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GREENHOUSE GAS EMISSION REDUCTION ON COLLECTION LOGISTICS OF END-OF-LIFE CONSUMER ELECTRONICS CONSIDERING ENVIRONMENTAL INFORMATION

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Abstract. *Greenhouse gas emission due to logistics activities has reached its all-time highest level since observations first began. Negative effects to humans and the natural environment have raised global warning issues in the efforts to seriously reduce greenhouse gas emission. This study focuses on environmental friendly routes which were determined based on environmental information to reduce the amount of greenhouse gas emission Further analysis is also performed to compare the effects when the study is operated in different vehicle dispatch cycles. As a result, PRP can reduce the greenhouse gas emission even though the total traveling distance has increased than those from VRP. Also, by changing dispatch cycles from 3 to 5 times/week can minimize the amount of greenhouse gas emission.*
Keywords: Pollution Routing Problem (PRP), Vehicle Routing Problem (VRP), Ant Colony Optimization (ACO), Greenhouse gas emission, Environmental information

1. **Introduction.** According to the 5th IPCC (Intergovernmental Panel on Climate Change) report, current greenhouse gas emission level is the highest ever recorded since it was first raised as a global issue and has caused severe negative effects on both humans and the natural environment [1].

Due to recent climate changes, several global efforts, such as the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, Kyoto Protocol in 1997, Bali Action Plan in 2007 and Paris Agreement in 2015, have taken effect thus far. Domestically, the South Korean government issued a nationwide 37% BAU (Business As Usual) reduction target of greenhouse gas emission by 2030 [2].

According to the Korea Greenhouse Gas Inventory and Research Center, 690.6 million-ton CO_2eq of greenhouse gas was emitted in 2014, which is about 135.6% increase since 1990. Figure 1 illustrates the overall domestic greenhouse gas emission levels.

As shown in Table 1, among Korean domestic energy industries, 88.7 million-ton CO_2eq (about 14.9%) of greenhouse gas was emitted from the transportation sector. More specifically, 96.3% of the transportation sector's pollution was predominantly from major road systems. In efforts to reduce greenhouse gas emission from roads, the nation targets the city of Seoul to begin restricting the usage and operation of old diesel cars and trucks in 2017 and hopes to expand this movement to outer suburbs of Seoul by 2020.

In 2015, the Korean government introduced the Emissions Trading System (ETS), which was originally implemented by the European Union back in 2005 to resolve environmental problems [3]. The continuing resource depletion of rare metals is another global issue that brought forth EU's regulation of Waste Electrical and Electronic Equipment (WEEE) and Japan's increased level of responsibility for the recycling of disposed consumer electronics.

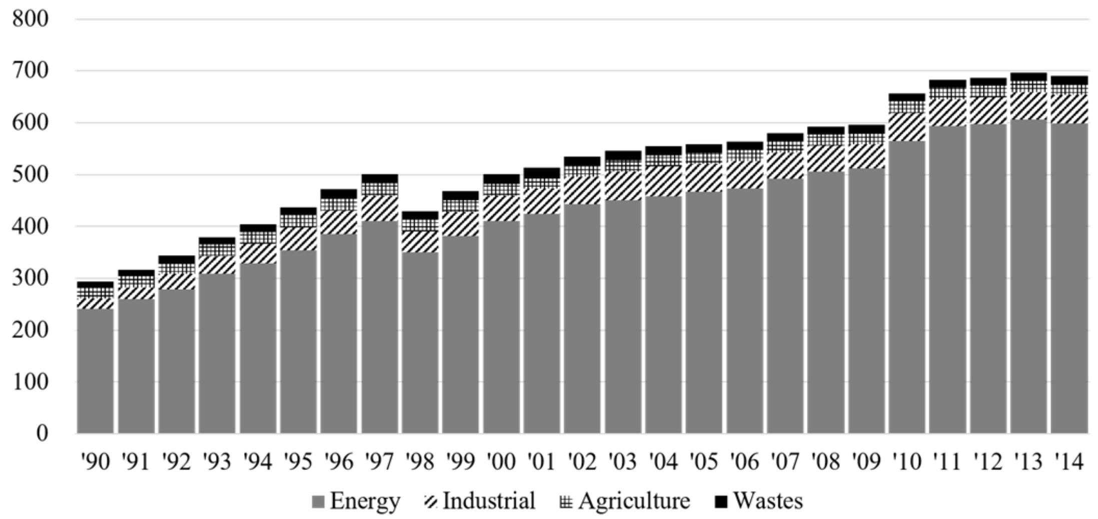

FIGURE 1. Domestic greenhouse gas emission levels

TABLE 1. Greenhouse gas emission levels from domestic energy industries

(Unit: million-ton CO_2eq)

