal Location and Number of Waste Bins

In order to enhance the current MSW collection services in Um Gafa district, the present work also investigated the inadequacy of existing collection bins. An appropriate technology like GIS can help to find the adequate number and optimal location of the bins. For this, initially the existing bin locations were analyzed based on the service area of each bin by creating a service zone around the bin. The preferable walking distance of the people to drop their MSW to the collection bin is less than or equal to 40 m (Ahmed, 2006). As such, the service area covered by the existing bins was analyzed with proximity distance of 40 m for existing collection bin.

The minimum number of bins required was calculated on the basis of waste generation in Um Gafa district. It is given by the following equation (Anwar, 2009):

$$N = \frac{W}{\rho_w \times S \times Fl \times CF} \quad (12)$$

where, N is the number of collection bins, W is the total quantity of waste generated per day (kg), ρ_w is the density of waste (kg/m^3), S is the size of bins (m^3), Fl is the average filling rate of the bin, and CF is the collection frequency.

Another option to find the optimum location of bins was explored based on population density and landuse, without violating the 40-m service zone. To achieve this, the land uses in the district were grouped into residential, commercial, farms and public uses. Then, the amount of waste generated from each land use was estimated and the needed collection bins were determined. The bins where then allocated manually with reference to waste generation, population density and road network (intersections) and without referencing to the existing bin locations. Following that route optimization based on distance was carried out, with the implementation of traffic rules (U-turns and curb approach policies).

Chapter 4: Results and Discussion

4.1 Actual Distance and Time Spent

Figure 4.1 illustrates the tracing of the journey made by the 18-m^3 compaction truck during collection of domestic waste from Um Gafa district as collected from the field. The collection is made by a team of 3 persons; the driver and two collectors in the truck. The amount of waste collected during a trip is around 16.8 tons per day. The distance traveled by the truck is 85.7 km and lasts 9 hours and 6 minutes, including 2.1 hours of driving, 6.4 hours to load/unload bins, and 30 min break. The average time for collecting one bin that obtained from field is 36 sec, while the average speed of the truck is 40 km/hr. The fuel consumption was 32.8 L. The estimated emission of CO_2, CO, HC, and NOx by SIDRA TRIP were 44200, 425, 68, and 17 g, respectively, as shown in Table 4.1.

Figure 4.1: Current waste collection route in Um Gafa area

Table 4.1: SIDRA TRIP output for current vehicle trip

Event data	Value
Total travel distance (km)	85.7
Total travel time (hr)	9.1
Fuel consumption (L)	32.8
CO emissions (g)	425
CO_2 emissions (g)	44200
HC emissions (g)	68
NOx emissions (g)	17.9

4.2 Optimized Cases

Due to violations of the traffic policies that have been noticed during waste collection, four cases have been investigated. These cases include: Case 1 in which route optimization was carried out with the implementation of traffic rules (U-turns and curb approach policies), Case 2 in which optimization was done without implementing traffic rules (U-turns and curb approach policies), Case 3 where optimization was conducted with implementing only U-turns policy, and Case 4 in which optimizations with done by implementing only curb approach policy. The details of the above cases in terms of travelled distance and spent time obtained through the use of ARC GIS along with the associated emissions obtained using SIDRA TRIP are presented below.

For Case 1, route optimization based on distance is carried out with the implementation of traffic rules (U-turns and curb approach policies) as shown in Figure 4.2. We noticed that waste collection is performed with a decreased distance

(80.3 km) and less working hours (8 hr, 54 min). This is associated with reduced fuel consumption (31.2 L). Table 4.2 shows also the reduction in pollutant emissions relative to those currently emitted. The reduction achieved is 3.6% in CO_2, 1.6% in CO, 1.2% in HC, and 2.8% in NOx.

