Designing Cross-Subsidy Mechanisms for Multi-Modal Transportation Systems

Center for Transportation, Environment, and Community Health
Final Report

by

Ruoyun Chen and Linda Nozick

May 31, 2018

DISCLAIMER

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2.Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Designing Cross-Subsidy Mechanisms for Multi-Modal Transportation Systems		5. Report Date May 31,2018 6. Performing Organization Code
7. Author(s) Linda Nozick (ORCID ID 0000-0002-5629-3733) Ruoyun Chen (ORCID ID 0000-0002-0706-8222)		8. Performing Organization Report No.
9. Performing Organization Name and Address Civil and Environmental Engineering Cornell University Ithaca, NY 14850		10. Work Unit No. 11. Contract or Grant No. 69A3551747119
12. Sponsoring Agency Name and Address U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final Report 11/31/2016 – 05/31/2018 14. Sponsoring Agency Code US-DOT
15. Supplementary Notes		

16. Abstract

Despite large investments in passenger transportation infrastructure, congestion has increased at an alarming pace and at substantial societal costs. Congestion was estimated to cost $124 billion in 2013 and to rise to about $186 billion by 2030. Empirical evidence demonstrates that public transit is effective in alleviating congestion as well as the environmental impacts that result from congestion. What's more, public transportation is the mode that provides access to jobs, goods and services that are critical to economic mobility for those on the lower rungs of the economic ladder. Hence, this project focused on the development of modeling tools to support the design of cross-subsidy mechanisms in multi-modal passenger transportation networks by integrating road congestion pricing and multi-modal transportation services design.

17. Key Words	18. Distribution Statement		
Tolls, Optimization, Network Design	Public Access		
19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

Designing Cross-Subsidy Mechanisms for Multi-Modal Transportation Systems

Ruoyun Chen and Linda Nozick

Introduction

Traffic congestion has experienced significant growth and poses a substantial threat to the sustainability of many urban environments. Congestion pricing, as a mechanism to alleviate congestion, has extensively studied in the context of traffic management while remaining unpopular in practice among public. Opponents argue that equity issue could arise by implementing congestion pricing since people value time and monetary cost differently. More specifically, wealthier people tend to opt to utilize the toll routes during rush hour, while lower income individuals opt out under congestion pricing schemes. Therefore, congestion pricing diverts the traffic generated by the lower income groups and limits their transportation options disproportionately. As a more affordable alternative to driving, public transportation has a great potential to address the equality of mobility issue. Researches show that poor public transit, which indicates low geographic mobility, is associated with higher rate of unemployment thus less opportunity to move upward economically (Kaufman et al., 2014; Chetty and Hendren, 2015). Empirical evidences also suggest that public transportation is effective to reduce traffic congestion (Texas Transportation Institute, 2012). Thus, to reduce traffic congestion while stemming the inequity associated with the pricing scheme, we propose to improve public transportation simultaneously with the implementation of congestion pricing. This research focuses on developing optimization model for simultaneous design of optimal toll scheme and the optimal investment allocation to public transit making use of those funds under user heterogeneity. We further examine the performance of the proposed mechanism on offsetting equity challenges derived from user heterogeneity, where the heterogeneity specifically refers to the level of income segregation, as well as the level of geographic household segregation by income.