Industry	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14
Energy Related	176.9	186	197.4	211.4	230	255.6	263.6	268.7	275	260.4
Manufacturing & Construction	135	136.4	142.9	147.5	137.1	161.3	182.8	180.1	182.2	194.1
Transportation	81.8	82.6	85	82.9	83.7	85.4	85.1	86.5	88.4	88.7
Others	66.3	61.6	59.9	57.9	55.2	56	55.4	55.1	53.6	49
Omission	3.1	3.3	3.5	3.5	3.3	3.9	4.1	4.4	4.5	4.2
Total	463.1	469.9	488.7	503.2	509.3	562.2	591.0	594.8	603.7	596.4

Since 2003, the South Korean government has introduced the Extended Producer Responsibility (EPR), which assigned industries the obligation to properly collect end-of-life consumer electronics from its manufacturers. Unfortunately, the nationwide recycling effort was still below 20% in 2007 [4].

In response, a Free Visit and Pick-up Service (FVPS) for collecting large end-of-life consumer electronics such as refrigerator, TV, and washer, was first introduced to the city of Seoul in 2012 to improve the nation's recycling rate.

In response, company K, which provides actual FVPS for study purposes, was selected as the target reverse logistics provider. Furthermore, in this study, Vehicle Routing Problem (VRP) and Pollution Routing Problem (PRP) comparisons between large and small collection areas were performed. Additionally, this study introduced frequency of dispatch cycle as a new consideration to reduce more greenhouse gas emission than the previous PRP calculated.

This study proceeds as the following. Chapter 2 explains the scope of study, mathematical model, and CO_2 emission model. Chapter 3 covers experimental results while the final results of this study are identified in Chapter 4.

2. Scope and Model of Research.

2.1. Scope of the study. The scope of this study, focusing on the routes between the consumers and mid-point collection bay for collecting disposed end-of-life consumer electronics, is illustrated in Figure 2. Two different areas (Area I and Area II) were considered in this study as Table 2. Area I (Dongjak-gu, Seoul) was reported as the

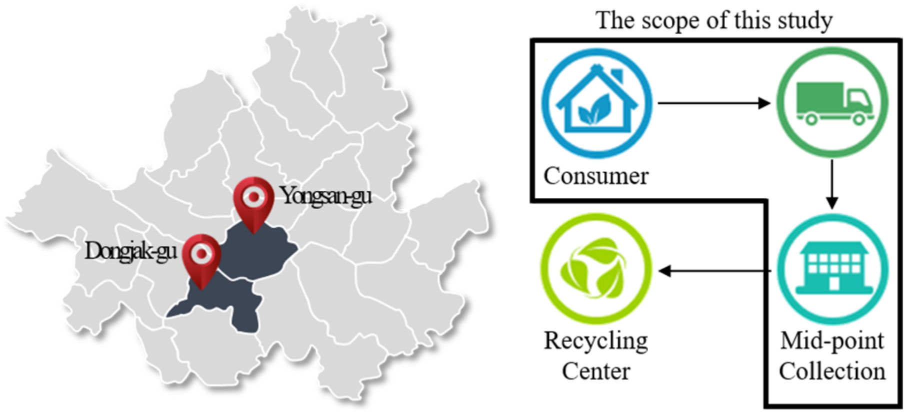

Figure 2. The scope of this study

Table 2. Collection amounts from free visit and pick-up service

Areas (in Seoul)	Number of vehicles available per week	Number of collected end-of-life consumer electronics per week
Area I (Dongjak-gu)	15	152
Area II (Yongsan-gu)	6	49

location with the most amount of collections and Area II (Yongsan-gu, Seoul) with the least amount.

In the case of Area I (Dongjak-gu in Seoul), total 15 vehicles were used to collect an average 152 end-of-life consumer electronics per week while a total 6 vehicles were used for 49 collections per week in Area II (Yongsan-gu in Seoul).

Google maps was used to calculate the latitudes and longitudes between consumers and the mid-point collection bay and the rectilinear distance between the two locations was calculated using the equation shown below [5].

$$\text{Rectilinear distance (km)} = \left(\begin{array}{l} |\text{latitude of origin} - \text{latitude of destination}| \times 110996.8 \\ + |\text{longitude of origin} - \text{longitude of destination}| \times 87754.2 \end{array} \right) \div 1000$$

2.2. **Mathematical model.** An important strategy for supply chain management in logistics industry is to optimize the routes for delivering goods from supplier to customer [6].

Dantzig and Ramser [7] first introduced the VRP which can be applied to many real field situations. However, because of its NP-hard characteristic, it is difficult to find optimal solutions for even small issues. Therefore, load capacity, distance, delivery due-date, and customer priority were considered together for finding better solution [8].

