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CORDON PRICING CONSIDERING AIR POLLUTANTS EMISSION

ABSTRACT

This paper considers the issue of air pollutants emission for the optimal and sustainable determination of cordon location, toll level, and price of park and ride (P&R). Although air pollutants emission decreases within the cordon by the implementation of cordon pricing scheme, it may increase outside the cordon and the whole network. Hence, air pollutants emission may only transfer from inside of the cordon to its outside. Therefore, in this paper, a multi-objective bi-level optimization model is developed. A solution algorithm is also presented based on the second version of strength Pareto evolutionary algorithm (SPEA2). The results reveal that this multi-objective model can be a useful tool for the sustainable and optimal design of the cordon and P&R scheme. In addition, cordon pricing is a multi-objective problem. Therefore, it is necessary to consider air pollutants emission. By choosing another non-dominated result in the solution space, air pollutants emission outside the cordon and the whole network can be reduced without a significant reduction in social welfare.

KEY WORDS

cordon location; toll level; park and ride; air pollutants emission; sustainable development; SPEA2 method;

1. INTRODUCTION

Traffic congestion has become one of the most severe social problems in modern societies. For years, adding additional capacity has been the solution for the rising level of congestion [1]. However, such an approach is subject to many spatial and financial constraints. Furthermore, providing more road space has been proven to be self-defeating in congested areas, because increased capacity will soon be occupied by induced travel demands [2, 3]. Thus, in order to alleviate roadway congestion, road congestion pricing has been introduced.

Congestion pricing was first suggested by investigating a sample of a congested road and expressing some ideas about externalities and optimal congested charges by Pigou (1920). The fundamental concept of pricing is so simple: prices should be higher under congestion conditions and lower at less congested times and locations in order to prevent excessive use [4]. Recently, road pricing issue has widely attracted the attention of economists and transportation researchers, due to growing prominence and changing nature of urban transportation problems faced by modern cities [5-7].

Road pricing theory is based on the fundamental economic principle of marginal cost pricing. It indicates that the users who use congested roads have to pay a toll which is equal to the difference between marginal social cost and marginal private cost in a way that social surplus increases [8]. The marginal cost pricing, unlike its full theoretical basis, is of little practical interest. Therefore, the second-best pricing method has attracted interest recently [4]. In the second-best pricing method, toll is only charged over a subset of links of the network. Four types of toll charging scheme in road network seem to be more popular: travel-distance based charging, travel-delay based charging, link-based charging, and cordon-based charging [9].

Recently, in some countries, a cordon pricing scheme has been used, instead of pricing on separate individual links, in order to reduce traffic demand in central congested urban areas [10-13]. In the second-best pricing, simultaneous determination of toll locations and toll level on a network is practically important [14-16]. In addition, the effect of value of time (VOT) on the pricing problems has been investigated in some of the previous studies [17]. In the presence of heterogeneous users with different VOTs, various network equilibrium models have been developed either by assuming a discrete set of VOTs for several distinct user classes or by a continuously distributed VOT across the whole population [18-23]. Moreover, in other studies, equity issues and revenue redistribution in congestion pricing have been investigated [24-28]. Recently, different types of toll design including time-toll, distance-toll, and speed-based toll have been considered for cordon-based pricing scheme [29, 30].

In terms of environmental impacts, differential distribution of environmental risk on users and places has been examined in most studies [31]. Previous works have employed various spatial, analytical, and statistical techniques to examine the distribution and potential impacts of locally undesirable land uses

[32, 33]. In addition, a few studies have used GIS-based proximity analysis to examine environmental effects of transportation [34]. Moreover, some investigations have considered the environmental justice implications of transportation plans and policies [35]. In fact, most of these studies have been only focused on the environmental impacts of transportation projects. However, the issue of air pollutants emission in designing the cordon charging scheme have not been investigated.

We believe that the cordon charging scheme is a multi-objective problem. One of the ignored objective functions in this problem is air pollutants emission. In addition to social welfare objective function, air pollutants emission is effective in the cordon pricing scheme. In other words, by an increase in social welfare, air pollutants emission may not decrease in the network. Rather, it may only transfer from the inside of the cordon to its outside. Therefore, it may increase outside the cordon and the whole network. The present paper considers air pollutants emission as an objective function in the cordon charging and P&R scheme.

The rest of this paper is organized as follows. In Section 2, the problem of air pollutants emission is described by the implementation of cordon charging in an artificial network. In Section 3, a mathematical programming model is presented for the optimal and simultaneous determination of the cordon location, toll level, and price of P&R. In Section 4, a solution algorithm is presented for solving the developed model based upon the second version of strength Pareto evolutionary algorithm (SPEA2). In addition, an innovative method based on geometric coordinate is proposed for dealing with the logical constraint of meta-heuristic algorithms. In Section 5, the developed model is applied to the Sioux Falls network, as a numerical example, and the results of the developed model are illustrated and discussed. Finally, summary and concluding remarks are provided in Section 6.

