CO-ORDINATION OF ROAD USAGE CHARGES IN HONG KONG

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abstract: A co-ordinated planning of road usage charges is required especially in conditions of very constrained resources and rapid expansion of urban area such as in Hong Kong. In this paper, optimization method is used to enable the co-ordination of road usage charges to be planned systematically particularly when the trip matrix is not fixed and would be varied with changes in road usage charges. The optimization procedures would identify road usage charges that would minimize total network cost given physical network constraints. The developed model will advance this subject and help the authorities evaluate road usage charges schemes rapidly and consistently. The Hong Kong 2006 planning data and road network are used for application of the optimization method.

1. INTRODUCTION

Highway planning should point the way for major changes in both road network and usage charges and ensure that decisions made today will not prove inconsistent and irreconcilable with long-term goals. Hong Kong is expanding rapidly. To accommodate this expansion, some three billion dollars have been invested every year for the construction of new highways and transport infrastructure in Hong Kong. There are a large number of potential road projects to be chosen from, but there are practical constraints in terms of financial and construction industry capacities. Therefore, new transport infrastructure projects must be planned carefully so as to obtain the maximum benefits from the investment for the territory. The conventional approach has failed to deal satisfactorily with the impact of road usage charges on the investment of highway facilities as the latter was normally formulated with a fixed set of road usage charges.

The conventional approach to highway planning consists of four steps. First, a number of alternative highway networks and a set of road usage charges are proposed. Second, the land use planning data and the transport model are applied to estimate the traffic demand on each alternative road networks. Third, the performance of the alternative highway networks is evaluated against pre-selected planning goals. Finally, the preferred network is analyzed and designed in detail. The deficiency of the conventional approach lies in the difficulty of selecting suitable road usage charges for testing. The amount of computational effort involved has made it impractical to test a wide range of road usage charges. But if the effects of varied road usage charges are not examined, the real optimal road network could be missed.

For the purpose of strategic land use development planning, a Land Use Transport Optimization (LUTO) model was developed (Choi, 1986) for solving the problem of a joint optimization of land use plan and a transportation development plan. LUTO model has been being used for the strategic land use and transport development planning in Hong Kong (Choi, 1986; Leung and Lam, 1991). Since the task of transport planning is to determine cost-effective solutions for minimizing traffic congestion, a cost-effective solution to the transport problems should consist of a land use pattern, a transport system and a set of road usage charges that together bring demand and supply into balance. However, the road usage charges considered for studies have been seen as some fixed parameters in the model, anwignored the role of road usage charges as an alternative to highway investment. Based on the LUTO planning data, this paper examines how road usage charges to affect the travel demand and network performance. Tunnel tolls and petrol tax are the direct charges for road usage. In fact, these road usage charges are being used in Hong Kong and would affect the traffic demand directly. In the previous related studies, Beckman (1965) commented that " tolls are economically optimal if they induce an efficient use of the available road capacity". Dafermos and Sparrow (1971) showed that by the means of congestion tolls, we can force individuals to choose their travel paths leading to a system optimal resource allocation and toll patterns for a simple network with two paths. Similarly, Lam (1988) also demonstrated how road tolls affect the decision of transport investment and the role of road pricing in network design.

In fact it is necessary to consider the road usage charges simultaneously when designing a road network. Otherwise, it may end with expensive but inefficient solution. Road usage charges that as a way to reduce congestion, to provide a basis for investment decision, to assist traffic control, and so on, have been widely used. Distance-based charge such as distance license has been used in New Zealand (Starkie, 1988); Area License Scheme (ALS) has been implemented in Singapore since 1975 (McCarthy and Tay, 1992); in Norway the revenues from road tolls were directly linked to road improvement (Tretvik, 1992); and electronic road pricing system has been examined in greater detail in Hong Kong (Dawson and Brown, 1985) and will be demonstrated fully in Singapore in the near future.

This paper presents an optimization method which will enable the analysis of co-ordinated tunnel toll and petrol tax charges by optimizing an " objective function " while the travel demand in terms of origin-destination (O-D) matrix is not fixed and would be varied with changes in road usage charges. Case study will be shown based on Hong Kong road network adopted in the LUTO studies. We will use the optimization method to derive an optimal set of toll charging for the ten toll links and the desirable petrol tax in Hong Kong. In the next section, the search algorithm is formulated and the optimization method is then described. The application of the optimization method will be presented in which the total network travel costs are used as measure for evaluation of the road usage charges in Hong Kong. Finally, conclusion is given together with recommendation for further study.