PRP is the expanded concept of VRP and various environmental information, such as loading amount, velocity, road's slope, temperature, and driver's habit are considered together for finding solutions to reduce greenhouse gas emission. Almost all VRP studies only focus on minimizing the total cost, so there is still an insufficient amount of PRP studies being performed [9]. The following mathematical model for handling PRP was introduced by Bektaş and Laporte [10].

Parameters

k	=	Engine friction factor
N	=	Engine speed
v	=	Engine displacement
d_{ij}	=	Arc (i,j) of distance
x_{ij}	=	A binary variable equal to 1 if arc (i,j) appears in a solution and 0 otherwise
f_{ij}	=	Total amount of flow on each arc (i,j)
y_j	=	The time at which service starts at node j
z_{ij}^r	=	A binary variable equal to 1 if arc (i,j)
$\overline{v^r}$	=	R non-decreasing speed levels
w	=	The curb weight
s_j	=	The total time spent on a route that has a node $j \in N_0$ as last visited before returning to the depot
α	=	Constants
β	=	Constants
λ	=	Constants
γ	=	Constants

Objective Function

$$\min \sum_{(i,j)\in A} kNV\lambda d_{ij} \sum_{r=1} z_{ij}^r / \overline{v^r} + \sum_{(i,j)\in A} \omega\gamma\lambda\alpha_{ij} d_{ij} x_{ij} + \sum_{(i,j)\in A} \gamma\lambda\alpha_{ij} d_{ij} x_{ij} + \sum_{(i,j)\in A} \beta\gamma\lambda d_{ij} \sum_{r=1}^{R} z_{ij}^2 \left(\overline{v^2}\right)^2 + \sum_{j\in N_0} f_d s_j \tag{1}$$

$$\sum_{j\in N} x_{0j} = m \tag{2}$$

$$\sum_{j\in N} x_{ij} = 1 \quad \forall i \in N_0 \tag{3}$$

$$\sum_{i\in N} x_{ij} = 1 \quad \forall i \in N_0 \tag{4}$$

$$\sum_{j\in N} f_{ji} - \sum_{j\in N} f_{ij} = q_i \quad \forall i \in N_0 \tag{5}$$

$$q_i x_{ij} \le f_{ij} \le (Q - q_i)\, x_{ij} \quad \forall (i,j) \in A \tag{6}$$

$$y_i - y_j + t_i + \sum_{r\in R} d_{ij} z_{ij} / \overline{v^r} \le K_{ij}(1 - x_{ij}) \quad \forall i \in N_0,\ j \in N_0,\ i \ne j \tag{7}$$

$$a_i \le y_i \le b_i \quad \forall i \in N_0 \tag{8}$$

$$y_j + t_i - s_j + \sum_{r\in R} d_{j0} z_{i0}^2 \Big/ \overline{v^2} \le L(1 - x_{j0}) \quad \forall i \in N_0 \tag{9}$$

$$\sum_{r=1}^{R} z_{ij}^r = x_{ij} \quad \forall (i,j) \in A \tag{10}$$

$$x_{ij} \in \{0,1\} \quad \forall (i,j) \in A \tag{11}$$

$$f_{ij} \ge 0 \quad \forall (i,j) \in A \tag{12}$$

$$y_i \ge 0 \quad \forall i \in N_0 \tag{13}$$

$$x_{ij}^2 \in \{0,1\} \quad \forall (i,j) \in A,\ r = 1,\dots,R \tag{14}$$

Equation (1) represents the objective function which minimizes total energy consumption and travel time. Equation (2) restricts the total number of transportation vehicles.

Equations (3) and (4) represent only one visit of each node at a time while (6) restricts the load capacity of vehicle. Equations (7), (8) and (9) are time restrictions and (10) represents the optimal velocity.

According to Lin et al. [11], adoption of heuristics algorithms which consider time, cost, and other environmental information, can reduce the time needed for finding the optimal solution. Therefore, they are applied in many different areas thus far. This study also implemented the Ant Colony Algorithm (ACO) for comparing the results of VRP and PRP.

2.3. **CO_2 emission model.** The calculation of energy consumption has been studied continuously with different considerations. Bowyer et al. [12] developed model by considering the characteristics of transportation vehicle and expanded the model with four different driving situations such as normal, idle, reducing, and accelerating situations. Ardekani et al. [13] calculated the energy consumption with considering transportation vehicle, driver's habit and traffic situation. Barth et al. [14] developed the calculation model by comprehensively considering three different modules of velocity, engine power, and energy consumption.