2. PROBLEM OF AIR POLLUTION WITH CORDON PRICING

To illustrate the issue of air pollutants emission, an artificial network with four nodes and four links is used as shown in *Figure 1*. The artificial network consists of two different OD pairs, from 1 to 4 and 2 to 4. Travel demands from origin 1 to destination 4 and from origin 2 to destination 4 are considered 400 and 300, respectively. The length of each link is shown inside the parentheses. Travel cost functions are equal to:

$$t_1(v_1) = 2.5 + \frac{v_1}{400} \quad (1)$$

$$t_2(v_2) = 1.0 + \frac{v_2}{200} \quad (2)$$

$$t_3(v_3) = 1.0 + \frac{v_3}{400} \quad (3)$$

$$t_4(v_4) = 0.5 + \frac{v_4}{400} \quad (4)$$

First, it is assumed that there is no cordon pricing scheme; so, all the links are toll-free (Case 1). Second, it is supposed that charging a toll is equal to 0.5 minute in link 4 (Case 2). Assuming the application of deterministic user equilibrium (DUE), traffic volume and average speed of traffic flow in the links can be estimated in two cases. Then, by considering the link length and equilibrium traffic volume, we can calculate the total air pollutants emission in each link and the network in two cases (*Table 1*).

Thus, the corresponding ratios of the air pollutants emission after and before implementation of cordon charging scheme in each link and the network are presented in *Table 2*.

Table 1 – Total air pollutants emission in two cases

Link	Traffic volume (vehicle)		Speed (km/h)		Total air pollution (kg)	
	Case1	Case2	Case1	Case2	Case1	Case2
1	275	325	60	56	4.61	5.61
2	125	75	48	49	0.47	0.28
3	300	300	50	50	1.25	1.25
4	425	375	32	34	5.13	4.37
Network					11.46	11.50

Table 2 – Comparison of the results in two cases

Link	1	2	3	4	Network
Ratios of air pollution	1.22	0.59	1.00	0.85	1.004

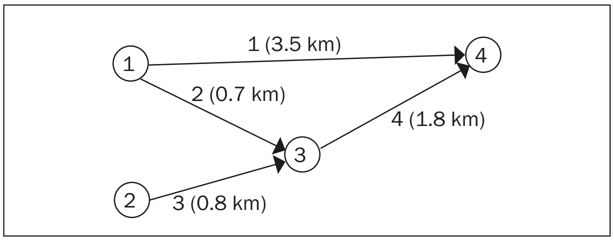

Figure 1 – A simple artificial network

The comparison of results of the air pollution emission in two cases, without and with cordon pricing shows that the implementation of cordon charging scheme may increase air pollutants emission in the whole network. In other words, although air pollutants emission decreases within the cordon (link 2), this policy may only shift air pollutants emission from inside of cordon to the outside.

3. MODEL FORMULATION

The issue of cordon pricing scheme is a transportation network optimization problem with user equilibrium constraints [36-38].

3.1 The lower level of the developed model and its solution algorithm

In fact, the lower level problem in cordon charging is user equilibrium. For solving the user equilibrium problem, the following assumptions are considered:

1) Travel demand is elastic.
2) There are three transportation modes in the network, namely private car, taxi, and bus.
3) P&Rs exist at the cordon boundary.

Note that for solving the user equilibrium problem the elastic demand based upon an iterative diagonalization process is changed to the fixed demand and then solved; after each step, the convergence of the demand is examined. The steps of the solution algorithm for a lower level problem are as follows:

Step 0: Assuming initial travel time using Expressions 5,

$$t_a^C = t_a^0, t_a^T = t_a^C = t_a^0, t_a^B = 1.2t_a^C = 1.2t_a^0 \tag{5}$$

where t_a^C, t_a^T, and t_a^B are travel time of cars, taxis, and buses in link '*a*', respectively. t_a^0 is free flow travel time in link '*a*'.

Step 1: Calculating the minimum travel costs of each mode between OD pair 'w' using Expressions 6 to 8,

$$u_w^C = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^C + \delta_a\tau_a)\Big] \tag{6}$$

$$u_w^T = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^T)\Big] \tag{7}$$

$$u_w^B = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^B)\Big] \tag{8}$$

where u_w^C, u_w^T, and u_w^B are minimum travel costs of cars, taxis, and buses between OD pair $w \in W$, respectively. τ_a is toll level in link '*a*'. If link '*a*' is tolled, δ_a is one; otherwise, it equals zero. If link '*a*' belongs to path '*k*' between origin '*r*' and destination '*s*', $\delta_{a,k}$ is one; otherwise, it is zero.

Step 2: Calculating the travel demand of modes between OD pair 'w' using Expression 9,

$$d_w^m = Q_w \exp(-\gamma_w\mu_w)\frac{\exp(a_m u_w^m + b_m)}{\sum_{m=C,T,B}\exp(a_m u_w^m + b_m)} \tag{9}$$

where a_m and b_m are constant coefficients that are calibrated by network data. d_w^m is travel demand between OD pair $w \in W$ with mode '*m*'. Q_W is initial total travel demand between OD pair '*w*'. γ_w is demand elasticity coefficient between OD pair '*w*' that is related to network condition. μ_w is minimum travel cost between OD pair '*w*'.