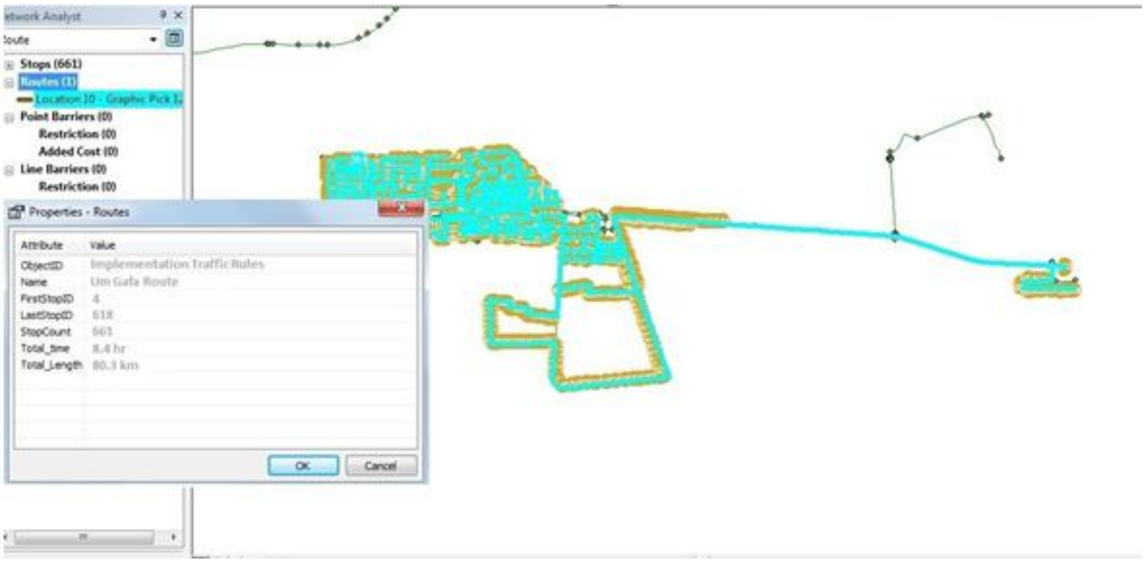


Figure 4.2: Route optimization by implementing U-turn and curb approach policies

Table 4.2: SIIDRA TRIP output for Case 1 vehicle trip

Event data	Value
Total travel distance (km)	80.3
Total travel time (hr)	8.9
Fuel consumption (L)	31.2
CO emissions (g)	418
CO_2 emissions (g)	42600
HC emissions (g)	67.2
NOx emissions (g)	17.4

For Case 2, route optimization based on distance is carried out without implementing traffic rules (U-turns and curb approach policies) as shown in Figure 4.3. For this case, we found out that the travel distance of the truck is short (73.6 km) with a total working duration of 8 hr and 34 min including break time. The fuel consumption is reduced to 28.1 L. The reduction in the emissions were 7% for CO_2, 3.5% for CO, 3.5% for HC and 8.5% for NOx, as shown in Table 4.3.

Figure 4.3: Route optimization without implementing U-turn and curb approach policies

Table 4.3: SIDRA TRIP output for Case 2 vehicle trip

Event data	Value
Total travel distance (km)	73.6
Total travel time (hr)	8.5
Fuel consumption (L)	28.1
CO emissions (g)	410
CO_2 emissions (g)	41000
HC emissions (g)	65.6
NOx emissions (g)	16.1

For Case 3, route optimization based on distance was carried out with implementing only U-turns policy as shown in Figure 4.4. The travel distance of the vehicle in this case is 76.6 km with total time of 8 hr and 40 min. The associated fuel consumption is 29.8 L. The reduction in emission was 4.7% for CO2, 2.4% for CO, 1.9% for HC and 7.3% for NOx, as shown in Table 4.4.

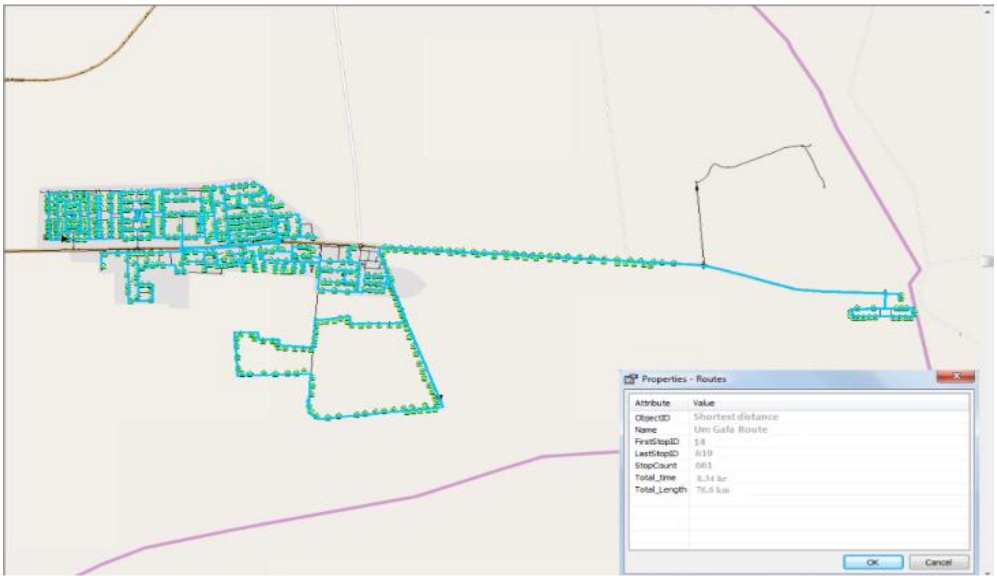


Figure 4.4: Route optimization by implementing U-turn policy only

Table 4.4: SIDRA TRIP output for Case 3 vehicle trip

Event data	Value
Total travel distance (km)	76.6
Total travel time (hr)	8.6
Fuel consumption (L)	29.8
CO emissions (g)	415
CO_2 emissions (g)	42120
HC emissions (g)	66.7
NOx emissions (g)	16.6

