Vehicle Routing Optimization for Improving Fleet Fuel Efficiency: A Case Study in Sydney, Australia

Hoda Karimipour, Vivian W. Y. Tam, Helen Burnie, and Khoa N. Le

***Abstract*—Vehicle Routing Problem (VRP) is a classic combinatorial optimization problem involved in many applications. VRP is even a big concern when the vehicle is a garbage truck, which travels approximately 100 km/day with the average consumption of 1 litre/km. For this reason, a small improvement in collection activities may result in significant savings in overall cost, fuel and therefore greenhouse-gas emissions. The primary goal of this research is to find ways to reduce overall travel distance for collection and transport of municipal solid waste from residential homes within the Blacktown City Area in order to reduce the fuel consumption and therefore greenhouse-gas emissions. Esri's ArcGIS 10.3 Network Analyst extension has been used in this study. To calculate optimal routes for solid waste collection, several inputs to the ArcGIS Network Analyst solver have been used including: collection points represented the depot start point, the home rooftops where the garbage is collected and the unload point. The results of this study show that: Using an optimized route instead of a regular route can reduce the total travelled distance by 8 km/day on the pilot site. The optimized route will reduce that individual truck's emissions by 5.5 kg CO2 per day for that collection area. This represents a reduction of about 8% for that particular collection.**

***Index Terms*—Fleet fuel efficiency, vehicle routing problem, greenhouse gases, transportation.**

I. Introduction

It has been estimated that of the total amount of money spent for the collection, transportation, and the disposal of solid waste around 60-80% is spent on the collection phase [1]. This provides great opportunity for research to find better cost saving measures for municipalities. In addition to the high cost in operation and maintaining municipal vehicles, there is concern that municipal solid waste (MSW) trucks have a negative impact on the environment due to the distances driven, fuel type, engine inefficiency, and exhaust emissions. Solid waste management comprises the generation, collection, transport, treatment, and disposal of solid waste from homes [2]. Routing optimization problems in waste management have typically been addressed with different types of mathematical algorithms. Routing algorithms use a measuring system called a path length for determining the ideal route to a defined destination. The optimal routes are then determined by comparing different paths. These paths can be calculated by different types of algorithms. Some of the routing algorithms used include Simulated Annealing, Tabu Search, Genetic Algorithm, Ant Colony Optimization, and Dijkstra's algorithm [1], [3], [4].

Vehicle Routing Problem (VRP) is a classic combinatorial optimization problem involved in many applications. Since its introduction by Dantzig and Ramser [5], VRP has been extensively studied. By considering additional requirements and various constraints on route construction, different VRPs have been formulated [6], [7]. VRP is a considerable concern when the vehicle is a garbage truck, which travels approximately 100 km/day with the average consumption of 1 litre/km. For this reason, a small improvement in collection activities may result in significant savings in overall cost, fuel and therefore greenhouse-gas emissions. Therefore, the optimization of routes for collection and transportation of municipal waste can be a crucial issue. This paper proposes the use of geographic information systems (GIS) to minimize fuel consumption, while taking into account the truck load and geographic features (e.g. slopes, relief) of the area where the waste is being collected.

The primary goal of this research is to find ways to reduce overall travel distance for collection and transport of municipal solid waste from residential homes within the Blacktown City Area in order to reduce the fuel consumption and therefore greenhouse-gas emissions.

The research for this paper aims to:

- Reduce the overall distance driven to collect and transport residential waste;
- Reduce fuel consumption during the waste collection process; and
- Decrease the greenhouse gases emitted by garbage trucks.

II. Materials and Methods

A. Study Area

Blacktown City is the pilot area for this paper. Blacktown is a modern bustling city of 48 residential suburbs, home to 350,000 people. This is the second largest local government area by population in New South Wales, Australia. Covering an area earmarked for considerable residential development, with more than 4,000 developments approved in 2015-2016 and a population increase of nearly 2.5% in 2016 [8], Blacktown City Council will experience an increasing domestic waste stream over the next few years. Australia's Nationally Determined Contribution to the 2015 Paris Agreement is to reduce its total greenhouse-gas emissions by 26-28% below its 2005 level. In line with this, Blacktown

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City Council is working to decrease its emissions. The biggest opportunities in reductions are from electricity, street lighting, gas, and transportation through improved fleet fuel efficiency. This study will investigate the opportunities for fleet fuel efficiency through route optimization for Blacktown City Council.

