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Estimation of Carbon Dioxide Emissions in a Waste Collection Vehicle Routing Problem

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ABSTRACT

Recently there has been increasing concern regarding environmental impacts due to carbon dioxide (CO2) emissions caused by waste collection activities, apart from the active industrialization efforts. In this context, evaluation of environmental impacts in Waste Collection Vehicle Routing Problem (WCVRP) is highlighted. As such, this paper investigated CO2 emissions based on solution derived from a prior study of the benchmark waste collection problem. With that, the fuel-based and distance-based methods had been employed to estimate CO2 emissions. Both methods were selected due to their applicability and suitability in the estimation of CO2 for WCVRP. The results showed that the distance-based method produced less value of CO2 emissions (approximately 7.1 % decrement) and lower value of fuel consumption (approximately 1.77 % of fuel saving), when compared to the fuel-based method. Besides, it is important to note that the reduction of CO2 emitted depends on distance travelled, fuel consumption, and emission factors. Thus, reduction in travelled distances and fuel usage do aid in mitigating vehicle emissions.

Keywords:
Waste collection Vehicle Routing Problem (WCVRP), fuel-based method, distance-based method, CO2 emissions

1. Introduction

Since 2006, concerns on environmental impacts of the Vehicle Routing Problem (VRP) have increased [1] due to several sustainability issues, such as increment in the level of carbon emissions that results in high pollution [2,3] and high generation of waste [4]. According to Han and Ponce-Cueto [4], there is scarcity of studies in attempting to combine economic and environmental objectives. As for VRP, most of the prior studies preferred to minimise economic impacts, including operational costs [5]. Moreover, environmental concern has become an important issue due to the increasing population growth and waste generation. Hence, better utilisation of vehicles in the vehicle routing system should be ascertained in order to achieve a sustainable transportation system.

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A sustainable transportation system has a significant effect on the environment because carbon dioxide (CO_2) is mostly emitted from direct burning of fuels.

The Intergovernmental Panel on Climate Change (IPCC) has identified three direct greenhouse gases (GHG) emitted due to transportation activities, which are CO_2, nitrous oxide, and methane. Nevertheless, CO_2 appears to be the largest composition amidst the GHG emissions [2].

Several factors have contributed to CO_2 emissions, which are driven to environmental impact, such as travelled distance, mode of transportation, equipment, load, and operation [2]. Then, Úbeda, Faulin, Serrano and Arcelus [6] also added some other factors towards CO_2 emissions, including speed, weather conditions, driving style, road slope, and accidents. In addition, Demir [7] stated that fuel consumption, which is directly related with vehicle speed, is a primary factor that has contributed to CO_2 emissions.

In this context, designing a vehicle routing model that is economically and environmentally sustainable is the main objective [3]. Therefore, this paper looked into the environmental impacts of Waste Collection Vehicle Routing Problem (WCVRP) in terms of CO_2 emissions of vehicles.

This paper is organised as follows. Section 2 presents several past studies pertaining to estimation of CO_2 emissions in VRP. Next, Section 3 depicts the methodology employed in this study, including the method used to minimise travelled distance and the calculation of CO_2 emissions. Next, Section 4 presents the results and lastly, the study is concluded in Section 5.

2. Previous Studies

Calculation of CO_2 emissions has been widely applied in logistic activities, road transportation, and vehicle routing. Nevertheless, this paper only highlights prior studies related to estimation of CO_2 emissions in VRP variants. For example, a related study on carbon emission was conducted by Kuo and Wang [8] to optimise routing plan by reducing fuel consumption after considering issues related to travelled distance, speed, and loading weight. With that, a model that measured fuel consumption and Tabu Search to optimise vehicle route had been proposed.

Next, Úbeda, Arcelus and Faulin [9] studied Pollution Routing Problem (PRP) by conducting a case study at a Spanish food distribution sector called 'Eroski' in Spain. Their study sought minimum travelled distance and reduced CO_2 emissions by employing the distance-based method, the Mole and Jameson's (1976) method, and the Nearest Neighbourhood Insertion algorithms. Their computational results proved that Eroski could indeed improve its efficiency objectives in terms of economic and ecological perspectives.

Meanwhile, Demir [7] analysed fuel consumption and CO_2 emission in freight transportation by proposing speed optimisation algorithm (SOA) and Adaptive Large Neighbourhood Search algorithm. The results exhibited that the comprehensive modal emission model was indeed the most suitable model for their study and that the proposed approaches were apt in providing rapid and exceptional solution.

Jabali, Woensel, and de Kok [10] analysed travel time, fuel, and CO_2 emission cost in emission-based time-dependent VRP (E-TDVRP) by considering vehicle speed limit. Their study proposed Tabu Search (TS) to solve E-TDVRP, which had been tested on sets of instances from Augerat *et al.*, [11]. The experimental results suggested that reducing CO_2 emissions did decrease the cost incurred, which had been further influenced by vehicle speed limits.