Step 3: Modifying car travel demand due to the existence of P&Rs at the cordon boundary; some drivers may shift from private cars to taxis or buses. The modification procedure includes:

a) Identifying car travel demand whose destination is within the cordon;
b) Determining the nearest P&R to origin '*r*' and destination '*s*' as a mid-point '*p*';
c) Calculating the minimum travel costs of modes. Based upon the mid-point (P&R 'p'), minimum travel costs of modes is calculated under three conditions (car only, car-taxi, and car-bus) using Expressions 10 to 13,

$$u_{rp}^C = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^C)\Big] \tag{10}$$

$$u_{ps}^C = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^C + \tau_a)\Big] \tag{11}$$

$$u_{ps}^T = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^T) + \theta_p\Big] \tag{12}$$

$$u_{ps}^B = \min\Big[\sum_{a\in A}\delta_{a,k}(t_a^B) + \theta_p\Big] \tag{13}$$

where u_{rp}^C is minimum travel costs by cars from origin '*r*' to P&R '*p*'. u_{ps}^C, u_{ps}^T, and u_{ps}^B are minimum travel costs by cars, taxis, and buses from P&R '*p*' to destination '*s*', respectively. θ_p is the price of P&R '*p*'.

d) Modifying car travel demand based upon the minimum travel costs by combining different conditions, travel demand by cars and other modes assuming the independence of alternatives is modified using Expressions 14 to 17,

$$(d_w^C)^{new} = (d_w^C)^{old} \cdot \frac{\exp(a_C(u_{rp}^C + u_{ps}^C) + b_C)}{\exp(a_C(u_{rp}^C + u_{ps}^C) + b_C) + \sum_{m=T,B}\exp(a_m(u_{rp}^C + u_{ps}^m) + b_m)} \tag{14}$$

$$d_{rp}^C = (d_w^C)^{old} - (d_w^C)^{new} \tag{15}$$

$$d_{ps}^{T} = d_{rp}^{C} \cdot \frac{\exp(a'_T u_{ps}^{T} + b'_T)}{\exp(a'_T u_{ps}^{T} + b'_T) + \exp(a'_B u_{ps}^{B} + b'_B)} \quad (16)$$

$$d_{ps}^{B} = d_{rp}^{C} \cdot \frac{\exp(a'_B u_{ps}^{B} + b'_B)}{\exp(a'_B u_{ps}^{B} + b'_B) + \exp(a'_T u_{ps}^{T} + b'_T)} \quad (17)$$

where $(d_w^C)^{old}$ and $(d_w^C)^{new}$ are initial and modified travel demand by cars between OD pair '*w*', respectively. d_{rp}^C is new travel demand by private cars from origin '*r*' to P&R '*p*'. d_{ps}^T and d_{ps}^B are new travel demand by taxis and buses from P&R '*p*' to destination 's', respectively. a_j, b_j, a'_j, and b'_j are constant coefficients calibrated by network data.

Step 4: Solving auto-assignment problem with fixed demand; if the demand between each OD is d_w, then the equilibrium model with fixed demand is formulated as follows [39].

$$Min \sum_{a \in A} \int_0^{v_a} t_a(v_a) dv \quad (18)$$

subject to:

$$\sum_{r \in R_w} f_{rw} = d_w, \quad w \in W \quad (19)$$

$$v_a = \sum_{w \in W} \sum_{r \in R_w} f_{rw} \delta_{ar}^{w}, \quad a \in A \quad (20)$$

$$f_{rw} \geq 0, \quad r \in R_w, \quad w \in W \quad (21)$$

where f_{rw} is the flow on route '*r*'. d_w is the demand between OD pair $w \in W$. v_a is the flow on link $w \in A$. *A* is the set of links in the network. *W* is the set of OD pairs. R_w is the set of all routes between OD pair $w \in W$. δ_{ar}^{w} is one if route '*r*' between OD pair $w \in W$ uses link $a \in A$, and zero otherwise.

Step 5: Updating the travel time for private cars using the BPR equation,

Step 6: Assigning taxi demand based on the updated time of private cars using auto-assignment; then, taxi volume is determined in the network.

Step 7: Adding the equivalent volume of taxis to the volume of private cars and estimating new travel time based on the BPR equation.

Step 8: Performing transit assignment using Optimal Strategies method [40],

Step 9: Estimating the volume of the bus in the links; bus demand (person) in the links is converted into bus volume (vehicle) using passenger coefficient.

Step 10: Adding the equivalent volume of bus in the links; bus volume in the links is converted into bus equivalent volume and then is added to the previous equivalent volume.

Step 11: Updating the travel time for private cars; link travel time of private cars is updated based on new equivalent passenger car using the BPR equation.

Step 12: Verifying the convergence criterion for multi-modal assignment; if Expression 22 is satisfied, proceed to step 13; otherwise, proceed to step 4.

$$\sum_a \left| \frac{v_a^{n+1} - v_a^n}{v_a^n} \right| \leq \varepsilon \quad (22)$$

where v_a^n and v_a^{n+1} are the equivalent traffic flow in link '*a*' in two successive iterations.

Step 13. Verifying the convergence criterion for demand; if Expression 23 is satisfied, proceed to step 14; otherwise, proceed to step 1.

$$\sum_{m=C,T,B} \left| \frac{(d_w^m)^{n+1} - (d_w^m)^n}{(d_w^m)^n} \right| \leq \varepsilon \quad (23)$$

where $(d_w^m)^n$ and $(d_w^m)^{n+1}$ are demands of mode '*m*' between OD pair '*w*' in the two successive iterations.

Step 14: Termination of multi-modal traffic assignment; outputs of this step are traffic volumes of private cars, taxis, and buses in the links of the network.