For Case 4, route optimization based on distance was conducted with implementing only the curb approach policy (Figure 4.5). Under this scenario, waste could be collected with a total distance of 79.2 km and duration of 8 hr and 48 min. Fuel consumption associated with this case is 31.1L. The consequent reduction in the emissions is 3.8% for CO2, 1.9% for CO, 1.5% for HC and 4.5% for NOx as shown in Table 4.5.

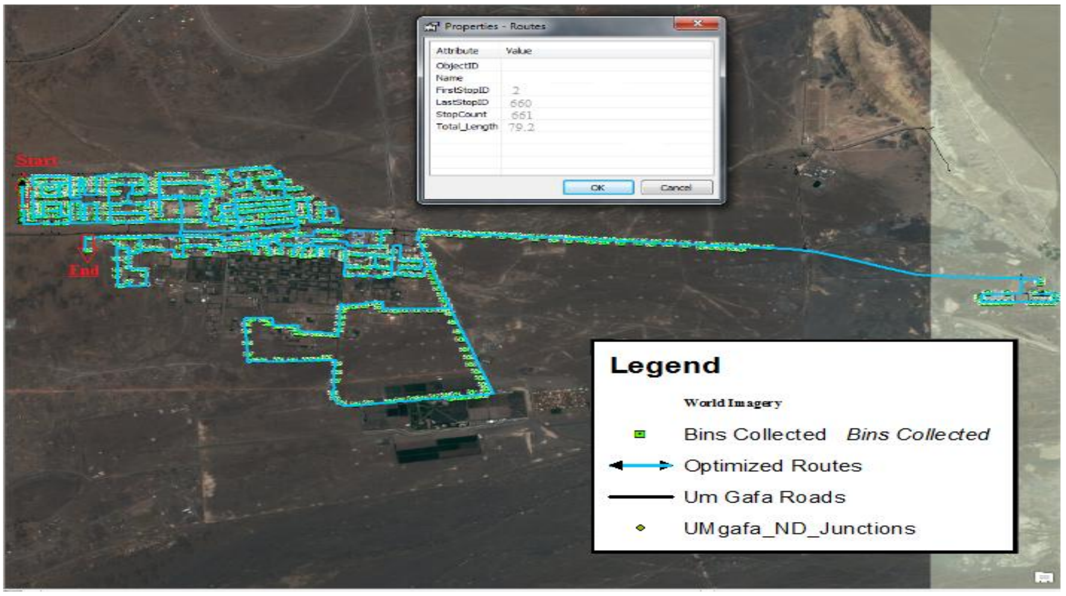
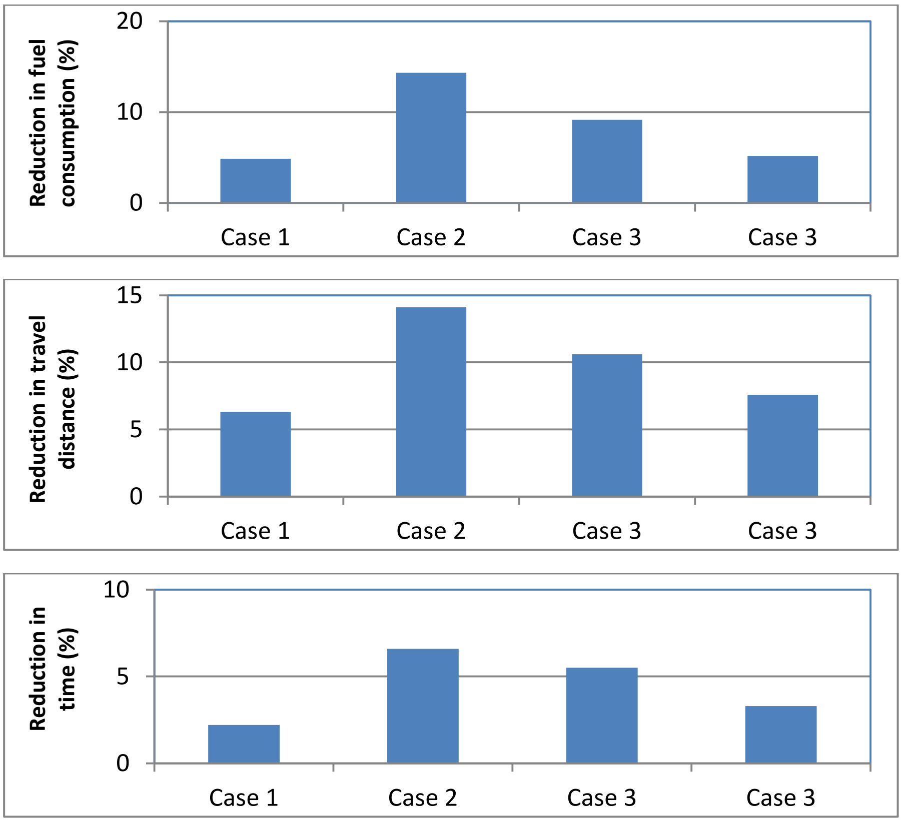


