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ESTIMATION OF FUEL CONSUMPTION OF VEHICLES FOR THE TRANSPORTING AND COLLECTING PHASES OF SOLID MUNICIPAL WASTE COLLECTION – ECONOMICS, CONSIDERING CLIMATE CHANGE

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Abstract
The fuel consumption of vehicles used in the municipal waste collection was analyzed. A simple, but useful method was developed to estimate the fuel consumption of the vehicles for the transporting and collecting work phases. The results show the consumption norms of the typical collecting vehicles, working in a rural environment. It can be seen that the three-axis cars consume 20% more fuel while transporting and 30% more fuel while collecting waste. The efficiency of their utilization is much better, because they are able to collect 97% more waste, than the two axis ones. For rural service the average time requirement to reach the service area is around 30% of the workday, so the use of three-axis vehicles makes a significant saving. The saving in fuel means not only financial benefit but plays a very important role in decreasing the emission of CO_2*.*

Keywords*: waste collection, fuel consumption, GHG emission, climate change*

Introduction

Transportation economics aspects

Main activities in the waste management system are the collection and the transport of waste. These activities require energy, primarily fuel (Eisted, Larsen, & Christensen, 2009), accordingly they are expensive municipal services (Faccio, Persona, & Zanin, 2011).

Waste collection was divided by Faccio et al into three classes of commercial, residential and roll-on–roll-off fields (Faccio, Persona, & Zanin, 2011).

Tavares highlights that the collection of solid municipal waste accounts for more than 70% of the total waste management budget (Tavares, Zsigraiova, Semiao, & Carvalho, 2009). The collection of solid waste is done by heavy load trucks. Most of them are highly specialized collection vehicles with compaction of the waste, but their quality and age are various (Larsen, Vrgoc, Christensen, & Lieberknecht, 2008).

This part of waste business means two main activities of:
- transport, and
- collection

Transport can be divided into the following subtasks (Larsen, Vrgoc, Christensen, & Lieberknecht, 2008):
- driving of the empty truck from the garage to the start of the collection route,
- driving of the full truck from the final stop on the collection route to the unloading point, and
- driving of the empty truck from that point either back to the garage
- or to a new collection area if more than one area is serviced on the same day..

Collection is the activity of collecting waste by the truck following a prescribed route in the residential or commercial areas. Collection can be divided further into the following subtasks (Eisted, Larsen, & Christensen, 2009):
- driving between stops,
- idling,
- loading and
- compaction of waste on the vehicle.

Collection starts with the loading of the first bin into the car and stops when no more waste is loaded (Larsen, Vrgoc, Christensen, & Lieberknecht, 2008)

The usual method for collecting municipal solid waste is the door-to-door collection. Eisted examined the service of single-family houses, where the waste owner carries the waste bins close to collecting route and the collection car empties it (Eisted, Larsen, & Christensen, 2009). While loading and unloading bins, trucks have to keep their engines running (Faccio, Persona, & Zanin, 2011).

Tavares by means of COPERT shows that fuel consumption during waste collection and transportation is influenced by the travelled distance and by the actual operating conditions of a given vehicle. COPERT is a computer program that calculates road vehicle fuel consumption. Considering vehicle specific parameters, COPERT also takes into account different driving conditions such as the type of the driving situation, vehicle load and road gradient (Tavares, Zsigraiova, Semiao, & Carvalho, 2009).

Larsen describes the fuel consumption in litres of diesel used per tons of waste collected. Larsen underlines that fuel consumption for transport can be estimated from real-case measurements or calculated by transport simulation software (Larsen, Vrgoc, Christensen, & Lieberknecht, 2008).

Final report of Directorate General Environment strengthens that the costs of waste collection have typically been reported in the past as per ton costs for residual waste and / or for different materials. However such measuring of the costs in a weight basis gives only a partial picture of the performance in collection systems, especially in the case of residual wastes (Eunomia, Research & Consulting, 2001).

Apaydin and Gonollu examine the emissions from waste collecting vehicles in city environment, and they count with an average value 0.3321 l/km (Apaydin & Gonollu, 2008). Research of Tavares includes that fuel consumption is also influenced by a third spatial dimension that quantifies road slope (Tavares, Zsigraiova, Semiao, & Carvalho, 2009). The fuel consumption for transport by trucks will depend on factors such as number of axles, carrying capacity, driving behaviour, and is often expressed as energy per mass unit or per distance unit or as a combination of both.

