

A Study of Both Optimal Locations and Toll Levels Road Pricing Using Genetic Algorithm

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Abstract: This paper takes advantage of a GA based Bi-Level Programming Problem to find the optimal scheme of second-best road pricing problem, the method optimizes locations and toll levels simultaneously. The highlight of this paper is that the case study was taken on the actual network of Nagoya Metropolitan Area instead of a numeral network, in order to evaluate the effect of the method, we made comparison between a cordon pricing scheme and the same number of links tolled optimal locations and toll levels schemes. The result showed that under the situation of the same number of links, the optimal locations and toll levels scheme works better than the cordon pricing one.

Key words: Road Pricing, Second-Best, GA, BLPP

1. INTRODUCTION

In recent years many cities are suffering from the heavy traffic congestion, accompanying with the development in economics and technologies, it became much easier to get vehicles, car ownership in the urban area increases greatly. The sharp increase of car ownership had led to a series of problems in the metropolitan area, especially the congestion, safety and environmental problems, to deal with these situations, researchers had brought out kinds of methods both in technologies and policies. As an effective traffic control method, road pricing had attracted much attention. London, Singapore and Stockholm had implemented various forms of congestion pricing and received effective result. Through the method of road pricing, traffic demand, traffic destination, departure time and trip routes of vehicles had been changed, unnecessary trips had been decreased, and operating situation of the whole network was improved greatly.

Road pricing came from the opinion that road users are actually paying fewer cost than the cost (Marginal Cost) they should pay, and through a charging method it will make the traffic condition move toward an optimal one, this kind of pricing is called first best pricing. Under the assumption that all links can be charged, the first best road pricing can be solved by system optimization assignment. But in fact the first best pricing is not practically appealing, because the high cost of operation and poor public acceptance, the first best pricing can hardly be implemented in the practical projects.

Recent years, as a more practical method the second-best road pricing problem received ample attentions by researchers. Yang and Huang (1997) made the investigation of principle of marginal cost pricing and gave out the general model of link congestion toll with elastic demand, this model can be used not only in first best pricing but also in the alternative second-best pricing. Verhoef (2002) proposed a method to find second-best toll levels, in the study only a subset of all links can be charged. Sherpherd et al. (2004) stated the GA based approach can be used for large-scale network, but in the paper the case was only a mini network with few links. Sumalee et al. (2005) developed a method based on GA making a comparison of judgmental and optimal road pricing cordons. Zhang et al. (2004) and Sumalee (2004) present the research about cordon based second-best congestion pricing, both papers focused on the design method of cordon applied in GA. Zhang et al. (2004) did the research on variable demand equilibrium under second-best pricing with the parameterized pricing scheme. Santos (2004) simulated cordons in eight towns and estimated the impacts of schemes using SATURN (Simulation and Assignment of Traffic to Urban Road Networks), the paper compared the benefit between single cordon pricing and double cordon pricing. Mauyama et al. (2007) compared the cordon and area based road pricing using model of elastic demand. Kanamori et al. (2008) used a semi dynamic model of stochastic UE evaluating the effect of cordon road pricing. Paper previously mentioned mostly focused on numerical case study with small scale network.

Actually, under given toll level of certain network it is unknown where should be charged to get the optimal effect, the cordon pricing in central business district is more practical but might not be an optimal one, and furthermore the pricing scheme with uniform toll level doesn't work better than a scheme with more-than-one toll level. The objective of this study is to compare the cordon pricing under a certain toll level with optimal locations and toll levels pricing which get from a GA based bi-level programming problem, in the study all the cases were made based on the detailed Nagoya Metropolitan Area road network. In order to compare the effect of cordon pricing with optimal locations and toll levels pricing, the number of two cases is the same, the cordon pricing scheme is charged in uniform toll level and the optimal locations and toll levels pricing scheme is charged in various toll levels.

The paper is organized as follows. In the next chapter, we will discuss the Bi-Level Programming Problem model for the second-best road pricing and the method of GA is applied to solve the problem, in this chapter we will show the details of coding method of GA, which is different to other papers mentioned previously. In chapter 3 the case study will be taken on the actual network of Nagoya metropolitan area, a comparison between cordon pricing scheme and optimal both locations and toll levels road pricing scheme. Chapter 4 give out the results of the case study and make analysis on the results, and the final conclusions are provided in the chapter 5.