For this study, Council's waste collection Truck nNo. 634 was selected to investigate the applicability of a route optimization model for improving fleet fuel efficiency. The regular route of this truck was used to obtain the current travel time and travel distance. Figure 1 shows the map of Blacktown City and the collection area for Truck No. 634.

B. Route Optimization Using ArcGIS Network Analyst

Software, Esri's ArcGIS Network Analyst extension allows users to perform complex calculations to solve vehicle routing problems. The program performs analysis over a network of connected edges and decides fleet routing, travel directions, closest facility, service area, and location allocation. In the application for route optimization, network dataset edges represent the road network being traversed. Network Analyst allows the user to dynamically model genuine network situations. These conditions can include speed limit, traffic volume at different times of the day, one-way streets, turn restrictions, obstacles, road conditions, and limitations.

Network Analyst mainly uses Dijkstra's algorithm, which is a simpler algorithm that finds the shortest or lowest cost path between two points. This algorithm preserves balance between evaluating a near optimal path to travel with one that is computationally practical. Dijkstra's algorithm divides the network dataset into lines or edges, with each edge representing a traversable or non-traversable piece of the network. In addition, each network edge also has an associated cost, which represents the effort to travel that specific segment of road. These costs are calculated using one of two different criteria. The distance criterion is based on total edge length, and the time criterion measures edge length and time to traverse a segment [1]. The algorithm creates nodes or junctions at the start, end, and intersection of all edges; this defines the network by confirming there is transitivity between edges and junctions through the entire connected road network. The software calculates the cost to reach a node then determines the least cost path to travel to the next node. This continues until a final destination point is reached. These steps create only a temporary and partial solution. Once the initial cost is calculated between all the stops, the software applies a Tabu-Search heuristic process. This re-evaluates and confirms, then re-establishes a more optimal path. This procedure continually runs to optimize the current path until no further optimization can be performed. The result is the least cost route to travel, along a path from a start to end point. Depending on number of points (stops) to make and complexity of the network, the analysis can take seconds or hours to complete.

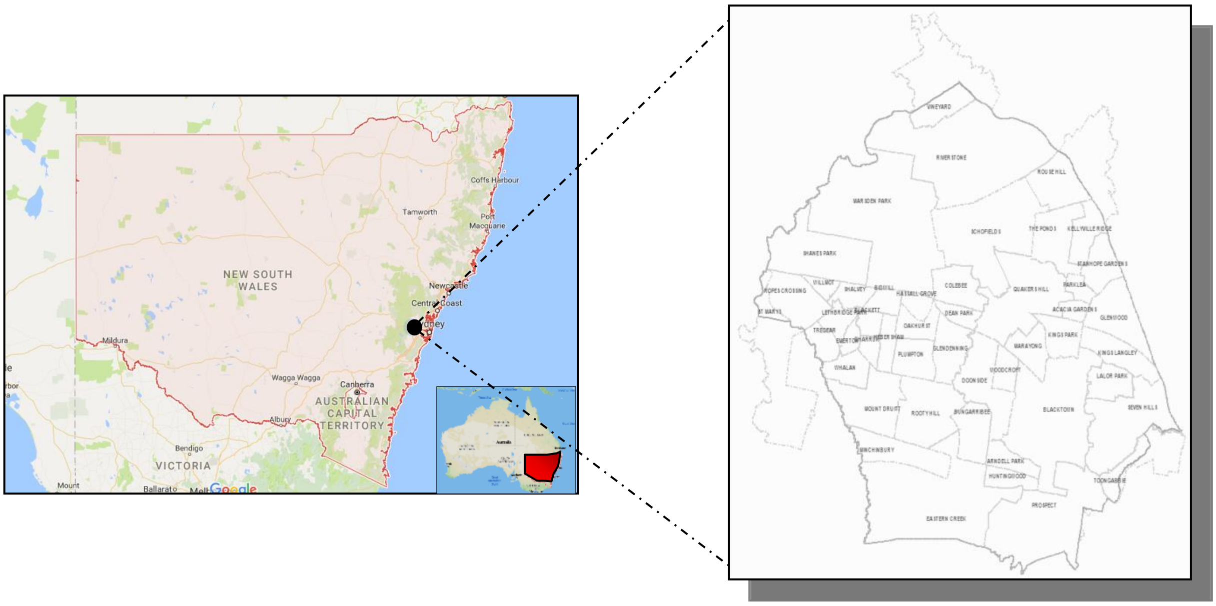

Fig. 1. The Blacktown City location in New South Wales, Australia.