Larsen et al. measured the diesel consumption for 14 different collection schemes in two municipalities in Denmark, yielding a total of 254 measurements. The observations showed a considerable variation between different collection schemes, ranging from 1,4– 10,1 liter diesel ton^{-1} of waste. Larsen emphasizes that the input parameters are often highly variable and hard to determine for larger collection areas (Larsen, Vrgoc, Christensen, & Lieberknecht, 2008). Sonesson states that there are few empirical methods to calculate the fuel consumption for waste collection practices. Evaluation is mainly on a trial or error basis (Sonesson, 2000).
The method applied by Larsen was useful to estimate the average diesel consumption of collection trucks in the specified collection schemes, but it was necessary to perform a relatively large number of measurements, because of high standard deviation. The standard deviation was about 30%, suggesting that even within the same type of area, the diesel consumption per ton of waste collected varied substantially. The study did not reveal any causes for this variation. Possible causes could be the variation in waste or population density within the area; the differences in drivers' behaviour; or the variation caused by using trucks of different size within the same area. Most measurements were done for residual household waste. Collection of residual household waste in rural areas with long distances and small amount waste per stop had given the highest diesel consumption. The total amount of diesel used for collection and transport of waste can be estimated from the obtained results by combining them with generic data for diesel consumption intransportation methods (Larsen, Vrgoc, Christensen, & Lieberknecht, 2008).

Sonesson finds several factors that influence the fuel consumption, such as distance, number of stops, traffic situations, how skilful the crew are and the type of truck. He calculates the fuel consumption for collection as a function of number of stops and fuel consumption per stop. In Sonesson's study the lifting of dustbins is performed hydraulically (Sonesson, 2000).

The knowledge of valid fuel consumption is neccessary for waste route optimization, because the most frequently used optimization objectives are the cost and the route length (Beliën, De Boeck, & Van Ackere, 2012).

Climate change aspect

In 2010 the total greenhouse gas emission was 49 Gt CO_2 equivalent. 14.3% of it has been emitted from transportation (Core Writing Team, 2014). In 2007 about 19.5% of total greenhouse gas (GHG) emissions in Europe were caused by transport (van Essen, et al., 2011).

As a matter of climate change and GHG emission the IPCC Working Group III drafts the need to decrease energy consumption by enhancing vehicle performance and increasing of transported loads (Sims, et al., 2014). This suggestion must be used in waste collecting and transportation as well.

The CO2 emission, coming from municipal waste collection is estimated to change from 0,091 to 0,557 kg CO_2equivalent ton^{-1} km^{-1} (Eisted, Larsen, & Christensen, 2009).

Bogner in a presentation shows that with waste prevention and minimization, as well as with waste elaboration through recycle and reuse we can reach positive or negative energy balance, as well (Bogner J. E., 2009). While he does not give more details, apparently the waste prevention has an decreasing effect on energy need, while energy balance of recycling and reuse depends on many factors e.g. on the actual materials, on the distance, on the technology etc.

However the major GHG emissions from the waste sector are from the landfill in form of CH_4, while the incineration of fossil carbon results less emissions of CO_2. National data are not available to quantify GHG emissions associated with waste transport. Reductions might be achieved through less collection frequencies, with higher routing efficiencies (Bogner J. M., 2007).

The IPCC Working Group III tells the fuel consumption of a new heavy duty truck is 25-32 liter/100 km, while CO_2 equivalent intensity of diesel is 3.2 kg/l (Sims, et al., 2014). As it will be visible later, the fuel consumption of waste collecting vehicles is significantly higher.