2. SEARCH ALGORITHM

Given a road network with m toll links and d_f petrol tax, let h_i denote the increase (or decrease if negative) of the charge of ith toll link and of petrol tax with respect to a reference charge $Y^0 = (y^0_1, y^0_2,...y^0_m, d^0_f)$. Hence for each $(h_1,h_2,...h_m,h_{m+1})$, there corresponds an usage charge in which the toll charge of the ith toll link is given by $y_i=y^0_i+h_i$ and the petrol tax is given by $d_f=d^0_f+h_{m+1}$. For each usage charge $Y=(y^k_i+y_2,...y_m,d^k_f)$, let f(Y) be the total network travel cost. The objective is to find an optimal usage charges Y^* such that $f(Y^*)$ is a minimum.

In order to guarantee optimality or to arrive at a small neighborhood of the minimum point, a grid-point search algorithm would be required particularly when the trip matrix is not fixed. The algorithm was introduced by Cheng and Ng (1994) and is adopted in this study. The proposed algorithm contains the following three basic steps.

Step 1: Full local exploration

Let Y^k be the K th approximation of y^k_i and d^k_f to the minimum and h be the step-length. We evaluate the objective function f(Y) at two sets of points about Y :

$$Y^{k+1} = Y^k \pm he_i \qquad i= 1,...,n. \qquad (1)$$

$$Y^{k+1} = Y^k \pm he_i \pm he_j \qquad i = 1,...,n;\ j = 1,...,n \text{ and } j \neq i. \qquad (2)$$

if $f(Y^{k+1}) \leq f(Y^k)$ for some choice of i and j, then the function values at an additional set of 2(n-2) points about Y^{k+1} will be evaluated, namely,

$$\underline{Y}^{k+1} = Y^{k+1} \pm he_r \qquad r = 1,...,n \text{ and } r \neq i \text{ and } r \neq j. \qquad (3)$$

If $f(\underline{Y}^{k+1}) \leq f(Y^{k+1})$ for some choice of r, replace Y^{k+1} by $\underline{Y}^{k+1}$ and continue with partial local exploration. In case that no point around Y^k has lower function value, reduce the step-length and repeat the full local exploration at Y^k. The process will terminate when the step-length is less than a prescribed tolerance.

Step 2: Partial local exploration

Let $b = Y^{k+1} - Y^k$ and evaluate f at the following set of points about Y^{k+1}:

$$Y_s = Y^{k+1} + b \qquad (4)$$

$$Y_s = Y^{k+1} + b - h\varepsilon_i e_i, \qquad i= 1,...,n; \qquad (5)$$

where $\varepsilon_i = -1$ or 1 according to the sign of the i th coordinate of b; if $\|b\| = \sqrt{2}\,h$ and n = 2 or $\|b\| = \sqrt{3}\,h$ and n = 3.

$$Y_s = Y^{k+1} + b \pm he_i \qquad i = 1,...,n;\ e_i \neq b; \text{ Otherwise.} \qquad (6)$$

If $f(Y_s) \leq f(Y^{k+1})$ for some choice of i, then make exploratory move as depicted in the following **Step 3** along the $Y_s - Y^k$ direction. Otherwise, reduce the step-length and start full exploration again at Y^{k+1}.

Step 3: Exploratory movement

Let $M = Y_s - Y^k$ and evaluate f at the following set of points:

$$Y^{k+2} = Y_s + M \qquad (7)$$

$$Y^{k+2} = Y_s + M + he_i \qquad i = 1,...,n; \text{ and b is not along the direction of M.} \qquad (8)$$

If $f(Y^{k+2}) \leq f(Y_s)$, replace Y^k by Y_s and Y_s by Y^{k+2}. Then repeat the procedure above until no longer decreases. Afterwards, restart the full local exploration at Y_s.

3. OPTIMIZATION METHOD

The previous studies merely investigated how the road usage charges to affect the total network travel time where the O-D matrix is fixed. In this case, the trip distribution and modal split are assumed constant and only the choice of route is varied. However, travel costs not only affect route choice but also affect the modal split and trip distribution in long-term planning of highway network. In this paper, we will investigate road usage charges such as toll charges and petrol tax how to affect the modal split, trip distribution and route choice, and thus to attain an optimal highway network planning by means of these fiscal measures on road usage.

