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Development of a Model for a Cordon Pricing Scheme Considering Environmental Equity: A Case Study of Tehran

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Abstract: Congestion pricing strategy has been recognized as an effective countermeasure in the practical field of urban traffic congestion mitigation. Despite the positive effects of congestion pricing, its implementation has faced problems. This paper investigates the issue of environmental equity in cordon pricing and a park-and-ride scheme. Although pollution decreases inside the cordon by implementation of cordon pricing, air pollutants emission may increase in some links and in the whole network. Therefore, an increase in air emissions in the network means more emission outside the cordon. In fact, due to the implementation of this policy, air pollutants emission may transfer from inside to outside the cordon, creating a type of environmental inequity. To reduce this inequity, a bi-level optimization model with an equity constraint is developed. The proposed solution algorithm based on the second version of the strength Pareto evolutionary algorithm (SPEA2) is applied to the city network in Tehran. The results revealed that it seems reasonable to consider environmental equity as an objective function in cordon pricing. In addition, we can create a sustainable situation for the transportation system by improving environmental inequity with a relatively low reduction in social welfare. Moreover, there are environmental inequity impacts in real networks, which should be considered in the cordon pricing scheme.

Keywords: cordon pricing; environmental equity; park-and-ride; multi-modal network; multi-objective bi-level optimization; SPEA2

1. Introduction

In developing countries in particular, cities have experienced a rapid growth in transport-related challenges, including pollution, congestion, accidents, environmental degradation, and energy depletion [1]. Traffic congestion is one of the factors that leads to enormous economic costs. Many of these costs, which are due to inefficient social choices by individual users, can be prevented. Thus, in order to alleviate roadway congestion and economic costs in some regions, congestion pricing has been introduced. In fact, it is an effective tool for travel demand management (TDM) and it can increase revenues. Congestion pricing strategy has been recognized as an effective countermeasure in the practical field of urban traffic congestion mitigation [2]. Congestion pricing was first suggested by Pigou [3] through the investigation of a congested road and the expression of some ideas about externalities and optimal congestion charges. After Pigou's idea of using road pricing for adjusting road traffic congestion, intellectual and practical developments have occurred. Recently, the road pricing issue has widely attracted economists and transportation researchers, due to the growing prominence and changing nature of urban transportation problems that a modern city faces [4–6].

Road pricing theory is based on the fundamental economic principle of marginal cost pricing. It indicates that users who use congested roads have to pay a toll, which is equal to the difference between marginal social costs and marginal private costs in a way that social surplus increases. The first-best pricing design or marginal cost pricing, unlike its full theoretical basis, is of little practical interest due to its operating costs and public acceptance. Therefore, the second-best pricing method, which is considered best from a practical perspective, has attracted many researchers recently [7]. In the second-best pricing method, only a toll is charged over a subset of links in the network. There are four types of toll charging schemes in a road network that seem to be popular [8]. They are travel-distance based charging, travel time based charging, link-based charging and cordon-based charging.

Recently in some countries, a cordon pricing scheme has been used to reduce traffic demand in central congested urban areas [9–12]. In cordon pricing, simultaneous determination of toll locations and toll levels in a network is practically important [13–15].

Despite the positive effects of congestion pricing, its implementation has faced problems. Political and public disinterests are the reason why not enough attention has been paid to its equity impact. The issue of social and spatial equity has been discussed as a pretext to justify political unacceptability of road pricing. It has been extensively challenged in the related literature [16–22]. However, regarding the environmental equity, many studies have been done only on the importance of its measurement. These studies have examined the differential distribution of environmental risk on users and places [23]. Nagurney (2000) discusses several environmental paradoxes. She shows that total emissions can increase if a link is added to a network (Paradox 1), travel demand decreases (Paradox 2), and the cost of using a link declines (Paradox 3) [24]. May *et al.*, (2002) found that welfare gains and CO reductions are strongly and positively correlated [9]. Banister (2008) [25] and Ho *et al.*, (2008) [26] investigated the effects of the London congestion charging scheme on air quality. Namdeo and Mitchell (2008) examined the effects of cordon charges and distance charges on vehicle emissions in Leeds, UK [27]. They found that emissions dropped within the inner cordon, and either increased or decreased outside the cordon. Ecola and Light (2009) summarized the results of two studies and found that congestion pricing had a positive, but fairly small, impact on environmental equity [28]. They also argued that the London, Stockholm, and Milan charging schemes have environmental benefits that consist of only a small fraction of the benefits from time savings. Beria (2015) reported the economic and environmental impacts of the new "Area C" charge in Milan [29]. Previous studies have employed various spatial analytic and statistical techniques to examine the distribution and potential impacts of locally undesirable land uses [30,31]. Other studies on the equity analyses of transportation have focused mainly on differences in accessibility [32], travel opportunity [33], and safety issues [34]. In addition, few studies have used GIS-based proximity analysis to examine the environmental effects of transportation [35]. Moreover, some studies considered the implications of environmental justice in transportation plans and policies [36].

Therefore, most of the studies regarding this issue have only examined the environmental equity impacts of transportation projects. It is believed that the implementation of congestion pricing changes the emissions related to the roads of the network depending on the location of the cordon. In other words, three different conditions may occur with respect to the roads of the network. For example, air pollutants emission may increase in some roads of the network. However, air pollutants emission may decrease in other roads of the network. Some of the roads of the network may remain unchanged. Similarly, users who live around the roads may face different conditions of air pollutants emission. Those users who live around roads with high air pollutants emission are influenced. These users will be faced with environmental inequity due to the implementation of the cordon pricing scheme and then they will be negatively affected. However, those users who live close to roads with low air pollutants emission will enjoy the implementation of a cordon pricing scheme. Thus, this paper investigated this environmental inequity in the network that users face.