Additionally, Erdogan and Miller-Hooks [12] initiated the Green VRP (G-VRP) as a mixed integer linear program. In relation to [12], Taha, Fors, and Shoukry [13] studied G-VRP to minimise travelled distance and to reduce CO_2 emission. A mathematical model and an exact solution were proposed to solve the problem. The proposed approach was run by using G-VRP benchmark datasets introduced by Erdogan and Miller-Hooks [12]. Their results extended the problem for further studies by using the proposed approach.

Meanwhile, Pradenas, Oportus, and Parada [14] studied VRP with backhaul and time window (VRPBTW) to minimise CO_2 emissions emitted by vehicles. The study proposed a mathematical formulation and Scatter Search (SS) metaheuristic to measure the amount of CO_2 emission. The proposed approach was tested on 100 randomly distributed customers based on the cases highlighted by Gélinas *et al.*, [15]. Their results showed that travelled distance and operation cost increased if the required energy decreased. Thus, the amount of fuel consumption and CO_2 emission decreased as well.

In a study carried out by Jabir, Panicker and Sridharan [16], a combination of Ant Colony Optimisation (ACO) algorithm with VNS (ACO-VNS) was proposed to solve multi-depot CVRP by considering CO_2 emissions. The proposed algorithms were tested on problem instances based on real-life delivery of products by carboy. Their results showed that the route with minimum cost was not environmental-friendly due to CO_2 emissions, which relied on the varying travelled distances and the weight of the vehicle.

Qian and Eglese [17] studied VRP with time-varying speeds in order to minimise CO_2 emissions. A metaheuristic method called column generation-based Tabu Search algorithms had been proposed and tested on real traffic data of a London road network. The computational results showed that the proposed approach generated a reduction of three percent for GHG emissions.

On top of that, Turkensteen and Hasle [3] examined the effect of CO_2 emissions due to consolidation of shipments by using CVRP, VRPB, VRPPD, and Euclidean instances. This study used the carbon assessment method, which included distance driven and load factor. The results showed minimised emissions when small vehicles were used for delivery and the pickup locations were relatively in distance of each other. However, the carbon emissions seemed insignificant or surged if the vehicle made many stops for delivery and pickup before returning to the depot.

In a nutshell, estimation of CO_2 has been mostly discussed in the light of several VRP variants, including G-VRP and PRP, but none from the stance of WCVRP. Hence, this paper estimated CO_2 emissions in WCVRP by using fuel-based and distance-based methods.

3. Methodology

This section describes the methods used to estimate CO_2 emissions by using fuel-based and distance-based methods, as proposed by Úbeda *et al.*, [6, 9], as well as Zadek and Schulz [18]. In this paper, CO_2 emissions had been calculated based on solutions of WCVRP, as proposed by Benjamin and Beasley (2010, 2013).

Due to the intricacy of the problem, Benjamin and Beasley [19-20] solved WCVRP benchmark dataset generated by Kim, Kim, and Sahoo [21] by employing a heuristic approach called DIC algorithm. This dataset consisted of ten test problems. The total number of customers began from 99 until 2092 customers, which involved a single until 19 disposal facilities. Table 1 summarizes the main characteristics and the solutions for the benchmark problems. This solution generates the minimum total travelled distance in miles; which had been converted into kilometres so as to suit the emission factor.

Table 1
Solutions from Benjamin and Beasley [19-20]

Problem	Total number of customer	Capacity allowed for vehicle per day (yard)	Minimum total travelled distance (miles)	Minimum total travelled distance (km)
102	99	400	184.31	296.62
277	275	2200	315.74	508.13
335	330	400	200.253	322.28
444	442	400	89.12	143.42
804	784	10000	723.50	1164.36
1051	1048	800	2550.92	4105.30
1351	1347	800	914.91	1472.40
1599	1596	800	1378.01	2217.69
1932	1927	2000	1282.32	2063.69
2100	2092	2000	1773.53	2854.21

The two methods employed to calculate the estimation of CO_2 emissions were fuel-based and distance-based methods [9,18]. The fuel-based method refers to a calculation of CO_2 emissions based on aggregated fuel consumption data, whereas the distance-based method reflects calculation of CO_2 based on the travelled distance. Both methods applied equivalent emission factors to calculate CO_2 emissions.

3.1 Fuel-based Method

This method estimates CO_2 emissions based on aggregated fuel consumption data associated to fuel heat content, fraction of carbon in fuel that oxidised, and carbon content coefficient. This method incorporated three main steps

I. Collection of data on travelled distance based on vehicle type and fuel type (kilometre or ton-kilometre).
II. Conversion of travelled distance into fuel used values by referring to fuel economy factors.
III. Conversion of fuel used values into CO_2 emissions by multiplying the result obtained in (ii) with fuel-specific factors

Table 2 presents instances of fuel economy factors for various types of vehicles.