The transport model that is used in the LUTO system is a feasible tool for evaluation of the performance of road usage charges in highway network planning. When a set of road usage charges is given, we can use the LUTO transport model to assess their effects on travel demand in terms of O-D matrices, link flow pattern and so on. The total highway network travel cost will be used as the performance measure for evaluation of the varied road usage charges.

Given a set of road usage charges Y^k, the LUTO transport model can be employed to obtain the objective function value (Y^k). However, it takes about 100 minutes for the LUTO run in a PC-486. Therefore, if we have many variates, i.e. road usage charges, needed to be optimized, the computational time will be enormous and unacceptable. In view of this, a heuristic optimization method is proposed to optimize the road usage charges when the modal split and O-D matrices are not fixed. The flow chart of the heuristic approach is displayed in Fig.1 while the optimization model is presented in Fig.2. The optimization procedure of road usage charges is discussed in detail as follows:

Set number of iteration K=1

STEP 1 : Run LUTO transport model with reference road usage charge Y^k to obtain:
Output : Link choice proportion; (result of traffic assignment);
Behavioral cost matrices; and
Objective function value $F(Y^k)$.

If K=1, go to STEP 3.

STEP 2 : Check $|F(Y^k)-F(Y^{k+1})|$

If $|F(Y^k)-F(Y^{k+1})|$ (given stopping criterion) go to STEP 5,
otherwise, go to STEP 3.

STEP 3 : Run the optimization model
- Step 3.1 : Grid-point search.
- Step 3.2 : Update behavioral cost
- Step 3.3 : SLUT (including trip generation, distribution and modal split)
- Step 3.4 : Traffic Assignment.
- Step 3.5 : Objective function evaluation
- Step 3.6 : If objective function no longer decreases, go to Step 3.7. Otherwise, go back to Step 3.1.
- Step 3.7 : Stop; output optimal road usage charges Y^{k+1}