Literature Review

Congestion pricing has been widely studied. On the topic of the congestion pricing revenue allocation, researchers suggested that the revenue should be returned to the travelers via tax reduction to benefit low-income drivers and non-drivers (Litman, 1996; Adler and Cetin, 2001; Arnott and Small, 1994; Bernstein, 1993; DeCorla-Souza, 1995; Eliasson, 2001; Goodwin, 1989; Kalmanje and Kockelman, 2004; Poole, 1992). More recently, researchers developed models focusing on the cross-subsidization between road network and public transit (Yang et al., 2004; Nie and Liu, 2010; and Liu et al., 2009), where the cross-subsidization is realized by transit fare reduction by using the congestion pricing revenue. However, elasticity research shows that travelers are approximately twice as sensitive to travel time reduction as they are to fare reduction (Cervero, 1990; Dygert et al., 1977; Kemp, 1973; Kraft and Domencich, 1972; Mayworm et al., 1980). Empirical evidence also shows that increase in automobile costs is effective in improving transit penetration whereas decrease in transit fares is not as effective at attracting automobile travelers (Gaudry, 1975; McLynn and Goodman, 1973; Wang & Skinner, 1984). Motivated by the above, we propose to improve public transit by lowering transit travel time across transit network with the investment raised by pricing the road network. We specifically consider the income segregation and geographic segregation of travelers with different income levels. It could be inferred that the pattern and level of geographic segregation could significantly impact the resultant investment allocation to transit that serves different areas. Thus, the proposed scheme allows transit investment allocation to vary across transit lines. With regard to the toll optimization, over the past few decades, optimal toll design under user heterogeneity has been investigated by various researchers (Small, 1982; Cohen, 1987; Arnott et al., 1992, 1994; Lindsey, 2004; Small et al., 2005; van den Berg and Verhoef, 2011b; Liu and Nie, 2011; Hall, 2013). The simultaneous optimization of investment allocation over transit network along with toll price design on road network gives rise to a more complex network design problem and requires a more complex solution procedure as a result. The network design problem (NDP) with discrete decision variables is a combinatorial optimization problem that is NP-hard. Common approaches are based on various assumptions to simplify the problems (Dantzig et al., 1979; Steenbrink, 1974; Boyce et al., 1973; Holmberg and Hellstrand, 1998; Poorzahedy and Turnquist, 1982; Poorzahedy and Turnquist, 1982; Kim, 1990;

Yang and Yagar, 1994; Wong and Yang, 1997; Chiou, 1999; Gao and Song, 2002; Gao et al., 2004). Heuristic methods have also been adopted to identify near-optimal solutions, such as simulated annealing, genetic algorithm, tabu search and ant system (Cantarella et al., 2002; Friesz et al., 1992; Lee and Yang, 1994; Poorzahedy and Abulghasemi, 2005; Yin, 2000). In this research, we retain the combinatorial nature of NDP and adopt a branch and bound procedure to address with the integrality constraint on some decision variables.

Model

The formulation developed in this research is a nested Stackelberg game expressed as a bi-level optimization model. The upper level model identifies the optimal feasible set of toll prices and optimal investment allocation across the transit system, and the lower level computes the mode split and link assignment by origin-destination pair responding to the upper level decisions. In the lower level, the distribution of automobile traffic across a road network is governed by the principle that each individual driver selects the path that minimizes their travel disutility (Wardrop, 1952). And the automotive share between taking transit and driving is estimated by the logit model. The travel disutility for an individual is measured in units of time by converting the travel cost to time via the corresponding value of time (VOT) for each income class of individuals. The transit travel time is composed by the in-vehicle travel time, which is supposed to be constant, and the waiting time, which is determined by the transit headway. As we propose to improve the transit system by decreasing travel time, in this model, the investment allocated to a certain transit line is converted to the headway reduction on that transit line, where the investment is derived from the collected toll revenue. The objective of upper level model is the maximization of social welfare measured by the total travel time of all travelers. To minimize this total, the upper level model optimizes over the toll prices on certain arcs and the amount of those funds used to subsidize each transit route.