The rest of this paper is organized as follows. In Section 2, the environmental inequity issue is described by the implementation of cordon charging in an artificial network. In Section 3, the structure of the proposed model is presented. In Section 4, the method and algorithm for the solution of the proposed model are presented based on the second version of the strength Pareto evolutionary algorithm (SPEA2). In addition, an innovative method based upon geometric coordinate is proposed for dealing with the logical constraint of meta-heuristic algorithms. In Section 5, the developed model is applied to the Tehran network, as a real numerical example, and the results of the developed model are illustrated and discussed. Finally, a summary and concluding remarks are provided in Section 6.

2. Problem of Environmental Inequity Associated with Cordon Pricing

To illustrate the issue of environmental inequity, an artificial network with 4 nodes and 4 links is assumed, as shown in Figure 1. The artificial network consists of two different OD pairs, from 1 to 4 and 2 to 4. Fixed travel demand from origin 1 to destination 4, and from origin 2 to destination 4 are considered as 400 and 300, respectively. The length of each link is shown inside the parentheses. The'travel cost functions are assumed to be equal to:

$$t_1(x_1) = 2.5 + \frac{x_1}{400} \tag{1}$$

$$t_2(x_2) = 1.0 + \frac{x_2}{200} \tag{2}$$

$$t_3(x_3) = 1.0 + \frac{x_3}{400} \tag{3}$$

$$t_4(x_4) = 0.5 + \frac{x_4}{400} \tag{4}$$

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 (Pigouvian level) is equal to 0.5 min in link 4 (Case 2). Assuming the application of deterministic user equilibrium (DUE), traffic volume and the average speed of traffic flow in the links can be estimated. Then, by considering the link length and equilibrium traffic volume, we can calculate the total air pollution emission in each link and the network in two cases using Equations (39) and (47) (Table 1).

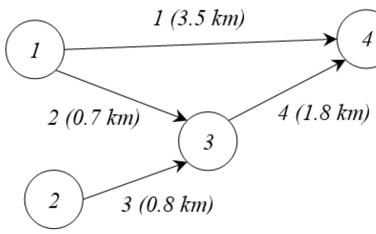

Figure 1. Simple artificial network showing the problem of environmental inequity.

Table 1. Total emission in two cases (without and with toll).

Link	Traffic Volume (Vehicle)		Speed (km/h)		Total Air Pollutants Emission (kg)	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
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

Thus, the corresponding ratios of air pollution emission after and before implementation of the pricing scheme in each link and the network are shown in Table 2.

Table 2. Ratios of air pollution after and before implementation of cordon pricing.

Ratios of Air Pollution Emission	**Link 1**	**Link 2**	**Link 3**	**Link 4**	**Network**
	1.22	0.59	1.00	0.85	1.004

A comparison of the results of air pollution emission in the two cases shows that:

(1) The implementation of the cordon charging scheme may increase air pollution emission in the whole network. In other words, this policy may only shift air pollution emission from the inside to the outside of the cordon.
(2) Three situations for air pollution emission in the links may occur by the implementation of the cordon charging scheme:

- Air pollution emission does not change.
- Air pollution emission increases and users around these streets (links) are faced with higher emission, and they are influenced by environmental injustice.
- Air pollution emission decreases and users around these streets (links) are faced with lower emission and more benefits.

Therefore, the implementation of cordon pricing may lead to distribution of injustice of air pollution emission in the network. This inequity can be called environmental injustice.

3. Model Development

Cordon pricing is a toll paid by users (private cars) to enter a restricted area, usually within a city center, as part of a demand management strategy to relieve traffic congestion within that area. The issue of the cordon pricing scheme is a transportation network optimization problem with user equilibrium constraints [37–39].

3.1. The Lower Level of the 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 cars, taxis, and buses.
(3) Park-and-Rides (P&Rs) exist at the cordon boundary.

Note that for solving the user equilibrium problem, elastic demand based upon an iterative diagonalization process is changed to the fixed demand and is 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 (Figure 2):

Step 0. Assuming initial travel time using Equation (5),

$$\mathrm{t}_{\mathrm{a}}^{\mathrm{C}} = t_a^0, t_a^T = \mathrm{t}_{\mathrm{a}}^{\mathrm{C}} = t_a^0, t_a^B = \alpha\, \mathrm{t}_{\mathrm{a}}^{\mathrm{C}} = \alpha\, t_a^0 \tag{5}$$

where α is a constant coefficient that is assumed to be 1.2 [40]. It must be noted that all variables are defined at the end of the paper in the notational glossary.

Step 1. Calculating the minimum travel costs of each mode between OD pair "w" with respect to the path, "k" assuming that taxis and buses do not pay tolls using Equations (6)–(8),

$$\mathrm{C}_{\mathrm{w}}^{\mathrm{C}} = \min\left[\sum_{a\in A} \delta_{a,k}(t_a^C + \delta_a \tau_a)\right] \tag{6}$$

$$\mathrm{C}_{\mathrm{w}}^{\mathrm{T}} = \min\left[\sum_{a\in A} \delta_{a,k}(t_a^T)\right] \tag{7}$$

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

where, if link "a" is tolled, δ_a is one; otherwise, it equals zero; if link "a" belongs to path "k" between origin "o" and destination "d", $\delta_{a,k}$ is one; otherwise, it is zero.