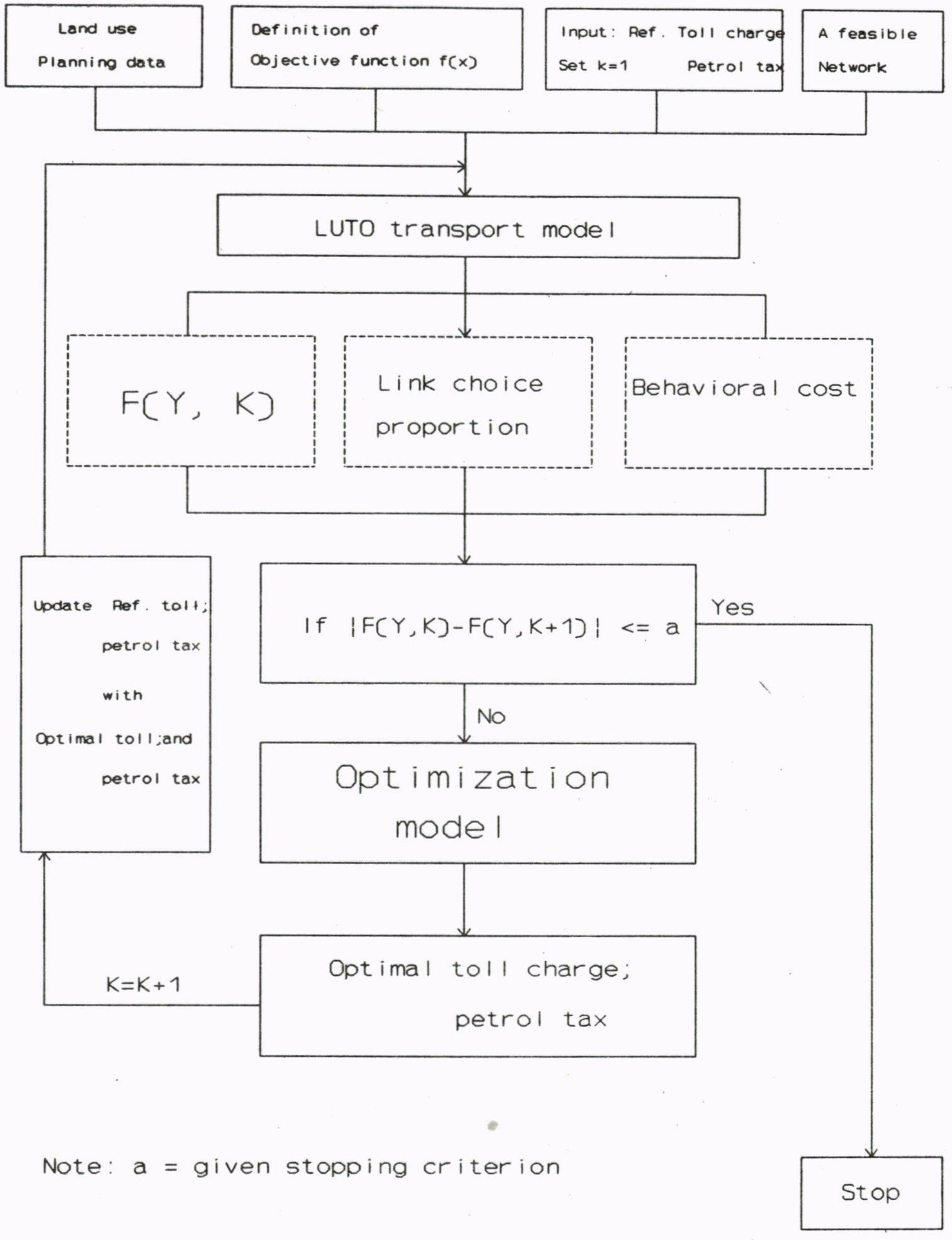

Figure 1 Optimization Procedure of Road Usage Charges

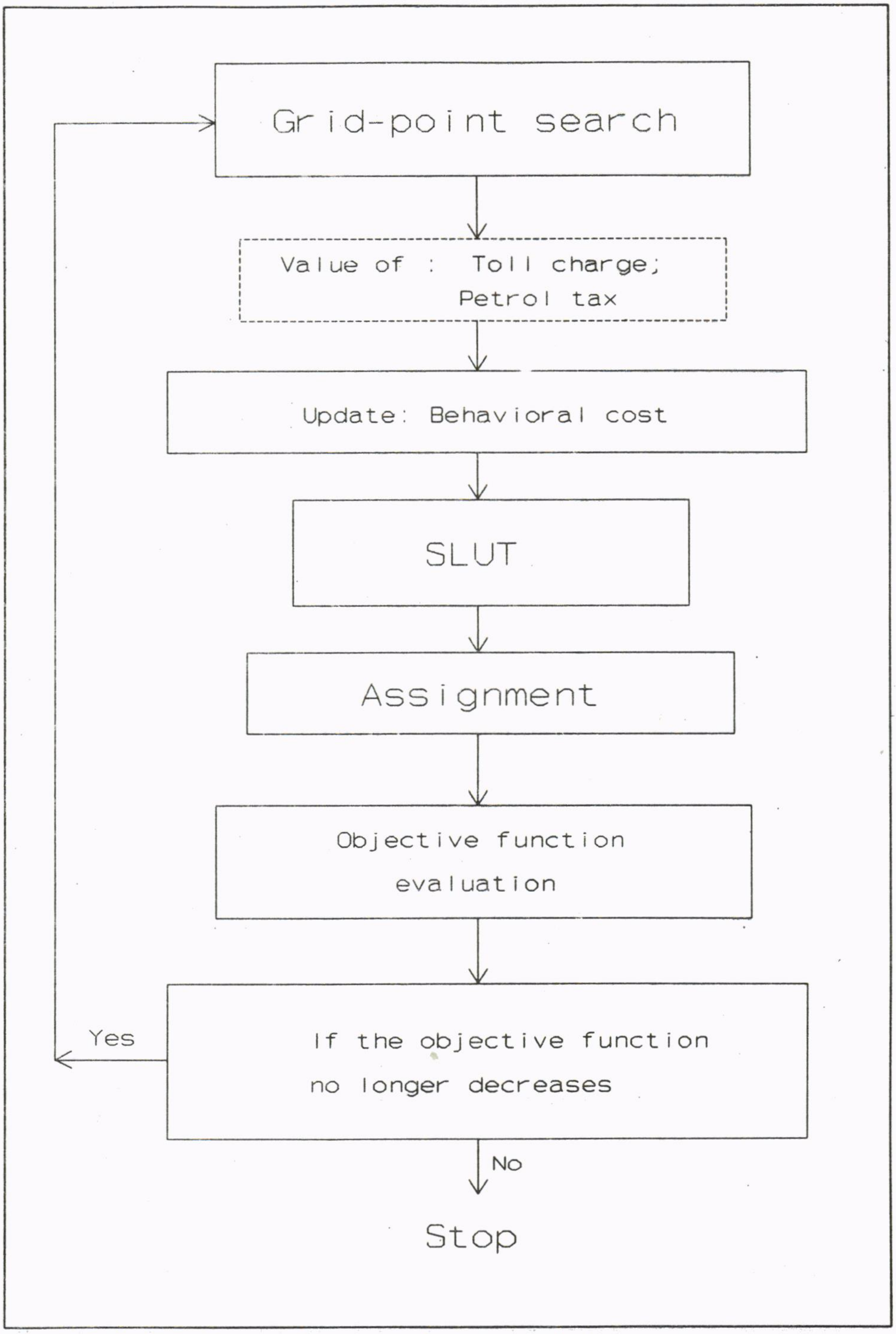

Figure 2 Flow Chart of Optimization Model

STEP 4 : Update reference road usage charges Y^k with Y^{k+1} and set $k = k + 1$, go to STEP 1.

STEP 5 : Stop, output results.

In STEP 1, by running the LUTO transport model , we can get the objective function value $F(Y^k)$ that is corresponding to the reference road usage charges. The link choice proportion, which is the proportion of trips by O-D pair through the particular links, will be fixed at each iteration and be used in STEP 3 for the optimization process. The behavioral cost matrices include all zone pair's behavioral cost by mode, i.e. the behavioral cost generalized of travel from zone i to zone j by private car, good vehicle and public transport.

In STEP 3 - the optimization model, we use grid-point search algorithm for searching the optimal road usage charges.

Step 3.2 is the key point in the optimization process. Subject to the road usage charges output from the grid-point search, we update the behavioral costs accordingly. Let B.cost(i,j) be the behavioral generalized cost of trips from zone i to zone j by mode. For instance, B.cost(i,j) by private car consists of 3 components - toll charge, parking charge and operating cost related to distance. Therefore, B.cost(i,j) can be obtained as below.

$$B.cost(i,j)=Ta*\delta_{ija}+P_j+D_f*d(i,j)+T_f*t(i,j) \qquad (9)$$

where Ta = Toll charge on link a.
δ_{ija} = 1 if trips from zone i to zone j through toll link a;
= 0 otherwise.
P_j = Parking charge at zone j.
D_f = Distance factor (including petrol tax).
$d(i,j)$ = Travel distance from zone i to zone j.
T_f = Time factor.
$t(i,j)$ = Travel time from zone i to zone j.

With the use of equation (9) we can update the behavioral cost by private car with various road usage charges.

