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SERVICE CONSTRAINTS ON A SIMPLE GIS BASED CURBSIDE WASTE COLLECTION MODEL

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Abstract: Waste collection expenditure alone made up about 47% of the annual residential waste management budget at City of Regina in 2005. Optimized waste collection routes, such as using Geographic Information System tools, help reduce the waste collection system's collection time, labour cost, fuel consumption, and environmental footprint. For North American cities and towns with a front-of-street curbside collection program, a bin or collection point is typically serviced on the truck's passenger side. However, it was found that this service constraint was not explicitly considered in many GIS-based studies. The objectives of this study are to apply the truck's passenger side constraint and other service constraints to a small study area in Regina, and to investigate their effects on overall travel distance and collection time using different scenarios. A simple GIS-based door-to-door collection model with various service constraints is developed and studied. In some scenarios, the "one-way road" rule is applied in the modeling to force waste collecting vehicles to service the collection points only at the truck's passenger side. In another scenario, a single collection point is assumed to be shared between two individual waste generation sites to increase efficiency. The results suggested that the model approach with the truck's passenger side constraint provides more realistic results. In this study, conventional GIS modelling approaches with no service constraints underestimate the travel distance in collection zones by 60.9%. Also, sharing a collection point among waste generators could reduce collection time by at least 12.5% when compared to the status quo.

1 INTRODUCTION

Waste collection cost in industrial countries accounted for more than 50% of the total expenditure on solid waste management (Sanjeevi and Shahabudeen 2016). In Regina, Canada, waste collection expenditure made up about 47% of the residential waste management budget (City of Regina, 2005). Optimization of residential collection routes increases collection efficiency, and also helps to reduce travel distances, labor costs and the fuel consumption of trucks. Emissions from these collection vehicles, and the associated environmental impacts, will also be reduced.

Geographical Information System (GIS) techniques are widely studied for waste collection optimization (Vijay et al. 2005, Alvarez et al. 2008, Karadimas and Loumos 2008, Zamorano et al. 2009, Zsigraiova et al. 2013, Boskovic and Jovicic 2015, Gallardo et al. 2015, Son and Louati 2016, Nguyen et al. 2017). By applying GIS to identify the shortest routes for waste collection trucks, a 9.9% to 71.8% reduction in total truck travel distances are attainable (Zamorano et al. 2009, Malakahmad et al. 2014, Abdelli et al. 2016; Sanjeevi and Shahabudeen 2016; Son and Louati 2016; Nguyen et al. 2017). A reduction in total collection time, in the range of 14.3% to 62.0%, is also reported (Thanh et al. 2009; Zsigraiova et al. 2013, Son and Louati 2016). It is found that most of these GIS-based studies focused on waste collection systems in larger areas, and the distances between collection points are relatively large. Trucks in these studies are often allowed to access generation sites and collection points using both sides of road without imposing traffic direction constraints. On the contrary, trucks in a door-to-door curbside collection system collect wastes using the passenger's side of the trucks for reasons including ease of operation and lower traffic impacts. As such, traffic direction constraints are necessary for realistic modeling results, especially for smaller residential areas.

Truck fuel consumptions, collection time, and emissions in curbside waste collection were studied and reported by a number of studies (Nguyen and Wilson 2010, Maimoun et al. 2013; Maria and Micale 2013; Edwards et al 2016; Maimoun et al. 2016). Some of the key factors affecting truck fuel consumption and emissions were the distance between two collection points, truck speed, and truck idle time (Nguyen and Wilson 2010, Edwards et al. 2016). The truck speeds reported in curbside collection studies appear to change with distance between stops and traffic density. Edwards et al. (2016) found that the average truck speed between stops in urban area was 7 km/h, whereas the figures for semi-urban and rural areas were 9 km/h and 15 km/h, respectively. Curtis and Dumas (2000) found that the waste collection truck speed was 8 km/h, with an average travel distance of 23 m between stops. Abdelli et al. (2016) suggested similar results, with a collection truck speed of less than 10 km/h in their studies. Boskovic et al. (2016) and Maimoun et al. (2016) both used an average truck speed of 10 km/h. A higher truck speed of 16 km/h - 20 km/h was reported by Maria and Micale (2013) for a longer truck travel distance between stops range of 145 m to 315 m. Idling time (lifting time) per stop reported in waste collection literature were generally between 8.3 seconds to 8.7 seconds (Nguyen and Wilson 2010, Maimoun et al. 2015, Edwards et al. 2016).