Illustrative Case Study

An illustrative case study is developed based on the highway network structure for the cordon-based Electronic Road Pricing (ERP) system in downtown Singapore (Liu, 2011). The highway network consists of 33 nodes and 104 links, where each node represents an origin/destination of travelers. We assume a stylized population made up of three classes defined by three distinct values for VOT, estimated by the hourly income and referred to as Lower class, Middle class, and Upper class. Each class is assumed to have a population of 21,600, and the three classes of users are distributed among 9 origin-destination pairs. A transit network is developed assuming that all origin-destination trips can be made using transit. To examine the performance of proposed scheme on user heterogeneity, we consider three VOT distributions with different levels of variation but same average value, which is VOT1 (low variation), VOT2 (high variation), and VOT3 (no variation). We also consider three levels of geographic segregation as “Uniform” (no segregation), “Mixed” (medium segregation), and “Split” (completed segregation). We experience with all the possible scenarios combining different levels of income segregation and different levels of geographic segregation. The computational time of the proposed algorithm require running the user-equilibrium models 11,340 times averagely, and 90% of the progress made in reducing the objective function value was accomplished with about 48% of those models being solved. The results suggest that the total travel disutility of all travelers experience an average decrease by 25% after implementing the optimal toll and transit improvement suggested by the proposed cross-subsidy scheme throughout all the scenarios. As for the user heterogeneity concerns, we observe that lower income individuals benefit more from the mechanism when there is larger income inequality, while there is the possibility that some the middle and upper income travelers experience increases in generalized travel disutility. And when the sorting of residential distribution is more uneven, it is easier to subsidize lower income individuals by tolling the road network and investing in their local transit line. We illustrate the inequality in the benefit distribution of the proposed cross-subsidy mechanism with Lorenz curves (Lorenz, 1905) in Figures 1 and 2. In the figure, top x percentage of household is plotted on the x-axis, and the y-axis gives the percentage of the total generalized travel disutility reduction. Since we have observed that the lower income class benefit more from the proposed mechanism, the Lorenz curves in Figure 1 and 2 rank the population from higher income to lower income on the x-axis, which is the reverse of the common use of the Lorenz curve to evaluate income inequality. Figure 1 and Figure

2 also give the Gini coefficient (Gini, 1912), which is the ratio of the darker grey area between the Lorenz curve and the diagonal (the line of perfect equality) and the triangular area which is all the area beneath the line of perfect equity. The inequality of benefit distribution quantified by Figure 1 and Figure 2 can be interpreted as how much more the lower income users benefit than the higher income users. The grey areas along with the corresponding Gini coefficients confirm that for a certain level of geographic segregation, the benefit distribution inequality is higher when there is higher income inequality. And given a certain level of income variation, the inequality in the benefit distribution is higher when there is more geographic segregation.

Conclusion

This research develops a bi-level optimization model comprised of interacting Stackelberg games to simultaneous optimize optimal toll prices on the charged links over road network and the investment allocations to the different routes in a transit network given multi-class travelers. A new solution procedure based on a hybrid algorithm to solve the problem has been developed. We specifically examine the performance of proposed mechanism on the heterogeneous travelers, where the heterogeneous is evaluated from two aspects, income variation and geographic segregation, respectively. The model and the solution procedure have been applied to an illustrative example, and the results demonstrate the potential for this framework to identify tolling and associated transit improvements that can offset the equity challenge of congestion pricing related to economically disadvantage individuals (generally with all individuals better off than prior). It also shows that higher levels of geographic segregation based on income class makes it easier to target specific populations to raise revenue and as well as specific populations to receive the benefits that stem from the collection of those revenues. Further, with higher income inequity, higher income individuals are harder to shift from highway, thus they are easier to be targeted for tolls, and the lower income group can be subsidized more. There are opportunities for future research in three areas. First, as ride-hailing service has attracted close to 5 million members globally and is projected to rise to above 250 million users in five years (Institute of Transportation Studies at University of California, Davis, 2017), we are now working on extend the model to include ride-hailing mode, to examine the potential effect resulted from the rapidly growing deployment of ride-hailing service. Second, this research has only considered modifying the headway on existing routes. It may be that important benefits can be achieved by modifying the transit routes themselves. Finally, the static and deterministic representation of peak period commuting we have adopted could be extended to address dynamic and stochastic travel demands.