Follow the Step 3.2, run the SLUT sub-model which is part of the LUTO transport model including trip generation, trip distribution and modal split. The updated O-D matrices by modes can then be obtained corresponding to the updated behavioral cost.

In Step 3.4, use the link choice proportion that output from STEP 1 to assign O-D flows onto each link so as to get the link flow pattern. It should be noted that in the optimization model, the link choice proportion is fixed, the behavioral costs and the O-D matrices are changing corresponding to the various road usage charges. So, it leads to a simplified optimization procedure. This procedure can save much computational time used in the assignment process and achieve a reasonable result. This will be showed in the following case study.

4. CASE STUDY

The 2006 LUTO planning data and road network, for the case that the Hong Kong airport is not re-located, are used for application of the proposed optimization method. It consists of 51 zones and 345 links of which only 10 links are with toll charges. The locations of the ten toll links are shown in Figure 3 while their reference tolls are listed as in the following Table 1.

Table 1 Road Tunnels and Reference Tolls

ROAD TUNNEL NUMBER	NAME OF ROAD TUNNEL	TUNNEL TOLL (HK$)
		PRIVATE CAR
1.	Aberdeen Tunnel	6.0
2.	Western Harbour Tunnel	21.0
3.	Cross Harbour Tunnel	14.0
4.	Eastern Harbour Tunnel	9.0
5.	Tseng Kwan O Tunnel	6.0
6.	Tate's Cairn Tunnel	6.0
7.	Lion Rock Tunnel	6.0
8.	Route 16 Tunnel	6.0
9.	Route 5	6.0
10.	Route 3	6.0

NOTE: All values are expressed in 1981 price level.

In this case study, only the road usage charges for private car will be changed while those for goods vehicle are fixed.

Given the initial point, namely, the reference toll charges for private car:
= (6.0, 21.0, 14.0, 9.0, 6.0, 6.0, 6.0, 6.0, 6.0, 6.0).

The reference petrol tax factor (d^0_f) is 1.0. With the use of the LUTO model, the total network travel cost (initial estimate $f(Y^0, d^0_f)$) of 1808.00 thousand vehicle hours are obtained. The results of alternative road usage charging schemes are shown in Table 2.