2. MODEL FORMULATION

The optimal locations and toll levels pricing can be regarded as the link congestion toll in the network, so the problem can be depicted as a bi-level second-best pricing model, and subject to the standard traffic equilibrium problem. The problem can be solved by GA, this algorithm had been proved very useful in solving the large-scale network problem. In this study, because the optimal locations and toll levels are determined simultaneously, the coding method of GA is a little different with the general method of optimal locations with uniform toll level, we will show the details in the later part of this chapter.

2.1. Upper Level

The upper level model can be evaluated to maximize the social welfare getting from the tolled network. Because the theoretical background of road pricing is based on the economic principle of marginal-cost, that is the change in total cost that arises when the quantity produced changes by one unit. As for road pricing, it means that the changes in social cost(marginal-cost) that increases when a new vehicle enter the network, the individual driver can only perceive the cost(average-cost) he personally bears, so it is necessary for drivers paying a toll between social cost he caused and average cost he perceived in order to improve the social welfare. Here the social welfare can be defined as

$$\text{Max} \quad SW = UB - SC \quad (1)$$

Which is between the user benefit and the social cost on the network, and user benefit (UB) is evaluated by the following formulation:

$$UB = \sum_{w \in W} \int_0^{d_w} D_w^{-1}(x) dx \quad (2)$$

w is the OD pair, W is the set of OD pairs, d_w is the demand between OD pair, $D_w^{-1}(x)$ is inverse demand function, its value depends on the travel cost on the network. The social cost is formulated as:

$$SC = \sum_{a \in A} v_a t_a(v_a) \quad (3)$$

A is set of links, v_a is the flow on link a which belongs to links set A , $t_a(v_a)$ is travel time on link a , which is the function of link flow. Then the social welfare can be expressed as following formulation:

$$SW = UB - SC = \sum_{w \in W} \int_0^{d_w} D_w^{-1}(x) dx - \sum_{a \in A} v_a t_a(v_a) \quad (4)$$

Demand function is set as:

$$D_{rs}(C_{rs}) = D_{rs}^0 \exp \left[\sigma \left(1.0 - \frac{C_{rs}}{C_{rs}^0} \right) \right] \quad (5)$$

D_{rs}^0 is the Demand of minimum generalized travel cost during assignment, C_{rs}^0 is minimum generalized travel cost, σ is the Price elasticity for the demand.

2.2. Lower Level

The lower level model is the user equilibrium with variable demand:

$$\text{Min } Z(x, d) = \sum_a \int_0^{x_a} t_a(\omega) d\omega - \sum_{rs} \int_0^{d_{rs}} D_{rs}^{-1}(\omega) d\omega \quad (6a)$$

Subject to

$$f_k^{rs} \geq 0 \quad (6b)$$

$$d_{rs} \leq \bar{d}_{rs} \quad (6c)$$

$$d_{rs} = \sum_k f_k^{rs} \quad (6d)$$

In the formulation, f_k^{rs} is the flow on kth path between OD pair rs, d_{rs} is the demand between od pair, \bar{d}_{rs} is the upper bound of demand between origin r to destination s, $D_{rs}^{-1}(x)$ is Inverse Demand function, its value depends on the travel cost. (Because the solving algorithm of variable demand UE problem is complicated, we can't depict it here in details, if someone want the detailed algorithm of user equilibrium with variable demand please read Urban Transportation Network, chapter 6, Sheffi, 1985 for reference.)

The form of travel time is evaluated as:

$$t_a(x_a) = t_0 \left[1 + \alpha (v/c)^\beta \right] + \text{toll} / \text{VOT} \quad (7)$$

In this formulation, the toll is determined by the toll level, once the toll level is determined, the toll money will be a certain value.

In order to make the problem practicable, we choose several subsets of all links in the network as the candidate toll links, only links of the subsets can be selected. These subsets are determined empirically and we choose links into various combinations as road pricing schemes, when a link is selected into one combination, it means that this link is charged. For a practical network, the total number of combinations is huge, even they are selected from a subset. It may be very hard to go through all combinations for the time cost in the optimal result finding procedure. GA is capable to find out the optimal result because its favorable procedure of natural selection, the detailed procedure of the method is introduced below:

- Step 1.* (Initialize population) Randomly select links from the subset and randomly generate toll levels
- Step 2.* (Fitness evaluation) Employ the model to obtain the optimum schemes from each combination of toll links.
- Step 3.* (Selection) Select schemes with higher values of social welfare for reproduction.
- Step 4.* (Crossover and mutation) Pair the populations and randomly exchange the toll

links between pairs. Randomly change some toll links and toll level.
Step 5. (Verification of stopping criterion) if the convergence criterion has not been satisfied, go to step 2 to continue the next generation; otherwise stop the program.

