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ABSTRACT

The problem addressed in this research is to determine usage prices for a system with multiple modes of transportation with the objective of reducing congestion. With multiple modes, these prices can take on several forms. On road networks, the usage prices refer to the tolls collected from motorists for access to certain streets and highways. On a transit system, the usage prices are the fares the riders have to pay to travel on, for example, buses and subways. The basic concept in this proposal is to employ the market force to allocate limited road and transit capacities among travelers by their need to travel and their willingness to pay. The idea involves charging congested routes higher prices. When willing to pay higher prices, travelers can travel with reduced congestion during peak periods, using the modes, and along the routes of their choosing.

EXECUTIVE SUMMARY

This research project proposes an algorithm for solving the problem of determining a flow distribution that meets an objective in a multimodal transportation system and offers a methodology for setting tolls and providing subsidies to encourage users to utilize the transportation system in the most efficient manner.

The problem of determining a flow distribution that meets certain criteria (e.g., user equilibrium or system optimal) on a transportation network with multiple modes of transportation is extremely large in practice, particularly when there are many travel options. Currently available software, particularly commercial, is not capable of solving this problem on commonly available computers. In this research, we propose an algorithm using a column generation technique to solve this problem. Although it may not be as efficient as others on small and medium-sized problems, our column generation technique can solve larger problems.

We also show how to construct toll-pricing problems using the results from our algorithm. One pricing problem uses the revenue from tolling to completely subsidize the discounts on transit fares. Although they reduce congestion to its minimum level, tolls constructed in this manner make users worse off when compared to the situation without any tolling intervention. To make tolling more appealing to the public, we formulate and solve the problem of finding Pareto-improving tolls. Although not necessarily to the minimum level, this type of tolls reduces congestion while ensuring that no one is worse off.

CHAPTER 1: BACKGROUND

1 PROBLEM STATEMENT

In their Urban Mobility Report, Schrank and Lomax (2005) conclude that traffic congestion has increased too rapidly and in areas of all sizes. The total hours of delay due to congestion grew from 0.7B hours in 1982 to 3.7B hours in 2003 and the total amount of ‘wasted’ fuel grew from 0.4B to 2.3B gallons during the same period. When measured in 2003 dollars, the cost of congestion (delay and fuel costs) grew from $12.5B in 1982 to $63.1B in 2003. They report that congestion has become a problem too complex for only one technology or one service to be ‘the solution’ and its increasing trends indicate an immediate need for improvements. They also recommend a ‘balanced approach’ involving a multitude of technologies and methodologies such as travel demand management, transit improvements, information technology, and capacity expansion. The research reported herein addresses the first two.

Although transportation economists (see, e.g., Pigou, 1920, and Vickrey, 1952) have been advocating congestion pricing as a mechanism for controlling congestion and managing travel demand for quite some time, it is only recently that this idea has become practical. When compared to the alternative of building more roads, congestion pricing, in particular via electronic tolling, is now more attractive (see Arnott and Small, 1994) and has been adopted successfully in countries around the world. Singapore implemented its Area Licensing Scheme to restrict vehicular traffic into the city’s central area in 1975 and renamed it ‘Electronic Road Pricing’ in 1988 to reflect the use of new technology. In Norway, the first toll ring was operational in Bergen in 1986 and, subsequently, two additional toll rings were established in Oslo (1990) and Trondheim (1991). More recently, the city of London introduced in February 2003 a £5 daily fee on cars entering the city center. Today, the fee is £8 if paid on the day of travel and £10 if paid by midnight of the following day. In spite of public resistance to the concept of tolling, some cities in the United States have also adopted congestion pricing in recent years. This is due in part to the Congestion Pricing Pilot Program established by Congress in 1991 that authorized the Federal Highway Administration to enter into cooperative agreements with up to 15 state or local governments to establish, maintain, and monitor congestion pricing projects. In 1999, this program was given a broader scope and named the Value Pricing Pilot Program.