Most collection optimization studies using GIS focused on the design and optimization of waste collection with transfer stations in larger areas without traffic direction constraints. In the present study, GIS optimization techniques were applied to a small residential neighborhood with a door-to-door curbside collection system. The objectives of this study are (i) to model door-to-door waste collection by applying various realistic service constraints using GIS, and (ii) to investigate the impact these constraints have on total collection time using different scenarios. The "one-way road" rule was applied in the GIS modeling to force waste collecting vehicles to service collection points at the truck's passenger side only along a given street. A total of 3 scenarios were considered in the study to evaluate the effects of service and operational constraints on collection distance and time.

2 METHODOLOGY

2.1 Study Area, Current Waste Collection Service and Field Measurements

The selected study area is located in the Hillsdale area in south Regina covering an area of 0.88 km^2, with about 675 households (Figure 1). The average number of people per home in the study area was about 2.39 (City of Regina, 2015). The distances between the doors of any two houses, measured parallel to the curb, in the study area range from 9 m to 20 m. Roads in the study area are mainly residential roads with a width ranging from 8.5 m to 9.5 m (OpenStreetMap 2017). The City's only landfill is located in the north east corner of the city and the road distance between the study area and this landfill is about 15 km.

The residential waste generation rate was approximately 16.65 kg/household·week (City of Regina, 2005). Thus, the total waste generation in the study area was about 11.24 tonnes/week. Currently, automated front-of-street collection (curbside collection) service is provided weekly (bi-weekly in the winter) in the study area. A 240 L or 360 L garbage bin and a 320 L blue recycling bin are provided to each household. Homeowners are responsible for taking their bins to the curb on the collection day. The capacity of waste collection truck is 22 m^3, with side-loading at the truck's passenger side for material collection.

According to literature, truck speed and average travel distance between waste generation sites are important parameters in door-to-door collection system modelling. The truck speeds reported in literature were generally from locations with mild climates and no or limited winter driving conditions. A field study during winter driving conditions was conducted within the study area in January 2018 to measure the actual vehicle speeds and travel distances using a passenger car for scenarios with (i) a single collection point at each house, and (ii) a single collection point shared by two houses. A total of 36 potential truck stops were considered and a Garmin GPSMAP 64s handheld was used to determine the geophysical data. For scenarios with a single collection point per house, 9 m to 20 m average travel distances were recorded, with an average truck speed of 9 km/h. For the scenario with shared collection point, 21 m to 40 m average travel distances were recorded, with an average truck speed of 12 km/h. Both parameters agreed well with literature and winter driving conditions appear to have no to little observable impacts on travel distance and truck speed, at least for the conditions encountered in the present study.