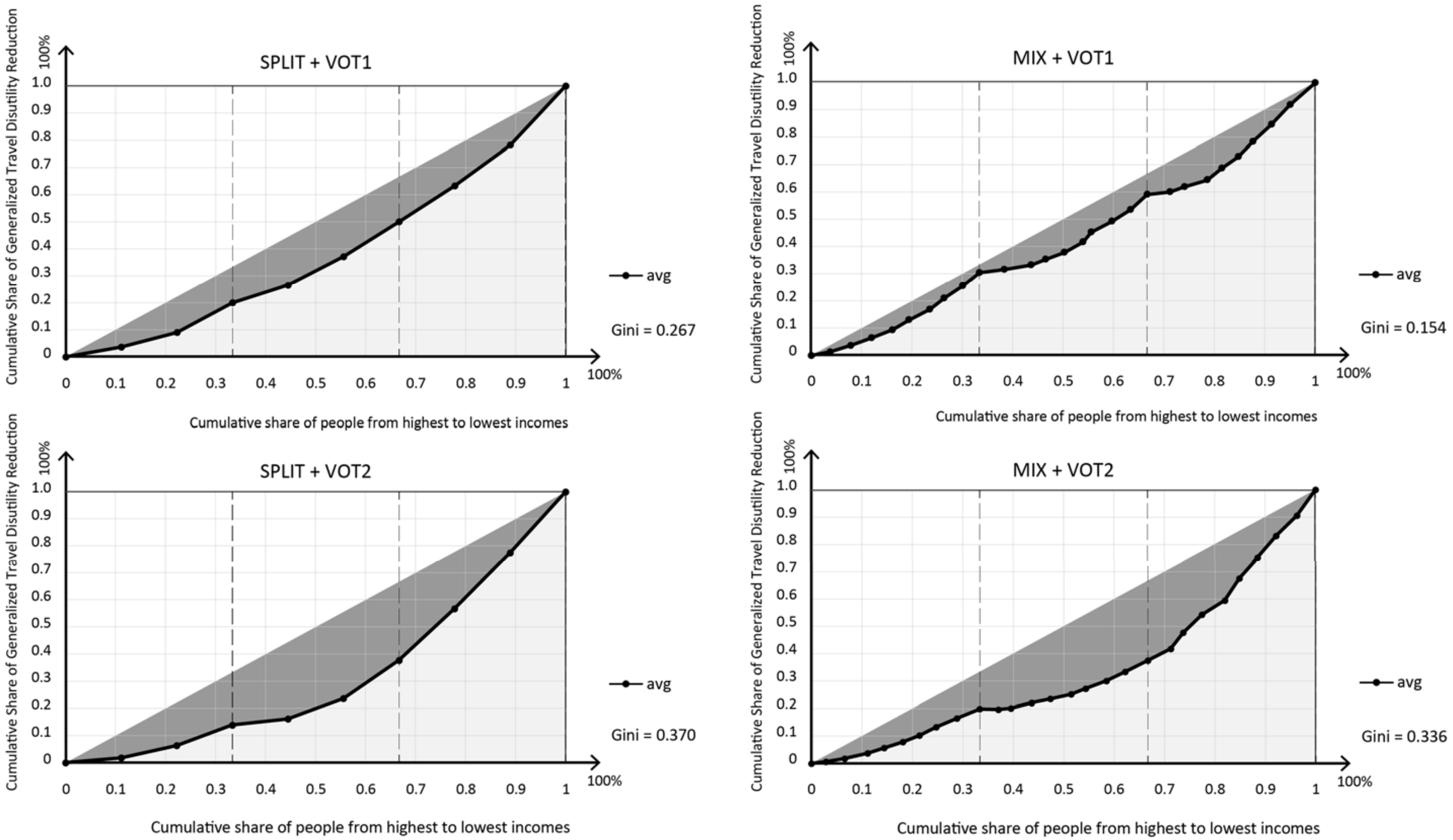

Figure 1. Inequality curve on benefit redistribution for Split and Mix cases given VOT1 & 2