While these congestion-pricing projects do reduce congestion, Hecker (2003) testified to the Joint Economic Committee, United States Congress that they are not always able to demonstrate benefits for the full range of users. Those who are financially able to use tolled highway lanes may see a reduction in travel time. On the other hand, there is little system wide reduction in travel times in some cases and congestion may increase on alternative routes or outside tolled areas. In addition, congestion pricing in and of itself is often thought of as a factor that encourages ridesharing and use of public transportation. Although this is true for the Singapore’s Area Licensing Scheme, Evans et al. (2003) report that the shift to alternative modes in the United States is non-existent in some cases.

The literature on congestion pricing has been growing at a rapid pace due to the interest stimulated in part by the increasing traffic congestion in major metropolitan areas as well as the development of new technology. However, much of the literature in transportation science as well as our own work have been focusing on models with a single mode of transportation, some of which are well solved and others belong to difficult classes of optimization problems and are subjects of our on-going research.

2 RESEARCH OBJECTIVE

The objective of this research is to develop models and methods for determining congestion tolls for a system with multiple modes of transportation. Typically, congestion pricing or tolling is used to alleviate traffic congestion on roads and highways. However, when applied to transit systems, congestion pricing addresses the fare structures of buses, trains, and subways, in order to encourage their riderships and reduce congestion on the road network. Because of the synergism between the different modes of transportation, congestion pricing can lead to a greater reduction in travel delay when applied simultaneously to multiple modes. In particular, the models proposed herein are useful in performing the functions such as:

- Provide mechanisms to aid transportation planners in determining optimal pricing schemes for roads and highways and the fare structure of transit systems
- Provide the means to predict impacts of pricing on urban traffic flows and on transit system usage
- Provide the means to quantitatively compare congestion pricing schemes
- Assist planners in determining the efficiency of existing and proposed pricing schemes
- Provide information essential to the financial and political success of congestion pricing programs.

3 SCOPE OF STUDY

The scope of this study is limited to developing mathematical models and algorithms to solve them. The latter are implemented and tested using a modeling language such as GAMS (see Brooke et al., 1992) and network data from the literature.

CHAPTER 2: RESEARCH APPROACH

Our approach for congestion pricing in multi-modal transportation systems addresses the problem in a static setting and consists of the following components.

- Multi-modal network: Similar to others in the literature (for example, Boile et al., 1994, De Cea et al., 2005, Fernandez et al., 1994, and Garcia and Marin, 2005), our multi-modal network consists of several networks. Each one defines all possible routes between origins and destinations for one travel option, and is graphically independent of the others. On the other hand, the link flows from these networks are combined together when determining the link travel times so that travelers using different travel options experience the same delay on each link.

- Traffic Assignment Models: There are two key models useful in congestion pricing. One is called a user equilibrium model (or, more simply, user model) and useful for predicting how users travel to their destinations. This model assumes that users always choose the least cost path and, when equilibrium is reached, every user has no (cost) incentive to switch to a different route. In other words, every utilized path between every OD has the same cost at equilibrium. The other model is called a system optimal model or, more simply, system model. The solution from a system model yield a ideal flow distribution, i.e., one with the maximum total social benefit (see, e.g., Yang, 1999, and Maher et al., 2005), total expected utility (see, e.g., Small and Rosen, 1981, and Ying and Yang, 2005) or net partial use benefit (see, e.g., Hamdouch et al, 2007).