Figure 4.5: Route optimizations with implementing only curb approach policy

Table 4.5: SIDRA TRIP output for Case 4 vehicle trip

Event data	Value
Total travel distance (km)	79.2
Total travel time (hr)	8.8
Fuel consumption (L)	31.1
CO emissions (g)	417
CO_2 emissions (g)	42500
HC emissions (g)	67
NOx emissions (g)	17.1

Figure 4.6 compares between the improvements in travel distance, fuel consumption, travel time and emitted gases of the considered cases relative to current conditions. The results showed that the four investigated cases lead to some saving in fuel consumption compared to that under current conditions because of reduced collection time and reduced distance. Consequently, emitted pollutants will be less. Case 2 (which is based on route optimization without implementing traffic rules) could be considered the closest to be compared with the data obtained for the current collection route. In Case 2, the travel distance was reduced to 73.6 km (compared to 85.7 km under the current conditions). This results in a fuel reduction of about 14.3% and a reduction of CO_2 emission by 7.2%. Case 1, however, should be the one adopted which involves implementation of traffic rules. Compared to the current situation, Case 1 results in fuel reduction of 5% and in CO_2 emissions of 3.6%.



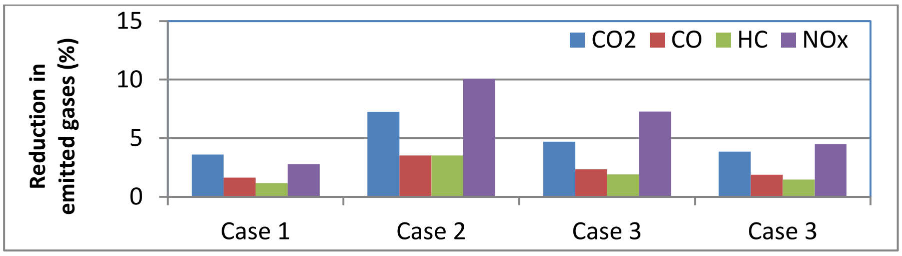


Figure 4.6: Improvements in travel distance, fuel consumption, travel time and emitted gases of the considered cases relative to current conditions

4.3 Optimal Location and Number of Waste Bins

With the purpose of analyzing the existing locations, service zones were created around the bins with people preferable distances to check the existing collection bin proximity distance. From Figure 4.7, the total area covered by existing bins with 40-m service zone is 127% of Um Gafa area and about 37% of the bins are located very close to each other in some locations such as commercial areas and farms. Thus, higher number of bins is serving the same location as shown in Figure 4.8.

Figure 4.7: Existing collection bins with 40-m service zone

Figure 4.8: Existing collection bins near farms

At present, there are 661 collection bins that are located in Um Gafa district, with a capacity of 1.3 m^3 each. The bulk density of the waste in the bin is about 120 kg/m^3 and the total daily quantity of waste collected in the area is 16,800 kg. Waste in the area is collected once a day. The total capacity of the bins is 859.3 m^3 (661×1.3 m^3) which could accommodate 103 ton (859.3×120/1000), thus the bins on the average are 16.5% full. Observation made during the site visit revealed that some bins were more than 50% full, while others were less than 10% full and some of them were even empty.

According to Ahmed (2006), the average filling of bins should be over 30% and less than 60% to account for seasonal influences. Assuming an average filling rate of the bins of 45% and using Eq. (12), the minimum number of bins that are required for collection of generated MSW in Um Gafa area at the present time is:

$$N = \frac{16800\ kg}{120\text{kg/m3} \times 1.3m3 \times 0.45 \times 1} = 240 \text{ bins}$$

This reveals that there is 63% excess of bins in the area based on the quantity of waste generated in the district.