The detailed progress of GA in this study is showed in the fig.1. During the initial procedure, the information of network and its subset, OD data and model parameters are all read by program. The fitness of all schemes will be evaluated in the next procedure, in this procedure is the lower level programming plays the core. With respect to a certain scheme, there will be an assignment of variable demand user equilibrium for it, and after the assignment the social welfare, user benefit, and social cost will be given out.

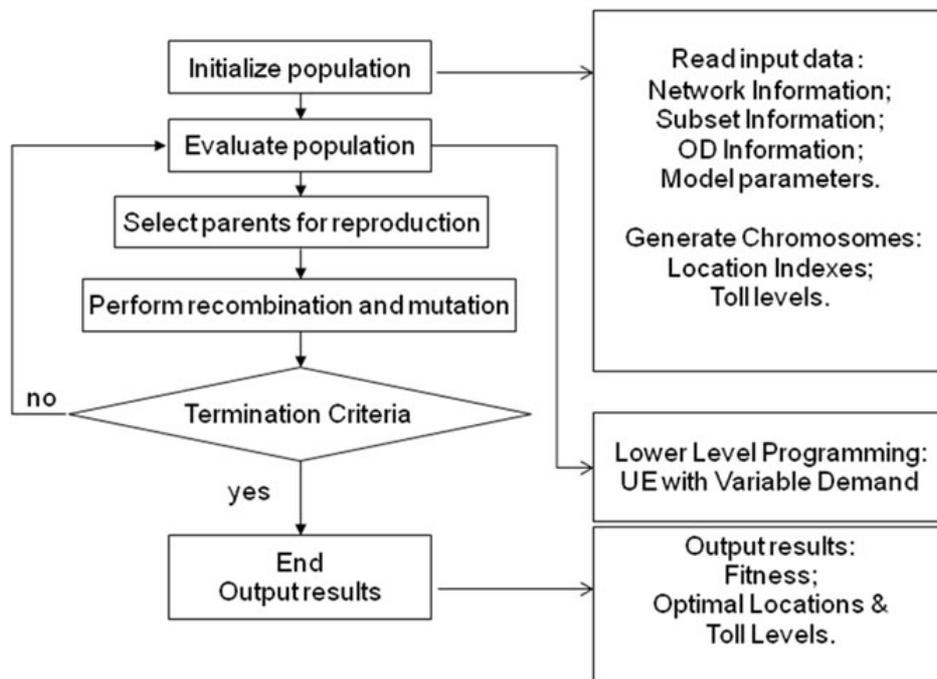


Fig 1 Progress of GA

Fig 2 shows the detailed structure of one chromosome, one chromosome is representing a toll scheme, a combination of toll links, the length of chromosome is twenty and there are three rows in one chromosome, the first row is the index of genes; the second row is representing the toll links index, in fig 2 the first number 231 of means the link of ID 231 in the subset is selected as toll link; the third row is representing the toll levels of toll links, for example, number 2 means this link is charged by the toll level 2, in this study we set three toll levels for toll links.