C. Application of GIS in Waste Management

Esri's ArcGIS 10.3 Network Analyst extension has been used in this study. In the application for route optimization, network dataset edges represent the road network being traversed. Network Analyst allows the user to dynamically model genuine network situations. These conditions can include speed limits, one-way streets, turn restrictions, obstacles, road conditions, and the other limitations.

The most critical functional requirement of the system was to calculate optimal routes for solid waste collection. The outputs should show travel distance, drive time and greenhouse-gas emissions then comparisons among different resulting routes could be conducted for the different scenarios. To be able to calculate optimal routes, the system was also required to store the service order and depot locations. The service order area is in the suburb of Seven Hills, located in the South East of Blacktown City. The area includes about 30 streets/alleys from which household garbage is collected. A road network dataset representing all the streets within Blacktown City was also needed to be compiled in order to properly perform route optimization calculations through the ArcGIS Network Analyst extension. The road edges and junctions had to have coincident geometry for the route optimization calculations to perform properly [4]. Finally, the existing collection route needed to be compiled for comparing current and new routes.

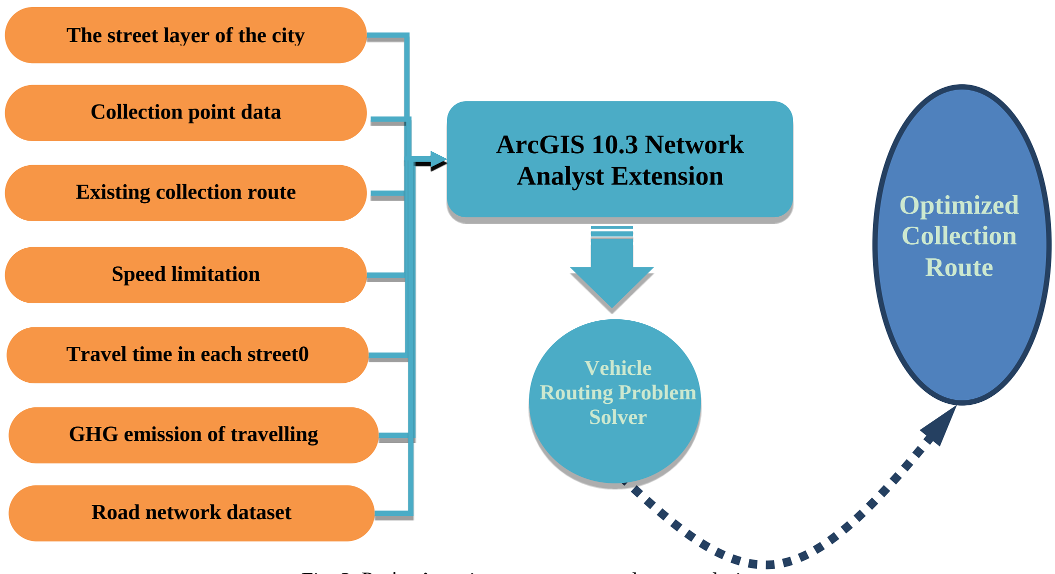

Fig. 2. Project's major components and system design.

D. System Analysis and Design

Displays the project's major components and how they integrated into the workflow. To calculate optimal routes for solid waste collection, there were several inputs to the ArcGIS Network Analyst solver. Collection points represented the depot start point, the rooftops of homes where the garbage is collected and the unload point [4]. The unload point is the UR-3R, (Urban Resources-Reduction, Recovery and Recycling), which is an alternative waste treatment facility located in the southern part of the city. In the UR-3R process, municipal waste is sorted using the inherent properties of material such as size, shape and density. There are three main categories: recyclable, organics and non-recyclable inorganic material [9]. A waste collection vehicle in New South Wales is generally known as 'a garbage truck'. These side-loading trucks, have automatic 'arms' that pick up a bin at the kerbside and empty it into the truck. The driver then moves along the street to the next bin. There is no need for people to run along near the truck to empty the bins into it [10].