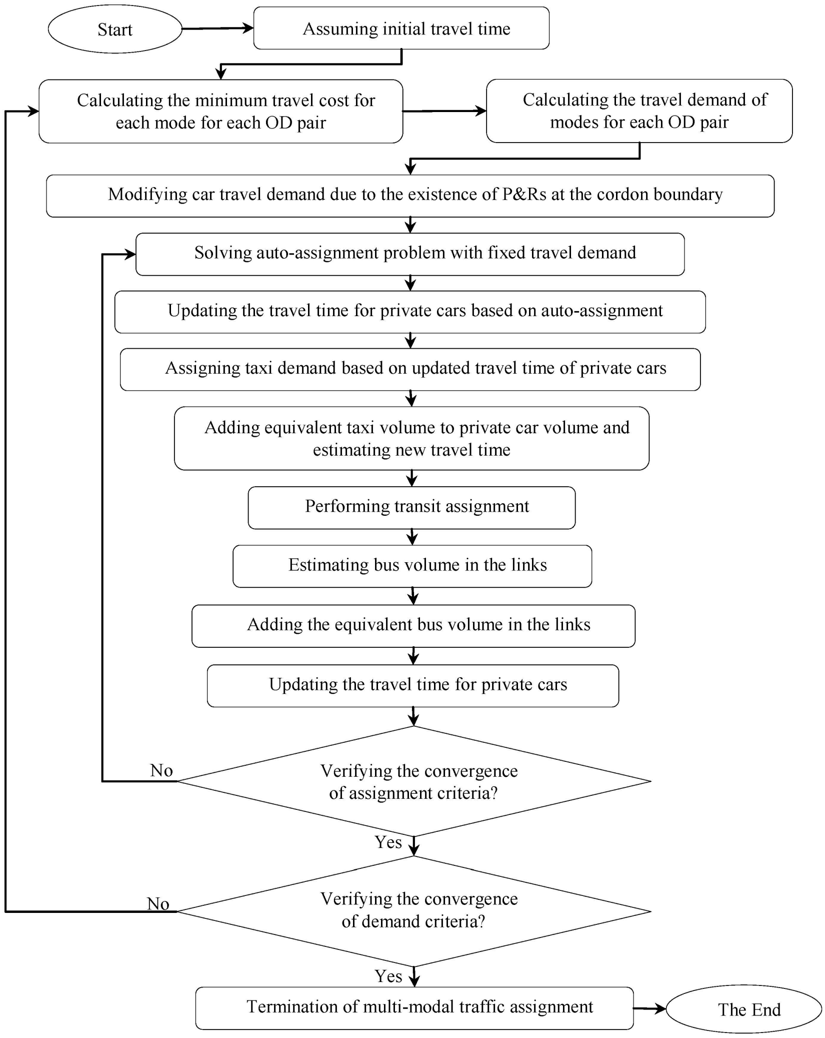

Figure 2. Solution algorithm for the lower level problem.

Step 2. Calculating the travel demand of modes (cars, taxis, and buses) between OD pair "w" assuming the independence of irrelevant alternatives using a multinomial Logit model Equation (9),

$$d_w^m = D_w \exp(-\gamma_w \mu_w) \frac{\exp(a_m C_w^m + b_m)}{\sum\limits_{m=C,T,B} \exp(a_m C_w^m + b_m)} \tag{9}$$

where a_m and b_m are constant coefficients that are calibrated by network data; γ_w is demand elasticity coefficient between OD pair "w" that is related to the network condition; and μ_w is the minimum travel cost between OD pair "w" that is obtained by Equation (10),

$$\mu_w = \ln\left(\sum_{m=C,T,B} \exp(c_m C_w^m + d_m)\right) \tag{10}$$

where c_m and d_m are constant coefficients.

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 closest P&R to the origin "*o*" and destination "*d*" as a mid-location "*p*" ("*p*" is an index of P&R locations);
(c) Calculating the minimum travel costs of modes with respect to the path "*k*". Based on the mid-location (P&R "*p*"), the minimum travel costs of modes are calculated under three conditions (car without mode change, car-taxi, and car-bus) using Equations (11) to (14),

$$C_{op}^{C} = \min\left[\sum_{a\in A}\delta_{a,k}(t_a^C)\right] \tag{11}$$

$$C_{pd}^{C} = \min\left[\sum_{a\in A}\delta_{a,k}(t_a^C+\tau_a)\right] \tag{12}$$

$$C_{pd}^{T} = \min\left[\sum_{a\in A}\delta_{a,k}(t_a^T)+\theta_p\right] \tag{13}$$

$$C_{pd}^{B} = \min\left[\sum_{a\in A}\delta_{a,k}(t_a^B)+\theta_p\right] \tag{14}$$

where if link "a" belongs to path "k" between origin "o" and destination "d", $\delta_{a,k}$ is one; otherwise, it is zero.

(d) Modifying car travel demand based on the minimum travel costs by combining different conditions (car-car, car-taxi, and car-bus), travel demand by cars and other modes assuming the independence of irrelevant alternatives is modified using Equations (15) to (18),

$$(d_w^C)^{new} = (d_w^C)^{old} \times \frac{\exp(a_C(C_{op}^C + C_{pd}^C) + b_C)}{\exp(a_C(C_{op}^C + C_{pd}^C) + b_C) + \sum\limits_{m=T,B}\exp(a_m(C_{op}^C + C_{pd}^m) + b_m)} \tag{15}$$

$$d_{op}^C = (d_w^C)^{old} - (d_w^C)^{new} \tag{16}$$

$$d_{pd}^T = d_{op}^C \times \frac{\exp(a'_T C_{\mathrm{pd}}^T + b'_T)}{\exp(a'_T C_{\mathrm{pd}}^T + b'_T) + \exp(a'_B C_{\mathrm{pd}}^B + b'_B)} \tag{17}$$

$$d_{pd}^B = d_{op}^C \times \frac{\exp(a'_B C_{\mathrm{pd}}^B + b'_B)}{\exp(a'_B C_{\mathrm{pd}}^B + b'_B) + \exp(a'_T C_{\mathrm{pd}}^T + b'_T)} \tag{18}$$

where a_i, b_i, a'_i, and b'_i are constant coefficients calibrated by network data.