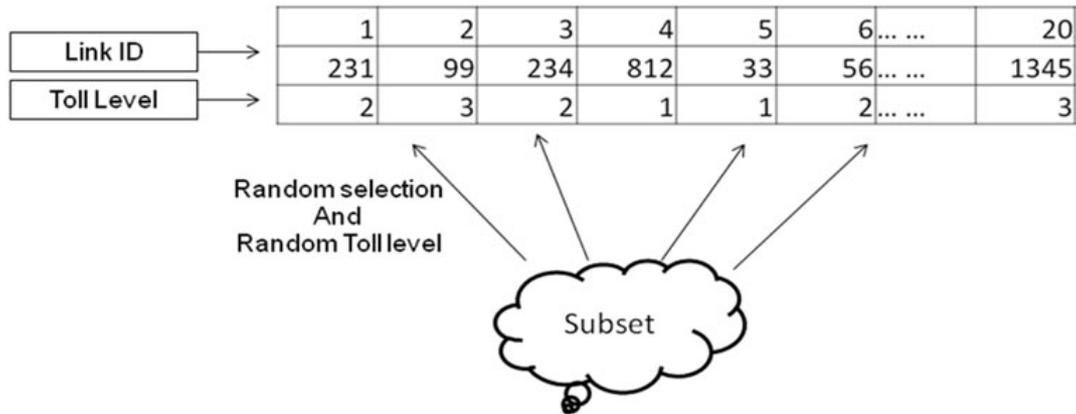


Fig 2 Structure of chromosome

3. Case study on Nagoya Metropolitan Area Network

The case study was applied on the Nagoya metropolitan area network, the network is composed of 4209 one-direction links and there are totally 279 traffic zones among the city area. We use the personal trip (PT) data conducted in 1996 to simulate the traffic flows on the network. The unit of traffic flows put on the network is standard PCU, and we assume the value of time of the vehicle drivers is 83.4 Japan Yen per minute. The previous chapter had mentioned there are three optional toll levels for one toll link, the details of the toll levels are shown in table.1.

Table 1 setting of three toll levels

Toll Level	Toll Money (Japanese Yen)
1	200
2	300
3	500

During the initial process for the model, the toll level is given to the toll link randomly together with link location, but once it is given, the toll level will not change for this scheme in the current generation, only in the procedure of crossover and mutation it has the chance to be changed.

In order to compare the optimal locations and toll levels pricing with the cordon pricing, we introduce three cases for the case study, details of these cases are introduced in the following paragraph:

Case A. Cordon pricing. In this case we choose the cordon area of central business district of Nagoya city, and because during this area there are totally twenty links are toll links, we set the same number of links schemes for comparison. In the cordon area, the toll level is uniform, because the limitation of cordon pricing itself, there is only one toll level can be set for cordon pricing.

Case B. Optimal locations and toll levels of artery roads subset pricing. The subset of this case is selected from artery roads of urban central area of Nagoya road network, we choose the roads with no less than 4 lanes among the area as well as the links are not the express links or actual toll links.

Case C1. Optimal locations and toll levels of urban central area roads subset pricing.

The subset of this case is selected from urban central area of Nagoya road network, this subset includes the subset of Case B, the links in the subset also excludes the express links and actual toll links.

Case C2. Optimal locations and toll levels of cordon area roads subset pricing. The subset of this case is selected from the cordon area, the same special area as Case A, we set this subset to examine with same toll links and same toll space whether the case of optimal locations and toll levels will get better result, this subset has 108 one way links and almost all of them are artery roads.

Fig 3 is showing the locations and ranges of 3 subsets in the road network of Nagoya city, subset of Case A is the combination of links in the red cordon line of top right image, all links of the combination are one-direction links, the vehicles will be charged only when they enter the cordon; subset of Case B is the bold blue links in left bottom image, these links are the artery roads of the city central area with no less than 4 lanes, considering the actual situation, we didn't include the express way links and the actual toll links into the subset of case B; subset of Case C1 is the bold green links in right bottom image, all the links of the city central area are introduced in the subset, as well as Case B express way links and actual toll links are excluded from the subset; Subset of Case C2 shares the same area of Case A.

