University Transportation Research Center - Region 2

Final Report

Evaluating the Role of Private Investment in Infrastructure Assets

Performing Organization: Cornell University

October 2015

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

Technology Transfer

UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

Project No(s):
UTRC/RF Grant No: 49198-19-26

Project Date: October 2015

Project Title: Evaluating the Role of Private Investment in Infrastructure Assets

Project's Website:
http://www.utrc2.org/research/projects/Management-of-New-York-State-Infrastructure-Assets

Principal Investigator(s):

Dr. H. Oliver Gao
School of Civil and Environmental Engineering
Cornell University
Ithaca, NY 14853
Tel: (607) 254-8334
Fax: (607) 255-9004
Email: hg55@cornell.edu

Co-author(s):
Omid M. Rouhani
Post Doctoral Research Associate
School of Civil and Environmental Engineering
Cornell University
Hollister Hall, Room #462
Ithaca, NY 14853

Richard Geddes
School of Civil and Environmental Engineering
Cornell University
Ithaca, NY 14853
Email: rrg24@cornell.edu

Performing Organization:
Cornell University

Sponsor(s):
University Transportation Research Center (UTRC)

To request a hard copy of our final reports, please send us an email at utrc@utrc2.org

Mailing Address:

University Transportation Reserch Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: 212-650-8051
Fax: 212-650-8374
Web: www.utrc2.org

Board of Directors

The UTRC Board of Directors consists of one or two members from each Consortium school (each school receives two votes regardless of the number of representatives on the board). The Center Director is an ex-officio member of the Board and The Center management team serves as staff to the Board.

City University of New York
Dr. Hongmian Gong - Geography/Hunter College
Dr. Neville A. Parker - Civil Engineering/CCNY

Clarkson University
Dr. Kerop D. Janoyan - Civil Engineering

Columbia University
Dr. Raimondo Betti - Civil Engineering
Dr. Elliott Sclar - Urban and Regional Planning

Cornell University
Dr. Huaizhu (Oliver) Gao - Civil Engineering

Hofstra University
Dr. Jean-Paul Rodrigue - Global Studies and Geography

Manhattan College
Dr. Anirban De - Civil & Environmental Engineering
Dr. Matthew Volovski - Civil & Environmental Engineering

New Jersey Institute of Technology
Dr. Steven I-Jy Chien - Civil Engineering
Dr. Joyoung Lee - Civil & Environmental Engineering

New York University
Dr. Mitchell L. Moss - Urban Policy and Planning
Dr. Rae Zimmerman - Planning and Public Administration

Polytechnic Institute of NYU
Dr. Kaan Ozbay - Civil Engineering
Dr. John C. Falcocchio - Civil Engineering
Dr. Elena Prassas - Civil Engineering

Rensselaer Polytechnic Institute
Dr. José Holguín-Veras - Civil Engineering
Dr. William "Al" Wallace - Systems Engineering

Rochester Institute of Technology
Dr. James Winebrake - Science, Technology and Society/Public Policy
Dr. J. Scott Hawker - Software Engineering

Rowan University
Dr. Yusuf Mehta - Civil Engineering
Dr. Beena Sukumaran - Civil Engineering

State University of New York
Michael M. Fancher - Nanoscience
Dr. Catherine T. Lawson - City & Regional Planning
Dr. Adel W. Sadek - Transportation Systems Engineering
Dr. Shmuel Yahalom - Economics

Stevens Institute of Technology
Dr. Sophia Hassiotis - Civil Engineering
Dr. Thomas H. Wakeman III - Civil Engineering

Syracuse University
Dr. Riyad S. Aboutaha - Civil Engineering
Dr. O. Sam Salem - Construction Engineering and Management

The College of New Jersey
Dr. Thomas M. Brennan Jr - Civil Engineering

University of Puerto Rico - Mayagüez
Dr. Ismael Pagán-Trinidad - Civil Engineering
Dr. Didier M. Valdés-Díaz - Civil Engineering

UTRC Consortium Universities

The following universities/colleges are members of the UTRC consortium.

City University of New York (CUNY)
Clarkson University (Clarkson)
Columbia University (Columbia)
Cornell University (Cornell)
Hofstra University (Hofstra)
Manhattan College (MC)
New Jersey Institute of Technology (NJIT)
New York Institute of Technology (NYIT)
New York University (NYU)
Rensselaer Polytechnic Institute (RPI)
Rochester Institute of Technology (RIT)
Rowan University (Rowan)
State University of New York (SUNY)
Stevens Institute of Technology (Stevens)
Syracuse University (SU)
The College of New Jersey (TCNJ)
University of Puerto Rico - Mayagüez (UPRM)

UTRC Key Staff

Dr. Camille Kamga: *Director, Assistant Professor of Civil Engineering*

Dr. Robert E. Paaswell: *Director Emeritus of UTRC and Distin*guished Professor of Civil Engineering, The City College of New York

Herbert Levinson: *UTRC Icon Mentor, Transportation Consultant and Professor Emeritus of Transportation*

Dr. Ellen Thorson: *Senior Research Fellow, University Transportation Research Center*

Penny Eickemeyer: *Associate Director for Research, UTRC*

Dr. Alison Conway: *Associate Director for Education*

Nadia Aslam: *Assistant Director for Technology Transfer*

Nathalie Martinez: *Research Associate/Budget Analyst*

Tierra Fisher*: Office Assistant*

Bahman Moghimi*: Research Assistant;*
Ph.D. Student, Transportation Program

Wei Hao*: Research Fellow*

Andriy Blagay: *Graphic Intern*

Membership as of January 2016

Disclaimer

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.