GHG emissions are released by transportation are carbon dioxide and nitrous oxide. The second one accounts for less than 1% of the global warming impact of carbon dioxide emitted from vehicles, so it can be ignored according to Smith et al. An estimation of a 2001 study ranges 4.2 -12 kg CO_2 / ton of waste (Smith, Brown, Ogilvie, Rushton, & Bates, 2001). In practice there are big differences in the amount of collected waste from week to week at the same area, while the fuel consumption is quite steady. So the CO_2 amount / ton of waste are a misleading measure. In addition, it is important to count not only the CO_2 emission but also CH_4 and N_2O. That is why the use of CO_2 equivalent is introduced and applied widely. Litman gives useful data for emission of diesel consumption: combustion of one liter diesel produces 2730 g CO_2, 0.0605 g CH_4 and 0.2 g N_2O, which means in total CO_2 equivalent 2793 g CO_2/liter of diesel. This value is the highest amongst of all studied fuels (gasoline, diesel, ethanol, aircraft fuel, jet fuel) (Litman, 2012).

Korzhenevych et al. studied the external costs of transportation. They recognise congestion costs, accident costs, air pollution costs, noise costs, costs of up- and downstream processes, marginal infrastructure costs and climate change costs. They count the cost of climate change at the central value of €90/CO_2 equivalent tonne. (Korzhenevych, et al., 2014)

Materials and methods

In the present study the mileage and fuel consumption of the vehicles for the municipal waste collection were registered. The database was created for the first half of 2015.

The transport and the collection kilometer value were registered to the way-bill separately, for each car. The vehicles left the site every morning with a full tank, and they refueled on-site when the daily route was completed. Thus, a set of 500 Diophantian equations were available for the further analysis.

To solve this problem both the travelling and the collecting kilometer were averaged. Next, to exclude the individual rough errors, the data, differing with more then + -20%, from the mean value were not taken into consideration. Also those data were deleted that referred to the special cases, where having completed the mixed waste collection other types of activity (eg. green waste collection) were carried out. (Although the mileage of waste collections can be determined accurately, there was no refueling between these actions, so the transporting and collecting fuel consumptions could not be separated correctly.)

Table 1 shows a small sample for the raw data set consisting of vehicle, date, transport and collection distances, as well as the fuel consumption.

Table 1 Sample of the raw database

Vehicle	Date	Transport, km	Collection, km	Fuel, liter
...				
MAN 26.310 Variopress	2015.02.05	150	40	71,936
MAN 26.310 Variopress	2015.02.09	138	30	95,332
MAN 26.310 Variopress	2015.02.10	182	33	86,549
MAN 26.310 Variopress	2015.02.11	144	35	72,732
MAN 26.310 Variopress	2015.02.12	136	25	58,638
MAN 26.310 Variopress	2015.02.16	143	35	86,469
MAN 26.310 Variopress	2015.02.17	187	30	94,632
MAN 26.310 Variopress	2015.02.18	148	38	79,701
MAN 26.310 Variopress	2015.02.23	142	31	80,593
MAN 26.310 Variopress	2015.02.25	143	27	75,222
MAN 26.310 Variopress	2015.03.02	142	31	80,76
MAN 26.310 Variopress	2015.03.04	143	36	70,505
MAN 26.310 Variopress	2015.03.09	143	28	77,53

Personal compilation

The resulted data per vehicles were analyzed with a heuristic trial and error method in Microsoft Excel, so fuel consumption values of both the transporting and the collecting phase were determined. The previously not used raw data (more than 20% deviation) provided an opportunity to test the resulted values. The distribution of working hours per activity was taken into account on the basis of a survey made in year 2012.

Results and discussion

Analysis of transportation economics

The studied waste management firm performs waste management as public service provider for 113 settlements. Half of the population is served in one big city, the other half is served at 112 small settlements. The 112 municipalities are called together as a “region”. This paper aimed to analyse the fuel consumption of the region routes. As it is shown in the literature, in many cases they used the existing transport programs. However the operation with waste compacting vehicles is significantly different from any other carriage work. Other studies use the liter per ton value, which is significantly distorted due to deviation of the collected amount. There are many other factors that influence the fuel consumption.

The mixed municipal waste collection is performed with compacting vehicles. The vehicles leave the site in the morning and after travelling some distance they reach the daily area of work. The fuel consumption of the vehicles made up of two main phases:

1. The departure from and return to the site that includes the emptying at the landfill. This could be split into many parts when the route consists many municipalities;
2. The waste collection at the municipalities, which is the actual service. This can have multiple parts, as well.