- Toll Pricing Problems: We consider two types of tolls, first and second best. First-best tolls are those that reduce congestion to its minimum level possible and assume that every link in the road network is tollable. When the latter is not true or there are additional tolling restrictions, it may not be possible to reduce congestion to its minimum level. In this case, such tolls are called "second-best" in the literature. In this research, we focus on one type of second-best called "Pareto-improving."
  - First-best tolls: The idea of reducing congestion to its minimum level possible has been advocated by many in the literature. The basic idea is to determine tolls that would cause travelers, who are encouraged only by their own travel costs, to choose routes or travel strategies that lead to a system optimal flow distribution. When there is only one mode, economists (for example, see Arnott and Small, 1994) generally set the toll on each link equal to its marginal cost. However, Hearn and Ramana (1998) demonstrate under some mild assumptions that first-best tolls must satisfy a linear system and tolls other than marginal costs exist. In fact, the number of first-best tolls is infinite and the same is also true in a multi-modal setting. We propose and solve several optimization models for selecting first-best tolls that optimize secondary objectives, such as minimizing the revenue for tolling in order to lessen the financial impact on the public and minimizing the number of facilities for toll collection.
  - Pareto-improving tolls: Although they reduce congestion to its minimum level, first-best tolls are extreme and often make some users worse-off when compared to the situation without any tolling intervention. The latter makes first-best tolling unappealing to the public. In fact, Hau (2005) points out the first-best tolls based on marginal costs are

"mostly likely doomed to be political failure." To make tolling more appealing, we propose the concept of Pareto-improving tolls in a separate project dealing with congestion pricing in a single-mode transportation system. In theory, Pareto-improving tolls ensure that no user is worse off while decreasing the level of congestion. In this research, we examine Pareto-improving tolls in a multi-modal setting.

CHAPTER 3: FINDINGS AND APPLICATIONS

The findings from this research include the following:

- We extended the user and system model in Hamdouch et al. (2007) to take into account the case with more than two mixed options and other system objectives. In particular, these models make the following assumptions:
  - The total demand for each origin-destination (OD) pair is fixed. However, travelers have the flexibility to choose one among a list of possible transportation options such as SOV, HOV, walk-metro, SOV-train, SOV-subway, walk-subway, etc., where SOV and HOV represent a solo driver in a private vehicle and a vehicle with a driver and one or more passengers, respectively. The remaining options are mixtures of two (and possibly more) modes and we refer to them as "mixed" options. For example, "walk-metro" represents travelers walk to metro stations, use metro lines to reach final destinations, and walk from there to their destinations. The remaining mixed options are similarly defined.
  - The travelers' choice of a transportation option follows a multinomial logit model and depends on the travel cost (generally consists of time and tolls) associated with each transportation option.
  - The travelers are homogenous, i.e., there is only one user class.
  - For each transit (or public transportation) systems such as bus, subway, and commuter trains, we assume that each transit line runs at a fixed frequency and with known capacity.
  - When traveling on a transit system, many combinations of transit lines (or paths in a network to transit lines) generally link origins to destinations. Instead of assuming that a traveler chooses a single path, we assume that travelers use travel strategies (for example, see Spiess and Florian, 1989) instead. In our setting, each strategy can be represented as a hyperpath or a subnetwork consisting of one or more simple paths from an origin to a destination.

  Under the above assumptions, the feasible region can be described as a system of linear equalities and inequalities.

- In practice, the user and system model are extremely large and require a large amount of computational resource to solve. To solve these problems more efficiently, we developed a column generation technique that consists of a master problem and, potentially, many subproblems. (See Lawphongpanich et al., 2010.) The master problem is the user or system problem formulated in terms of path flows and restricted to use paths generated in previous iterations or a priori. There is a subproblem for each travel option and OD pair. When the travel option corresponds to, e.g., using SOV or HOV, the subproblem reduces to the standard shortest path problem. For options involving a transit system, our technique finds a shortest hyperpath by solving a linear program similar to the one proposed in Spiess and Florian (1989).

- For small and medium networks, our experiments show that the above column generation technique does not offer any computational advantage over commercial optimization software. However, the column generation technique can solve large problems in a reasonable amount of time on our computer (2 GHz Dell Computer with 2,037 MB of RAM) while commercial software cannot due to insufficient memory. (See Lawphongpanich et al., 2010)
- We extended the two toll pricing models developed in our previous research (see, Hamdouch et al., 2007) to our user and system model.
- In addition, we also extended our Pareto-improving toll models to the multi-modal setting. The model belongs to a class of difficult optimization problems called mathematical programming with complementarity constraints. We used a technique we developed in a separate project called manifold suboptimization (see Lawphongpanich and Yin, 2010) to solve the problem. Our numerical results show that Pareto-improving tolls are more effective in a multi-modal setting than a single mode. Using the same parameter settings, Pareto-improving tolls in multi-modal setting reduce more congestion than those with a single mode of transportation. We surmise that this is due to the synergistic effects between modes. (See Wu et al., 2009.)
- The models and algorithms mentioned above can be applied to any multi-modal transportation network.