A network dataset of Blacktown City roads was constructed to ensure all street segments are connected at junctions. Additional GIS layers were incorporated into the VRP solver to enable accurate representation of potential routes travelled. For example, speed limitation and travel time were included in the model. A raster DTM file was imported into ArcGIS and included the elevation and topographic relief information for the study area. These data were used to perform test calculations of slope for each road segment within the city. Also, different layers for calculating greenhouse-gas emissions have been added to the model including CO_2, N_2O and CH_4 emissions for travelling each section of the street.

With all the inputs and parameters set up, the VRP solver can construct a new optimized route with optimal sequencing. The route was evaluated for accuracy and route parameters were then adjusted accordingly. Multiple route solver iterations were run until an optimal collection route was identified.

E. Research Scope

The scope of the project is to develop a detailed road network dataset for the study area, which includes total meters, total minutes, and GHG emission between each two nodes. This involved exploring how different settings for the network analyst parameters affect the optimization results. The results from the new routes were examined and compared to existing routes. While Blacktown City is divided into 5 garbage collection areas, this analysis focused on one collection area.

F. Data Sources

All project data were collected from one of three sources. The client for this project was the Blacktown City. The city has its own functioning GIS department which supplied the collection areas, parcel data, route data, junction's data, in a GIS compatible format. Relevant sections of the Council, which oversees city sanitation collection, supplied data specific to the garbage collection process. The data included operational hours, vehicle capacity, fuel type, driver information, existing collection routes, The location of the UR-3R waste treatment facility, and current collection patterns. The QOL supplied the residential collection locations in table format. The project required road data features for the entire City of Blacktown. This feature class provided detailed analysis of each road segment with matching attribute information such as: road width, lanes, speed, classification, name, and date of modification

G. GHG Emission Calculation

The Australian National Greenhouse Accounts Factors were used to calculate the GHG emissions from the truck transportation along the identified paths. According to this standard, fuels used for transport purposes produce slightly different methane and nitrous oxide emissions than if the same fuels were used for stationary energy purposes. This Factors list also includes a range of optional emission factors for post-2004 vehicles and heavy vehicles conforming to

Euro design standards.

Estimates of emissions from the combustion of individual fuel types are made by multiplying a (physical) quantity of fuel combusted by a fuel-specific energy content factor and a fuel specific emission factor. This is performed for each relevant greenhouse gas (in this case, carbon dioxide, methane and nitrous oxide). Total greenhouse emissions are calculated by summing the emissions of each fuel type and each greenhouse gas. The following formula has been used to estimate greenhouse gas emissions from the combustion of each type of fuel listed used for transport energy purposes [11].

$$Eij = \frac{Qi \times ECi \times EFijoxec}{1000}$$

where:

Eij is the emissions of gas type (j), carbon dioxide, methane or nitrous oxide, from fuel type (i) (CO2-e tonnes).

Qi is the quantity of fuel type (i) (kilolitres or gigajoules) combusted for transport energy purposes

ECi is the energy content factor of fuel type (i) (gigajoules per kilolitre or per cubic metre) used for transport energy purposes If Qi is measured in gigajoules, then ECi is 1.

EFijoxec is the emission factor for each gas type (j)

III. Results and Discussions

The result of the route optimization for the study truck has been shown in Fig. 3

This figure shows the location of the bins that need emptying and the path that should be travelled from Council's depot to the collections area and then to the UR-3R facility at Eastern Creek, where the truck unloads. Compared to the regular route this optimized one will reduce the travel distance by 8 km/day for the pilot truck

In addition, the CO_2, N_2O and CH_4 emissions from this optimized route have been calculated. To calculate the emissions of the total route, the emissions for each section of each street were calculated and then the optimized route pieced together. This enabled the total emissions of the route to be extracted. As shown in the Fig. 3, the total emissions of the route are 69.78 Kg. This optimized route, will reduce the daily CO_2 emissions by 5.5 kg for this collection area. That means if this path is travelled by the pilot truck one day per week for 52 weeks per year, it annually reduces emissions by 1386 Kg of CO_2 compared with the regular route. If the routes of all 400 trucks owned by Blacktown City Council can be optimized between 4 to 8 Km per day like the pilot truck, the average greenhouse-gas emissions reduction would be between 300 to 600 tonnes per year.