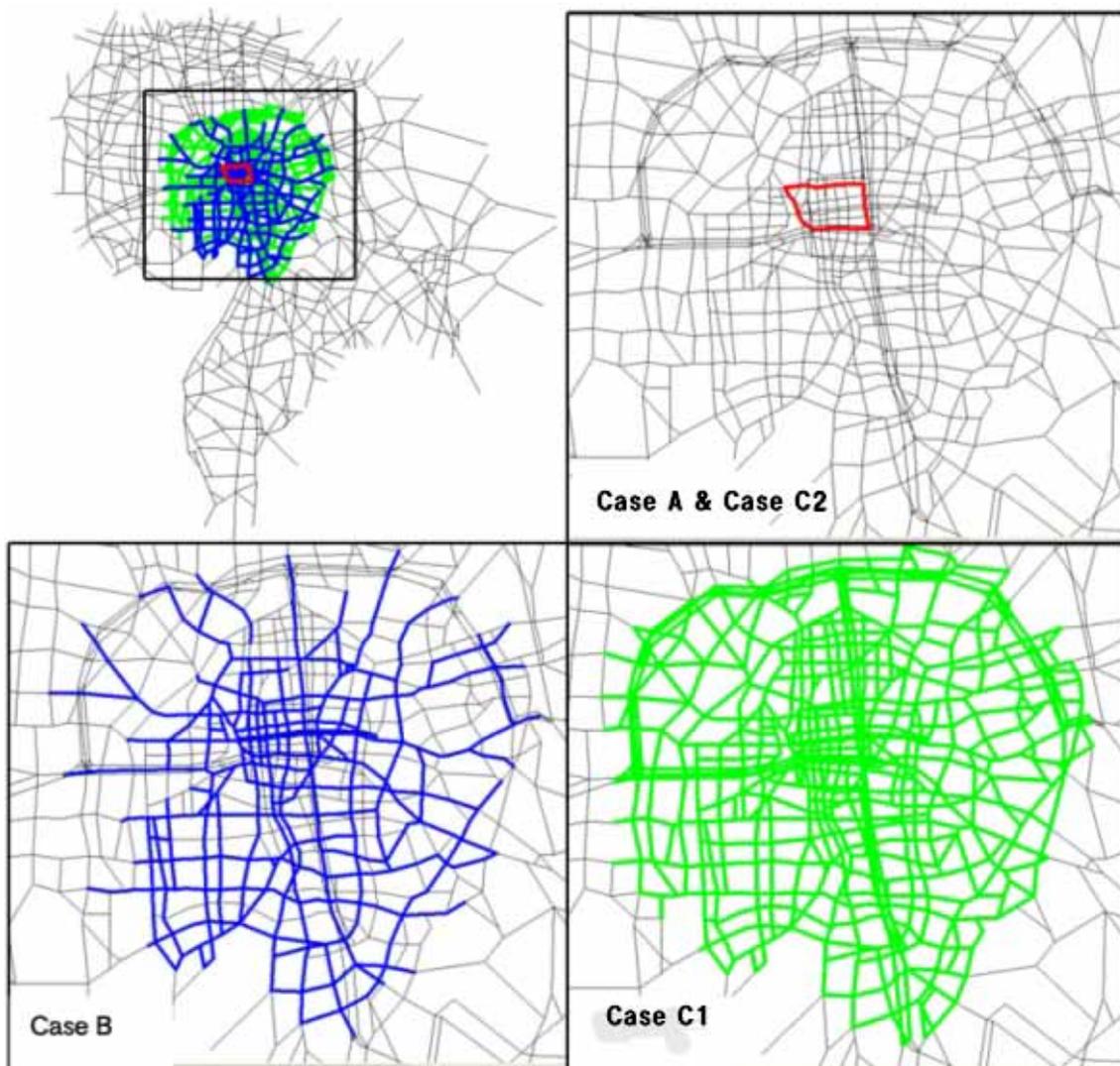


Fig 3 Cases of the study

4. Results of Case Study

By introducing the road pricing schemes on the network, traffic flows are affected in different aspects: most drivers will try to change the trip routes, some will shift the departure time or shift the traffic mode to another such as subway. But from the point of traffic condition on the whole network, it is moving toward system optimum, in other words, the network becomes less congested and the users of the network will benefit from it.

We got the results of four cases applying the GA based BLPP model, as we expected, the results showed that the optimal locations and toll levels cases achieved better results than the cordon pricing case. In fig 4, we can see that the Case A get the lowest value, in both Case B and Case C1, the value of social welfare is better than the cordon pricing, we can also get that the Case C2, which is of same area and toll link numbers as Case A, its value is lower than Case B and Case C1, but higher than Case A, detailed values are shown in Table 2. Through the comparison we can know from the point of social welfare optimal locations and toll levels pricing scheme is more attractive even with the same link number and toll area, though cordon pricing scheme is more feasible and easier to realize.