If there is no change in toll charges at all the toll links and only the petrol tax can be varied, the proposed optimization method yields a total network travel cost of 1802.85 thousand vehicle hours. Figure 4 shows the effects of change of the petrol tax on the highway network performance in terms of total generalized cost and total travel time. It is found that the total network travel time is generally in the descent direction while the total generalized cost of travel is not convex in response to the change of petrol tax. In order words, if the objective is to minimize the total highway network travel time, the highest acceptable petrol tax should be chosen. Similarly, it would be optimum to raise tolls to a level where no one can afford to travel. Therefore, the optimization of network travel time is an inappropriate objective function.

In view of this, it is more appropriate to minimize the total network travel cost. With the use of the proposed the grid-point search method, the total network travel cost of 1782.97 thousand vehicle hours was attained with the following road usage charges:
Y^{**} = (6.0,23.18,24.96,16.46,6.00,8.40,8.41,3.07,3.00,6.00), and d^{**}_f = 1.96.

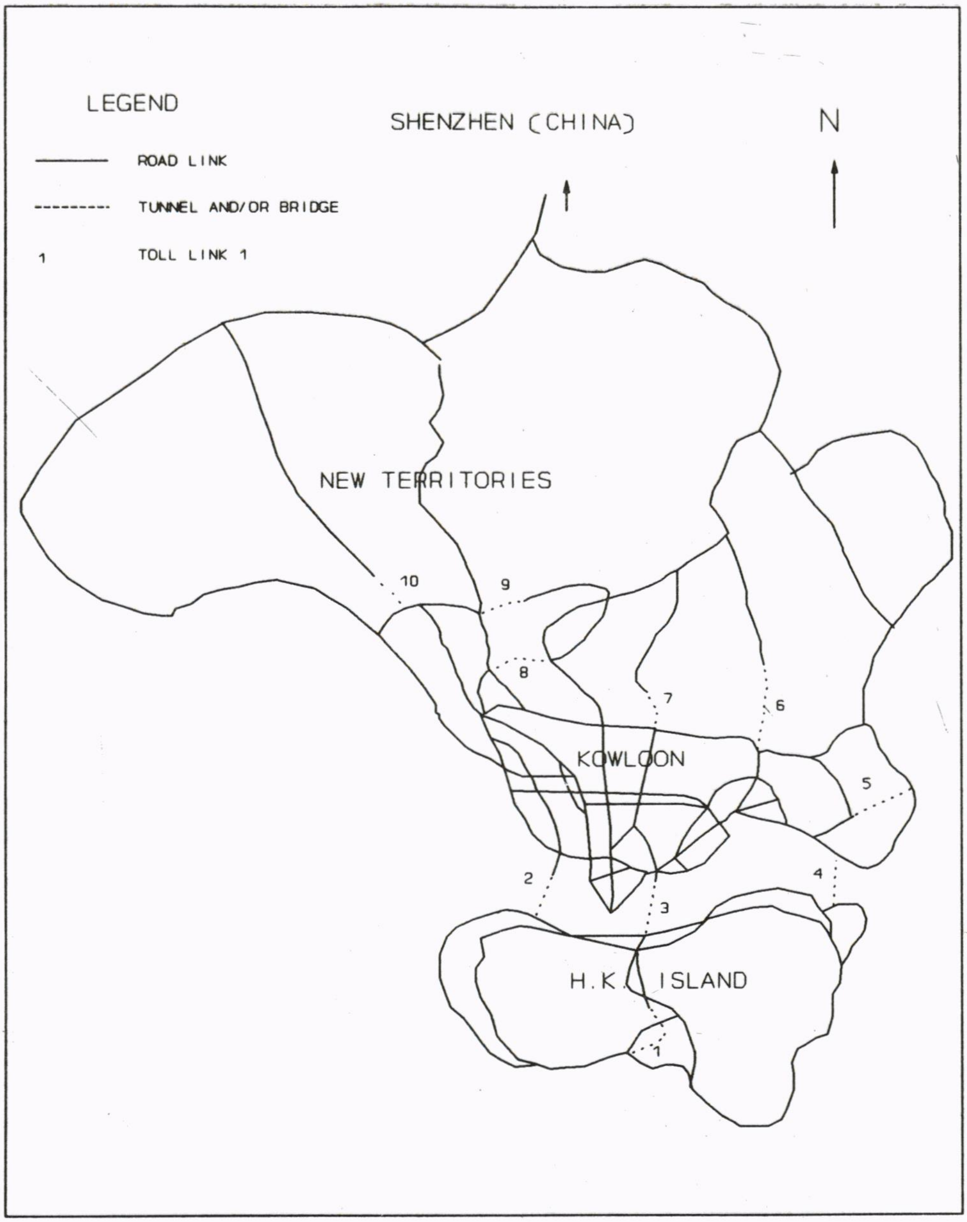

Figure 3 Locations of Toll Links of Hong Kong

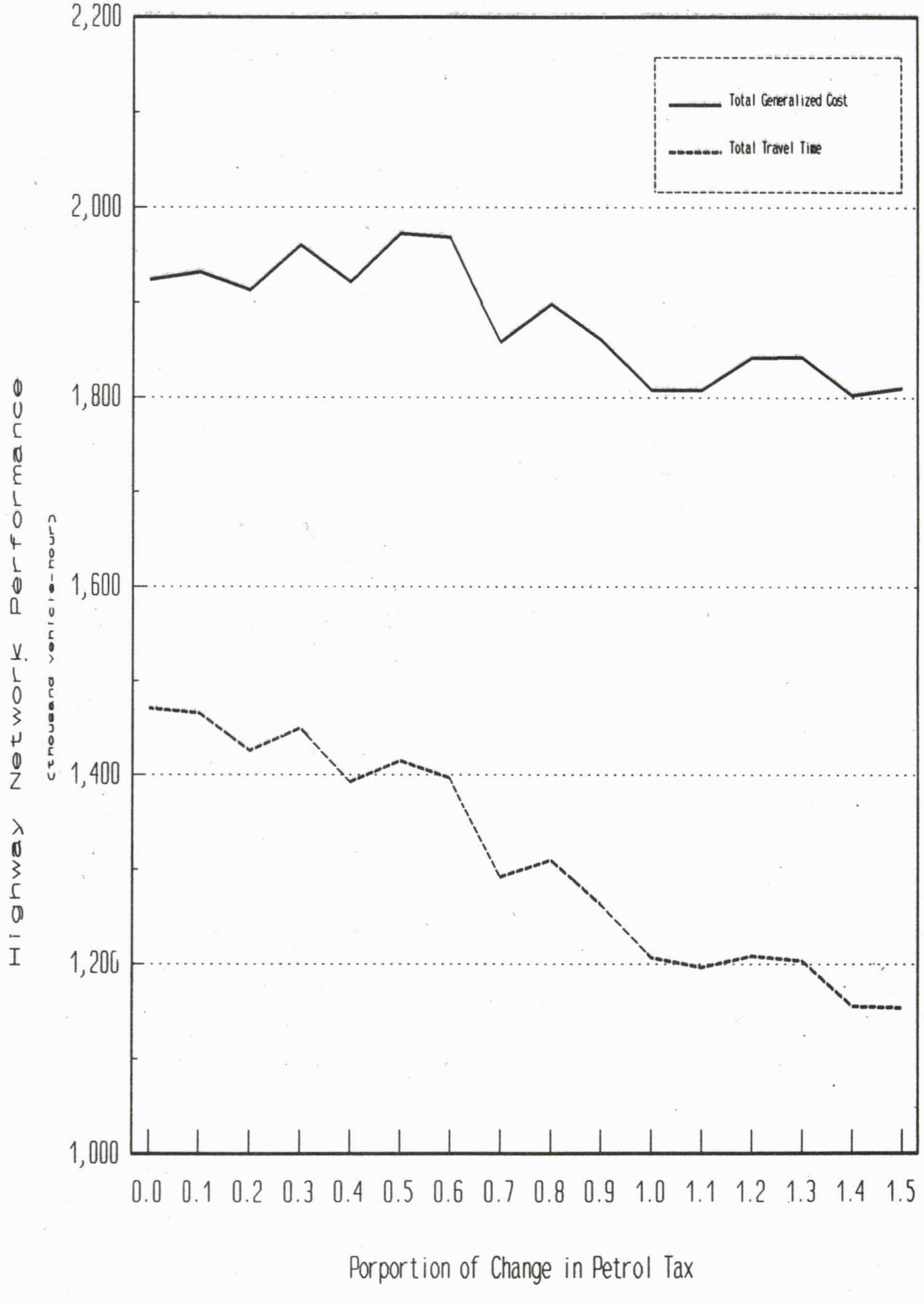

Figure 4 Effects of Change in Petrol Tax on Highway Network Performance

Table 2 Optimal Road Tolls and Petrol Tax

NAME OF ROAD TUNNEL	TUNNEL TOLL (HK$)			
	Reference Charges of **LUTO**	Optimal Charges of **Scheme 1**	Optimal Charges of **Scheme 2**	Optimal Charges of **Scheme 3**
	Private car	Private car	Private car	Private car
1. Aberdeen Tunnel	6.0	6.0	11.70	6.00
2. Western Harbour Tunnel	21.0	21.0	28.18	23.18
3. Cross Harbour Tunnel	14.0	14.0	25.52	24.96
4. Eastern Harbour Tunnel	9.0	9.0	17.55	16.46
5. Tseng Kwan O Tunnel	6.0	6.0	8.00	6.0