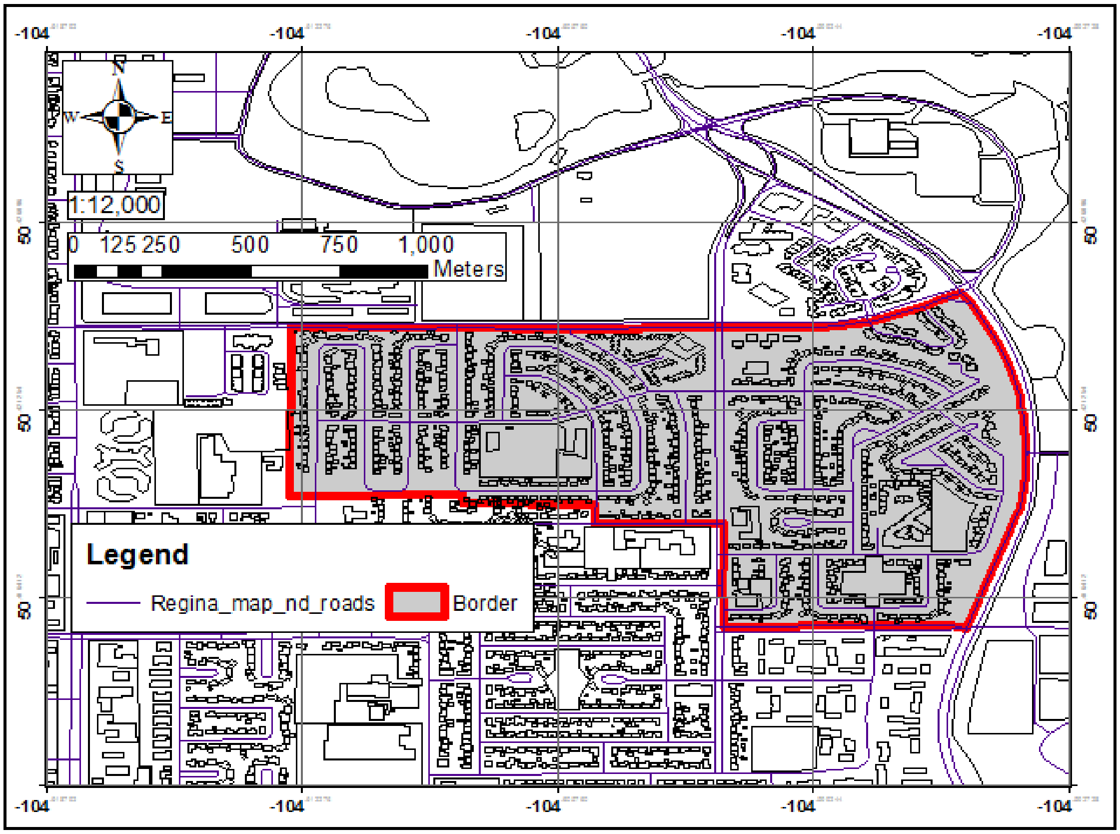


Figure 1: The study area (Open Street Map, 2017)

2.2 Conventional GIS Modelling with no Service Constraints (Scenario A)

Vehicle route problem - Network Analysis (ArcGIS version 10.5) was used to analyze and optimize truck collection routes. Inputs for the model included: (i) a road network, (ii) order locations, and (iii) route class (Figure 2). The road network was derived from OpenStreetMap (2017), and contained details such as the width and length of roads, traffic direction (one way/two way roads), and truck speed and height restrictions. In our conventional modeling approach (Scenario A), the road network was modeled such that trucks could collect waste at either side intermittently along a road, with the system objective of minimizing truck travel distance. Order location data consisted of pickup time at a stop, time windows, and waste volume per stop. Time windows were chosen from 8 am to 8 pm in this study. Waste volume per stop was calculated from the waste generation rate (16.65 kg/household·week), average waste density, and number of households per stop. The route class contained the capacity of trucks (22 m^3), depot and landfill locations, and other constraints.

2.3 Curbside Waste Collection with Service Constraints (Scenario B)

Similar to Scenario A, the Scenario B inputs consisted of the road network, order locations, and route class. The major difference between Scenarios A and B was the modeling of the roads. In Scenario B, each road segment was modelled as two individual one-way roads in the opposite direction to force trucks to collect materials on the passenger side only. Other inputs such as truck speed and height limits, pickup time at a stop, waste volume, time windows, truck capacity, depot/landfill locations, and other constraints were identical to Scenario A. The truck collects waste at every single house and there are a total of 675 orders (houses). Some key input parameters of the model are provided in Table 1. Default values of the GIS vehicle route problem were used for other parameters.