Given that the bins on the average are only 16.5% full, one may suggest reducing the collection frequency from once per day to once every two days in order to improve the filling rate. Although with this option two trips or two vehicles are needed on the collection day, the overall time and travel distance could be reduced as compared to daily collection. This, however, could have complications due to the hot weather conditions in the area, which can develop unpleasant situation due to waste decomposition.

Another option is to reduce the bin size from 1.3 m^3 to 1.1 m^3. This will improve the filling rate, but it will not affect the time of collection of bins. Reducing the bin size to less than 1.1 m^3, will change the collection services from alley to door-to-door and will require more collection staff. Such an option could, however, be considered in case source sorting is adopted in future.

The current location of some bins in Um Gafa is not based on landuse and population density (CWM-AD, 2015). Hence, there is a necessity to reduce the number of bins on the road. One option is to change the size of the bins from 1.3 m^3 to 3 m^3 near commercial and farms areas. With this option, smaller bins serving commercial centers and farms will be replaced by fewer, large ones. This would positively influence routing optimization by reducing the number of stops, thus saving the working time; as most of the collection time is spent for bin loading and emptying. Fuel consumption and corresponding gas emissions are functions of work performed for stopping and accelerating, actual driving, traffic-related stops and lifting and compacting the waste (Sonesson, 2000).

Collection bins were allocated manually to find the optimum number of bins assuming a 40-m service zone and changing bin size from 1.3 m^3 to 3 m^3 near commercial and farm areas. As shown in Figure 4.9, we found that the optimum number of bins is 572, and the total area covered by these bins is 110% of the actual area. It must be mentioned that, priority to new bin locations was given to existing bins and cross-roads in order to facilitate social acceptance. Also every two bins of size 1.3 m^3 were replaced by one bin of size 3 m^3 near commercial and farm areas, noticing that, the average time required for collecting a bin of 3 m^3 is 44 second (Amar, 2012).

Figure 4.9: Proposed locations of bins with 40-m service zone

After the relocation of the waste bins, optimization of waste collection vehicle routing was performed based on distance, with the implementation of traffic rules (U-turns and curb approach policies), as in Case 1. The optimal solution, as demonstrated in Figure 4.10, corresponds to 80.1 km of distance travelled by the waste collection vehicle. Thus, an improvement of 4% is gained when compared to Case 1. The improvement is more emphatic in terms of the total travel time; this is 8 hr and 6 min including break time. Table 4.6 shows the consequent reduction in pollutant emissions relative to those currently emitted. The reduction achieved is 7.4% in CO2, 9.2% in CO, 9.5% in HC, and 12% in NOx. This proves that, fuel consumption and corresponding gas emissions are functions of work performed for stopping, accelerating and decelerating.

Figure 4.10: Optimal waste collection vehicle trip with relocation of waste bins based on a 40-m service zone

Table 4.6: SIDRA TRIP output for optimal waste collection vehicle trip with bins relocation based on a 40-m service zone

Event data	Value
Total travel distance (km)	80.1
Total travel time (hr)	8.1
Fuel consumption (L)	29.6
CO emissions (g)	380

CO_2 emissions (g)	39500
HC emissions (g)	60.8
NOx emissions (g)	15.2

Another option to find the optimum location of bins is to allocate collection bins based on landuse and waste generation in Um Gafa district. To do so, the land uses in the district were grouped into residential, commercial (shops and small restaurants), farms and public uses (schools and gardens), then the amount of waste generated from each land use was estimated as described below.

In Um Gafa there are 617 large house and 32 buildings that consists of 4 apartments each. All the houses are adjacent to each other. However, 11 of the apartment buildings are isolated while the other 21 are adjacent to each other. The area also contains 21 commercial units, 4 schools, one garden and 23 farms. The generation rate per person in the houses and the apartments was estimated based on information provided by Abu Qdais et al. (1997) which is 2.33 kg/cap/d for large houses and 1.85 kg/cap/d for apartments. The number of residents in the house is taken as 10 and those in the apartment range between 4-5 persons with an average of 4.5 (SCAD, 2015).

There is a lack of waste generation rates from commercial, school and agricultural units in Abu Dhabi Emirate. Therefore, generation rates of commercial and school units were based on information provided by CalRecycle (2006), those for gardens were based on information provided by NY CEQR (2011), while those for agricultural units were based on a conducted site survey. The average number of employees in the existing commercial units was estimated to be 5 based on a site survey, while the area size of the garden and the farms was measured by ArcGIS. The number of students in the school (i.e., 400) represents the average among the 4 different schools in the area. As for the garden, the number of visitors (based on the sold tickets) fluctuates from 80-100 during a weekday but reaches 350 during weekends. As such, the assumption is made that there are 400 visitors of the garden each day. For the farms, the daily waste generation rate was based on observations made on site of the filling rate of the bins. Generally, the bins are 40% full.