Step 4. Solving the 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 [41,42]:

$$Minimize \sum_{a\in A}\int_0^{x_a} t_a(x_{\mathrm{a}})dx \tag{19}$$

subject to

$$\sum_{r\in R_w} f_{rw} = d_w, \quad w\in W \tag{20}$$

$$x_a = \sum_{w\in W}\sum_{r\in R_w} f_{rw}\delta_{\mathrm{ar}}^{\mathrm{w}}, \qquad a\in A \tag{21}$$

$$f_{rw} \geqslant 0, \quad r \in R_w, \quad w \in W \tag{22}$$

where $\delta_{\mathrm{ar}}^{\mathrm{w}}$ 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 taxis volume to the volume of private cars and estimating new travel time based on the BPR equation (Equation (40)).

Step 8. Performing transit assignment using the Optimal Strategies method [40].

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

Step 10. Adding the equivalent bus volume in the links; bus volume in the links is converted into bus equivalent volume and is then 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 (Equation (40)).

Step 12. Verifying the convergence criterion for multi-modal assignment; if Equation (23) is satisfied, proceed to step 13; otherwise, proceed to step 4.

$$\sum_{a} \left| \frac{x_a^{n+1} - \mathrm{x}_{\mathrm{a}}^{\mathrm{n}}}{\mathrm{x}_{\mathrm{a}}^{\mathrm{n}}} \right| \leqslant \varepsilon \tag{23}$$

where x_a^n and x_a^{n+1} represent the equivalent traffic flow in the link "a" in two successive iterations.

Step 13. Verifying the convergence criterion for demand; if Equation (24) is satisfied, proceed to step 14; otherwise, proceed to step 1.

$$\sum_{m=C,T,B} \left| \frac{(d_w^m)^{n+1} - (d_w^m)^n}{(d_w^m)^n} \right| \leqslant \varepsilon \tag{24}$$

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 Structure of the Proposed Model Considering Environmental Equity

3.2.1. The Upper Level Structure of the Cordon Pricing Model without Environmental Equity

The upper level of cordon pricing is to maximize the social welfare function by estimating the optimal values of a set of decision variables (with respect to the toll level and cordon location) as follows [43]:

$$F_1 = Max\ SW = Max(\sum_{w \in W} \int_0^{d_w} D_w^{-1}(w)dw - \sum_{a \in A} t_a^C x_a^C - \sum_{a \in A} t_a^T x_a^T - \sum_{a \in A} t_a^B x_a^B) \tag{25}$$

$$0 \leqslant \tau \leqslant \tau_{\max} \tag{26}$$

$$0 \leqslant \theta \leqslant \theta_{\max} \tag{27}$$

where constraint Equations (26) and (27) refer to the maximum and minimum values of the toll level and price of P&R, respectively.

3.2.2. Definition of the Environmental Equity Function

Generally, equity is defined as fair distribution of cost and benefit. In fact, it is almost impossible to ensure that the benefits and costs resulting from the implementation of cordon pricing will be the same for all users. However, to reduce the environmental inequity, we can reduce the increase in total air pollutants emission in the network. Hence, by reducing air pollutants emission in the network, air pollutants emission decreases both inside and outside the cordon. Thus, environmental inequity can decrease for users outside of the cordon. Therefore, inequality Equation (28) can describe the environmental equity as a constraint.

$$\left(\frac{E^{Total}}{\overline{E}^{Total}}\right) \leqslant \gamma \tag{28}$$

where $\overline{E}^{Total}$ and E^{Total} represent total air pollutants emission in the network before and after the cordon pricing scheme, respectively, which are obtained from the results of a lower level of optimization problem.

The parameter γ is a given suitable positive constant that determines the degree of equitability of air pollution emission distribution. Thus, inequality Equation (28) can be considered as an environmental equity constraint. The smaller value of parameter γ refers to a more equitable distribution of air pollution emission among all network users. If $\gamma < 1$, then all users who live outside the cordon (similar to its inside) will enjoy a reduction in air pollutants emission of at least $100(1-\gamma)\%$, derived from the cordon pricing scheme. However, if $\gamma > 1$, it means that there may be users outside of the cordon who suffer from higher air pollutants emission costs resulting from the cordon pricing plan, but the air pollutants emission increase cannot be more than $100(\gamma-1)\%$.

3.2.3. Upper Level Structure of Model Considering Environmental Equity

Finally, the following optimization model with constraint considers the environmental equity impacts in the upper level of the model.

$$F_1 = Maximize\ SW = Maximize(\sum_{w\in W}\int_0^{d_w} D_w^{-1}(w)dw - \sum_{a\in A} t_a^C x_a^C - \sum_{a\in A} t_a^T x_a^T - \sum_{a\in A} t_a^B x_a^B) \tag{29}$$

subject to

$$\left(\frac{E^{Total}}{\overline{E}^{Total}}\right) \leqslant \gamma \tag{30}$$

$$0 \leqslant \tau \leqslant \tau_{\max} \tag{31}$$

$$0 \leqslant \theta \leqslant \theta_{\max} \tag{32}$$

Moreover, we can change inequality Equation (30) into Equation (33) as a single objective function and add it to the main objective function in the model [44].

