Optimization of fuel consumption for municipal solid waste collection in Al Ain city, UAE

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Abstract. Fuel consumed in collecting municipal solid waste (MSW) accounts for a major portion of the cost of waste management. In this study, several cases were developed using the ArcGIS Network Analyst to establish optimum conditions for MSW collection in Um Gafa district in Al Ain city, UAE. A GIS model was created based on data collection and GPS tracking of collection route and bins position in the area. Results show that current waste collection at Um Gafa does not strictly follow U-turn and curb approach policies. When route optimization is applied for similar conditions, a saving of 14.3% in fuel consumption is gained. Two models were tested 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 land use. By adopting model 1, the number of bins was reduced by 12%, while in model 2 the number of bins was reduced by 20%. Model 2 showed higher superiority, compared to model 1, in terms of fuel consumption.

1. Introduction

Waste collection is the most fuel intensive step in waste management. It accounts for 40 to 60% of the allocated budget for municipal solid waste (MSW) management [1]. Thus, implementation of vehicle routing techniques for MSW collection is necessary for effective decision making. In general, two different approaches have been reported for optimization of MSW collection including the use of operational research [2-13] and the use of geographic information systems (GIS) [14-19].

Generally, models that are based on the operational research methodology do not provide the flexibility and responsiveness needed in real time logistic problems and thus are difficult to apply in practice. Moreover, most of these models do not account for heterogeneous vehicle fleets or maximum loading capacity of trucks. However, the GIS approach is capable of effective handling, display and manipulation of geographic and spatial information as demonstrated by several investigators [14, 16, 19].

The United Arab Emirates (UAE) is confronted with enormous solid waste management challenges that could strain municipal financial resources and the handling of the ever increasing waste volumes. Nonetheless, the government is working hard to reduce the waste generation rate, and started privatizing solid waste management in order to meet the waste collection and disposal demand.

However, limited effort has been directed towards assessing the cost of waste services and increasing their cost effectiveness. Particularly, no work has been done to optimize fuel consumption during MSW collection. Thus, the main objective of this study was to develop a GIS-based model to calculate fuel consumption of vehicles that collect MSW. The model was then used to explore optimum conditions for waste collection in Um Gafa area in the city of Al Ain. Results of this study can be used to improve the efficiency of the waste management system in Al Ain City, thereby reducing the cost of waste collection which could ultimately results in environmental benefits.

2. Methodology
The approach followed in this work consisted mainly of three main steps. First, develop a GIS-based model to explore different scenarios to arrive at the optimal route for waste collection in the study area. Second, calculate fuel consumption and emitted greenhouse gases under the current conditions and for the explored scenarios without altering waste bin numbers or locations. Third, investigate the adequacy of the number and positions of existing collection bins and conduct route optimization of the proposed bins location. Before proceeding with the details of the methodology, a brief description of the study area is introduced.

2.1. Site description
Al Ain City covers an area of approximately 13,100 km², with a population of 650,221 as of 2015 [20]. The topography of Al Ain is nearly flat with the exception of the area of Hafeet Mountain. Management of MSW in the city is currently under the control of the Center of Waste Management – Abu Dhabi (CWM-AD). From a waste collection perspective, the city is divided into the north and south zones. Collection of waste from each zone is carried out by two private companies (MBM Dalla and Lavajet). Collected MSW is sent to a sorting station at Seeh Al Hemmah, nearby the compost plant. The station also receives wastes from the transfer stations in the peripheral townships. Organic-rich materials are diverted to the compost plant, recyclable wastes are collected and stored for further marketing, and the remaining unwanted materials are transported to a central single-lined landfill located about 18 km west of the transfer station.

Studies by the CWM-AD [21] estimated that Al Ain City produced between 1.4 to 1.7 kg/cap/day of solid waste between 2011 and 2015. The total amount of waste produced in 2015 in the city was about 2.5 million tons. Non-hazardous waste formed 99.6% of the total produced waste. Out of the total non-hazardous waste generated, MSW totaled 327,627 tons, 59% of which was disposed in a sanitary landfill while 17% was composted, 16% was recycled, and 8% was disposed in some dumpsites.