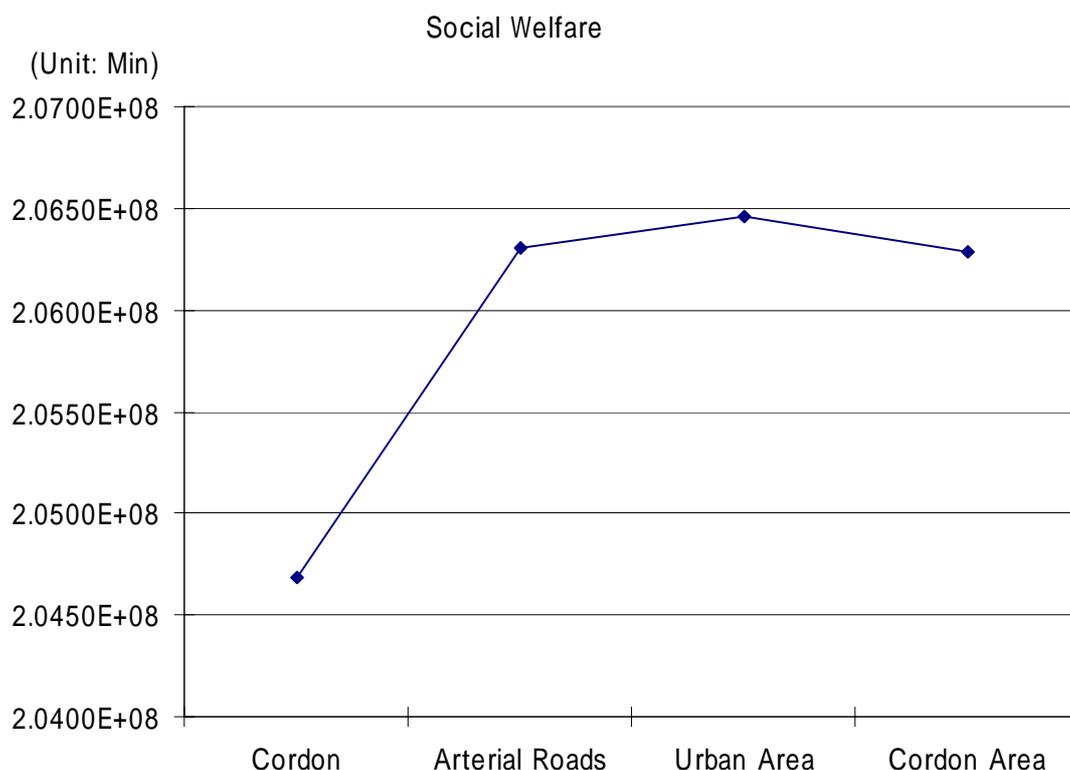


Fig 4 Comparison between 4 cases

Table 2 Values of 4 cases (Unit: Min)

	Social Welfare	User Benefit	Social Cost
Cordon	2.046811E+08	3.470531E+08	1.423719E+08
Arterial Roads	2.063013E+08	3.482907E+08	1.419894E+08
Urban Area	2.064630E+08	3.487312E+08	1.422682E+08
Cordon Area	2.062883E+08	3.485062E+08	1.422178E+08

Fig 5 shows the result of Case C1, the left part of image is the locations of links in the network, the bold red links are toll links of the scheme, we can see the most links tend to locate at the central part of urban central network or at the corridors. The right part of image is link IDs and toll levels of links.

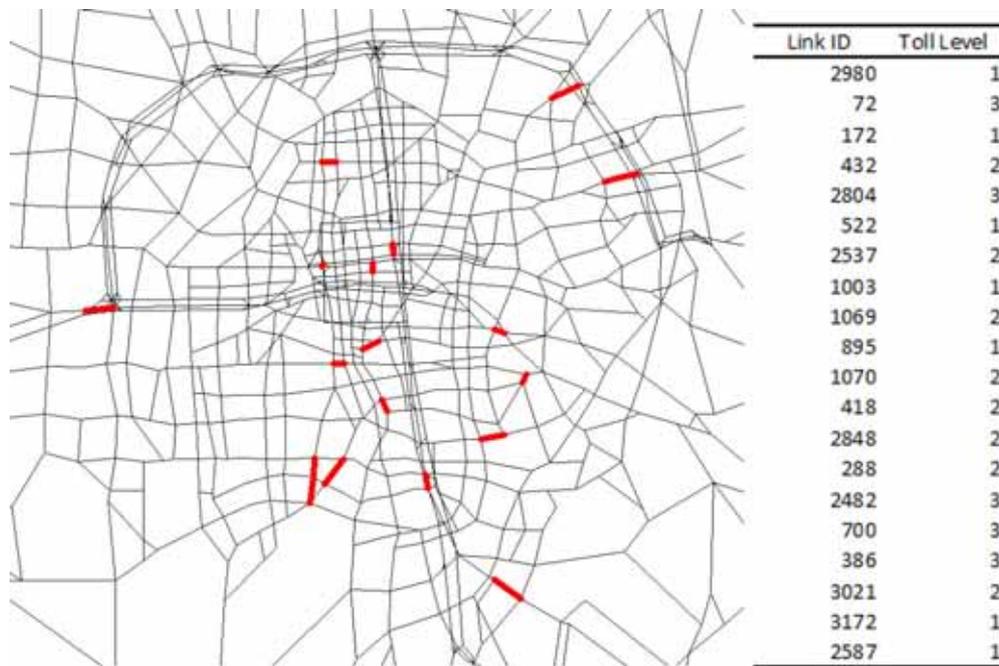


Fig 5 Result of Case C1

Besides the comparison between four cases, we had also made another comparison between different numbers of toll links for Case C1, the toll link numbers are from 8 to 20, and 30 toll links scheme is introduced to compare the effects with the schemes of less toll links. Table 3 is the results we computed for these cases and Fig 6 shows the value trend with the different toll link numbers.