3.2 The upper level of the developed model considering air pollutants emission

The upper level of cordon pricing is to maximize the social welfare function [41].

$$F_1 = Max \quad SW = Max(\sum_{w \in W} \int_0^{d_w} D_w^{-1}(w) dw - \sum_{a \in A} t_a^C \cdot v_a^C - \sum_{a \in A} t_a^T \cdot v_a^T - \sum_{a \in A} t_a^B \cdot v_a^B) \quad (24)$$

subject to:

$$0 \leq \tau \leq \tau_{max} \quad (25)$$

$$0 \leq \theta \leq \theta_{max} \quad (26)$$

where $D_w^{-1}(w)$ is the inverse of the demand function. d_w is total final demand of different modes for OD pair after demand convergence. v_a^C, v_a^T, and v_a^B are flow for cars, taxis, and buses in link '*a*', respectively. t_a^C, t_a^T, and t_a^B are travel time for cars, taxis, and buses in link '*a*', respectively. Constraints 25 and 26 refer to the maximum and minimum values of toll and price of P&R, respectively.

As mentioned before, air pollutants emission may transfer from inside the cordon to its outside. Therefore, we can reduce air pollutants emission in the whole network, which actually means reducing air pollutants emission outside the cordon using the following model.

$$F_1 = Max \quad SW = Max(\sum_{w \in W} \int_0^{d_w} D_w^{-1}(w) dw - \sum_{a \in A} t_a^C \cdot v_a^C - \sum_{a \in A} t_a^T \cdot v_a^T - \sum_{a \in A} t_a^B \cdot v_a^B) \quad (27)$$

$$F_2 = Min(E^{Total}) = Min(\sum_{a \in A} E_a^{Total}) \quad (28)$$

subject to:

$$0 \leq \tau \leq \tau_{max} \quad (29)$$

$$0 \leq \theta \leq \theta_{max} \tag{30}$$

where E_a^{Total} and E^{Total} present the total emission in link '*a*' and the whole network, respectively.

Thus, the developed model guarantees that emission will decrease outside the cordon and network along with an increase in social welfare.

In this paper, three types of air pollutants are considered which include carbon monoxide (CO), carbon hydrate (HC), and nitrogen oxides (NOx). Therefore, the total emission of air pollutants in each link is as follows:

$$E_a^{Total} = w_1 E_a^{CO} + w_2 E_a^{HC} + w_3 E_a^{NOx} \tag{31}$$

where w_1, w_2, and w_3 are the constant coefficients that indicate the importance of each of the air pollutants.

Moreover, Expression 32 is used for air pollutants emission model.

$$E_a^i = a_i + b_i \overline{S}_a + c_i \overline{S}_a^2 + \frac{d_i}{\overline{S}_a} \tag{32}$$

where E_a^i is the emission of pollutant '*i*' in link '*a*' (g/km/veh). $\overline{s}_a$ is average speed of traffic flow in link '*a*' (km/h). a_i, b_i, c_i, and d_j are constant coefficients.

4. SOLUTION ALGORITHM OF THE DEVELOPED MODEL

4.1 Method and solution algorithm

Pricing problem is a non-convex optimization problem, for which it is difficult to find the optimum solution using standard optimization methods. Therefore, it is necessary to apply a global optimization method to solve the developed model. In addition, multi-objective optimization models are more complex than single-objective optimization models and different methods of solution should be applied [42].

Evolutionary algorithms (EAs) are one of the popular algorithms to solve multi-objective optimization. The first actual implementation of what is now called a multi-objective evolutionary algorithm (MOEA) is Schaffer's vector evaluation genetic algorithm (VEGA), which was introduced in the mid-1980s, mainly aimed to solve problems in machine learning [43, 44, 45]. Since then, a wide variety of algorithms has been proposed in literature [46-48].