Two criteria were utilized to determine the number and size of bins to be assigned for each landuse. First, the bin should be at most 45% full with a bulk density of about 120 kg/m^3. Second, the bin location should adhere to a 40-m service zone. A summary of the results is listed in Table 4.7 and the details of the entries in the table are described below.

Based on an average filling rate of 45%, 205 bins of 1.3 m^3 are needed to serve the houses. However, based on a 40-m service zone, 392 bins are needed with each bin serving two adjacent houses. Thus, 392 bins (1.3 m^3 each) are used for houses. As for the apartments, 11 bins (1.3 m^3 each) are needed to serve the 11 isolated apartment buildings and 12 are needed to serve the 21 adjacent apartment buildings with two buildings served by one bin. For commercial units, 3 bins (3 m^3 each) are needed to serve the 6 adjacent commercial units and 15 bins (1.3 m^3 each) are needed to serve the 15 isolated commercial units. All 4 schools are isolated from each other, so one bin (4 m^3) is needed to serve each school. Meanwhile, one bin (4 m^3 size) is needed to serve the garden. For the farm units, 8 bins (3 m^3 each) are needed to serve the 16 adjacent farm units and 7 bins (1.3 m^3 each) are needed to serve the 7 isolated ones.

Table 4.7: Generation rate and number of bins

Source	**Number of units**	**Units of measurement**	**Daily generation rate per unit**	**Total daily quantity (kg)**	**Number of bins**	**Size of bins (m^3)**
Large houses	617	kg/person/d	2.33×10	14,376	392	1.3
Apartments	128	kg/person/d	1.85×4.5	1,066	23	1.3
Commercial units	21	kg/employee/d	11.3×5	1,190	15 3	1.3 3
Schools	4	kg/student/d	0.5×900	1,800	4	4
Gardens	1	kg/visitor/d	0.45×400	180	1	4
Farms	23	$kg/m^2/d$	0.4×1.3×120	1,435	8 7	3 1.3

It should be mentioned that the total estimated waste generation based on the entries in Table 4.7 is 20,047 kg, which exceeds by 20% the 16,800 kg collected daily. This is due to some conservative assumptions made in the generation rates of the different units. Nonetheless, if all the bins used are of 1.3 m^3 size, then the number of bins needed, if distributed based on population density and waste generation, will be 485. This number is about 20% less than those actually present on site. As indicated before, selection of other bin sizes (such as 3 m^3 or 4 m^3 bins), is made, whenever possible, in order to reduce the collection time.

After that collection bins were allocated manually with reference to waste generation, population density and road network (intersections) and without referencing to the existing bin locations as shown in Figure 4.11. Route optimization based on distance is carried out, with the implementation of traffic rules (U-turns and curb approach policies) as shown in Figure 4.12. For this case, we found out that the travel distance of the truck is 78.8 km, shorter than that of Case 1 (80.3 km). Furthermore, a major reduction in working hours is achieved (6 hr and 42 min including break time) as compared to 8.9 hr of Case 1. Fuel consumption is reduced to 27.1 L as opposed to 31.2 L of Case 1. Reductions in gaseous emissions were 10.6% for CO2, 25% for CO, 14% for HC and 20% for NOx, as shown in Table 4.8.

Figure 4.11: Proposed locations of bins based on waste generation and population density

Table 4.8: SIDRA TRIP output for optimal waste collection vehicle trip with bins relocation based on waste generation rate

Event data	Value
Total travel distance (km)	78.8
Total travel time (hr)	6.7
Fuel consumption (L)	27.1
CO emissions (g)	311
CO_2 emissions (g)	38054
HC emissions (g)	57.4
NOx emissions (g)	13.8