Table 2
Instances of fuel economy factors

Vehicle Type	Fuel Consumption (l / 100 km)	Fuel Economy Factor (kg CO_2 / km)
Gasoline light truck	16.8	0.4002
Pick-up trucks	13.8	0.3296
Large pick-up truck	15.7	0.3735
Diesel heavy truck	33.6	0.8700

In this paper, it had been assumed that a large pick-up truck generated by diesel fuel was used for waste collection activity. Thus, the estimated fuel economy factor is 0.3735 kg CO_2 for each kilometre the vehicle travelled. Next, instances of heating values and emission factors for various types of fuel are tabulated in Table 3.

Table 3
Instances of heating values and emission factors [18]

Fuel type	Heating value (GJ / l)	Emission Factor (kg CO_2 / GJ)
Gasoline / Petrol	0.0344	69.25
Diesel	0.0371	74.01
Propane	0.0240	62.99
Kerosene	0.0357	71.45

As for diesel fuels, the heating values appear to be equivalent to 0.0371 GJ for a litre of diesel, while the emission factor is equivalent to 74.01 kg CO_2. These values were included in the fuel-based formula so as to estimate CO_2 emissions.

3.2 Distance-based Method

This method calculates estimation of CO_2 emissions based on distance-based emission factor. This particular method requires two main steps

i. Data collection on travelled distance based on vehicle type and fuel type (kilometre or ton-kilometre).
ii. Conversion of the distance travelled into CO_2 emissions by multiplying the results obtained in (i) with distance-based emission factor.

Table 4 displays the distance-based emission factor derived from a study conducted by Ubeda *et al.*, [6,9].

Table 4
Distance-based emissions factors [6,9]

State of vehicle	Weight laden (%)	Fuel Consumption (l/100 km)	Fuel conversion factor (kg CO_2/l)	Emission factor (kg CO_2/km)
Empty	0	29.6		0.773
Low loaded	25	32.0		0.831
Half loaded	50	34.4	x 2.61	0.900
High loaded	75	36.7		0.958
Full loaded	100	39.0		1.018

In this paper, it had been assumed that the fuel type of the vehicle was diesel, which is estimate to be 2.61 kg of CO_2 for a litre of diesel consumed. In terms of load factor, it was predicted that an average of the vehicle load was high loaded (75% of weight laden). Thus, the emission factor of the vehicle is equivalent to 0.958 kg CO_2/km. This emission factor was included in the distance-based formula to determine CO_2 emissions.

4. Results

This paper calculated CO_2 emissions based on the solutions derived from minimum total travelled distance, as presented in Table 1. Estimation of CO_2 emissions for WCVRP was determined by using fuel-based and distance-based methods.

4.1 Fuel-based Method

The calculation of CO_2 emissions involved the estimations of fuel used based on distance travelled and fuel economy factors. Thus, fuel used value was calculated by using the following Eq. 1

$$\text{Fuel used} = \text{Travelled distance} \times \text{Fuel economy factor} \tag{1}$$

In this paper, the solutions of minimum travelled distance are presented in Table 1. The fuel economy factor for large pick-up truck has been estimated to be at 0.3735 kg CO_2 for each kilometre of vehicle travelled (refer to Table 2).

Next, the fuel used value was integrated in the CO_2 emissions formula by multiplying it with heating value and emission factor, as presented in Table 3. The calculation of CO_2 emissions based on fuel-based method can be simplified in the following Eq. 2

$$CO_2 \text{ emissions} = \text{Fuel used} \times \text{Heating value} \times \text{Emission factor} \tag{2}$$

Therefore, the outcomes for estimation of CO_2 by using fuel-based method are summarised in Table 5.

Table 5
Estimation of CO_2 emissions (Fuel-based method)

Benchmark Problem	Travel distance (km)	Fuel used	Heating values (GJ/l)	Emission factor (kg CO_2/GJ)	Emissions (kg CO_2)
102	296.62	110.7876	0.0371	74.01	304.1973
277	508.13	189.7866	0.0371	74.01	521.1104
335	322.28	120.3716	0.0371	74.01	330.5128
444	143.42	53.56737	0.0371	74.01	147.0837
804	1164.36	434.8885	0.0371	74.01	1194.104
1051	4105.30	1533.33	0.0371	74.01	4210.172
1351	1472.40	549.9414	0.0371	74.01	1510.013
1599	2217.69	828.3072	0.0371	74.01	2274.342
1932	2063.69	770.7882	0.0371	74.01	2116.408
2100	2854.21	1066.047	0.0371	74.01	2927.122

4.2 Distance-based Method

The distance-based method involves the conversion of travelled distance, as presented in Table 1, into CO_2 emissions by multiplying it with emission factors (refer to Table 4). Hence, the calculation of CO_2 emissions can be simplified as given in the following Eq. 3

$$CO_2 \text{ emissions} = \text{Travelled Distance} \times \text{Emission factors} \tag{3}$$

The results for the estimation of CO_2 by using distance-based method is summarised in Table 6.