To carry on this study, an area within Al Ain City called Um Gafa was selected. Um Gafa is located in the south zone of Al Ain (figure 1) and covers an area of approximately 44.6 km², with a population of 6,772 in 2015 [20]. Um Gafa area 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, the area includes 6 roundabouts and has no traffic signals. The area contains 617 large houses and 32 buildings, each consisting of 4 apartments. All the houses are adjacent to each other. Twenty-one of the apartment buildings are adjacent to each other, while the 11 others are isolated. The area also contains 21 commercial units, 4 schools, one garden and 23 farms. It should be mentioned that Um Gafa area 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.
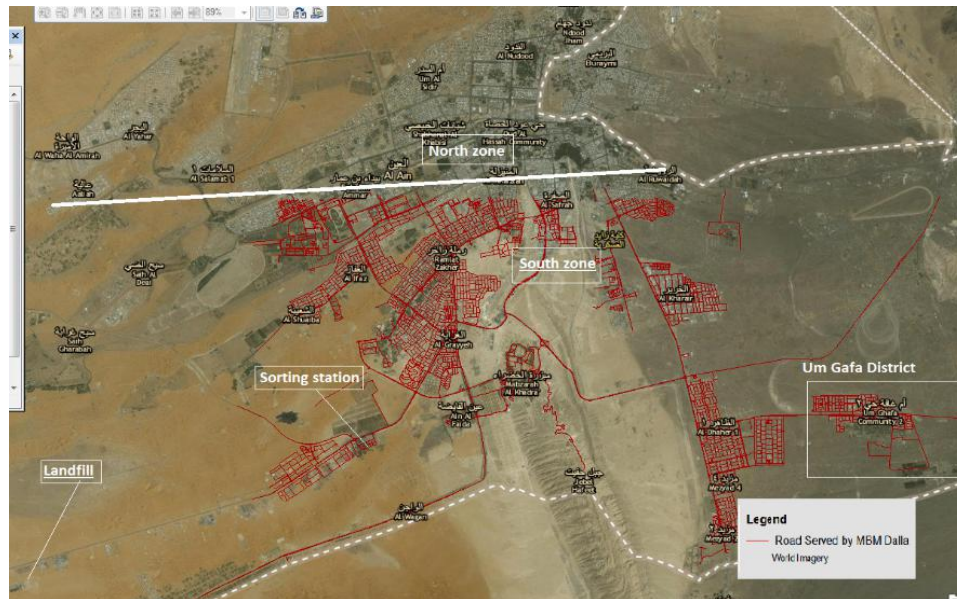
Figure 1. Location of Um Gafa area and waste management facilities in Al Ain City.

Collection of MSW in the Um Gafa is carried out by MBM Dalla on behalf of CWM-AD. MSW collection service in Um Gafa follows a communal collection system, by which waste is carried out manually and/or mechanically. The total number of waste bins in the area is 661 each of 1.3 m^3. 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 an 18-m^3 loaded compaction truck operated using diesel fuel. The collection is made by a team of 3 persons; the driver and two collectors in the truck. 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.

2.2. Data collection and model development

In this study, a GIS-based model using ArcGIS Network Analyst tool was developed in order to establish optimum conditions for MSW collection in Um Gafa area, with an objective of minimizing fuel consumption. The GIS model was created based on data collection and GPS tracking of collection route and bins position. The ArcGIS Network Analyst tool provides network-based spatial analysis including routing, travel directions, closest facility, and service area analysis. It enables users to dynamically model realistic network conditions, including turn restrictions, speed limits, height restrictions, and traffic conditions [22]. The tool uses the Dijkstra's Algorithm [22] in order to solve the routing problem.

In developing the GIS-based model, spatial data were created from existing maps by manual digitizing. For this purpose, a shape file of Al Ain map was collected from Al Ain Town Planning Department including attributes data (area boundary, name and type of roads and their width and traffic volume details). Errors detected in the collected map (i.e., duplicate objects, undershoots and zero length objects) have been corrected manually. U-turn and curb approach polices have been collected from Al Ain Transportation Police Department. 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 during their duty. 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. Data that were added manually to the generated maps include one-way and two-way roads, U-turn polices, curb approach polices, driving time, and service time of the bins.