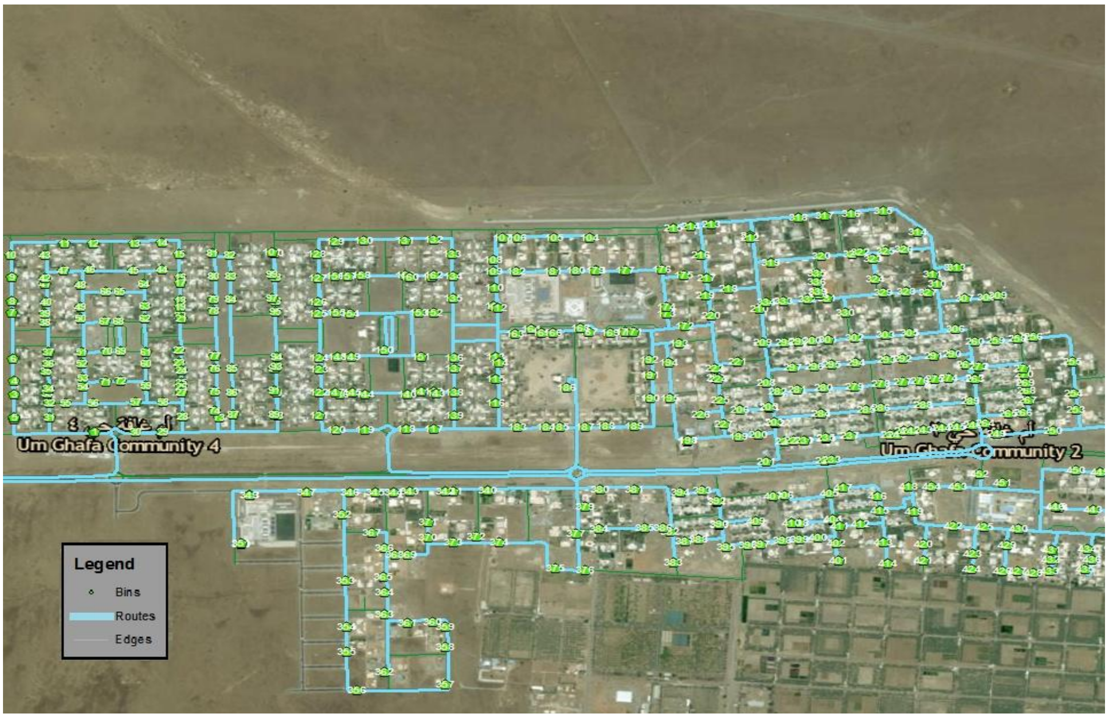


Figure 4.12: Optimal waste collection vehicle trip with locations of bins based on waste generation and population density

Figure 4.13 compares between the improvements in travel distance, fuel consumption, travel time and emitted gases of Case 1 (abiding to traffic rules but with the same bin locations) and cases with bins relocation relative to current conditions. The results showed that there are significant improvement with the bin relocation approaches in terms of fuel consumption compared to that under current conditions and of Case 1 majorly because of reduced collection time. Consequently, emitted pollutants will be less by about 10-20%. The figure also shows that relocation of bins based on landuse gives the best results in terms of fuel consumption because of its significant reduction of collection time and to a lesser extent its reduction of travel distance.