6. Tate's Cairn Tunnel	6.0	6.0	8.53	8.40
7. Lion Rock Tunnel	6.0	6.0	8.07	8.41
8. Route 16 Tunnel	6.0	6.0	9.28	3.07
9. Rock 5 Tunnel	6.0	6.0	11.42	3.00
10.Route 3 Tunnel	6.0	6.0	11.70	6.00
Proportion of Change in Petrol Tax	1.0	1.4	1.0	1.9
Total Network Travel Cost (in thousand Vehicle-hour)	1808.00	1802.85	1802.66	1782.97
Total Network Travel Time (in thousand Vehicle-hour)	1206.73	1155.54	1189.49	1070.92

Notes: **LUTO** - Land Use and Transport Optimization.
Scheme 1 - Change petrol tax only.
Scheme 2 - Change road tolls only.
Scheme 3 - Change both road tolls and petrol tax.

5. CONCLUSION

The facts illustrated by the case study are the important ones from the viewpoint of highway planning. The direct road usage charges such as toll pricing and petrol tax can improve the highway network performance. However, the imposition of an appropriate set of tunnel tolls and petrol tax can reduce the total network travel cost more effectively than just optimizing either tunnel tolls or petrol tax separately. It is necessary to consider the road usage charges simultaneously when planning highway network.

A heuristic optimization approach is proposed in this paper. The LUTO transport model and grid-point search algorithm are the basic tools for the optimization procedure. It merits attention that the trip matrices are not fixed and would be varied with changes in road usage charges. This makes the heuristic optimization approach promising for real problems.

On the other hand, the system objective should be carefully determined at different objectives would result from different road usage charges. These phenomena should be further illustrated for cases of (1) maximizing revenue, (2) minimizing total marginal cost of travel, and (3) minimizing total vehicular emissions. With the advance of the electronic road pricing technology, the zone pricing system will be feasible in practice and their effects on the network performance should be further studied.