Table 1: Key input parameters

Parameters	Description	Unit	Value	Remarks
Capacity of truck	Maximum volume of waste that a truck can hold	L	22,000	Based on existing capacity of trucks
Pickup time	The time required for a truck to service an order (house)	min	0.15	Selected from literature
Truck traveling speed in Scenarios A and B	Truck speed when collecting waste at every single house	km/h	9	From field study
Truck traveling speed in Scenario C	Truck speed when collecting waste at a shared collection point	km/h	12	From field study
Volume of waste at a household	Waste generation per week at a household	L	120	Based on waste generation rate and waste density

2.4 Curbside Waste Collection with Shared Collection Points and Service Constraints (Scenario C)

Literature review suggests truck speed increases with increasing travel distance between stops. Scenario C was similar to Scenario B except that two houses were served per stop using a common collection point. Order locations of the model were adjusted to allow waste collection from up to two houses per stop. The new arrangement helped reduce the number of stops and thus extended the travel distance between stops and increased average truck speed. The distances between two stops and the speed of collection truck were measured from the field study. A summary of the methodology in this study is presented in Figure 2.

3 RESULTS AND DISCUSSION

Outputs of the models (optimal truck routes and travel times) under different scenarios were compared to investigate the effects of service constraints and shared collection point in a door-to-door collection system in the study area.

3.1 Model with no Service Constraints (Scenario A)

A total of four routes were used to collect waste from 675 houses in the study area. The optimized truck travel distances and times for different scenarios are tabulated in Table 2. For Scenario A, the truck travel distance of each route varied from 27.12 km to 30.59 km while travel time ranged from 66 min to 76 min. The total truck travel distance was 115.93 km, whereas the overall travel time was 278 minutes.