2.Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Evaluating the Role of Private Investment in Infrastructure Assets

5. Report Date
October 2015

6. Performing Organization Code

7. Author(s)
Omid M. Rouhani, H. Oliver Gao, R. Richard Geddes

8. Performing Organization Report No.

9. Performing Organization Name and Address
School of Civil and Environmental Engineering
Cornell University
Ithaca, NY 14853

10. Work Unit No.

11. Contract or Grant No.
49198-19-26

12. Sponsoring Agency Name and Address
University Transportation Research Center
137th Street and Convent Avenue
New York, NY 10031

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Public Private Partnership (P3) projects are likely to fundamentally impact entire transportation systems. However, most studies are focused on system modeling rather than policy analysis, and few studies have examined the impacts of P3s on real-size transportation networks. Policy guidance for devising and administering P3 contracts to improve transportation system performance while maintaining profitability is lacking. Using the transportation network of Fresno, a middle-sized city in California as an example, this study considers alternative P3 approaches for profit maximization and system cost minimization at full urban transportation network scales. Based on system modeling results, we offer the following recommendations for policy makers to design and promote successful P3 projects in urban environments: (1) to promote a profitable and a socially beneficial system, toll rates should be set between profit-maximizing and system-optimal rates; (2) even though tolls (i.e., higher travel costs) on a few roads helps reduce travel demand they may, counter-intuitively, lead to higher total travel cost for the transportation system as a whole; (3) lower limit(s), in addition to upper limit(s), for tolls may be required to enforce system-optimal tolling and avoid undercutting; (4) a variable tolling scheme (i.e., temporally and spatially varying tolls) significantly reduces congestion and increases profits relative to flat tolls; and (5) public officials should provide a comprehensive plan regarding past, current, and future P3 projects along with detailed system-wide impact analysis of project implementation in order to promote a more sustainable transportation system.

17. Key Words
Public–private partnership; Road pricing; Transportation networks; Tolling regulation; System performance

18. Distribution Statement
This project has resulted in a journal publication, based on which this report is developed. Detail of the paper is listed below: Omid M. Rouhani, H. Oliver Gao, R. Richard Geddes, Policy lessons for regulating public–private partnership tolling schemes in urban environments, *Transport Policy*, Volume 41, July 2015, Pages 68-79,

19. Security Classif (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No of Pages

22. Price

Form DOT F 1700.7 (8-69)

Table of Contents

List of Figures

List of Figures

Evaluating the Role of Private Investment in Transportation Infrastructure Assets

Executive Summary

Public Private Partnership (P3) projects are likely to fundamentally impact entire transportation systems. However, most studies are focused on system modeling rather than policy analysis, and few studies have examined the impacts of P3s on real-size transportation networks. Policy guidance for devising and administering P3 contracts to improve transportation system performance while maintaining profitability is lacking. Using the transportation network of Fresno, a middle-sized city in California as an example, this study considers alternative P3 approaches for profit maximization and system cost minimization at full urban transportation network scales. Based on system modeling results, we offer the following recommendations for policy makers to design and promote successful P3 projects in urban environments: (1) to promote a profitable and a socially beneficial system, toll rates should be set between profit-maximizing and system-optimal rates; (2) even though tolls (i.e., higher travel costs) on a few roads helps reduce travel demand they may, counter-intuitively, lead to higher total travel cost for the transportation system as a whole; (3) lower limit(s), in addition to upper limit(s), for tolls may be required to enforce system-optimal tolling and avoid undercutting; (4) a variable tolling scheme (i.e., temporally and spatially varying tolls) significantly reduces congestion and increases profits relative to flat tolls; and (5) public officials should provide a comprehensive plan regarding past, current, and future P3 projects along with detailed system-wide impact analysis of project implementation in order to promote a more sustainable transportation system.

Background

In the New York metropolitan area, traffic congestion imposes large social and private costs. One estimate put the overall cost of traffic congestion to the New York region at $12 billion in 2011, the total highest congestion cost in the nation for a metropolitan area (Schrank et al., 2012). Over recent years, congestion costs have been constantly increasing. The major problem is that current investment levels have not kept pace with transportation system problems.

To address the problems in investment, public-sector and private-sector partners are increasingly interested in types of facilities, business models, and organizational structures underpinning successful public-private partnerships (P3s). Private participation through the provision of financial resources, risk-sharing, facility design, construction, operation, and maintenance can help improve the resiliency and sustainability of transportation infrastructure (Geddes, 2011). However, implementation of P3 projects raise a set of new and unknown challenges to ensure that private participation supports the public interest (Rouhani, 2009).

Implementation of P3s would provide a new source of financing for transportation projects within limited budget periods, incentivize a potential increase in the public transportation share, induce a reduction in transportation emissions, and improve transportation system performance. On the other hand, potential costs would increase financial expenses, long-term indebtedness of municipalities, the possibility of unforeseen challenges such as going out of business, unequal access to services, and general conflicts between the social and private goals of the transportation system provision.

Before state agencies are authorized to use P3 financing, policy makers should first develop a better understanding of the potential costs and benefits of this approach. If New York is going to join other states in allowing privately financed P3s, then lessons learned elsewhere, together with a study of the state's potential/constraints, may help avert costly mistakes.