$$F_2 = Maximize\left(\gamma - \left(\frac{E^{Total}}{\overline{E}^{Total}}\right)\right) \tag{33}$$

Therefore, the optimization model with a constraint is converted into a conventional multi-objective optimization model as follows:

$$F_1 = Maximize\ SW = Maximize(\sum_{w\in W}\int_0^{d_w} D_w^{-1}(w)dw - \sum_{a\in A} t_a^C x_a^C - \sum_{a\in A} t_a^T x_a^T - \sum_{a\in A} t_a^B x_a^B) \tag{34}$$

$$F_2 = Maximize\left(\gamma - \left(\frac{E^{Total}}{\overline{E}^{Total}}\right)\right) \tag{35}$$

subject to

$$0 \leqslant \tau \leqslant \tau_{\max} \tag{36}$$

$$0 \leqslant \theta \leqslant \theta_{\max} \tag{37}$$

Thus, this model is used to derive the most favorable trade-off between social welfare and environmental equity by the implementation of cordon pricing scheme.

3.2.4. Air Pollutants Emission Model

In this paper, three types of air pollutants are considered, which include carbon monoxide (CO), carbon hydrate (HC), and nitrogen oxides (NO_x) [45]. Therefore, the total emission of air pollutants in each link is as follows:

$$E_a^{Total} = w_1 E_a^{CO} + w_2 E_a^{HC} + w_3 E_a^{NOx} \tag{38}$$

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

Moreover, Equation (39) is used for the air pollutants emission model [46,47].

$$\mathrm{E}_{\mathrm{a}}^{\mathrm{i}} = a_i + b_i \overline{\mathrm{S}}_a + c_i \overline{S}_a^2 + \frac{d_i}{\overline{S}_a} \tag{39}$$

where a_i, b_i, c_i, and d_i are constant coefficients.

4. Solution Algorithm for the Developed Model

4.1. Method and Algorithm for Solution of the Proposed Model

The pricing problem is a non-convex optimization and NP-Hard 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 proposed model. In addition, multi-objective optimization models are more complex than single-objective optimization models and different methods of solution should be applied [48]. Although there are various ways to approach a multi-objective optimization problem, most studies in the area of evolutionary multi-objective optimization have concentrated on the approximation of the Pareto set [49]. The goal of approximating the Pareto set is itself multi-objective. 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 [50–52]. Since then, a wide variety of algorithms have been proposed in the literature [53–55].

SPEA2 is a member of Pareto-based approach group. The SPEA algorithm was introduced by Zitzler and Thiele [56]. This approach is conceived as a way of integrating different MOEAs. SPEA uses an archive containing non-dominated solutions that are previously found (the so-called external non-dominated set). 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 a multi-objective genetic algorithm (MOGA), since it is proportional to the number of solutions a certain individual dominates. In SPEA, the fitness of each member of the current population is computed according to the strengths of all external non-dominated solutions that dominate it. Additionally, a clustering technique called the "average linkage method" [57] is used to maintain diversity. However, the SPEA2 approach has three main differences with respect to its predecessor [58]: (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 neighbor 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. In fact, SPEA2 is an improved version of SPEA.

According to the proposed model and using the SPEA2 method, the steps of the algorithm for the solution of the proposed model are as follows (Figure 3):

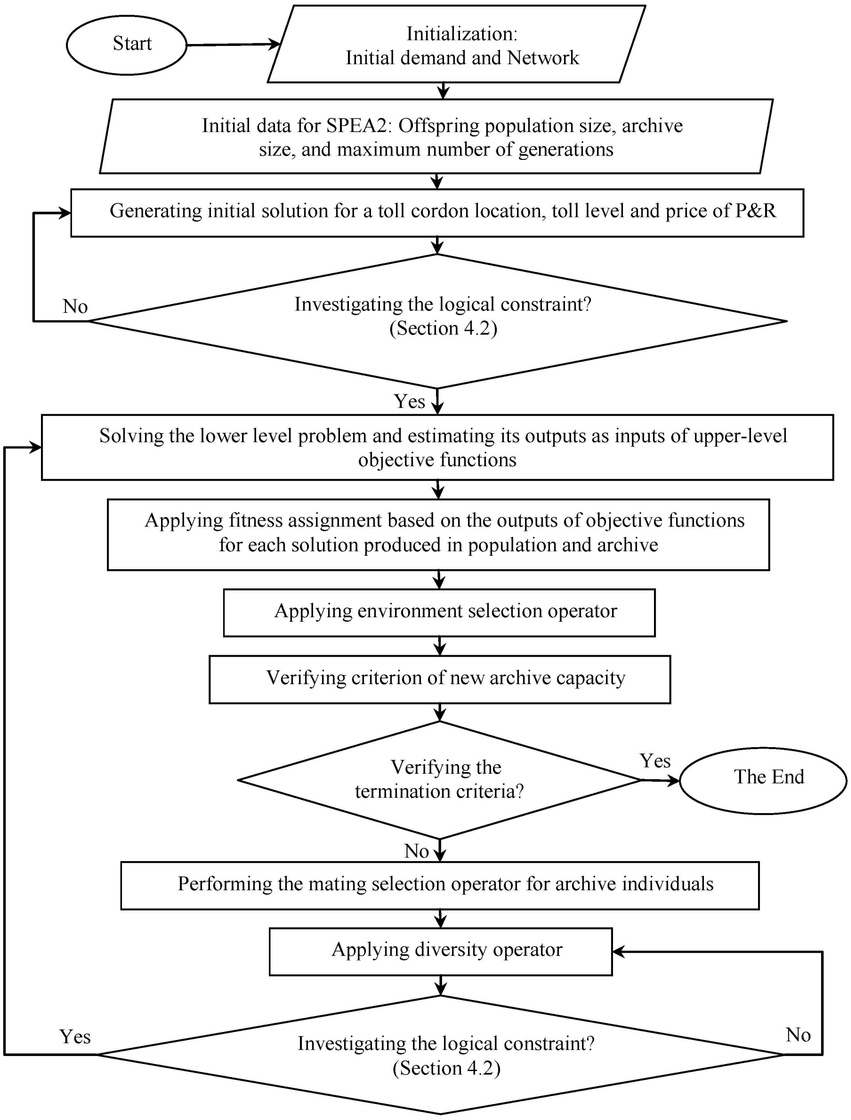

Figure 3. Algorithm for the solution of the developed model.