While collecting, the vehicle traverses every street in the given settlement and empties all the waste bins. It is important to note, that unlike the studied papers’ methods, they does not loading

the bins with the hydraulic system, but most of the bins are loaded manually, only the heavy ones will hang onto the lifting mechanism. Accordingly, the oil pump does not operate continuously, which reduces fuel consumption. The time requirement to finish the daily job is reduced because of the speedier work.
Major part of the vehicles has three axis, the rest has two axis. Every axis can hold approximately 8 tons of weight, so the average maximum laden mass for a 2 axis vehicle is 16 tons, for a 3 axis 24 tons. Table 2 shows the types of vehicles, the number of axis, the year of manufacturing, the size of the compacting structure, the cylinder capacity and the masses.

Table 2 Results for the various collecting vehicles

No	Type	Number of axis	Year of manufactu -ring	Size of compacting basket (m3)	Max. laden mass (kg)	Useful mass (kg)	Unladen weight (kg)	Cylinder capacity (cm3)
1.	Mercedes 1824	2	1995	16	17 000	4 150	12 850	9 572
2.	Mercedes Atego 1823	2	1999	16	17 000	4 330	12 670	6 370
3.	Mercedes Atego 1823	2	2000	16	18 000	5 300	12 700	6 370
4.	Mercedes Atego 1823K	2	2000	16	17 500	4 650	12 850	6 370
5.	Mercedes Atego 1529	2	2009	15	16 000	6 290	9 710	6 374
6.	Mercedes Actros 2531L	3	2003	20	24 000	8 460	15 540	11 946
7.	MAN 26.310	3	2004	18	23 500	8 600	14 900	10 518
8.	MAN 26.310	3	2004	18	23 500	11 400	12 100	10 520
9.	Mercedes Actros 2532L	3	2004	18	23 500	8 280	15 220	11 946
10.	Mercedes Actros 2632K	3	2007	20	24 000	8 460	15 540	11 946
11.	Mercedes Actros 2535L	3	2008	20	24 000	8 700	15 300	11 946
12.	Mercedes Actros 2532L	3	2009	25	26 000	10 690	15 310	11 946
13.	Mercedes Actros 2532D	3	2009	20	26 000	10 300	15 700	11 946
14.	Mercedes Actros 2532L	3	2006	20	23 500	12 010	11 490	11 946

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Rural waste collection is characterized by sharp separation of two phases of work: collection and transport. For both phases it is necessary to determine the consumption standards, as the vehicles' performances are significantly different. For the transport (which contains the travelling with no load, as well) is not necessary to distiquish the empty and loaded phase. For the collecting the work and the fuel consumption is characterized by the significant number of start-stops (up to 1000 pcs / work day) with the continuously growing weight. Table 3 shows the proportions of the phases in the rural waste collection service, based on the data collection and evaluation of 17 vehicles in 2012.

Table 3 Composition of the workflow of rural waste collection

Proportion of work phases in rural waste collection		
	Working hours	Proportion
Collecting	3255:08:00	68,1%
Transport	1295:17:00	27,0%
Emptying	143:01:00	3,0%
Repair	91:43:00	1,9%

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Table 4 summarizes the total kilometer value from the 2015 database. It is visible, that one third of all kilometres was used by collecting.

Table 4 Composition of distances in rural waste collection

Proportion of the kilometers		
	Km	Proportion
Collecting	11 409	32,8%
Transport	23 360	67,2%

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Based on the previously introduced method the reasonable approximation of fuel consumption per vehicle can be resulted. The results are shown in Table 5.

Table 5 Fuel consumption of the collecting vehicles

No	Vehicle	Fuel consumption of transport (l/100 km)	Fuel consumption of collection (l/100 km)	Number of axis
1.	Mercedes 1824	35	80	2
2.	Mercedes Atego 1823	30	71	2
3.	Mercedes Atego 1823	29	62	2
4.	Mercedes Atego 1823K	31	72	2
5.	Mercedes Atego 1529	25	56	2
6.	Mercedes Actros 2531L	36	81	3
7.	MAN 26.310	34	89	3
8.	MAN 26.310	31	80	3
9.	Mercedes Actros 2532L	34	82	3
10.	Mercedes Actros 2632K	38	96	3
11.	Mercedes Actros 2535L	43	101	3
12.	Mercedes Actros 2532L	36	87	3
13.	Mercedes Actros 2532D	35	90	3
14.	Mercedes Actros 2532L	36	93	3