The Port of New York and New Jersey already has P3 authority, but other key agencies, including the state DOT, do not. In January 2011, the Office of the State Comptroller released a report about New York's infrastructure crisis and P3s. The report noted that a large and growing gap exists between the state's infrastructure needs and its ability to pay for those needs. For instance, despite the high priority attached to the $5.2 billion project to replace the aging Tappan Zee Bridge, a financing plan has not been worked out for the project. The Tappan Zee Bridge project is the focus of potential P3 legislation (Poole, 2013).

Envisioning insufficient sources of funding for New York State's infrastructure, the state has authorized public authorities to use a simple form of p3 known as design-build contracting (DiNapoli, 2013). Policy makers in New York are now considering whether or not to authorize more sophisticated types of P3s that depend on private financial investments. The State Fiscal Year (SFY) 2013-14 Executive Budget includes a proposal for "design-build finance" P3s that for the first time would give private firms the authority to finance public infrastructure projects (New York State Senate, 2013). The next step of adding private finance to the existing design-build authority could be extremely important.

State Senator Greg Ball announced in September 2012 that he would introduce P3 legislation in the 2013 session of the legislature (Poole, 2013). The forthcoming New York legislation requires a more in-depth analysis of (1) the appropriate framework to evaluate P3 projects, (2) suitable business models to promote successful P3s under various conditions, and (3) potentially beneficial projects to be procured as P3s.

The increasing interest in P3s is coupled with an interest in establishing an infrastructure bank that would coordinate financing and efficiently finance the construction, rehabilitation, replacement, and expansion of infrastructure. On the other hand, the NYS2100 Commission (2013), in response to Governor Andrew Cuomo's request, recommends that the state should adopt a standard set of criteria for project selection and their prioritization. The private participation in procuring and financing projects could provide great opportunities for natural disaster risk management for New York State's transportation infrastructure.

Objectives

The major objectives of this project is to develop a comprehensive and inclusive framework and lessons/guidelines for designing socially beneficial, sustainable, and system-improving P3 projects. An important gap in our knowledge concerns the decision about which projects would become a suitable fit for P3 procurements. To evaluate the consequences (both benefits and costs) of these investments in a transportation system, we will begin by solving an investment decision problem for transportation system. The investment problem will shed light on the system-improving projects. The resulting projects with high returns on investment will complement the existing projects in the region's planning pipeline. In practice, to measure the benefits and costs of any project, we must first determine the criterion for appraising the approach.

Sustainable development is another concern when considering private sector participation in urban infrastructure projects (Koppenjan and Enserink, 2009). To pursue such development, we should distinguish between social sustainability (equal/affordable access to public services), environmental sustainability (impact on land use, air quality, and congestion), and financial sustainability (both short run and long run obligations). Insights about these aspects increase the public sector's understanding about the issues at stake when taking a P3 option into account. For example, investment in roads may facilitate the growing demand for travel but may have negative impacts on environmental quality. On the other hand, investment in public transit systems may not be profitable but may have a positive impact on sustainability, especially through land and real estate development.

One of our major goals is to provide lessons/guidelines about sustainable and unsustainable practices when considering/employing P3 projects. In fact, the challenge for governments is finding the right balance between promoting attractive and profitable investment opportunities for the private sector and safeguarding public interests. Also, we will provide insights about legal frameworks, measurable requirements and indicators, and incentive structures to ensure sustainability objectives that are transparent and predictable for both the public sector and the private sector.

Introduction

Declines in traditional funding sources combined with much needed investment suggest that a transformative policy change in the transportation sector is needed. The main transportation infrastructure funding source – fuel tax revenue – is falling as vehicular fuel efficiency rises and annual vehicle miles travelled declines (ASCE, 2013). Many segments of the U.S. transportation are old and in poor conditions (TRIP, 2011). Moreover, fuel taxes cannot provide the flexibility necessary to incentivize efficient use of transportation resources (Kim et al., 2008). Public Private Partnerships (P3s) have been viewed by many experts as an alternative mechanism to help address such problems. To tackle the intensifying challenges faced by the U.S. transportation system, both the public and private sectors should examine more innovative yet measured P3 models and accompanying legislation (Zhang, 2005; Chung et al., 2010; de Jong et al., 2010).

Our knowledge of system-wide effects of P3s is very narrow since the overemphasis of existing research is on project-specific studies. Furthermore, overall P3 success hinges on more than project-specific financial analysis. It is also critical to develop better insights regarding the range and types of regulatory processes to successfully support P3's in a transportation network (Chen and Subprasom, 2007; Rouhani and Niemeier, 2011).

Only a handful of studies have attempted to examine private ownerships on real-size networks. Zhang and Levinson (2009) evaluated the short-run and long-run network performance under alternative ownership structures (private/public and centralized/decentralized). Zhang (2008) analyzed the combination of pricing, investment, and ownership to study welfare impacts of road privatization on a large-scale network (the Twin Cities). Dimitriou et al. (2009) developed a game-theoretic formulation for the joint optimization of capacity investments and toll charges, examining practical issues such as the regulation of tolls on privately operated highways. Rouhani et al. (2013) used demand analysis and game theory concepts to model the effects of including a few concession projects on a number of system performance measures.

Existing studies have focused either on model development only (see above) or on real-life P3 projects analysis (e.g., Evenhuis and Vickerman, 2010). Key policy insights about how P3 projects affect a transportation system as a whole and how the P3 contracts should be regulated in urban transportation systems are conspicuously absent. This study attempts to fill the gap and provide policy insights by simulating recurrent congestion under various P3 project schemes on the Fresno road network. We mainly focus on regulating concession models that usually grant a private developer (usually a consortium) the right to collect tolls from an existing facility under a long-term contract while public sponsors retain monitoring and enforcement controls (Reason, 2009).