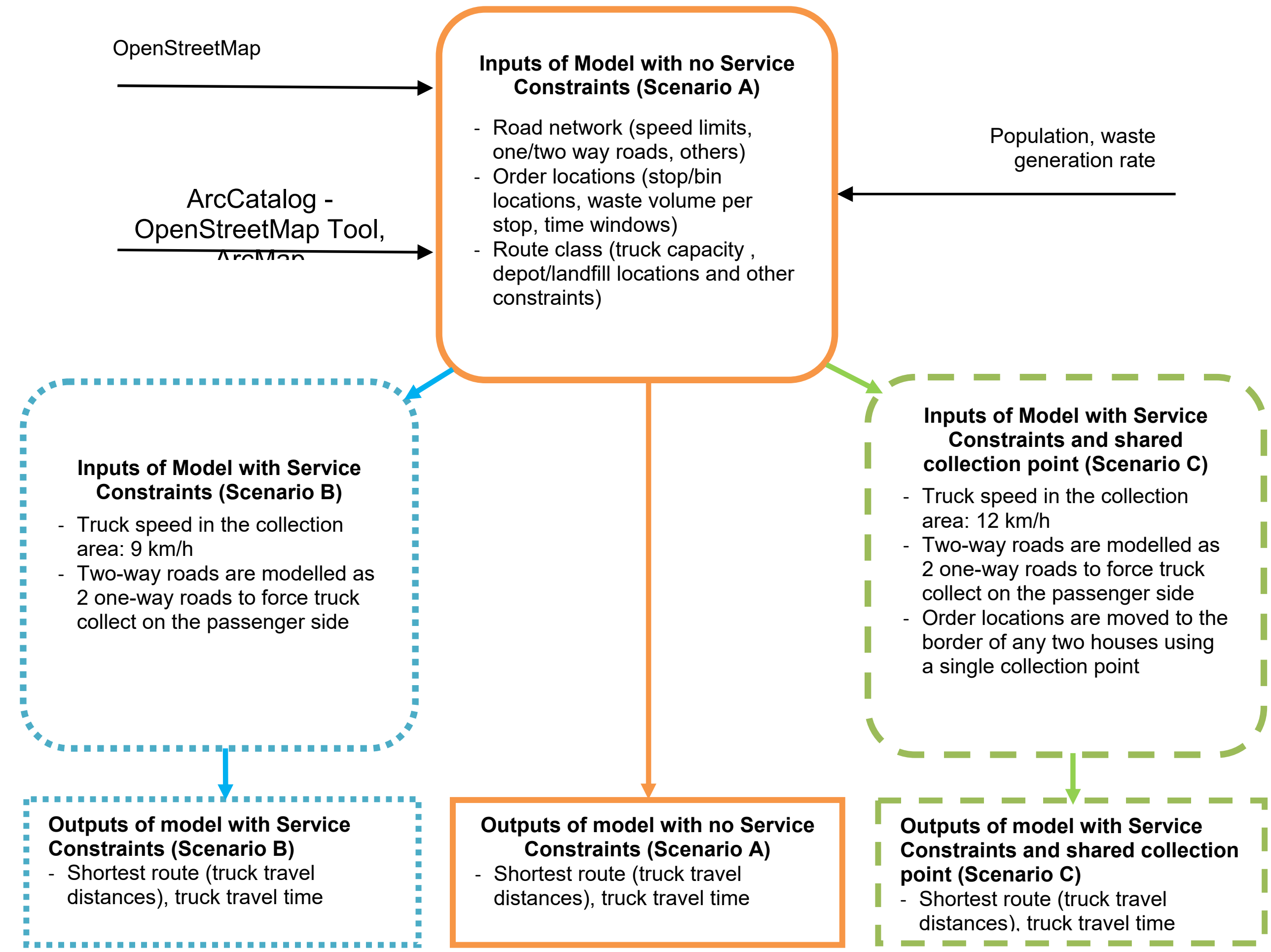


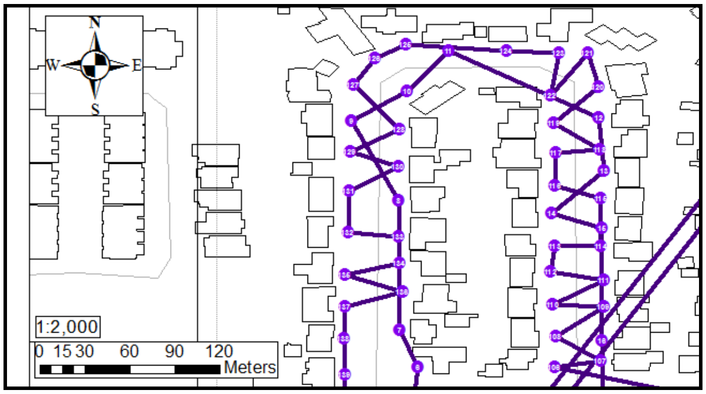
Figure 2: Summary of Methodology of this study

Although travel distance in route 2 (28.78 km) was lower than that of routes 3 and 4 in Scenario A (Table 2), route 2 truck travel time was considerably higher (76 min). This apparent discrepancy is partly due to a lengthier travel distance within the collection zone (5.08 km, Table 3). In this study, the truck speed within the collection zone was limited to 9 km/h in Scenario A, while truck speed outside the collection zone ranged from 50 km/h to 100 km/h. Collection on routes with lengthier travel distance and more customers (number of stops) within the collection zone generally takes more time due to these lower speeds.