Step 0. Initialization. Receiving initial information of the network including the initial demand of all modes (private cars, taxis, and buses) and supply of transportation facilities.

Step 1. Receiving input parameters of the SPEA2 method such as offspring population size, archive size, and maximum number of generations [59].

Step 2. Generating an initial solution for the cordon location, toll level, and price of P&R.

Step 3. Investigating the proposed outputs produced related to the cordon location by the SPEA2 method (see Section 4.2); if the outputs of the cordon location are suitable, proceed to Step 4. Otherwise, proceed to Step 2.

Step 4. Solving the lower level problem (user equilibrium) and estimating its outputs as the inputs of upper level objective functions.

Step 5. Applying the fitness assignment based on the outputs of objective functions for each solution produced in the population and archive (e.g., cordon location, toll level, and price of P & R) [59].

Step 6. Applying the environment selection operator; in this step, all the non-dominated solutions in populations and archives are transferred to a new archive [59].

Step 7. Verifying the criterion of the new archive capacity; truncation and sorting operators are used to complete the archive capacity [59].

Step 8. Verifying the termination criteria; if the stopping criterion is satisfied, the algorithm is finished and the final results (non-dominated set, e.g., cordon location, toll level, and price of P&R) are provided. Otherwise, proceed to Step 9.

Step 9. Performing the mating selection operator for archive individuals [58]; in this step, the binary tournament with replacement of a new archive is performed in order to fill in the mating pool.

Step 10. Applying the diversity operator [59]; the diversity operator consists of recombination and mutation operators. These operators generate a new population in the mating pool in order to continue the algorithm.

Step 11. Investigating the proposed outputs related to cordon location by the SPEA2 method (see Section 4.2); if the outcomes of the cordon location are suitable, proceed to Step 4. Otherwise, proceed to Step 10.

4.2. An Innovative Approach for Modification of SPEA2 Illogical Outputs with Respect to Cordon Location

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. In this problem, all generated nodes for cordon location should form a cordon boundary. In other words, there should not be any node inside the cordon that is not generated by SPEA2. To reject or modify SPEA2 output due to logical constraint, an innovative and reasonable method is 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 on 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 on 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 the cordon boundary (inside, outside, or on the boundary of cordon)?

(2) If the unselected node locations are located outside 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 on 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 the cordon boundary are calculated based on 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 proved 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 fewer 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 Discussions

In order to apply the proposed model and present the discussion, the real Tehran network is used as a numerical example. Tehran is the capital and largest city in Iran. The city of Tehran has a population of around 9 million. It is ranked 29th in the world by the population of its metropolitan area. The Tehran network is shown in Figure 4.

Figure 4. Tehran network.

The Tehran network consists of 8706 nodes and 12745 links. The travel cost function is the BPR equation as follows:

$$\mathrm{t_a}(x_a) = t_a^0\left[1.0 + 0.15\left(\frac{x_a}{C_a}\right)^4\right] \quad (40)$$

Equations (41) to (43) are used as the utility functions of modes [47].

$$\mathrm{u_w^C} = -0.1010\, t_w^C \quad (41)$$

$$\mathrm{u_w^T} = -0.2613 - 0.1096\, t_w^T \quad (42)$$

$$\mathrm{u_w^B} = -0.6936 - 0.1257\, t_w^B \quad (43)$$

To consider drivers' behavior change due to the existence of P & R at the cordon boundary, Equations (44)–(46) are used as the utility functions for shifting from cars to taxis or buses (car only, car-taxi, and car-bus) [47].

$$\mathrm{u_{car\ only}} = -0.0284\, t_{pd}^C \quad (44)$$

$$u_{\text{car-taxi}} = 1.21 - 0.0451\, t_{pd}^{T} \quad (45)$$

$$u_{\text{car-bus}} = 1.24 - 0.0432\, t_{pd}^{B} \quad (46)$$

To determine the weight of each pollutant, the clearance costs of a gram of each are used and the following results are obtained [47]:

$$E_a^{Total} = 0.19\, E_a^{CO} + 0.21\, E_a^{HC} + 0.6\, E_a^{NOx} \quad (47)$$

The coefficients of the air pollutants emission model are given in Table 3 based on each pollutant and vehicle type [47].

Table 3. Constant values for pollutants emission including CO, HC, and NO_x.

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 (NO_x)				
Car	+0.843	+0.017	0	0
Taxi	+0.850	+0.003	0	+26.56
Bus	−82.76	+1.902	−0.011	+1383

For the objective function (F_2) of environmental equity, γ is assumed to equal 1.05. Therefore, 5% environmental inequity is permitted outside of the cordon. Given the expressed assumptions, the algorithm of the developed model is implemented using Matlab software. Then, two objective functions (F_1 and F_2), which are social welfare and environmental equity, are considered simultaneously and non-dominated results (a set of optimal results) are extracted based on the SPEA2 method (with the maximum number of generation: 700). The position of non-dominated results in the objective space or Pareto front is depicted in Figure 5.