Our goal is to offer insights into the following fundamental issues: (a) the differentiation between profit/revenue-maximizing and system performance-optimizing pricing; (b) the merits of providing spatially- and temporally-variable tolling in comparison with flat-rate tolling; (c) the effects of toll collection costs on the results; and (d) the impacts of P3 projects on system-wide costs of travel including emissions and fuel consumption. We conclude the paper by suggesting a list of major factors that the public sector should take into account when planning for transportation-related P3 projects in an urban setting.

Methodology and Case Study

Modeling

The basic mathematical approaches are inherited from our previous studies, including modified traffic assignment (Rouhani and Niemeier, 2011), profit maximization (Rouhani et al., 2013), and general system cost minimization and spatial variation in tolls (Rouhani and Niemeier, 2013). To model different problems, we employ a bi-level programming framework. At the upper level, policy makers/private operators pursue two basic objective functions for system operation: transportation system general cost minimization (SGCM) and toll profit maximization problem (PMP). At the lower level, travelers react to the application of various toll schedules and modify their travel choices.

Here, for the sake of brevity, we provide only a brief description of the major problems considered in our analysis. The SGCM problem minimizes a monetary combination of total travel time, fuel consumption, and emissions costs over a transportation system. The SGCM also accounts for the social welfare loss resulting from reduced travel demand. The problem's decision variables are the toll rate on each of the candidate roads. Policy makers might use the resulting system-optimal rates as the basis for capping the toll rate.

The PMP simulates another problem: private firms solve for the profit (or revenue minus cost) maximization problem and find the corresponding optimal toll rate. However, the toll rate might be capped (limited) by P3 contracts, which could affect the optimal rate and the optimal profit. An important extension of the two basic models, called a "spatial variation model," is when the toll rate can vary across different segments of the tolled road. Spatial variation in tolls can induce a more profitable or efficient traffic flow pattern. The profit maximization model can also be extended by considering more than one profit-maximizing firm. The extended model must make an assumption about the firms' interactions. To simulate the interactions, we assume that each firm constructs a response function and determines its own toll non-cooperatively. The tolls will be set considering the best mutual responses and the Bertrand-Nash (B-N) equilibrium concept (Mallozzi, 2007).

All of the problems discussed above use a modified user equilibrium (UE) model in the lower level to simulate users' behavior. The modified UE assumes that users account for general costs of travel rather than travel time only. The modified model updates origin/destination (O/D) demand iteratively, considering the updated (higher) general costs of travel.

Assumptions

For simplicity, and because of modeling constraints, several basic assumptions in different aspects of the models are made as follows:

Transportation planning model:

- The transportation planning model used in this study is a static deterministic user equilibrium model (Sheffi, 1984);
- Neither the city of Fresno nor its planning model has a strong public transportation system. Therefore, the potential switch to a more efficient public transportation mode is not considered in our analysis; and
- The planning model is a single-user equilibrium model. Because of the variations in the value of time (VOT) for different classes of users, a single-user equilibrium model is inadequate for a comprehensive analysis of impacts across user classes. However, city-size models usually do not cover multi-class user equilibrium features and this study focuses mainly on the aggregate impacts on average users.

General Travel Costs:

- An average user values time at \$14/hour. Using the load factor of 1.4 persons/vehicle, the value of time for each vehicle is about \$20/hour (14×1.4);
- Based on California Air Resources Board's (CARB's) EMFAC (2011) model for mobile emissions inventory calculation, the emission factors are calculated using the VMT-weighted averages for different vehicle classes at different speeds;
- The assumed base unit emissions and fuel cost parameters are as follows: \$25/ton of CO_2, \$250/ ton of CO, \$7,000/ton of NO_x, \$3,000/ton of TOG, \$30,000/ton of PM_{10}, \$300,000/ton of $PM_{2.5}$, and \$4/gallon of gasoline (See Wang et al., 1994; McCubbin and Delucchi, 1999; AEA Technology Environment, 2005);

Tolling:

- For flat tolls, policy makers/road owners apply a constant mileage-based toll rate on the whole road (consisting of various segments). For variable tolls, the toll rate is different for each link of a road (spatial variation) and for each time period (temporal variation or peak vs. off-peak);
- The operating cost is \$0.2 per transaction, based on the estimated operating costs of various tolling agencies (Balducci et al., 2011): the operating costs of Toronto 407 and Dulles Greenway (both run by private agencies) averaged around \$0.3 per transaction in

2007, and operating costs for urban and multi-road agencies, with a higher number of transactions, averaged around $0.16 per transaction;

- For the capital cost of toll collection, we base our calculation on the average capital cost of Toronto 407 and Dulles Greenway. Using a 30-year payback period and a 5% discount rate, the annual average capital cost per mile will be $1.2 million. Accordingly, we assume capital costs of $1.2 million per mile for highways and $1.5 million per mile for arterials since arterials have a higher number of access points (i.e., more tracking devices).

In addition to the above basic assumptions, we ran a sensitivity analysis on the major parameters in the Results section. The sensitivity analysis clarifies the effect of deviations from the basic assumptions.

Case Study

We study the City of Fresno and use its transportation planning model with a calibrated base year of 2003 and future year of 2030. The Fresno network consists of 20,865 links and 1,852 traffic analysis zones. As shown in Figure 1, we selected three segments of roads transecting the urban area including two highways: SR168 and SR180; and one arterial: Shaw. This choice leaves the majority of the system toll free. Table 1 presents the main features of the selected roads for the do-nothing case (where no tolling scheme is applied). The roads were selected on the basis of profit potential and congestion reduction to encourage private participation and to reduce overall travel costs.