In this study, in order to calculate the amount of PRP's energy consumption which considers loading amount, velocity, and slope of the road as environmental information, MEET equation developed by Hickman et al. [15] was applied in this study. MEET equation is one of macroscopic models that adopt the average value of variables from each different route. The actual equations are as follows:

$$F = Emission \times GC \times LC \times D \tag{15}$$

$$Emission = 0.0617v^2 - 7.8227v + 429.51 \tag{16}$$

$$GC = A_6v^6 + A_5v^5 + A_4v^4 + A_3v^3 + A_2v^2 + A_1v + A_0 \tag{17}$$

$$LC = k + n\gamma + p\gamma^2 + q\gamma^3 + r/v + s/v^2 + t/v^3 + u/v \tag{18}$$

F: CO_2 emission, D: Distance, v: Vehicle speed, γ: Gradient, k, $n \sim u$: Coefficient, $A_0 \sim A_6$: Coefficient.

Equation (15) represents the amount of greenhouse gas emission and (16) is the amount of greenhouse gas emission according to velocity. Equation (17) represents the Gradient Correction (GC) of road's slope while (18) represents the Load Correction (LC) of the carrying capacity.

3. **Computational Experiments.** This study collaborated with the actual company in charge of the FVPS for collecting disposed end-of-life consumer electronics, company K, and applied its collection logistics to Area I (Dangjak-gu) and Area II (Yongsan-gu). The following results are described below.

As shown in Table 3, in Area I (Dongjak-gu), where larger amounts of end-of-life consumer electronics were collected, PRP reduced an average 2.7% of greenhouse gas emission despite traveling 6.5% more when compared to results from VRP. In addition,

Table 3. Results from Area I (Dongjak-gu)

Dispatch Cycles (per week)	VRP		PRP	
	Amount of Greenhouse Gas Emissions ($kgCO_2$)	Total Traveling Distance (km)	Amount of Greenhouse Gas Emissions ($kgCO_2$)	Total Traveling Distance (km)
3 times	58.93	206.40	57.20	214.31
4 times	56.53	195.00	53.50	214.11
5 times	46.59	169.90	48.30	184.04
6 times	51.00	169.00	48.40	179.56

it was further analyzed that increasing weekly dispatch cycles from 3 to 5 times/week resulted in a reduction to both distance traveled and greenhouse gas emission by an average of 15.9% and 18.2%, respectively.

Therefore, based on Area I (Dongjak-gu), it is the most optimal when dispatch cycle is set to 5 times/week using PRP method which results in a total traveling distance of 184.04 km and greenhouse gas emission of 48.30 $kgCO_2$.

As shown in Table 4, in Area II (Yongsan-gu), where smaller amounts of end-of-life consumer electronics were collected, despite average 14.1% increase in distance traveled, PRP reduced an average 9.1% of greenhouse gas emission compared to results from VRP. Also, as seen above in Area I, changing weekly dispatch cycles from 3 up to 5 times/week reduced both distance traveled and greenhouse gas emitted by an average of 9.3% and 12.0%, respectively.

Table 4. Results from Area II (Yongsan-gu)

Dispatch Cycles (per week)	VRP		PRP	
	Amount of Greenhouse Gas Emissions ($kgCO_2$)	Total Traveling Distance (km)	Amount of Greenhouse Gas Emissions ($kgCO_2$)	Total Traveling Distance (km)
3 times	15.21	49.90	12.90	53.40
4 times	12.75	42.70	11.90	51.15
5 times	12.28	46.20	11.80	49.55
6 times	13.11	43.40	12.30	58.10

Therefore, in Area II (Yongsan-gu), 5 times/week dispatch cycle with the PRP method is identified as the optimal solution with a total traveling distance of 49.55 km and greenhouse gas emission of 11.80 $kgCO_2$.

4. **Conclusions.** The study collaborated with the company in charge of FVPS, company K, for collecting disposed end-of-life consumer electronics. Efforts to find environment friendly routes were researched by applying PRP which consider environmental information and VRP and comparing greenhouse gas emission levels between different areas with the most and least collection amounts.

In conclusion, despite a slight increase in total distance traveled, application of PRP can help reduce the amount of greenhouse gas emission in both Area I and Area II. Also, by increasing the dispatch cycle of vehicle operation from 3 times to 5 times/week, both greenhouse gas emission level and total distance traveled can be reduced in both areas.

As a result, the best condition for generating the smallest amount of greenhouse gas emission is adopting the 5 times/week dispatch cycle using the PRP instead of VRP.

This study only researched specifically selected areas within the city of Seoul. Further studies will be recommended to consider various urban and rural locations as well as multiple mid-point collection bays to provide more realistic study outcomes.

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