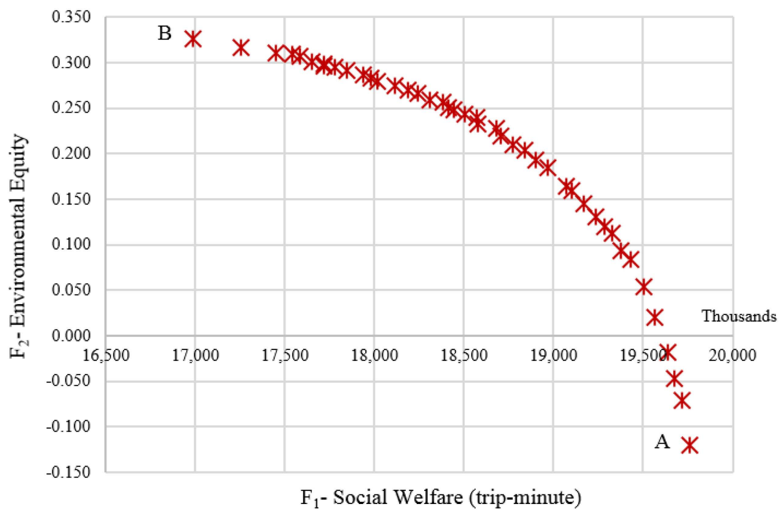

Figure 5. Pareto front in the objective space (F_1 and F_2).

The concave curve is formed by non-dominated results, which confirms the validity of the proposed model. This curve reveals that the cordon pricing scheme is a multi-objective problem, indicating that environmental equity will not necessarily increase due to an increase in social welfare. Based on the results of the proposed model with two objective functions (F_1 and F_2), we have:

(1) The social welfare objective function (F_1) changes in the range of 16,987,932 to 19,759,821 trip-minute. The best situation of social welfare (F_1: 19,759,821 trip-minute) is equivalent to −0.1209 in the environmental equity (F_2) (result "A" in Figure 5).

(2) The environmental equity objective function (F_2) changes in the range of −0.1209 to 0.3265. The best situation of environmental equity (F_2: 0.3265) is equivalent to 16,987,932 trip-minute in social welfare (F_1) (result "B" in Figure 5).

Therefore, the formation of the Pareto front in the objective function confirms that near the point of maximum social welfare there is a tradeoff between social welfare and environmental equity. Indeed, such a tradeoff is inevitable given two objective functions unless they achieve a maximum at the same point. Let X_A be the value of the decision variable (or variables) that maximizes objective function "A", and define X_B similarly for objective function "B". Starting at X_A, and moving toward X_B will surely reduce the value of objective function "A". In other words, it seems reasonable to consider cordon pricing as a multi-objective problem by considering environmental equity. If the social welfare objective function is more important than the environmental equity objective function for decision makers, they can choose result "A". If the environmental equity 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 the environmental equity objective function (F_2), while the social welfare objective function (F_1) is only reduced to 16.32%.

Therefore, we can create a sustainable situation for the transportation system by improving the environmental inequity with a reduction in social welfare. It should be noted that the value of this reduction depends on the value of time (VOT) of users and how much they value environmental equity.

Results of "A" and "B" in the objective space correspond to the specific features of cordon location, toll level, and price of P&R, as presented in Figure 6 and Table 4.

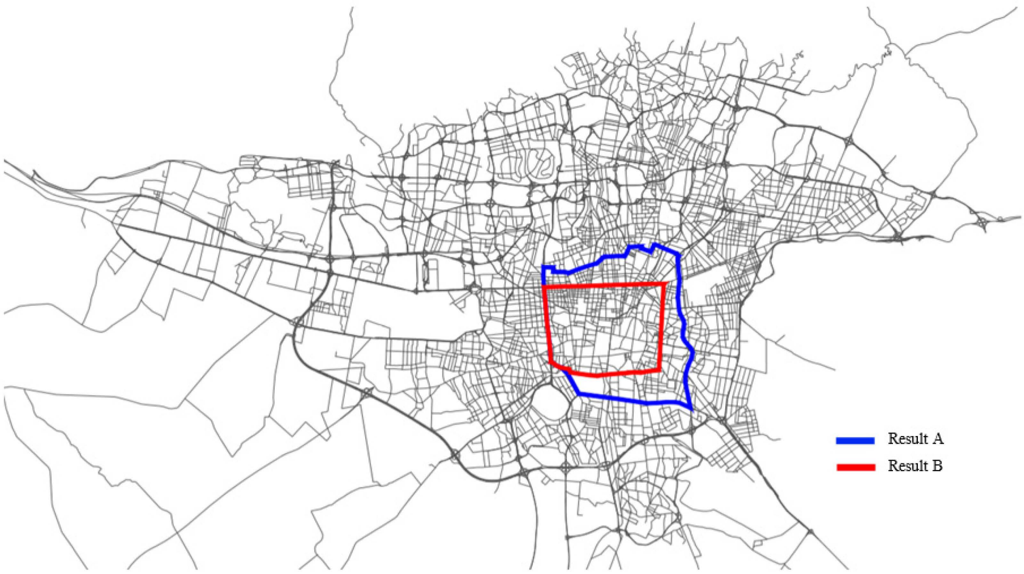

Figure 6. Cordon location in result "A" and "B".

Table 4. Features of solutions (results "A" and "B").