IV. Conclusion

This paper examined the applicability of vehicle route optimization on improving fleet fuel efficiency and reducing greenhouse-gas emissions. The pilot area was one garbage collection area of Blacktown City, Sydney, New South Wales, Australia. For this purpose, Esri's ArcGIS 10.3 Network Analyst extension was used. The most critical functional requirement of the system was to calculate optimal routes for solid waste collection. The outputs showed travel distance, drive time and greenhouse emissions before and after route optimization. The results of this study show that:

- Using the optimized route instead of the regular route can reduce the total travelled distance by 8 km/day on the pilot site.
- The optimized route will reduce that individual truck's emissions by 5.5 kg CO2 per day for that collection area. This represents a reduction of about 8% for that particular collection.
- The total reduction in fuel consumption for a similar garbage truck for approximately the same distance will be 193 litres per four-weeks, per truck.

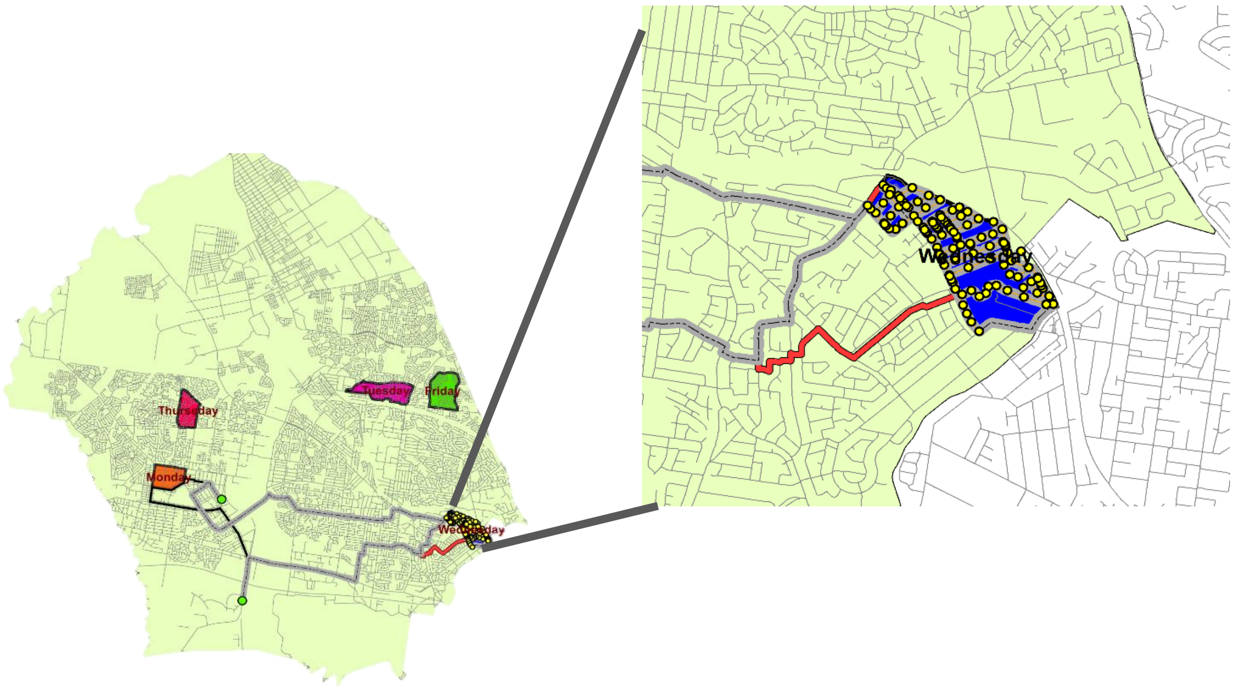

Fig. 3. The result of route optimization for waste collection.

Future studies in this field can consider the fuel efficiency effects of other factors, such as load and type of trucks.

Future work could focus on the effects of elevation, traffic load and the weight of the truck on the optimized routes. The impacts of driving behaviour on the fuel consumption is an additional area for future research.

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