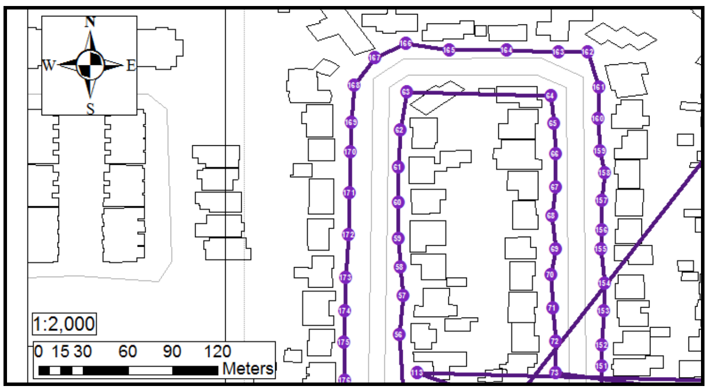
Table 2: Comparison of total travel distance and time

	Scenario A – no service constraints			Scenario B – with service constraints			Scenario C – with service constraints and shared collection point		
	Number of orders	Travel distance (km)	Travel time (min)	Number of orders	Travel distance (km)	Travel time (min)	Number of orders	Travel distance (km)	Travel time (min)
Route 1	180	27.12	68	159	30.86	83	135	30.79	69
Route 2	183	28.78	76	176	28.09	79	183	29.81	74
Route 3	162	30.59	68	183	31.94	86	183	27.13	71
Route 4	150	29.44	66	157	27.53	81	174	27.63	74
Total	**675**	**115.93**	**278**	**675**	**118.42**	**329**	**675**	**115.36**	**288**

Compared to Scenarios B and C, Scenario A has the lowest overall truck travel time (278 min, Table 2). However, a closer look of the proposed routes reveals the highly idealized nature of the routes. In Scenario A, the road network was modelled using single line segments from OpenStreetMap, and the network allowed trucks to collect waste on opposite sides of the road uninterruptedly. Figure 3a showed an example of the optimized truck routes in Scenario A. The optimized truck route shows a zigzag pattern, utilizing both sides of the road to minimize overall travel distance and time. The optimized routes in this case are less practical because the proposed operation may severely impact traffic flow and pose considerable road hazards to other road users (Figure 3a). It is believe that this modelling approach underestimated the total travel distance and time than the actual situation.



(a)



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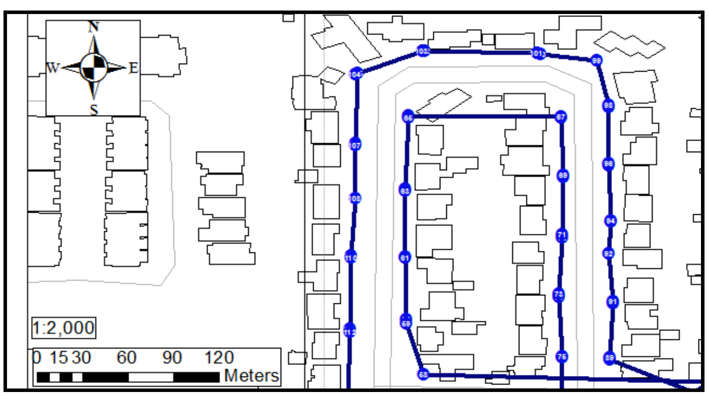

(c)

Figure 3: Examples of truck routes under the three scenarios: (a) Scenario A-conventional vehicle route problem with no constraints; (b) Scenario B-vehicle route problem with service constraints; and (c) Scenario C-vehicle route problem with service constraints and shared collection points

Table 3: Comparison of truck travel distances with or without service constraints within the collection zone

	Travel distance in collection zone (km) (Scenario A)	Travel distance in collection zone (km) (Scenario B)	Percentage of increasing distance (%)
Route 1	4.05	6.73	66.1
Route 2	5.08	6.39	25.8
Route 3	4.73	8.32	76.0
Route 4	3.87	7.08	83.2
Total	**17.73**	**28.52**	**60.9**