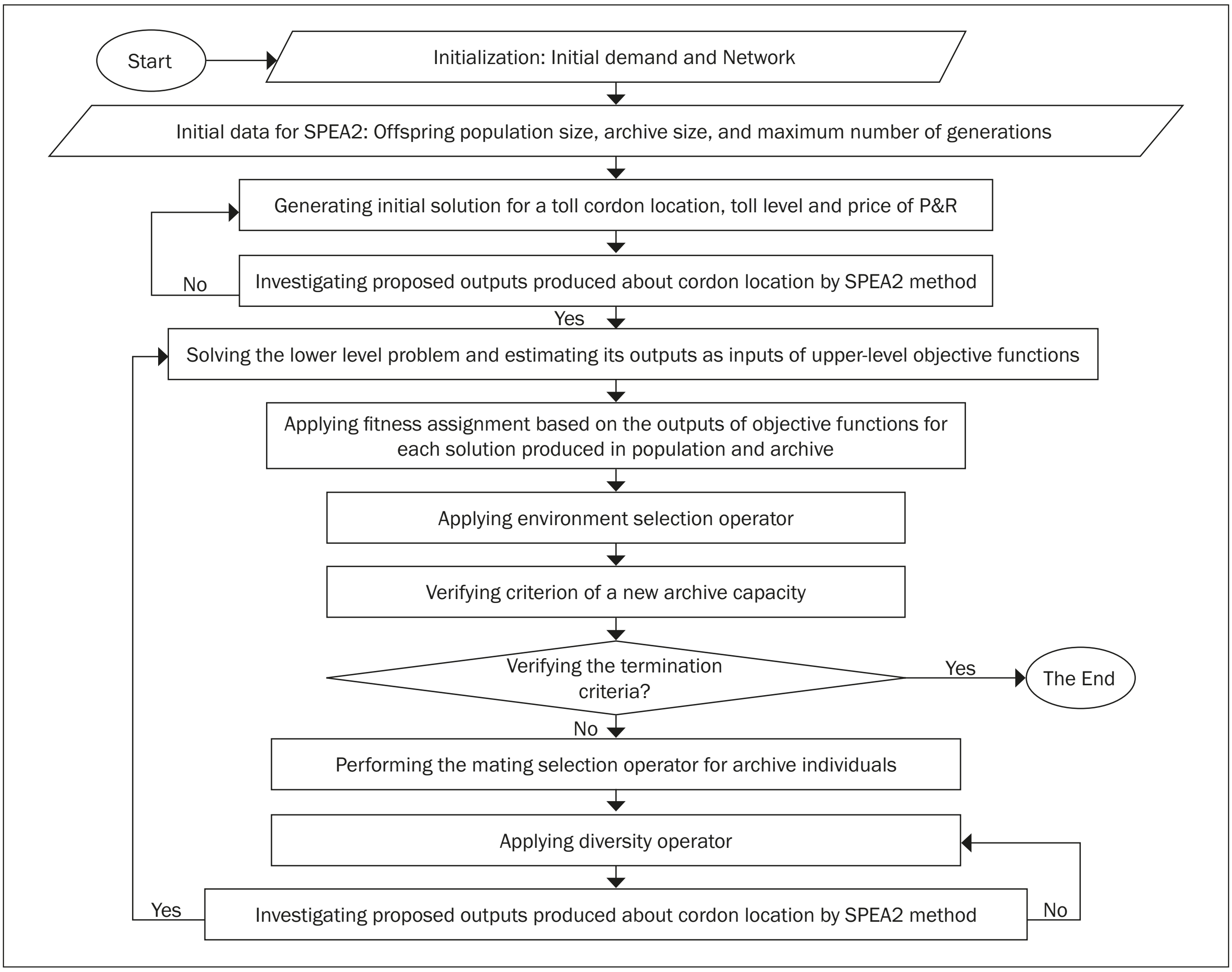

Figure 2 – Algorithm for the solution of the developed model

SPEA2 is a member of Pareto-based approach group. SPEA algorithm was introduced by Zitzler and Thiele [49]. SPEA uses an archive-containing non-dominated solutions which were previously found. In each generation, non-dominated individuals are copied to the external non-dominated set. For each individual in this external set, a strength value is computed. This strength is similar to the ranking value of MOGA, since it is proportional to the number of solutions dominated by a certain individual. In SPEA, the fitness of each member of the current population is computed according to the strength of all external non-dominated solutions that dominate it. Additionally, a clustering technique called 'average linkage method' is used to keep diversity. But, SPEA2 approach has three main differences with respect to its predecessor [50]: (1) It incorporates a fine-grained fitness assignment strategy which takes into account the number of individuals that dominate it and the number of individuals by which it is dominated for each individual; (2) It uses the nearest neighbour density estimation technique which guides the search more efficiently, and (3) It has an enhanced archive truncation method that guarantees the preservation of boundary solutions.

According to the developed model and using SPEA2 method [42], steps of the algorithm for the solution of the developed model are shown in *Figure 2*.

4.2 An innovative approach for logical constraint of SPEA2

Dealing with logical constraint is a major issue in the application of meta-heuristic algorithms. Because these algorithms use random processes to produce solutions, the outputs generated by such algorithms may be illogical in some cases. To reject or modify SPEA2 output due to logical constraint, an innovative and reasonable method has been developed in this study. This innovative method includes two stages as follows:

4.2.1 Specifying the cordon boundary

According to SPEA2 outputs, the cordon boundary is determined at this stage. Assuming the specified node coordinate and the network adjacent matrix, the following steps are taken to determine the cordon boundary.

Step 1: Determining the start node; based upon the coordinate of all the selected nodes by SPEA2, the node with maximum 'x' coordinate (x_{max}) and minimum 'y' coordinate (y_{min}) is determined as a starting node.

Step 2: Determining the mid-nodes; based upon the starting node and the road network adjacent matrix, the possible intermediate nodes are detected. Then, according to the angle created between the arcs connecting the starting node to potential mid-nodes and the horizon level (-x) (less than 360 degrees), the node connected to the arc with maximum angle is selected as the mid-node.

Step 3: Specifying the line equation; using the coordinate of the start node and mid-node, the line segment equation is specified.

Step 4: Verifying stopping criteria; if the mid-node is already selected in step 2, stop. Otherwise, take the mid-node as a new start point and proceed to step 2.

Finally, the cordon boundary will be determined based on the outputs of SPEA2.

4.2.2 Rejecting or modifying the cordon proposed by SPEA2

In fact, the suitability of the outputs generated by SPEA2 is a response to the two following questions:

1) What is the status of the location of other unselected nodes in relation to cordon boundary (inside, outside, or on the boundary of cordon)?
2) If the unselected node locations are located outside the boundary or on the boundary, it is accepted. Otherwise, the initial outcome of the algorithm will be modified or rejected.

Therefore, to answer these questions, the following steps are taken:

Step 1: Determining the basic node; a given node inside the cordon is selected as the basic node.

Step 2: Specifying the line segment equation for the unselected node; based upon the coordinate of the nodes, the equation of the line segment connecting the basic node to the unselected node is specified.

Step 3: Calculating the total number of cross points; the total number of cross points of the line segment is connected to the unselected node and all of the line segments of cordon boundary are calculated based upon the equations of those line segments.

Step 4: Investigating the location of unselected nodes in relation to the cordon boundary; an examination of the different examples has proven that, if the number of cross points (result of step 3) is even, the unselected node is located inside the cordon. Otherwise, the unselected node is located outside or on the cordon boundary.