Table 1 Main characteristics of the candidate roads.

	Name	**Length-private (Mile)**	**Freeflow speed (MPH)**	**AM Peak VMT (Base-hourly)**	**Off-peak VMT (Base-hourly)**
HW-1	SR168	4.92	65	70,265	28,009
HW-2	SR180	5.23	58	68,701	30,138
Arterial-1	Shaw	8.47	40	44,163	14,710

(Source: Transportation planning model, city of Fresno -2030 forecasts)

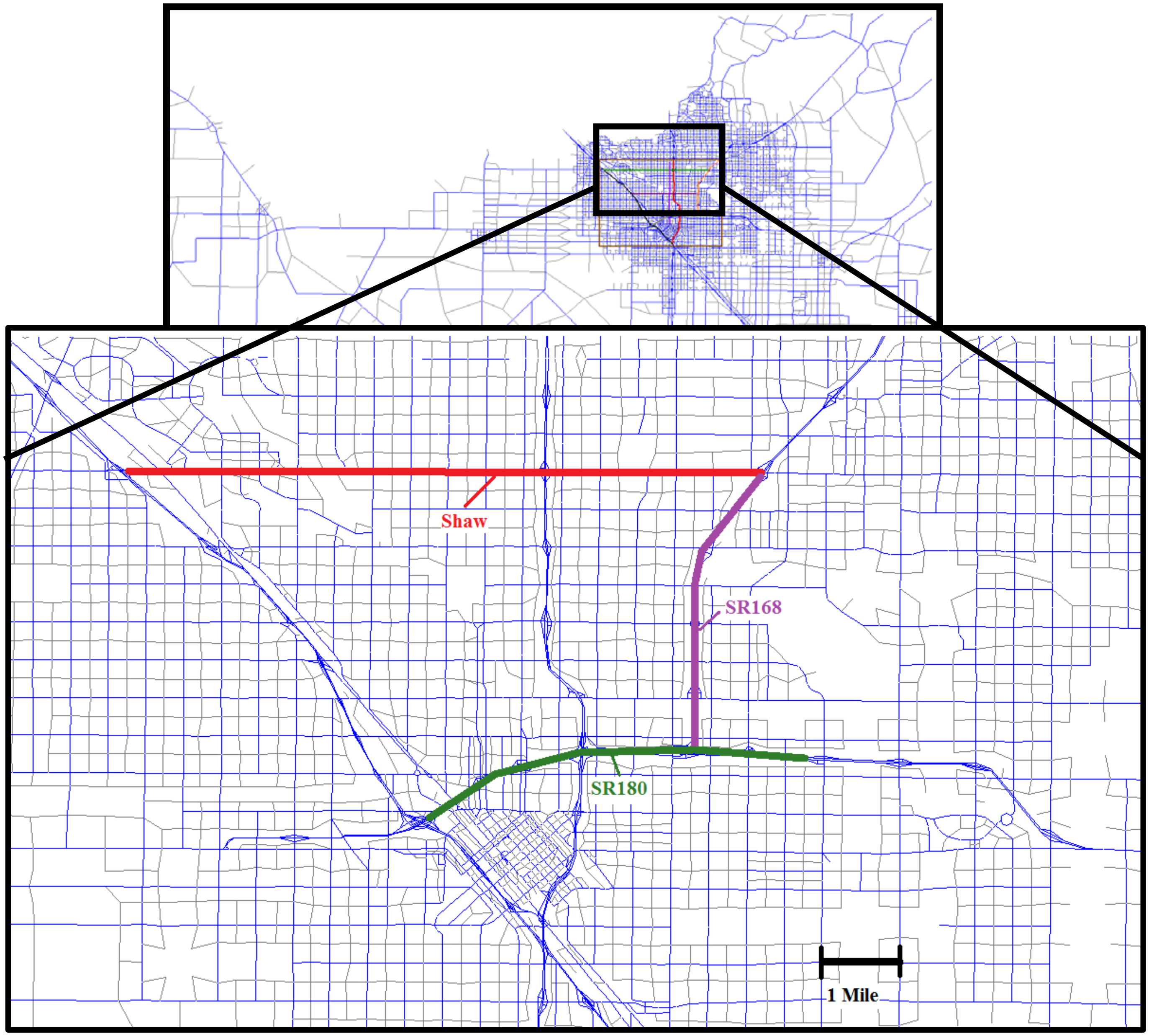


Figure 1 Road network of Fresno, California with P3 candidate roads.
(Source: Transportation planning model, city of Fresno)

Results

To generate policy insights into P3 best practices in urban environments, we solve for the SGCM and PMP problems under different conditions. Results are organized into the following subsections: (1) toll rates; (2) variations in tolls; and (3) sensitivity analysis. We begin the results section with a detailed examination of how toll rates should be designed to satisfy different objectives, and follow with a discussion of the benefits of temporal and spatial variations in tolling. Finally, we conduct a sensitivity analysis on some key parameters of the model to verify our results.