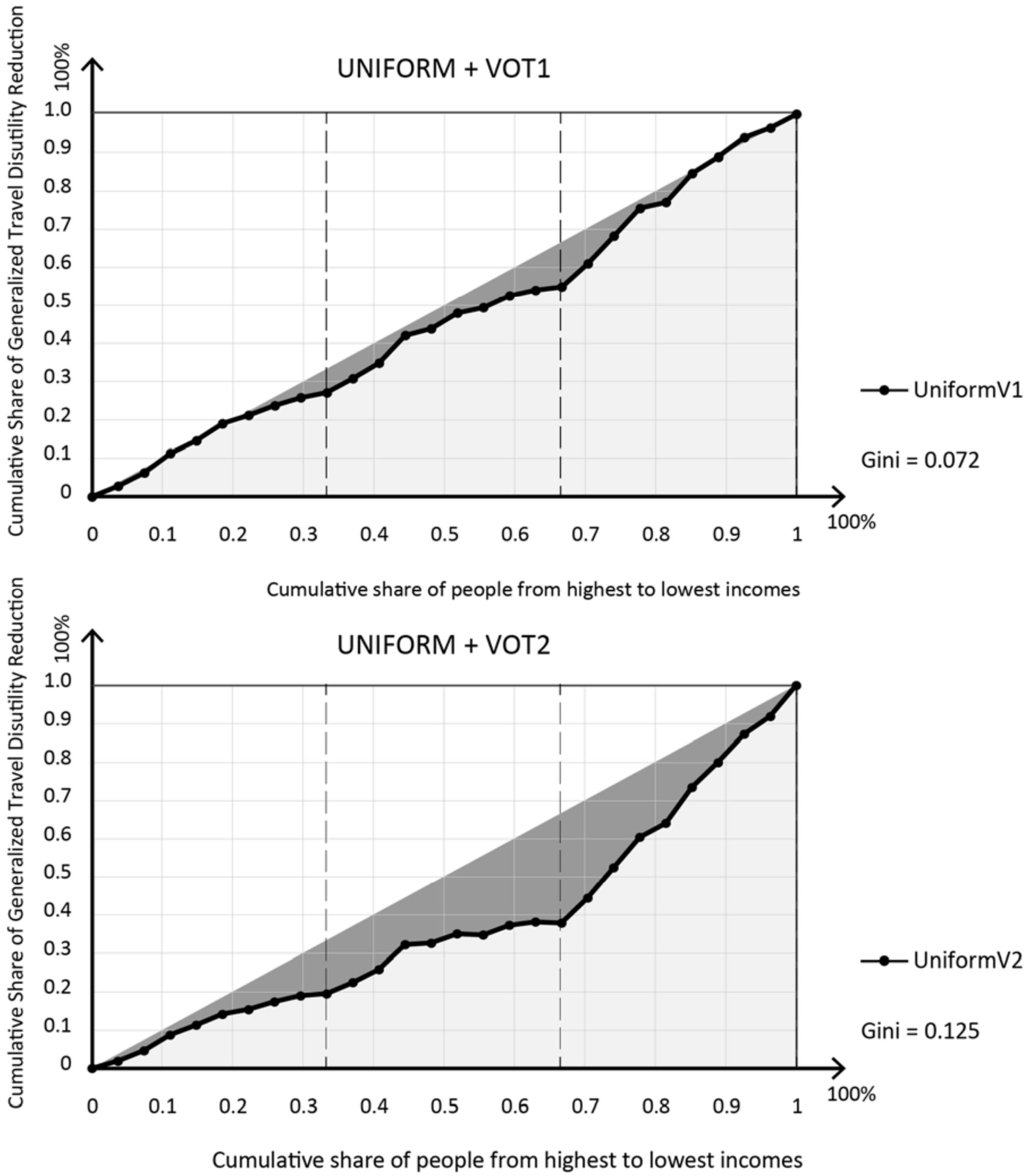

Figure 2. Inequality curve on benefit redistribution for Uniform cases given VOT1 & 2

Reference

Arnott, R., and Small, K. (1994). “The Economics of Traffic Congestion.” *American Scientist*, 82:446-455.