Step 5: Modifying or rejecting the proposed boundary cordon; if the number of unselected nodes inside the boundary is less than 5% of the total selected nodes, the unselected nodes inside the cordon are modified. Otherwise, the proposed boundary is rejected and new outputs should be generated by SPEA2.

5. NUMERICAL EXAMPLE AND DISCUSSION

In order to apply the developed model and present the discussion, the Sioux Falls network is used as a numerical example. The Sioux Falls network is shown in *Figure 3*.

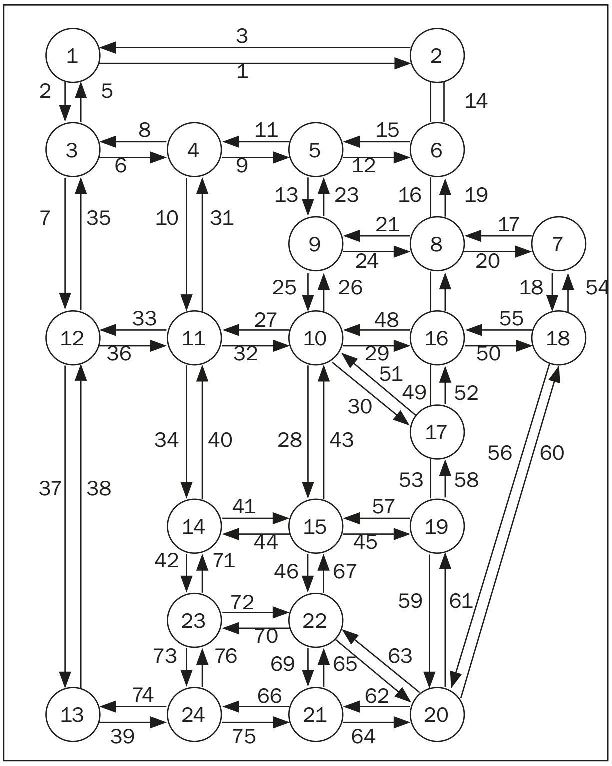

Figure 3 – Sioux Falls network

The Sioux Falls network consists of 24 nodes and 76 links. Travel cost function is as follows:

$$t_a(v_a) = t_a^0\left[1.0 + 0.15\left(\frac{v_a}{c_a}\right)^4\right] \quad (33)$$

where t_a^0 and c_a are the free flow travel time and capacity of link '*a*', respectively, that are given in *Table 3*.

In the Sioux Falls network, the four lines of bus are considered. Characteristics of bus lines service are shown in *Table 4*.

Travel demand of the Sioux Falls network presented in Wang et al.'s (2013) study is considered [51]. Expressions 34 to 36 are used as the utility functions of modes.

$$u_w^c = -0.0101 t_w^C \quad (34)$$

$$u_w^T = -0.2613 - 0.1096 t_w^T \quad (35)$$

$$u_w^B = -0.6936 - 0.1257 t_w^B \quad (36)$$

where t_w^C, t_w^T, and t_w^B are travel time by cars, taxis, and buses between OD pair $w \in W$, respectively.

To consider drivers' behaviour change due to the existence of P&R at the cordon boundary, Expressions 37 to 39 are used as the utility functions for shifting from cars to taxis or buses (car only, car-taxi, and car-bus).

$$u_{car\,only} = -0.0284 t_{ps}^c \quad (37)$$

$$u_{car\,taxi} = 1.21 - 0.0451 t_{ps}^T \quad (38)$$

$$u_{car\,bus} = 1.24 - 0.0432 t_{ps}^B \quad (39)$$

where t_{ps}^C, t_{ps}^T, and t_{ps}^B are travel time by cars, taxis, and buses between P&R '*p*' and destination '*s*', respectively.

Table 3. Free flow travel time and capacity of the network links

Link	FTT	Cap.	Link	FTT	Cap.	Link	FTT	Cap.	Link	FTT	Cap.
1	6	2,590	20	3	784	39	4	509	58	2	482
2	4	2,340	21	10	505	40	4	488	59	4	500
3	6	2,590	22	5	505	41	5	513	60	4	2,340
4	5	496	23	5	1,000	42	4	492	61	4	500
5	4	2,340	24	10	505	43	6	1,351	62	6	506
6	4	1,711	25	3	1,392	44	5	513	63	5	508
7	4	2,340	26	3	1,392	45	3	1,456	64	6	506
8	4	1,711	27	5	1,000	46	3	960	65	2	523
9	2	1,778	28	6	1,351	47	5	505	66	3	489
10	6	491	29	4	485	48	4	485	67	3	960
11	2	1,778	30	8	499	49	2	523	68	5	508
12	4	495	31	6	491	50	3	1,960	69	2	523
13	5	1,000	32	5	1,000	51	8	499	70	4	500
14	5	496	33	6	491	52	2	523	71	4	492
15	4	495	34	4	488	53	2	482	72	4	500
16	2	490	35	4	2,340	54	2	2,340	73	2	508
17	3	784	36	6	491	55	3	1,968	74	4	509
18	2	2,340	37	3	2,590	56	4	2,340	75	3	489
19	2	490	38	3	2,590	57	3	1,456	76	2	508

Table 4 – Characteristics of bus lines

Lines	Line 1	Line 2	Line 3	Line 4
Headway (min)	5	15	5	10
Speed (Km/h)	20	15	25	15
Stations (nodes)	11, 10, 16, 17, 19	2, 6, 8, 16	8, 9, 10, 15, 22, 21	1, 3, 12, 11, 10