3.1. Toll rates

Toll rates play an important role in P3 project analyses. To provide a general vision about the level of toll rates, we start by comparing our estimated toll rates for candidate roads (solving the problems in Section 2.1) to actual toll rates implemented on US toll roads. As shown in Table 2, our estimated profit-maximizing tolls range from 47 to 77 cents per mile for peak hours and 31 to 127 cents per mile for off-peak hours. These rates are generally higher than the average rate of 46 cents per passenger car (PC)-mile for the Chicago Skyway and 3 cents per PC-mile for the Indiana Toll Road, which is mainly a rural road (FHWA, 2011). Our calculated profit-maximizing rates are also higher than the Dulles Greenway tolls – 37 cents per mile for peak and 31 cents/mile for off-peak hours (Dulles Greenway, 2012), and definitely higher than value-added tolling – 15 cents per mile for peak and 5 cents for off-peak hours (Poole, 2011). The fact that profit-making rates are higher than actual rates adopted in real world suggests that for US toll facilities, toll ceilings effectively limit the tolls. However, revenue-optimal rates are mostly lower than real toll rates. For cases where toll collection costs are sunk (e.g., when toll collection infrastructure already exists, so road owners maximize revenues rather than profits), much lower toll rates are expected. Indeed, our estimated revenue-optimal rates are lower than the real rates.

Table 2. Comparison of toll rates: our estimated rates versus real rates (PC).

	Our study									**Real cases**		
	System optimal			**Profit optimal**			**Revenue optimal**			**Chicago Skyway**	**Indiana Toll Road**	**Dulles Greenway**
	HW1	**HW2**	**Art1**	**HW1**	**HW2**	**Art 1**	**HW1**	**HW2**	**Art1**			
Peak rate (Cents/mile)	25	27	22	47	73	77	33	44	41	46	3	37
Off-peak rate (Cents/mile)	32	25	12	31	59	127	20	17	18	-	-	31

On the other hand, system-optimal rates[1] found in this study are in the range of 12 to 32 cents per PC-mile, which are mostly lower than real rates applied on US toll facilities (FHWA, 2011). In fact, it appears that US toll rates are set between profit maximizing and system-optimal rates, possibly to address a combination of profit-making and congestion-reduction objectives. A side note is that toll rates should be set differently for alternative transportation network configurations, different travel demand levels, and different users' characteristics. In fact, our estimated profit-optimal and system-optimal rates differ dramatically from one candidate road to another and from one time period to another. Therefore, a simple comparison between the toll rates might not be valid for some cases.

An important policy insight about implementing different toll rates is their general effects on revenue, profit, and system performance. Figure 2 shows total hourly revenue, profit (revenue minus cost), and system-wide travel costs as functions of toll rates applied to Highway No.1–SR 168. The hourly values are estimated for peak hours (Figure 2–a–1&2) and for off-peak hours (Figure 2–b–1&2) applying different (spatially) flat dollars-per-PC-mile toll rates. The revenue and profit are estimated by solving two versions of the PMP problem: without toll collection costs (revenue maximization) and with toll collection costs (profit maximization), respectively. The system cost is estimated solving the SGCM problem.

The first observation in both Figures 2–a–1 and 2–b–1 is that the toll rates that optimize revenue, profit, and system travel costs are substantially different. For instance, optimal toll rates

---

[1] System-optimal rates minimize the total system travel costs including time, fuel, and emissions costs (excluding tolls since tolls could be viewed as money transfers between two groups and they do not affect system performance). These travel cost components are summed converting all these costs into monetary terms.

for revenue maximizing cases (sunk costs) are different from those of profit-maximizing cases (when the private developer should create and operate a toll collection system). In most cases, profit-optimal toll rates are higher than revenue-optimal toll rates.