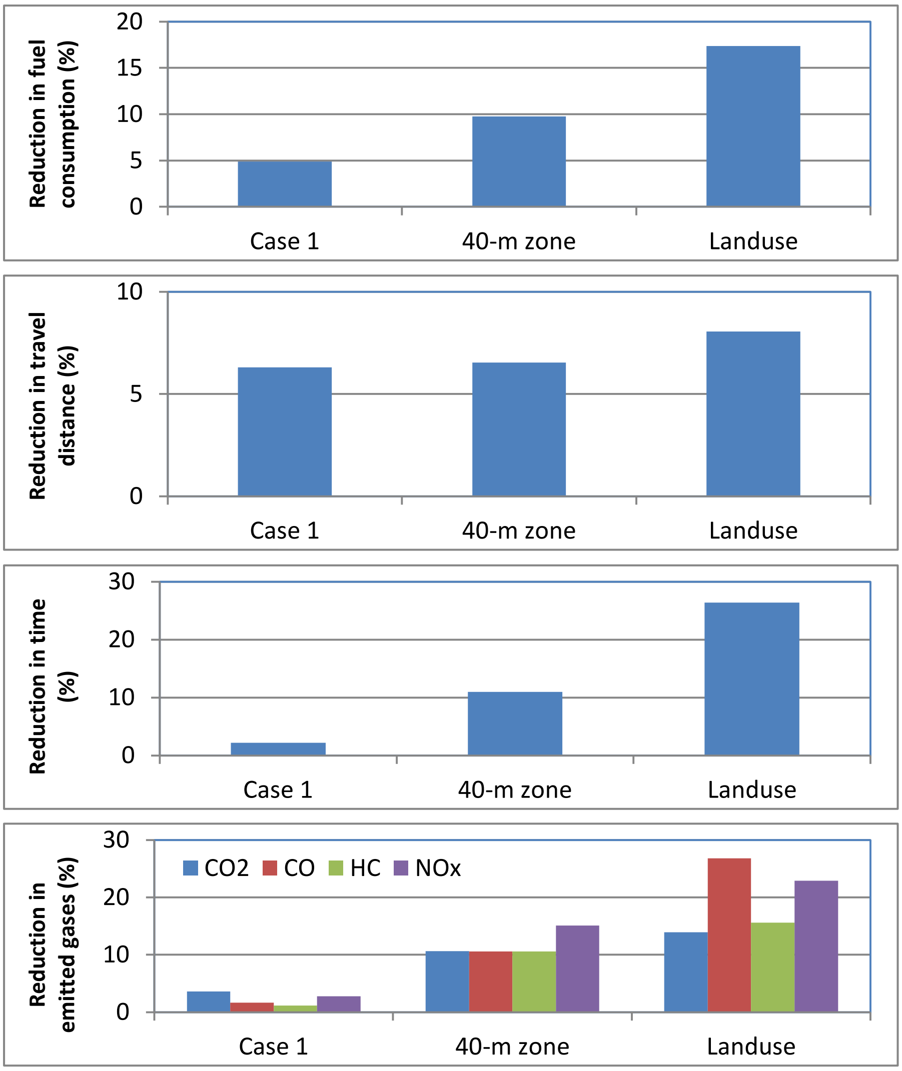


Figure 4.13: Improvements in travel distance, fuel consumption, travel time and emitted gases of Case 1 and examined cases with bin relocation relative to current conditions

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

In this study, an optimization was developed using the ArcGIS tool in order to improve the efficiency of collection and transportation of municipal solid waste in the Um Gafa district in Al Ain city.

Four cases were generated and analyzed to identify the optimal routes of waste collection: Case 1 is the optimized route with the implementation of traffic rules (U-turns and curb approach policies), Case 2 is the optimized route without implementing traffic rules (U-turns and curb approach policies), Case 3 is the optimized route with implementing only U-turns policy and Case 4 is the optimized route with implementing only curb approach policy. Case 2 simulates the current conditions where traffic rules are not implemented. Results show that with the use of route optimization a saving of 14.1% in travel time, 14.3% in fuel consumption, and 6.6% in collection time is gained. In addition, emitted gases will be reduced by 7.2% for CO_2, 3.5% for CO, 3.5% for HC, 10.1% for NOx.

Since traffic regulations have to be implemented as in Case 1, then the relative saving, would be about 6%, 2% and 5% in traveled distance, working time, and fuel consumption, respectively. For this case, gaseous emissions will be reduced by 3.6% for CO_2, 1.6% for CO, 1.2% for HC, and 2.8% for NOx.

Also in this study, GIS was used for investigating the adequate number and positions of existing collection bins. The present location of the collection bins was analyzed and new models were proposed with optimal number and location of bins, in which every two bins of size 1.1 m^3 were replaced by one bin of size 3 m^3 near commercial and farm areas. In model 1, bins were located according to the requirement of a 40-m service zone. With this approach, 12% of the bins were decreased. In model 2, the number and size of bins were estimated based on population density and landuse. This has resulted in 20% less bins than those actually present on site. Results of the optimal route for waste collection using the two models demonstrate that the proposed models are significantly efficient in terms of travel distance and collection time, with consequent fuel consumption and gas emissions savings. Furthermore, model 2 was found to be more efficient than model 1.

5.2 Recommendations

Findings of this study indicate that GIS-based optimized cases can provide significant improvements to the collection/transportation system of MSW and consequently to its financial and environmental costs. In addition, routing optimization in GIS environment evidenced the benefits of its use: It significantly simplifies the process, even for large sets of data for transportation network information and location, it computes easily the source–destination cost matrix, it finds the solution to vehicle routing problem smoothly and conveniently represents and visualizes the obtained results.

Although the study focused on Um Gafa area to demonstrate the effectiveness of the method, route optimization should be applied for the whole city of Al Ain. This could be mandated by the CWM-AD and requested from the operating companies.

Significant savings could be achieved by modifying waste bins with sensors to indicate if empty in order to reduce collection time. In this case, the vehicle will not stop at empty bins. So, it is recommended that future bins be supplied with sensors to reduce the collection time and thus fuel consumption.

It is suggested that a study be carried out to determine the waste generation rate for different landuses in Abu Dhabi Emirate. Such data are currently missing, but should be useful for better planning of bin numbers and sizes in existing and future locations.

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Appendix A

Containers Dimensions

Figure A1: Bin size: 1.3 m^3 - Height: 1.38 m - Width: 1.4 m - Depth: 1.05 m

Figure A2**:** Bin size: 3 m^3 - Height: 1.54 m - Width: 2.02 m - Depth: 1.54 m

Figure A3: Bin size: $4m^3$ - Height: 1.8 m - Width: 1.5 m - Depth: 1.9 m