Table 5 – Constants value for pollutants emission including CO, HC, and NOx

Mode	a	b	c	d
Carbon Monoxide (CO)				
Car	+32.58	0.574	+0.004	+310.3
Taxi	-46.67	+0.708	-0.003	+1410
Bus	+19.43	-0.330	+0.001	0
Carbon Hydrate (HC)				
Car	+0.901	-0.008	0	+63.68
Taxi	+3.153	-0.058	0	0
Bus	+10.12	-0.077	0	0
Nitrogen Oxides (NOx)				
Car	+0.843	+0.017	0	0
Taxi	+0.850	+0.003	0	+26.56
Bus	-82.76	+1.902	-0.011	+1383

To determine the weight of each air pollutant, the clearance costs of a gram of them are used and the following results are obtained:

$$E_a^{Total} = 0.19E_a^{CO} + 0.21E_a^{HC} + 0.6E_a^{NOx} \tag{40}$$

The coefficients of the air pollutants emission model are given in *Table 5* for each of the air pollutants and the transportation modes.

Given the expressed assumptions, the algorithm of the developed model (bi-level multi-objective optimization model) is implemented using Matlab software. Then, two objective functions (F_1 and F_2), which are social welfare and air pollutants emission, are considered simultaneously and non-dominated results (set of optimal results) are extracted based upon SPEA2 method (with the maximum number of generations: 300). The non-dominated results of the developed model are presented in *Table 6*.

Position of non-dominated results in the objective space or Pareto front is depicted in *Figure 4*.

The convex curve is formed by non-dominated results that confirms the validity of the developed model. This curve reveals that the cordon pricing scheme is a multi-objective problem, indicating that air pollutants emission will not necessarily decrease by an increase in social welfare. Therefore, the decision maker (DM) can choose each of all non-dominated results as an optimal result. This selection is exactly related to the decision maker.

Based upon the non-dominated results of the developed model with two objective functions (F_1 and F_2), we have:

1) The objective function F_1 changes in the range of 930,932 to 990,523 trip-minute. The maximum value of F_1 objective function (the best situation) (990,523 trip-minute) is equivalent to 22,289 kg in the objective function F_2 (result 'A' in *Figure 4*).
2) The objective function F_2 changes in the range of 22,289 to 22,037 kg. The minimum value of F_2 objective function (the best situation) (22,037 kg) is equivalent to 930,932 trip-minute in the objective function F_1 (result '*B*' in *Figure 4*).

If the social welfare objective function is more important than air pollutants emission (air quality) objective function for decision makers, they can choose result '*A*'. If the air pollutants emission (air quality) objective function is more important than the social welfare objective function, they can select result '*B*'.

Moreover, according to the non-dominated results of the developed model, we can conclude: by choosing another result (changing from result '*A*' to result '*B*') in the objective space, we can create the best situation for air pollutants emission objective function (F_2), while the social welfare objective function (F_1) is only reduced to 6.02%.

Results '*A*' and '*B*' in the solution space correspond to the specific features of cordon location, toll level, and price of P&R, as presented in *Table 7*.

Comparison of the results (changing from result '*A*' to result '*B*') shows that:

- Cordon area decreases (the number of the nodes in the cordon decreases);
- Toll level increases by 14.53%;
- Price of P&Rs decreases by 21.39%;

Table 6 – Non-dominated results of the developed model

Non-dominated results	F_1: Social welfare function	F_2: Air pollutants emission function
1	981,192.2	22,174.4
2 (A)	990,522.9	22,288.7
3	971,970.6	22,139.6
4	951,092.9	22,077.4
5 (B)	930,932.1	22,037.0
6	949,145.9	22,068.9
7	949,255.3	22,070.3
8	958,199.4	22,090.1

Table 7 – Features of non-dominated results 'A' and 'B'

Result	Nodes in the Cordon	Toll Level (h)	Price of P&R (h)
A	7, 10, 16, 17, 18	3.427	0.187
B	7, 10, 16, 17	3.925	0.147