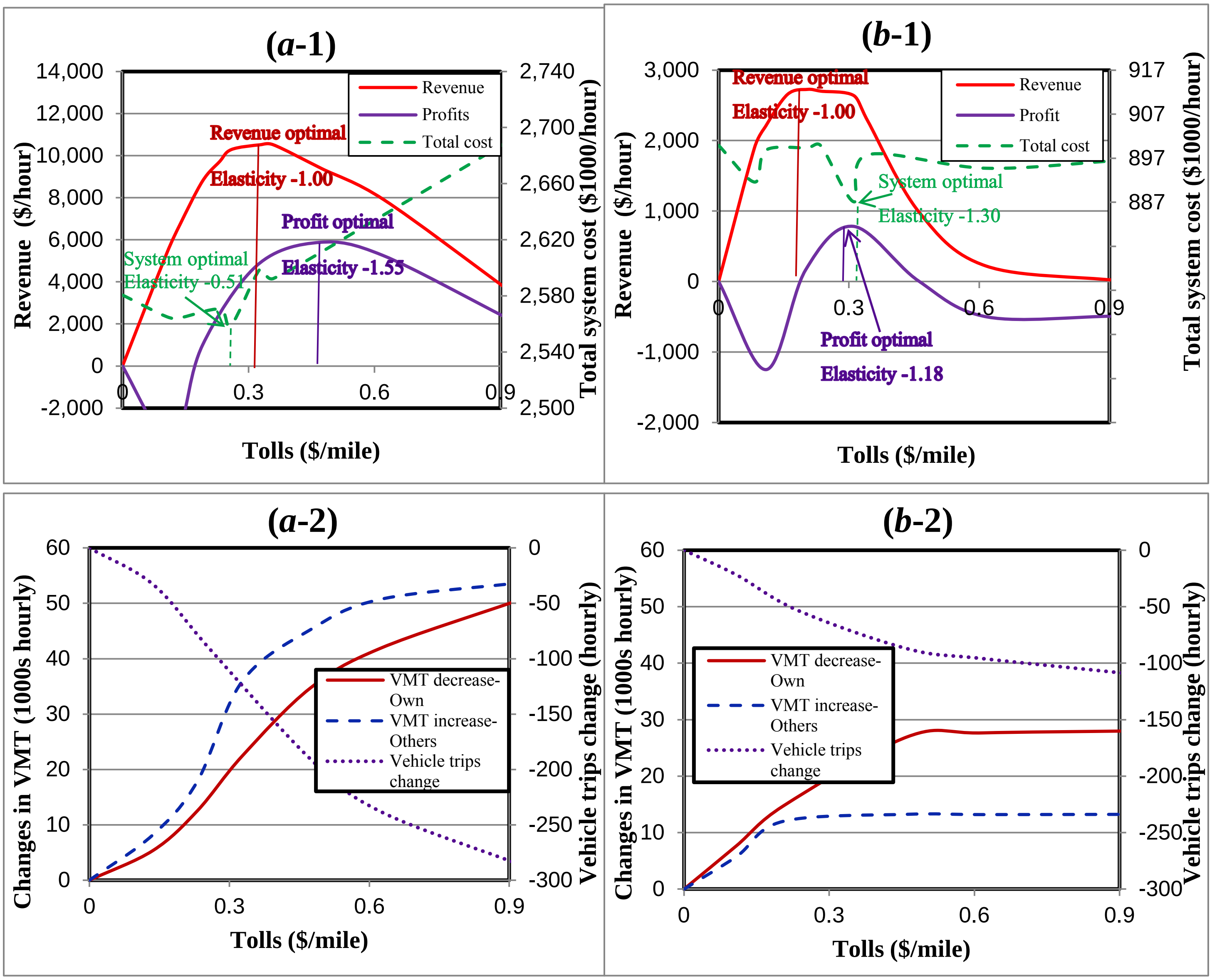


Figure 2. Total revenue, total profit, total system costs (1), and travel demand (2) when pricing Highway No. 1 for (*a*) peak and (*b*) off–peak hours

The difference in system-travel-cost between socially-optimal toll rates and profit- and revenue-optimal rates is of critical importance in devising P3 contracts. As can be seen in Figure 2–a–1, profit-optimal and even revenue-optimal rates result in higher total travel costs for the whole transportation system (system cost is the dotted line) than does the do-nothing condition (where the toll rate is zero). This result is important since implementing an unlimited toll scheme with a profit maximization goal might increase total system travel costs. The profit-optimal toll rate on Highway No.1 increases total system travel costs by around \$50,000 hourly (or about 2% relative to the no-toll case), resulting in a \$75 million annual increase in system travel costs including time, fuel, and emissions. The increase in system travel costs (excluding tolls) occurs despite the fact that implementing tolls increases private costs and thus decreases travel demand. This increase is specific to peak hours.

Another interesting policy insight is that the profit- and revenue-maximizing rates could be lower than the system-optimal rate, as shown in Figure 2–b–1 for off-peak hours. In fact, a profit maximizing operator may rationally charge less than system-optimal toll rates (which should be set as price caps in the P3 contracts). Therefore, from a systems perspective, not only should policy makers put a cap on toll rates for each time period, they should also set a lower limit on toll rates which stops road operators from undercutting the applied upper toll limit(s).

To better understand the above-mentioned results in terms of the changes in travel demand, we examine the effects of different toll rates on the transportation system in two aspects: (*i*) effects on the toll road; and (*ii*) effects on all other parts of the network. Figures 2–a–2 and 2–b–2 report changes in VMT for the toll (own) road and for all other (cross) roads, and changes in total number of trips, as the toll rate increases.

Figure 2–a–2 shows an interesting result for peak hours: although (own) VMT on the toll highway decreases as its toll rate increases, the VMT on other roads increases even more, and as a result total system VMT *increases* with the toll rate. Despite the decrease in total trips, high tolls could increase overall VMT since some users might decide to travel on longer paths to avoid tolls. However, for the low toll rates, these changes in VMT would lead to a lower system travel cost. The main reason is that candidate roads are initially highly congested, and the switch to other, less congested roads could reduce total travel costs as long as the marginal decrease in congestion on the toll road is significant. For off-peak hours (Figure 2–b–2), the decrease in own VMT outpaces the VMT increase on other roads, since travel demand is more elastic in off-peak hours; users are more willing to choose not to travel in off-peak than in peak periods.

As expected, the own-demand elasticities for revenue-optimal and profit-optimal toll rates are about -1 and lower than -1 (more than 1 in absolute terms), respectively.[2] But peak demand elasticities for system-optimal toll rates are totally different from off-peak elasticities. The main reason is that although own-elasticities could be an appropriate measure to calculate profits and revenues, they cannot provide a proper measure in finding system-optimal rates; these rates are determined by network and spillover effects. Based on our results, system-optimal rates for a road could result in inelastic demand (-0.51 in peak hours, Figure 2–a–1), and they could also result in elastic demand (-1.30 in off-peak hours, Figure 2–b–1) for the same road but under a different travel demand pattern.

Figure 3 shows total hourly revenue, profit, and the system-wide travel costs as functions of toll rates applied to Arterial No.1–Shaw. The difference between the system, revenue, and profit-optimal rates can also be observed for the arterial. Another observation is that tolling a road may provide positive profits under one level of demand (Figure 3–a–1 for peak hours), but tolling the same road does not always provide positive profits under another level of demand (Figure 3–b–1 for off-peak hours), even when the toll rates are set at optimal levels. This result has an important policy implication: a profit maximizing firm might only charge at peak hours, and set the toll rates at zero for off-peak hours, especially when the operating (not capital) cost is high relative to revenue, as could be the case for arterials with a larger number of exit and entrance points and low average per-mile travel on the road. As shown in Figure 3, a profit-maximizing road owner may rationally set the off-peak prices at zero and still make a positive profit with peak-hour pricing. This result is specifically valid for arterials.