CHAPTER 4: CONCLUSIONS AND SUGGESTED RESEARCH

1. CONCLUSIONS

Below are main conclusions from our research:

- Pareto-improving tolls attempt to reduce congestion while ensuring that no one is worse off when compared to the situation without any tolling intervention. In our previous research, we show that Pareto-improving tolls are relatively prevalent even though they may not lead to a significant reduction in congestion. The results from this research show that Pareto-improving tolls are also prevalent and yield more reduction in a multi-modal setting when there are coordinations between setting toll prices and transit fares.
- A column generation technique is effective at solving the user and system problem in a large multi-modal setting. The technique is also amenable for implementation on a high-performance computing platform.

2. SUGGESTED RESEARCH

The following is a list of possible research topics

- Make the multi-modal user and system problem more realistic by allowing the following:
  - Multiple classes of users
  - Elastic travel demand
- In our research, we assume that users always choose a least-cost path. However, other assumptions are possible and they should be investigated.
  - Stochastic multi-modal user equilibrium model: This model allows different users to perceive travel time differently and, therefore, choose different paths to reach their destinations.
  - Boundedly rational user equilibrium: The assumption that users always choose a least-cost path may not be realistic because some may switch to a least-cost path only when the latter offers a significant amount of saving. Users behave in this manner are said to be "boundedly rational" and we refer to those who always choose the least route as "perfectly" or "unboundedly" rational.
- Extend the multi-modal user and system problem to allow loading priorities and incorporate explicitly the physical capacity of transit vehicles. In the literature, models that implicitly incorporate capacities in the objective function may load passengers onto a transit vehicle that far exceeds its physical capacity. Other models may unexpectedly remove continuing passengers abroad a transit line when it stops at a station and there is an insufficient capacity to accommodate the boarding passengers. Loading priorities in conjunction with explicit capacity constraints is one way of alleviating this problem. On the other hand, incorporating

loading priorities and capacity constraints require addressing the transit component in a schedule-based setting. (See Hamdouch and Lawphongpanich, 2008 and 2010.)

LIST OF REFERENCES

1. Arnott, R., Small, K., “The Economics of Traffic Congestion,” *American Scientist,* 82, 1994, 446 – 455.

2. Boile, M.P., Spasovic, L.N., Bladikas, A.K., “Modeling Intermodal Auto-Rail Commuter Networks,” Research Report, National Center for Transportation and Industrial Productivity, New Jersey Institute of Technology, 1994

3. Brook, A., Kendrick, D., Meeraus, A., *GAMS: A User’s Guide*, The Scientific Press, South San Francisco, CA, 1992

4. De Cea, J., Fernandez, J. E., Dekock, V., Soto, A., “Solving network equilibrium problems on multimodal urban transportation networks with multiple user classes,” *Transport Reviews*, 25(3), 2005, 293–317.

5. Evans, J.E., Bhatt, K.U., Turnbull, K.F., “Road Value Pricing (Chapter 14),” TCRP Report 95, Transit Cooperative Research Program, Transportation Research Board, Washington, D.C, 2003

6. Fernandez, E., De Cea, J., Florian, M., Cabrera, E., “Network Equilibrium Models with Combined Modes”, *Transportation Science*, 28, 1994, 182-192

7. Florian, M., Hearn, D.W., “Network Equilibrium Models and Algorithms,” Chapter 6 of *Handbooks in Operations Research and Management Science, Volume 8: Netwok Routing*, M.O. Ball, T.L. Magnanti, C.L. Monma, and G.L. Nemhauser (Eds.), North-Holland, New York, 1995

8. Garcia, R., Marin, A., “Network equilibrium with combined modes: models and solution algorithms,” *Transportation Research Part B*, 39(3), 2005, 223-254.