From Table 3 and Fig 6, we can see the social welfare is increasing at first, but when the number of toll links exceed 16 it begin to decrease, the social welfare values of 18 and 20 toll links are less than the social welfare value of 16 toll links, we then add 30 toll links schemes to make comparison, but the result shows the social welfare value didn't increase together with the number increase of toll links.

Table 3 Results of different numbers of toll links for Case C1 (Variable toll, Unit: Min)

Toll links	Social Welfare	User Benefit	Social Cost
8	2.062053E+08	3.478819E+08	1.416766E+08
10	2.063682E+08	3.481763E+08	1.418081E+08
12	2.062747E+08	3.479207E+08	1.416460E+08
14	2.064667E+08	3.484057E+08	1.419391E+08
16	2.065516E+08	3.484062E+08	1.418547E+08
18	2.064266E+08	3.481836E+08	1.417569E+08
20	2.064630E+08	3.487312E+08	1.422682E+08
30	2.062438E+08	3.485735E+08	1.423297E+08

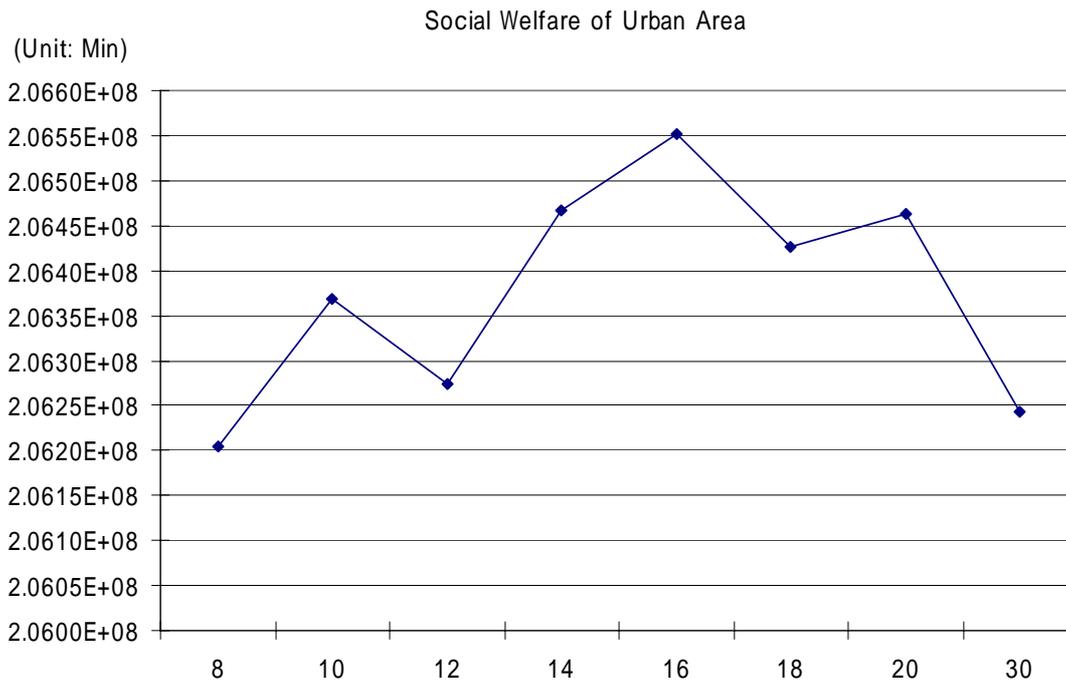


Fig 6 Comparison between cases of different numbers of toll links (Variable toll)

For the purpose of further comparison, another comparison is made. We set the uniform toll level as 300 Japanese Yen of all schemes of the same toll link number of 20, the results are of the similar trend as the variable toll levels cases. Table 4 shows the computed results of social welfare of uniform toll levels cases and Fig 7 is the picture of value trends, the results of this scenario are a little lower than previous variable toll level one, but in both scenarios the peak value occurs around 16-18 toll links.