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REFERENCES

Beckmann, M.J. (1965) On optimal tolls for highways, tunnels and bridges. in **Vehicular Traffic Science,** 331-341. American Elsevier, New York.

Cheung, B.K.S. and Ng, A.C.L. (1994) An Efficient and Reliable Algorithm for Nonsmooth Nonlinear Optimization. **Neural, Parallel & Scientific Computations** (To appear).

Choi, Y.L. (1986) Land use transport optimization (LUTO) model for strategic planning in Hong Kong. **Asian Geographer 5(2),** 155-176.

Dafermos, S. and Sparrow, F.T. (1971) Optimal resource allocation and toll patterns in user-optimized transport network. **Journal of Transport Economics and Policy 5(2),** 198-200.

Dawson, J.A.L. and Brown,F.N. (1985) Electronic road pricing in Hong Kong: A fair way to go ? **Traffic Engineering and Control 26(11),** 522-529.

Holland, E.P. and Atson, P.L. (1978). Traffic restraint in Singapore. **Traffic Engineering and Control 19(1),** 14-22.

Lam, W.H.K. (1988) Effects of road pricing on system performance. **Traffic Engineering and Control 29(12),** 631-635.

Leung, T.Y.C. and Lam, W.H.K. (1991) Transport Strategy for Hong Kong. **Proceedings National Transport Conference,** the Institution of Engineers Australia, Brisbane, Australia, 1-3 May 1991.

McCarthy, P. and Tay, R. (1992) Road pricing in Singapore: Too much of a good thing? **Selected Proceedings of the Sixth World Conference on Transport Research 3,** 2011-2033.

Starkie, D. (1988) The New Zealand road charging system. **Journal of Transport Economics and Policy 22(2),** 239-245.

Tretvik, T. (1992) The toll road alternative: Variations in choice behavior and values of time. **Selected Proceedings of the Sixth World Conference on Transport Research 3,** 2031-2042.