9. Hamdouch, Y., Florian, M., Hearn, D.W., Lawphongpanich, S., “Congestion Pricing for Multi-Modal Transportation Systems,” *Transportation Research Part B*, 41, 2007, 275 – 291.

10. Hamdouch, Y., Lawphongpanich, S., “Congestion Pricing for Schedule-Based Transit Networks,” *Transportation Science*, in print, 2010

11. Hamdouch, Y., Lawphongpanich, S., “Scheduled-based Transit Assignment Model with Travel Strategies and Capacity Constraints,” *Transportation Research Part B*, 42, 2008, 663 – 684

12. Hau, T.D., “Economic Fundamentals of Road Pricing: A Diagrammatic Analysis, Part I – Fundamentals,” *Transportmetrica*, Vol. 1, No. 2, 2005, 81 -117

13. Hearn, D. W., Ramana, M. V., "Solving Congestion Toll Pricing Models," in Equilibrium and Advanced Transportation Modeling, P. Marcotte and S. Nguyen (Eds.), Kluwer Academic Publishers, 1998, 109-124

14. Hearn, D. W., Yildirim, M.B., "A Toll Pricing Framework for Traffic Assignment Problems with Elastic Demand," *Current Trends in Transportation and Network Analysis: Miscellanea in Honor of Michael Florian*, Gendreau, M. and Marcotte, P. (Eds), Kluwer Academic Publishers, Dordrecht, The Netherlands, 2001

15. Hearn, D.W., Lawphongpanich, S., Ventura, J., "Finiteness in Restricted Simplicial Decomposition," *Operations Research Letters*, 4, 1985a, 125 – 130

16. Hearn, D.W., Lawphongpanich, S., Ventura, J., "Restricted Simplicial Decomposition: Computation and Extensions," *Mathematical Programming Study*, 31, 1985b, 99 – 118

17. Hecker, J.Z., "Reducing Congestion: Congestion Pricing Has Promise for Improving Use of Transportation Infrastructure," Testimony before the Joint Economic Committee, U.S. Congress, GAO-03-735T, United States General Accounting Office, 2003

18. Lawphongpanich, S., and Y. Yin, "Solving the Pareto-Improving Toll Problem via Manifold Suboptimization," *Transportation Research Part C*, 18, 2010, 234-246

19. Lawphongpanich, S., Y. Hamdouch, and Y. Yin, "Algorithms for Multi-Modal Traffic Assignment Problems with Applications to Toll Pricing," Technical Report, Dept. of Industrial and Systems Engineering, University of Florida, 2010.

20. Maher, M., Stewart, K., Rosa, A., "Stochastic social optimum traffic assignment.," *Transportation Research Part B*, 39(8), 2005, 753–767

21. Pigou, A.C., *The Economics of Welfare*, MacMillan, New York, NY, 1920.

22. Small, K. A., Rosen, H. S., "Applied welfare economics with discrete choice models. Econometrica," 49(1), 1981, 105–130

23. Spiess, H. and M. Florian, "Optimal Strategies: A New Assignment Model for Transit Networks," *Transportation Research B*, 23, 1989, 83-109

24. Vickrey, W. S., "The Revision of Rapid Transit Fare Structure of the City of New York," Finance Project, Mayor's Committee on Management Survey of the City of New York, Technical Monograph No. 3, New York, 1952

25. Wu, D., Y. Yin, and S. Lawphongpanich, "Pareto-Improving Congestion Pricing on Multi-Modal Transportation Networks," under review for publication, 2009.

26. Yang, H., "System Optimum, Stochastic User Equilibrium, and Optimal Link Tolls" *Transportation Science*, 33 (4), 1999, 354 – 360.

27. Ying, J., Yang, H., “Sensitivity analysis of stochastic user equilibrium flows in a bi-modal network with application to optimal pricing.,” *Transportation Research Part B*, 39(9), 2005, 769–795.