Arnott, R., de Palma, A., Lindsey, R., (1992). Route choice with heterogeneous drivers and group-specific congestion costs. Regional Science and Urban Economics 22 (1), 71–102.

Arnott, R., de Palma, A., Lindsey, R., 1994. The welfare effects of congestion tolls with heterogeneous commuters. Journal of Transport Economics and Policy 28 (2), 139–161.

Bernstein, D. (1993). Congestion pricing with tolls and subsidies. *In: Proceedings of the Pacific Rim Transportation Technology Conference*, *2*, 145–151.

Boyce, D. E., Farhi, A., & Weischedel, R. (1973). Optimal network problem: a branch-and-bound algorithm. *Environment and Planning A*, *5*(4), 519-533.

Cantarella, G. E., Pavone, G., & Vitetta, A. (2002). Heuristics for the network design problem. In *13th Mini Euro Conference, Bari, Italy* (pp. 408-413).

Cervero, R. (1990). Transit pricing research: a review and synthesis. *Transportation*, 17, pp. 117-139.

Chetty, R. and N. Hendren (2015). The impacts of neighborhoods on intergenerational mobility: childhood exposure effects and county-level estimates. *Mimeo*, Harvard University.

Chiou, S.W., (1999). Optimization of area traffic control for equilibrium network flows. Transportation Science 33, 279–289.

Clewlow, R. R., & Mishra, G. S. (2017). *Disruptive transportation: the adoption, utilization, and impacts of ride-hailing in the United States* (Vol. 7). Research Report–UCD-ITS-RR-17.

Cohen, Y., 1987. Commuter welfare under peak-period congestion tolls: who gains and who loses? International Journal of Transport Economics = Rivista Internazionale de Economia dei Trasporti 14 (3), 238–266.

Dantzig, G. B., Harvey, R. P., Lansdowne, Z. F., Robinson, D. W., & Maier, S. F. (1979). Formulating and solving the network design problem by decomposition. *Transportation Research Part B: Methodological*, *13*(1), 5-17.

DeCorla-Souza, P. (1994). Applying the cashing out approach to congestion pricing. *Transportation Research Record*, 34-34.

Dygert, P., Holcc, J. and Hill, D. (1977). Public Transportation Fare Policy. Washington, D.C.: U.S. Department of Transportation

Eliasson, J. (2001). “Road pricing with limited information and heterogeneous users: A successful case.” *Annals of Regional Science, 35*, 595–604.

Friesz, T. L., Cho, H. J., Mehta, N. J., Tobin, R. L., & Anandalingam, G. (1992). A simulated annealing approach to the network design problem with variational inequality constraints. *Transportation Science*, *26*(1), 18-26.

Gao, Z., Sun, H., Shan, L., (2004). A continuous equilibrium network design model and algorithm for transit systems. Transportation Research 38B, 235–250.

Gao, Z.Y., Song, Y.F., (2002). A reserve capacity model of optimal signal control with user-equilibrium route choice. Transportation Research 36B, 313–323.

Gaudry M. (1975). “An aggregate time-series model of urban transit demand: The Montreal case.” *Transportation Research* 9:249—258

Gini, C. (1912). Variabilità e mutabilità. *Reprinted in Memorie di metodologica statistica (Ed. Pizetti E, Salvemini, T). Rome: Libreria Eredi Virgilio Veschi*.

Goodwin, P. (1989). "The rule of three: A possible solution to the political problem of competing objectives for road pricing." *Traffic Engineering and Control, 30*, 495–497.

Hall, J.D., 2013. Pareto improvements from lexus lanes: the case for pricing a portion of the lanes on congested highways. In: Kuhmo NECTAR Conference.

Holmberg, K., & Hellstrand, J. (1998). Solving the uncapacitated network design problem by a Lagrangean heuristic and branch-and-bound.*Operations Research*, *46*(2), 247-259.

Kalmanje, S., and Kockelman, K. (2004). Credit-based congestion pricing: Travel, land value and welfare impacts. *Transportation Research Record, 1864*, 45–53.