Different layers of drawing were created including route analysis layer which contains information related to curb approach and override parameters. Each route is composed of three feature layers: stops, barriers, and routes. The stops feature layer stores the network locations that are used as stops in route analysis. Barriers, on the other hand, are used in route analysis to denote points where a route can't traverse. The route feature layer stores the resultant route of a route analysis.

2.3. Explored cases

The developed GIS model was used to investigate several case scenarios with the objective of optimizing travel distance. Fuel consumption and emitted green-house gases (GHGs) under the current conditions and for different explored scenarios were then determined using SIDRA TRIP software [23]. Due to lack of microscopic GPS data of the study area, the quick scenario analysis incorporated in SIDRA TRIP was used. Vehicle profile for heavy vehicles reported by Akcelik and Associates [24] was used. This was done by specifying the vehicle type, travel distance, travel time, number of stops, stop duration, road grade (slope of the road), average speed, average acceleration and average deceleration.

During the tracking of the current waste collection route in Um Gafa area, some violations of traffic rules have been noticed such as U-turn and curb approach policies. According to Abu Dhabi Traffic Engineering Department, the U-turn policy dictates that waste collection vehicles are 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. Thus, two cases have been investigated without re-locating the waste bins or changing their numbers. In Case 1, route optimization was done with the implementation of traffic rules. In Case 2, route optimization without implementing U-turn and curb approach policy. Case 2 could be used to make a comparison with the current situation, where U-turn and curb approach policies are not adhered to.

Another two cases (Case 3 and 4) were explored with the objective of finding the adequate number and optimal location of bins that should be used in the area. In Case 3, route optimization was done with bins relocation based on a 40-m service zone. In Case 4, route optimization was done with bins re-location based on population density and land use, without violating the 40-m service zone. For Case 4, the land use in the district was categorized as 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). For Case 3 and 4, route optimization was carried out with the implementation of the U-turn and curb approach policies.

3. Results and discussion

3.1. Current situation

Figure 2 illustrates the actual tracking of the journey made by waste collection truck in Um Gafa area. The amount of waste collected during a trip was around 16.8 tons per day. The distance traveled by the truck was 85.7 km and lasted 9.1 hours, including 2.1 hours of driving, 6.4 hours to load/unload bins, and 30 min break. The average time for collecting one bin as obtained from field was 36 sec, while the average speed of the truck was 40 km/hr. The fuel consumption was 32.8 L. The estimated emission of CO_2, CO, hydrocarbons (HC), and NOx by SIDRA TRIP were 44200, 425, 68, and 17 g, respectively.

3.2. Optimized cases without bins re-location

Table 1 summarizes the results of optimization of Case 1 and 2. The table also lists the parameter values of the current situation. Results showed that Case 1 and 2 lead to some saving in fuel consumption compared to that under current conditions because of reduced collection time and reduced distance. Consequently, emitted pollutants were reduced.
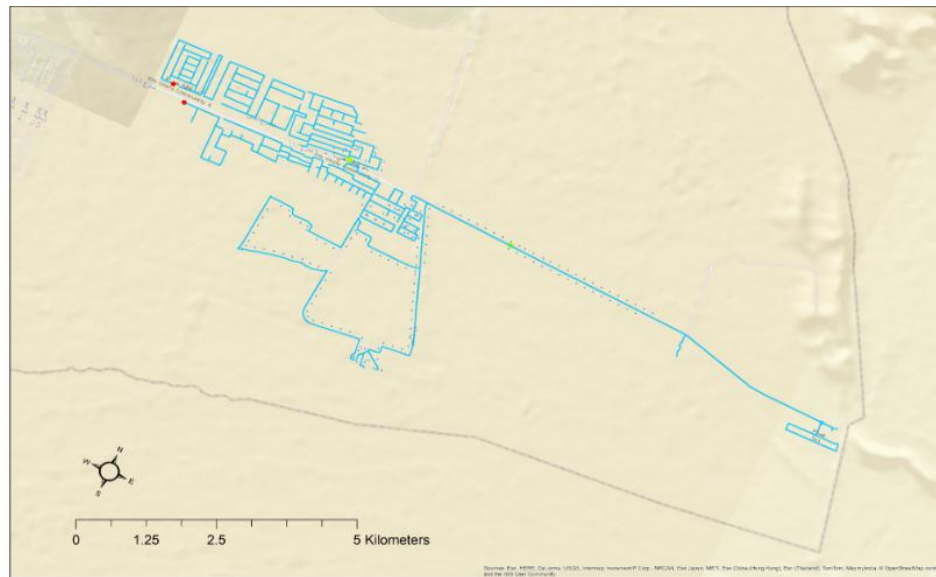
Figure 2. Current waste collection route in Um Gafa area.