Result	Toll Level (hour)	Price of P&R (hour)
"A"	6.486	0.341
"B"	7.741	0.282

A comparison of the results (changing from result "A" to result "B") shows that:

- Cordon area decreases by 43.22%;
- Toll level increases by 19.35%;
- Price of P&R decreases by 17.30%.

Therefore, we can improve the environment equity by selecting another result (result "B"). Hence, by the selection of this result, we should decrease the cordon area and price of P&R and increase the toll level. Note that these changes are not fixed and depend on the network and demand.

6. Summary and Conclusions

This paper investigated the issue of environmental equity in cordon pricing and a P&R scheme. The environmental inequity resulting from the introduction of a cordon pricing scheme in the artificial network was illustrated. Although the environmental emission decreases inside the cordon by the implementation of cordon pricing, air pollutants emission may increase in some links and the whole network. An increase in air pollutants emission in the network according to their decrease inside the cordon means more emission elsewhere in the network. In fact, due to the implementation of cordon pricing policy, air pollutants emission may transfer from one place to other places in the networks. In other words, air pollutants emission may shift from inside the cordon to its outside. Therefore, it creates a type of environmental inequity. To reduce this above-mentioned inequity, a multi-objective bi-level optimization model was developed. Then, an algorithm was presented according to the second version of the strength Pareto evolutionary algorithm (SPEA2) for solving the multi-objective bi-level optimization model. The proposed algorithm for solving the developed models was applied to the Tehran city network as a real numerical example and then the results of the model were analyzed.

The results showed that this model can be a useful tool for equitable and simultaneous design of cordon pricing and a P&R scheme. Further, the formation of the Pareto front in the objective function confirms the point of maximum social welfare and there is a tradeoff between social welfare and environmental equity. Indeed, such a tradeoff is inevitable given two objective functions unless they achieve a maximum at the same point. In other words, it seems reasonable to consider cordon pricing as a multi-objective problem by considering environmental equity. In addition, the results revealed that by searching in the solution space, it can reduce environmental inequity with relatively low reduction in social welfare. Therefore, we can create a sustainable situation for the transportation system by improving environmental inequity with a relatively low reduction in social welfare. Moreover, there are environmental inequity impacts in real networks, which should be considered in the cordon pricing scheme.

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Nomenclature

The following symbols are used in this paper:

A = the set of links in the network;
W = the set of OD pairs;
x_a = the flow on link a $\in A$;
$\mathrm{t_a^C}$ = travel time of cars in link "a";
t_a^T = travel time of taxis in link "a";
t_a^B = travel time of buses in link "a";
t_a^0 = free flow travel time in link "a";
$\mathrm{C_w^C}$ = minimum travel costs of cars between OD pair $w \in W$;
$\mathrm{C_w^T}$ = minimum travel costs of taxis between OD pair $w \in W$;
$\mathrm{C_w^B}$ = minimum travel costs of buses between OD pair $w \in W$;
$\mathrm{\tau_a}$ = toll level in link "a";
$\mathrm{\tau_{max}}$ = maximum of toll level;
$\mathrm{\theta_{max}}$ = maximum of price of P&R;
$\mathrm{d_w^m}$ = travel demand between OD pair $w \in W$ with mode "m";
$\mathrm{D_w}$ = initial total travel demand between OD pair "w";
$\mathrm{\gamma_w}$ = demand elasticity coefficient between OD pair "w";
μ_w = minimum travel cost between OD pair "w";
C_{op}^C = minimum travel costs by cars from origin "o" to P&R "p";
C_{pd}^C = minimum travel costs by cars from P&R "p" to destination "d";
C_{pd}^T = minimum travel costs by taxis from P&R "p" to destination "d";
C_{pd}^B = minimum travel costs by buses from P&R "p" to destination "d";
θ_p = price of P&R "p";
$(d_w^C)^{old}$ = initial travel demand by cars between OD pair "w";
$(d_w^C)^{new}$ = modified travel demand by cars between OD pair "w";
d_{op}^C = new travel demand by private cars from origin "o" to P&R "p";
d_{pd}^T = new travel demand by taxis from P&R "p" to destination "d";
d_{pd}^B = new travel demand by buses from P&R "p" to destination "d";
f_{rw} = the flow on route "r";
R_w = the set of all routes between OD pair $w \in W$;
$D_w^{-1}(w)$ = the inverse demand function;
d_w = the demand between OD pair $w \in W$;
d_w^C = travel demand of cars between OD pair "w";
d_w^T = travel demand of taxis between OD pair "w";
d_w^B = travel demand of buses between OD pair "w";
x_a^C = traffic flow for cars in link "a";
x_a^T = traffic flow for taxis in link "a";
x_a^B = traffic flow for buses in link "a";
$\mathrm{E_a^i}$ = the emission of pollutant "i" in link "a" (g/km/veh);
$\overline{S}_a$ = average speed of traffic flow in link "a" (km/h);
$t_a(x_a)$ = travel cost on link "a", which is function of link flow x_a;
C_a = the capacity of the link "a";
t_{pd}^C = travel time by cars between P&R "p" and destination "d";
t_{pd}^T = travel time by taxis between P&R "p" and destination "d";
t_{pd}^B = travel time by buses between P&R "p" and destination "d";
$\mathrm{u_w^C}$ = utility function of cars between OD pair $w \in W$;
$\mathrm{u_w^T}$ = utility function of taxis between OD pair $w \in W$;

u_w^B = utility function of buses between OD pair $w \in W$;
$u_{car\ only}$ = utility function for no shifting from cars to other modes in P&Rs;
$u_{car\text{-}taxi}$ = utility function for shifting from cars to taxis in P&Rs;
$u_{car\text{-}bus}$ = utility function for shifting from cars to taxis in P&Rs.

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