3.2 Model with service constraints and shared collection points (Scenario C)

The overall truck travel distances with service constraints were slightly higher than in Scenario A, ranging from 27.53 km to 31.94 km (Table 2). The overall truck travel times, on the other hand, were noticeably higher. For example, the total travel distance was increased by 2.49 km (2.2%) between Scenarios A and B, whereas the travel time went up by 51 minutes (18.4%). Table 3 showed that the truck travel distances within the collection zone were considerably higher in Scenario B than in Scenario A, with an average increase of 60.9%. It is interesting to note that Route 2 in Scenario B had a slightly higher distance than that of route 4 (Table 2). However, the corresponding truck travel time of route 2 (79 min) was lower than that of route 4 (81 min). This may be in part due to a relatively low travel distance within the collection area in route 2 (6.39 km, Table 2). In this scenario, the route served the highest number of households, 183 (route 3), and also had the highest overall travel time (86 min, Table 2).

Figure 4 shows a qualitative comparison between the optimized routes in Scenarios A and B. Routes in Scenario A (Figure 4, a1 – a4) contained fewer turns and was simpler due to the lack of service constraints. All optimized truck routes in Scenario B (Figure 4, b1 – b4) had lengthier travel routes than those of Scenario A. Overall, there was a 60.9% increase in truck travel distance in Scenario B when compared to those of Scenario A (Table 3). The percentage increases were lower in routes 1 and 2 (Table 3) because of the decreasing number of customers between Scenarios A and B on these routes (Table 2). Due to the trucks being forced to collect waste at only the passenger's side in Scenario B, higher total travel distances are modelled. Figure 3 highlights the potential benefits of modeling the vehicle route problem using two one-way roads rules, especially for door-to-door curbside collection in residential area. The conventional modeling approach, shown in Scenario A, appears to underestimate the true travel distance and time.

Results of the model with service constraints and shared collection points (Scenario C) are provided in Table 2. Overall truck travel distances varied slightly from 27.13 km to 30.79 km. Truck travel time ranged from 69 min to 74 min. Route 1 had the lowest truck travel time (69 min), partly due to it having the lowest number of customers (135). A larger average travel distance within the collection zone is observed with the establishment of the shared collection points (Figure 3c). Truck travel distances and travel times in Scenario C were lower than those in Scenario B. It is interesting to note that while the travel times were reduced by 12.5%, the travel distances went down by only 2.6%, when comparing Scenario's C and B, which both have service constraints but only Scenario C having shared collection points. The results suggested that the overall travel time is sensitive to the truck speed within the collection zone. It appears that the use of shared collection points may slightly enhance the door-to-door collection efficiency. However, certain social concerns with shared collection point operation such as the clean-up of the shared collection points and a lack of privacy may hinder the use of such a system and should be addressed in future studies.