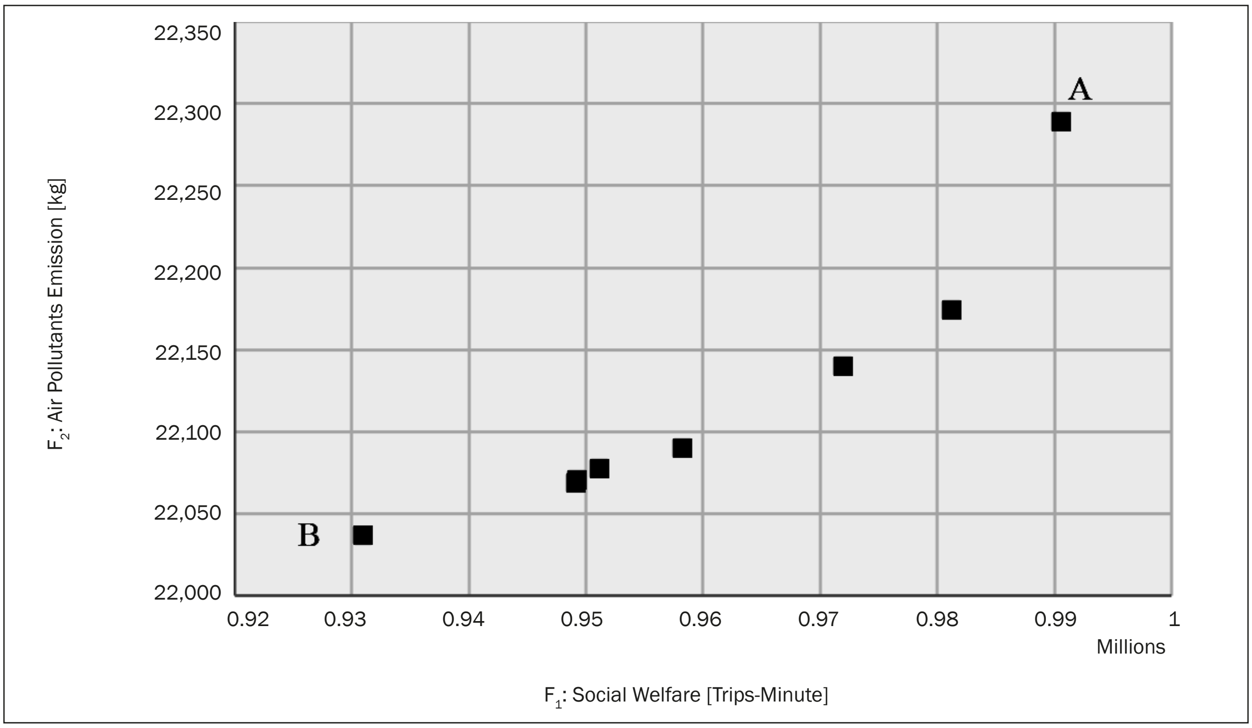

Figure 4 – Pareto front in the objective space (F_1 and F_2)

Therefore, air quality outside the cordon and the whole network can be improved by selecting another result (result '*B*'). So, by the selection of this result, we should decrease the cordon area and the price of P&R and increase the toll level. Note that these changes are not fixed and depend on the network and demand.

6. CONCLUSION

This paper considered the issue of air pollutants emission (air quality) in the cordon pricing and P&R scheme. It seems that, although the air pollutants emission decreases within the cordon by the implementation of cordon pricing, it may increase outside the cordon and the whole network. In fact, due to the implementation of cordon pricing policy, air pollutants emission may transfer from inside the cordon to its outside. Therefore, cordon pricing scheme is a multi-objective problem. To consider this problem, a multi-objective bi-level optimization model was developed. Then, an algorithm was presented according to the second version of strength Pareto evolutionary algorithm (SPEA2) for solving multi-objective bi-level optimization model. Afterwards, the developed model was applied to the Sioux Falls network as a numerical example.

The results showed that this model can be a useful tool for the simultaneous, optimal, and sustainable determination of cordon location, toll level, and price of P&R. Also, the results disclosed that the cordon pricing scheme is a multi-objective problem due to the formation of Pareto front in the objective space. Therefore, it is necessary to consider air pollutants emission (air quality) objective in cordon pricing and P&R scheme. In addition, there is air pollution problem in real-world networks, which should be taken into consideration in order to increase the public acceptance of users. Moreover, the results revealed that, by choosing another non-dominated result in the solution space, we can reduce air pollutants emission (air quality) outside the cordon and the whole network without a significant reduction in social welfare.

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ناونع

نتفرگ رظن رد اب نودروك و هدودحم یراذگتمیق
اوه یاهدنیالآ راشتنا

هدیکچ

یارب ار اوه یاهدنیالآ راشتنا ثحب هلاقم نیا
تمیق ،هدودحم و نودروک زرم رادیاپ و هنیهب نییعت
هچرگا .دریگیم رظن رد راوس- کراپ تمیق و ضراوع
یارجا اب هدودحم لخاد رد اوه یاهدنیالآ راشتنا
اما ،دبایم شهاک نودروک و هدودحم یراذگتمیق
لک و هدودحم جراخ رد تسا نکمم نآ راشتنا نازیم
یاهدنیالآ راشتنا نیاربانب .دبای شیازفا هکبش
لاقتنا نآ جراخ هب هدودحم لخاد زا اهنت تسا نکمم اوه
یزاسهنیهب لدم کی ،هلاقم نیا رد نیاربانب .دبای
نیچمره .تسا هدش هداد هعسوت یحطسود هفدهدنچ
یوق یلماکت شور ساسا رب لح متیروگلا کی
هعلاطم جیاتن .تسا هدش هئارا (SPEA2) 2 عون وترپ
رازبا کی دناوتیم هفدهدنچ لدم نیا دهدیم ناشن
و نودروک و هدودحم هنیهب یحارط یارب یدیفم
و هدودحم یراذگتمیق نینچمه .دشاب راوس- کراپ
رد نیاربانب .تسا هفدهدنچ هلئسم کی نودروک
کی ناونع هب اوه یاهدنیالآ راشتنا نتفرگ رظن
دهدیم ناشن هعلاطم نینچمه .تسا یرورض فده عبات
باوج یاضف رد رگید هدشن بولغم باوج باختنا اب
هدودحم جراخ رد ار اوه یاهدنیالآ راشتنا نازیم ناوتیم
رد هجوت لباق شهاک نودب ار هکبش لک و نودروک و
.داد شهاک یعامتجا هافر عبات

یدیلک تاملک

،راوس- کراپ ،ضراوع تمیق ،نودروک و هدودحم زرم
SPEA2. شور ،رادیاپ هعسوت ،اوه یاهدنیالآ راشتنا

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