The results of Case 2 (which was based on route optimization without implementing traffic rules) could be compared with those obtained for the current situation. For Case 2, the travel distance was reduced to 73.6 km (compared to 85.7 km under the current conditions). This resulted in fuel reduction of about 14.3% and a reduction of CO_2 emission by 7.2%. Case 1, however, should be the one adopted in case bins were not re-located because it involves adherence to traffic rules. Compared to the current situation, Case 1 results in fuel reduction of 5% and in CO_2 reduction of 3.6%.

Table 1. Results of the optimized cases without bins relocation.

Parameter	Current situation	Case 1	Case 2
Travel distance (km)	85.7	80.3	73.6
Travel time (hr)	9.1	8.9	8.5
Fuel consumption (L)	32.8	31.2	28.1
CO emissions (g)	425	418	410
CO_2 emissions (g)	44200	42600	41000
HC emissions (g)	68	67.2	65.6
NOx emissions (g)	17.9	17.4	16.1

3.3. Optimized cases with bins re-location

Currently, there are 661 collection bins in the study area, each with a capacity of 1.3 m^3. The bulk density of the waste in the bin is about 120 kg/m^3 and the daily quantity of waste collected in the area is 16.8 ton. Waste in the area is collected once a day. The total capacity of the bins is 859.3 m^3 which could accommodate 103 ton. Thus, the bins on the average are 16.5% full. Observations made during the site visit revealed that some bins were more than 50% full, while others were less than 10% full and some were even empty. According to Ahmed [25], the average filling of bins should range from 30% to 60%. Assuming a filling rate of 45%, the minimum number of bins that are required in the area at the present time can be calculated as:

$$N = \frac{W}{\rho_w \times S \times Fl \times CF} \qquad (1)$$

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. Thus, the minimum number of bins in Um Gafa area would be 240, which constitutes 36% of what is provided in the area. Hence, there is a necessity to explore the possibility of reducing the number of bins on the road subject to the condition that the preferable walking distance of people to drop their MSW into the collection bin does not exceed 40 m [25]. Two models were developed for optimum waste bins location and number. In model 1, bins were located according to the requirement of a 40-m service zone (Case 3). In model 2, the number and size of bins were estimated based on population density and land use (Case 4).

In Case 3, collection bins were allocated manually to find the optimum number of bins assuming a 40-m service zone. Meanwhile, the bin size was changed from 1.3 to 3 m^3 near commercial areas and farms. By doing so, smaller bins serving commercial centers and farms were replaced by fewer, larger ones. This would positively influence routing optimization by reducing the number of stops. We found that the optimum number of bins was 572. It should 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 areas and farms, noticing that, the average time required for collecting a bin of 3 m^3 is 44 sec [26]. After relocating the bins, optimization of vehicle routing was performed based on distance with the implementation of traffic rules. The results in table 2 show that the travel distance was shortened by 4% compared to Case 1 in table 1. The improvement was more emphatic in terms of the travel time, which was 8.1 hours including break time. Reductions in emissions were 7.4% for CO_2, 9.2% for CO, 9.5% for HC, and 12% for NOx.

Table 2. Results of the optimized cases with bins relocation.

Parameter	Case 3	Case 4
Travel distance (km)	80.1	78.8
Travel time (hr)	8.1	6.7
Fuel consumption (L)	29.6	27.1
CO emissions (g)	380	311
CO_2 emissions (g)	39500	38054
HC emissions (g)	60.8	57.4
NOx emissions (g)	15.2	13.8