Table 6
Estimation of CO_2 emissions (Distance-based method)

Benchmark Problem	Travel distance (km)	Emission factor (kg CO_2/km)	Emissions (kg CO_2)
102	296.62	0.958	284.162
277	508.13	0.958	486.7885
335	322.28	0.958	308.7442
444	143.42	0.958	137.3964
804	1164.36	0.958	1115.457
1051	4105.30	0.958	3932.877
1351	1472.40	0.958	1410.559
1599	2217.69	0.958	2124.547
1932	2063.69	0.958	1977.015
2100	2854.21	0.958	2734.333

4.3 Comparison Results

In order to identify the most viable method for calculating CO_2 emissions, this paper had compared the results obtained between fuel-based and distance-based methods. The comparison yields are portrayed in Table 7.

Table 7
Comparison Results between Fuel-based and Distance-based methods

Benchmark Problem	Fuel-based Method		Distance-based Method		Difference	
	Fuel used (l)	Emissions(kg CO_2)	Fuel used (l)	Emissions (kg CO_2)	Fuel used (l)	Emissions (kg CO_2)
102	110.7876	304.1973	108.8595	284.162	1.9281	20.0353
277	189.7866	521.1104	186.4837	486.7885	3.3029	34.3219
335	120.3716	330.5128	118.2768	308.7442	2.0948	21.7686
444	53.5673	147.0837	52.63514	137.3964	0.9322	9.6873
804	434.8885	1194.104	427.3201	1115.457	7.5684	78.647
1051	1533.33	4210.172	1506.645	3932.877	26.6849	277.295
1351	549.9414	1510.013	540.3708	1410.559	9.5706	99.454
1599	828.3072	2274.342	813.8922	2124.547	14.4150	149.795
1932	770.7882	2116.408	757.3742	1977.015	13.4140	139.393
2100	1066.047	2927.122	1047.495	2734.333	18.5519	192.789

Based on the results depicted in Table 7, the comparison involved fuel used and CO_2 emissions. As for the aspect of fuel used, the comparison results displayed that the distance-based method had lower value (approximately 1.77% fuel-saving), when compared to the fuel-based method for WCVRP benchmark datasets. Meanwhile, for CO_2 emissions, the distance-based method seemed to generate lower value (approximately 7.1% decrement), when compared to the fuel-based method. Besides, it is important to note that the minimised travelled distances do play an importance role in evaluating environmental impacts, particularly to reduce CO_2 emissions. Therefore, reduction in travelled distances and fuel used can aid in mitigating CO_2 emissions.

Based on the results reported, this paper suggests that the distance-based method appears to be the most appropriate and viable method to calculate CO_2 emissions in WCVRP because distance-based method produced less value of CO_2 emissions and lower value of fuel consumption, when compared to the fuel-based method. Distance-based method is a simple method applied to estimate CO_2 emissions in a waste collection problem for limited availability of data. This is in line with the study carried out by Ubeda *et al.*, [6,9], whereby the distance-based method was reported to be more appropriate to calculate CO_2 emissions. Nevertheless, the distance-based method appeared to exhibit a higher level of uncertainty, when compared to the fuel-based method, due to several factors, such as emission factors that fail to mirror the actual conditions.

5. Discussion and Conclusion

The rising concern regarding the environmental impacts due to CO_2 emissions is partly caused by waste collection activities, apart from industrialisation efforts. Hence, this paper highlights the importance of optimising vehicle routes through estimation of CO_2 emissions in waste collection activities. Besides, it is important to note that the reduction in CO_2 emitted highly depends on distance travelled, fuel consumption, and emission factors. Thus, reduction in travelled distances and fuel used seem to have significant roles in order to mitigate vehicle emissions.

As such, several methods, models, and formulations of CO_2 emissions are in existence, particularly those related to transportation and logistics activities. Nonetheless, estimation of CO_2 emissions in waste collection problem has never been addressed. Therefore, this paper contributes to the body of knowledge and practical purposes for being a pioneer for future studies, aside from assisting the waste management team in evaluating both economic and environmental impacts. Furthermore, in future, it would be crucial to develop and to enhance the existing tools or methods for calculating CO_2 emissions, which have a substantial ecological effect. Thus, CO_2 emissions will be further determined based on the real case of WCVRP so as to assist the responsible parties in devising the best strategy to reduce CO_2 emissions.

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