Kaufman, S., Moss, M., Tyndall, J., and Hernandez, J. (2014). Mobility, Economic Opportunity and New York City Neighborhoods, NYU Wagner Rudin Center for transportation policy & management.

Kemp, M. A. (1973). Some evidence of transit demand elasticities. *Transportation* 2:27—38

Kim, T.J., (1990). Advanced Transport and Spatial Systems Models: Applications to Korea. Springer-Verlag, New York, USA.

Kraft, G. and Domencich, T. (1972). Free Transit. *Readings in urban economics*. New York: Macmillan.

Lee, C. K., & Yang, K. I. (1994). Network Design of One-Way Streets with Simulated Annealing. *Papers in Regional Science*,*73*(2), 119-134.

Lindsey, R., (2004). Existence, uniqueness, and trip cost function properties of user equilibrium in the bottleneck model with multiple user classes. Transportation Science 38 (3), 293–314.

Litman, T. (1996). "Using road pricing revenue: Economic efficiency and equity considerations." *Transportation Research Record* 1558, 24–28, 1996.

Liu, Y., Nie, Y., (2011). Morning commute problem considering route choice, user heterogeneity and alternative system optima. Transportation Research Part B 45 (4), 619–642.

Liu, Z. (2011). Probit-based stochastic user equilibrium problems and their applications in congestion pricing. Dissertation for doctor of philosophy in the department of civil and environmental engineering national university of Singapore.

Mayworm, P, Lago A. and McEnroe, J. (1980). "Patronage Impacts of Changes in Transit Fares and Services." Washington, D.C.: Urban Mass Transportation Administration

McLynn, J. M. and Goodman, K. M. (1973). "Mode Choice and the Shirley Highway Experiment." Washington, D.C.: Urban Mass Transportation Administration

Poole, R. (1992). Introducing congestion pricing on a new toll road. *Transportation, 19*, 383–396.

Poorzahedy, H., & Abulghasemi, F. (2005). Application of ant system to network design problem. *Transportation*, *32*(3), 251-273.

Poorzahedy, H., & Turnquist, M. A. (1982). Approximate algorithms for the discrete network design problem. *Transportation Research Part B: Methodological*, *16*(1), 45-55.

Small, K., (1982). The scheduling of consumer activities: work trips. The American Economic Review 72 (3), 467–479.

Small, K., Winston, C., Yan, J., (2005). Uncovering the distribution of motorists' preferences for travel time and reliability. Econometrica 73 (4), 1367–1382. van den Berg, V.A., 2014. Coarse tolling with heterogeneous preferences. Transportation Research Part B 64, 1–23.

Steenbrink, P. A. (1974). Transport network optimization in the Dutch integral transportation study. *Transportation Research*, *8*(1), 11-27.

Texas A&M Transportation Institute (TTI). (2012). "TTI's 2012 URBAN MOBILITY REPORT." accessed electronically at http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/mobility-report-2012.pdf/ on July 1st, 2015

van den Berg, V.A., Verhoef, E.T., (2011). Winning or losing from dynamic bottleneck congestion pricing? The distributional effects of road pricing with heterogeneity in values of time and schedule delay. Journal of Public Economics 95 (7–8), 983–992.

Wang, G. H. and Skinner, D. (1984). "The impact of fare and gasoline price changes on monthly transit ridership: Empirical evidence from seven U.S. transit authorities." *Transportation Research* 18B: 29 – 41

Wardrop, J. G. (1952). Road Paper. Some Theoretical Aspects of Road Traffic Research. *Proceedings of the institution of civil engineers*, *1*(3), 325-362.

Wong, S.C., and Yang, H., (1997). Reserve capacity of a signal-controlled road network. Transportation Research 31B, 397–402.

Yang, H., Yagar, S. (1994). Traffic assignment and traffic control in general freeway-arterial corridor systems. Transportation Research 28B, 463–486.

Yin, Y. (2000). Genetic-algorithms-based approach for bilevel programming models. *Journal of Transportation Engineering*, *126*(2), 115-120.