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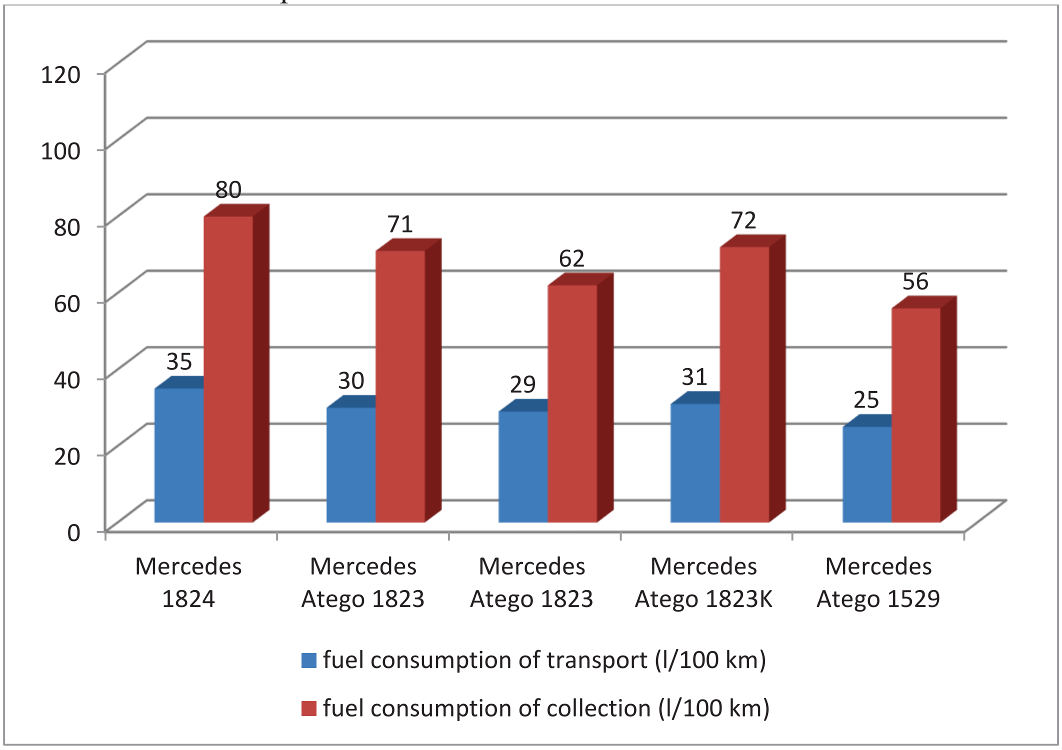
Fig. 1 visualizes fuel consumption values for 2 axis vehicles.

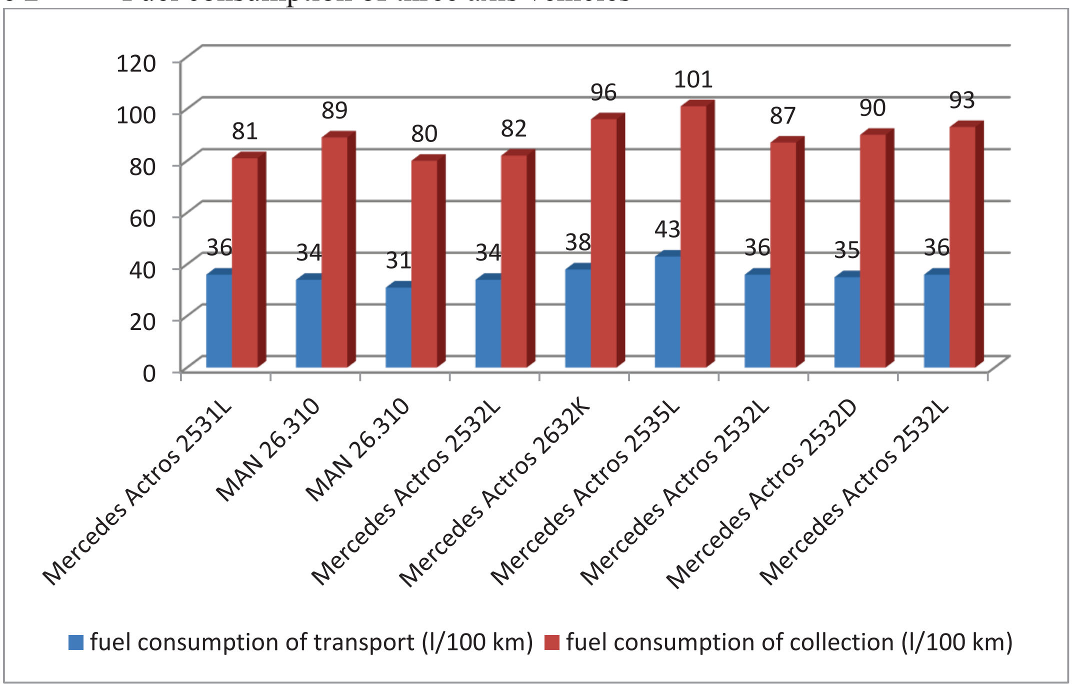
Figure 1 Fuel consumption of two axis vehicles