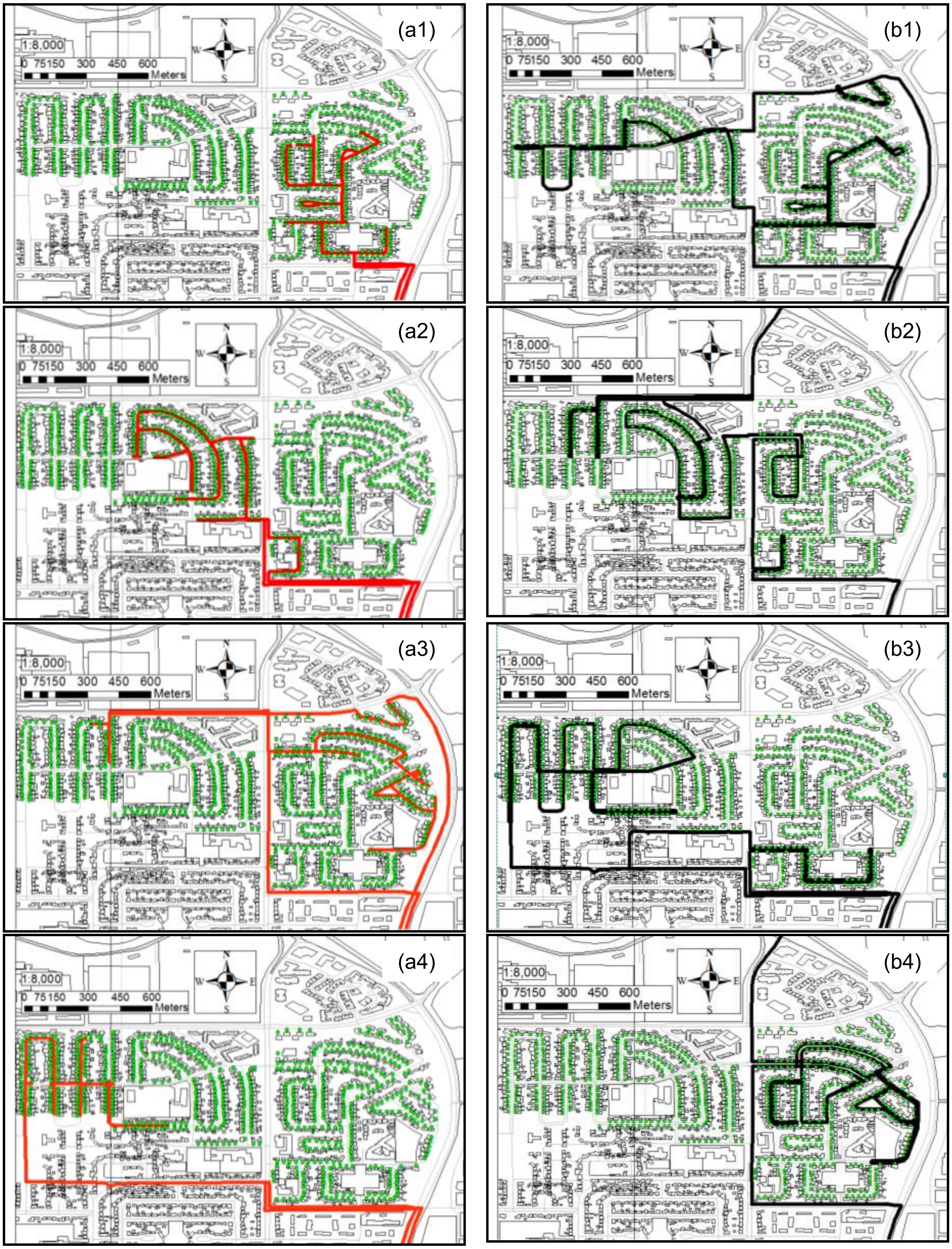

Figure 4: Comparisons of truck routes between Scenario A (a1 - a4) and Scenario B (b1 - b4)

4 CONCLUSIONS

The study examined three different GIS-based curbside waste collection models to estimate the optimal truck collection routes for a small residential area located in Regina, the capital city of Saskatchewan. The trucks in the model with no service constraints (Scenario A) are allowed to collect waste on both sides of the road to minimize overall travel distance. The lowest truck travel time of 278 min is obtained in this conventional modelling approach. The total truck distance and travelling time reported, however, are misleading due to the unrealistic routes this approach creates. By adjusting the road network and applying one-way rules, two models (Scenarios B and C) were developed. A 60.9% increase in the collection zone truck travel distance was observed in Scenario B. Results from this study suggest that Scenario B is a more realistic door-to-door curbside collection system model. To improve the collection efficiency, a model with service constraints and shared collection points was also investigated (Scenario C). The model was created to extend average truck travel distance between stops within the collection zone to increase truck speed. Compared to Scenario B, the overall truck collection time was reduced by 12.5% for the small study area considered in this study. These results highlight the importance of service constraints and average travel distances when modelling a door-to-door collection system using GIS tools.

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