Table 4 Results of different numbers of toll links for Case C1 (Uniform toll, Unit: Min)

Toll links	Social Welfare	User Benefit	Social Cost
8	2.061953E+08	3.477697E+08	1.415744E+08
10	2.063670E+08	3.481780E+08	1.418110E+08
12	2.062729E+08	3.479187E+08	1.416458E+08
14	2.062880E+08	3.482169E+08	1.419288E+08
16	2.065061E+08	3.483735E+08	1.418674E+08
18	2.064125E+08	3.486103E+08	1.421979E+08
20	2.063854E+08	3.483967E+08	1.420113E+08
30	2.062408E+08	3.485766E+08	1.423358E+08

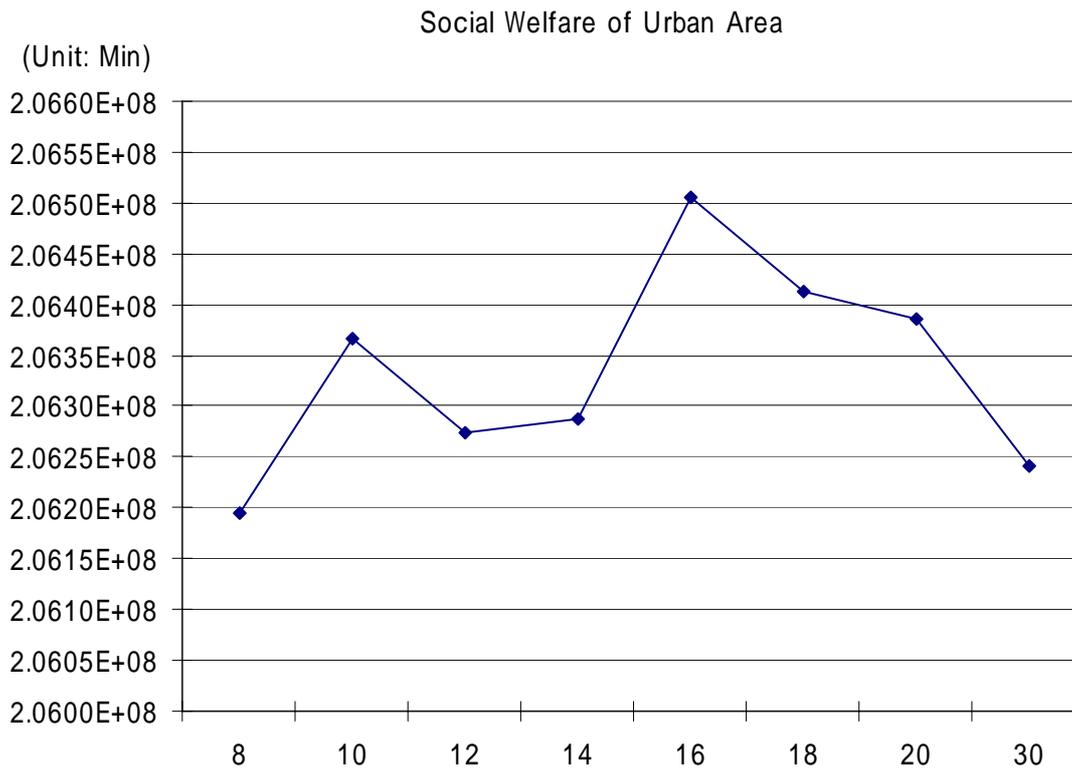


Fig 7 Comparison between cases of different numbers of toll links (Uniform toll)

5. Conclusion

In this study, we develop a Bi-level model based on GA to find out both optimal locations and toll levels simultaneously, and the case study was taken on the actual large-scale network of Nagoya Metropolitan Area. In order to compare the effect of method to other policy, we introduced four cases in the case study: the cordon pricing case, the optimal locations and toll levels pricing case use city central area artery road network, city central area road network and the cordon area road network, the comparison between the cordon pricing case and optimal both locations and toll levels cases had shown that the latter cases performed better than former, even for the same pricing area with same toll link number case of optimal both locations and toll levels, we can get the higher result than cordon case.

Furthermore, we had evaluated the effects the Case C1 using different number of toll links, and compare the results of uniform toll level with that of variable toll level. From both the results, the peak value occurred around 16-18 toll links, we thought that under this road pricing policy the maximum might exist in 16-18 toll links, this is the consideration for future study.

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