Personal compilation

Fig. 2 shows fuel consumption values for three axis vehicles.

Figure 2 Fuel consumption of three axis vehicles



Personal compilation

Table 6. shows the average fuel consumption values. As expected, the size of vehicle and the difference of load significantly affect the fuel consumption. The studied two-axle vehicles have an average age of 15 years, a 20-year-old and a 6 year old vehicle increases the standard deviation. The vehicles have a useful mass of an average 4.9 tons. Looking at the two axis cars,

it can be stated that the consumption of transport is at 30 l / 100 km with 3.2 l/100 km standard deviation, collecting consumption is at 68.2 l / 100 km with 8.3 l/100 km standard deviation value.
The nine three-axle vehicles have an average age of 9 years; their collecting structure is typically 20 m3. Average useful mass are 9.7 tons. The three-axed cars use to the transport 35.9 l / 100 km fuel with 3.1 l/100 km standard deviation, the collecting consumption is 88.8 l / 100 km with 6.7 l/100 km standard deviation value.

Table 6 Summary of the fuel consumption values

	Mean consumption of transport (l/100 km)	Mean consumption of collection (l/100 km)	Deviation for transport	Deviation for collection
2 axis vehicle	30.0	68.2	3.2	8.4
3 axis vehicle	35.9	88.8	3.1	6.7

Personal compilation

Analisys of GHG emission

Fuel saving by using 3-axis vehicles at rural area can be expressed both ecomically and in GHG emission, which is summarized in Table 7. At the analysed area the possible decreasing of fuel consumption is more than 4000 liter diesel/year, which means 11.4 t CO_2 equivalent less GHG emission.

Table 7 Comparison of fuel consumption of the different group of collecting cars

Cars	Average useful mass (t)	Km transport/year	Km collecting/year	Total fuel consumption (l/year)	CO_2 eq (t/year)
Mixed	7 973	46 720	22 817		
All 3 axis	9 656	38 577	22 817	34 101.2	95.2
All 2 axis	4 944	75 344	22 817	38 164.3	106.6

Personal compilation

Conclusions

The results show the consumption norms of average collecting vehicles, working in a rural environment. It is seen that the three-axis cars consume 20% more fuel while transporting and 30% more while collecting waste. The efficiency of their utilization is much better, because they are able to collect 97% more waste, than the two axis ones. For rural service the average time requirement to reach the service is around 30% of the workday, so the use of three-axis vehicles makes a significant saving.
There is a real possibility of decreasing of GHG by using of 3 axis vehicles only; the expected difference of emission is almost 12%. If the travelling distances are longer, the savings became more. In contrary, for urban collection (actually close distance to waste handling facility) the use of 2 axis vehicles seems to be more appropriate.
The obtained results can be used for the determination of the optimized collection on the basis of the costs and/or route lengths. Other possible use is to establish the standards of consumption for the collecting work.
It is important to note that the development of realistic standards is necessary to for each vehicle, individually. If it is unknown, than the average consumption values published in this paper can

be used, effectively (e.g. in the case of route planning). Further research is needed in the close-to-the-waste handling facility context waste collecting, where these results are also useful.

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