In Case 4, optimization of the bins location was based on land use and waste generation. To do so, the generation rate per person in houses and apartments was assumed to be 2.33 and 1.85 kg/cap/d, respectively [27]. The number of residents in the house was taken as 10 and those in the apartment ranged between 4-5 persons with an average of 4.5 [20]. No data were available for waste generation rates from commercial, school and agricultural units in the area. As such, waste generation rates of commercial and school units were based on information provided by CalRecycle [28], those for gardens were based on information provided by NY CEQR [29], while those for agricultural units were based on a conducted site survey during this study. Meanwhile, 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., 900) represents the average among the 4 different schools in the area. As for the garden, the number of visitors (based on the sold tickets) fluctuated from 80-100 during a weekday but reached 350 during weekends. Thus, the assumption was made that there were 400 visitors of the garden each day. For the farms, the daily waste generation rate was taken as 40% based on observations made on site. The number and size of bins assigned for each land use were then determined based on (1) a filling rate of the bin that does not exceed 45% with a bulk density of 120 kg/m^3 and (2) a service zone of each bin that does not exceed 40 m. A summary of the results is listed in table 3 and the details of the entries are described below.

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

Table 3. Generation rate at Um Gafa area and required number of waste bins.

| Source	Number of units	Unit of measurement	Daily generation rate per unit (kg/d)	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	1.3
					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/unit/d	0.4×1.3×120	1,435	7	1.3
					8	3

It should be mentioned that the total estimated waste generation based on the entries in table 3 is 20,047 kg, which exceeds the 16,800 kg collected daily by 20%. This is due to some conservative assumptions made in the generation rates of the different units. If all the bins used were of 1.3 m^3 size, then the number of bins needed, if distributed based on population density and waste generation, would 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), was made, whenever possible, in order to reduce the collection time.

Collection bins were allocated manually with reference to land use, population density and road network (intersections), but without referencing to the existing bin locations. Route optimization based on distance was then conducted as shown in figure 3. Results of the optimization (table 2) showed that the travel distance was 78.8 km shorter than that of Case 1 (80.3 km). Furthermore, a major reduction in working hours was achieved (6.7 hours including break time) as compared to 8.9 hours of Case 1. Fuel consumption was reduced to 27.1 L as opposed to 31.2 L of Case 1. Reductions in gaseous emissions were 10.6% for CO_2, 25% for CO, 14% for HC and 20% for NOx.

4. Conclusion

In this study, an optimization was developed using ArcGIS in order to improve the efficiency of collection and transportation of MSW in Um Gafa district in Al Ain City. Results show that with the use of route optimization a saving, relative to the current practice, of 14.3% in fuel consumption was gained. In addition, emitted gases were reduced by 7.2% for CO_2, 3.5% for CO, 3.5% for HC, 10.1% for NOx. Two models were developed for optimum waste bins distribution and number. 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 relative to the present ones. In model 2, the number and size of bins were estimated based on population density and land use. 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 emission savings. Furthermore, model 2 was found to be more efficient than model 1.
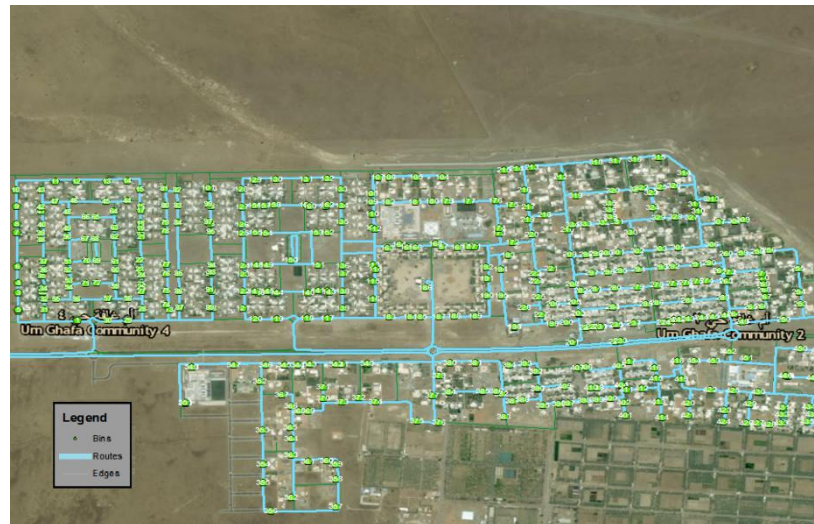
Figure 3. Optimal waste collection vehicle trip with bins located based on
land use and population density.

Acknowledgement

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