The estimated toll collection costs are substantial relative to their corresponding toll revenues (which can result in negative profits) due to high transaction points/costs, specific to urban systems. Hence, policy makers should favor using less expensive toll collection systems in urban settings. Privately-operating systems might provide such low-cost systems because of scale or learning economies that cannot be reached by government (De Bettignies and Ross,

---

[2] A profit maximizing firm sets its toll to maximize its profits ($\pi = p.q(p)$). The first order condition of the maximization with respect to own toll (p) is $q + p\frac{\partial q}{\partial p}$ = 0 or $q.(1 + \frac{\partial q/q}{\partial p/p})$ =0. So, when toll collection cost is zero, the firm maximizes revenues (profits) by setting a toll that results in an elasticity of -1, if there is no limit on tolls. When we add an increasing toll collection cost function with respect to q (decreasing with respect to tolls) to the analysis, the first order condition leads to a toll that induces demand elasticity lower than -1 (higher than 1 in absolute terms).

2004). In general, the travel demand trends with respect to tolls are similar to the highway's travel demand trends (Figure 2), but on a lower scale, since an individual arterial's effect on a system is generally less significant.

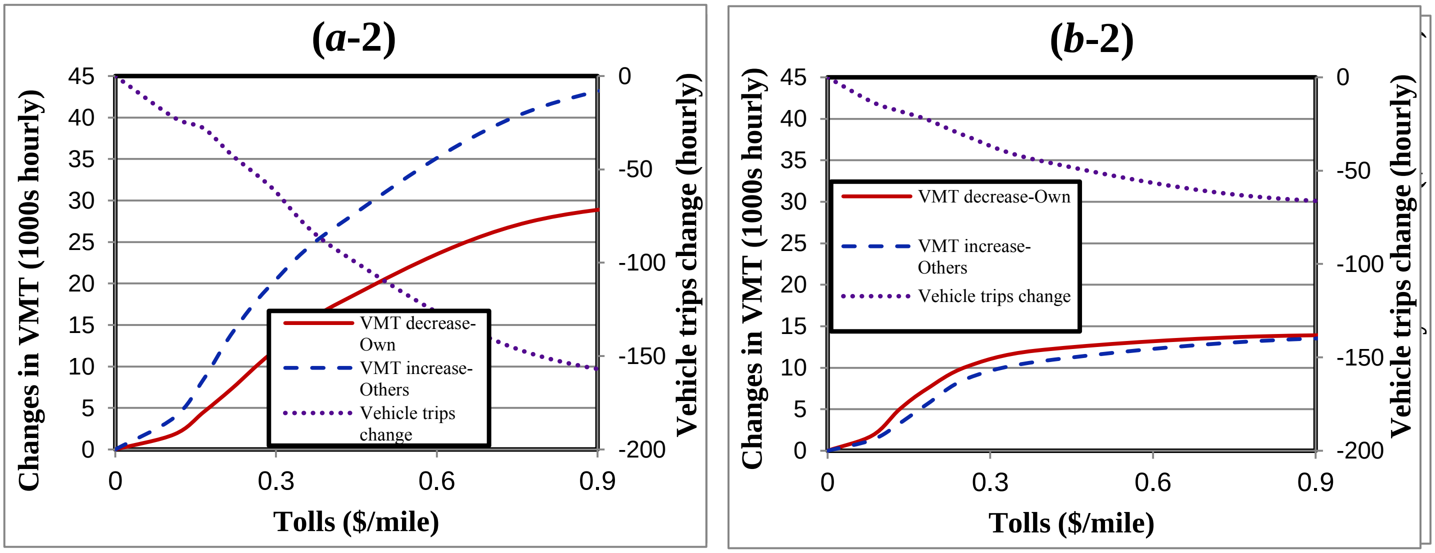


Figure 3. Total revenue, total profit, total system costs (1), and travel demand (2) when pricing Arterial No.1 for (*a*) peak (*b*) off-peak.

To account for different system cost components, we consider travel time, fuel consumption, GHG emissions, and the criteria pollutant emissions as the major travel cost factors in our analysis. For peak hours, Figure 4 depicts the total system travel time, fuel consumption, and $PM_{2.5}$ emissions as the toll rates on the candidate roads increase. The figures do not include GHG emissions based on the rationale that GHG emissions are linearly related to fuel consumption.

For peak hours (Figure 4), the general trend for all cost components is that first, as toll rate on a road increases, the system travel costs decrease. After travel costs hit their minimum, system travel costs increase with toll rates. The trend is a common trend for tolling both highways and the arterial. This result seems counter-intuitive since higher toll rates are expected to decrease travel demand, and as a result, reduce system travel costs. However, traffic volume spillovers (intensifying congestion and increasing VMT on un-tolled roads, as shown in Figures 2–a–2 and 3–a–2) have adverse effects on the system for peak periods. Based on Figure 4, the spillover effects are greater than the effects of lowering travel demand for peak hours if toll rates are high (more than \$0.3/mile for all roads).

Another important observation in Figure 4 is that the toll rates to minimize different travel cost components could be different from each other. For example, the optimal rate to minimize total travel time on Arterial No.1 is 21.9 cents per mile while the optimal rate to minimize total fuel consumption is 20.9 cents per mile. Although in some cases the difference is substantial (13.7 cents/mi minimizing total $PM_{2.5}$ vs. 25.4 cents/mi minimizing total time or total fuel consumption for the arterial), the optimal rates are usually the same or very close for different cost components.

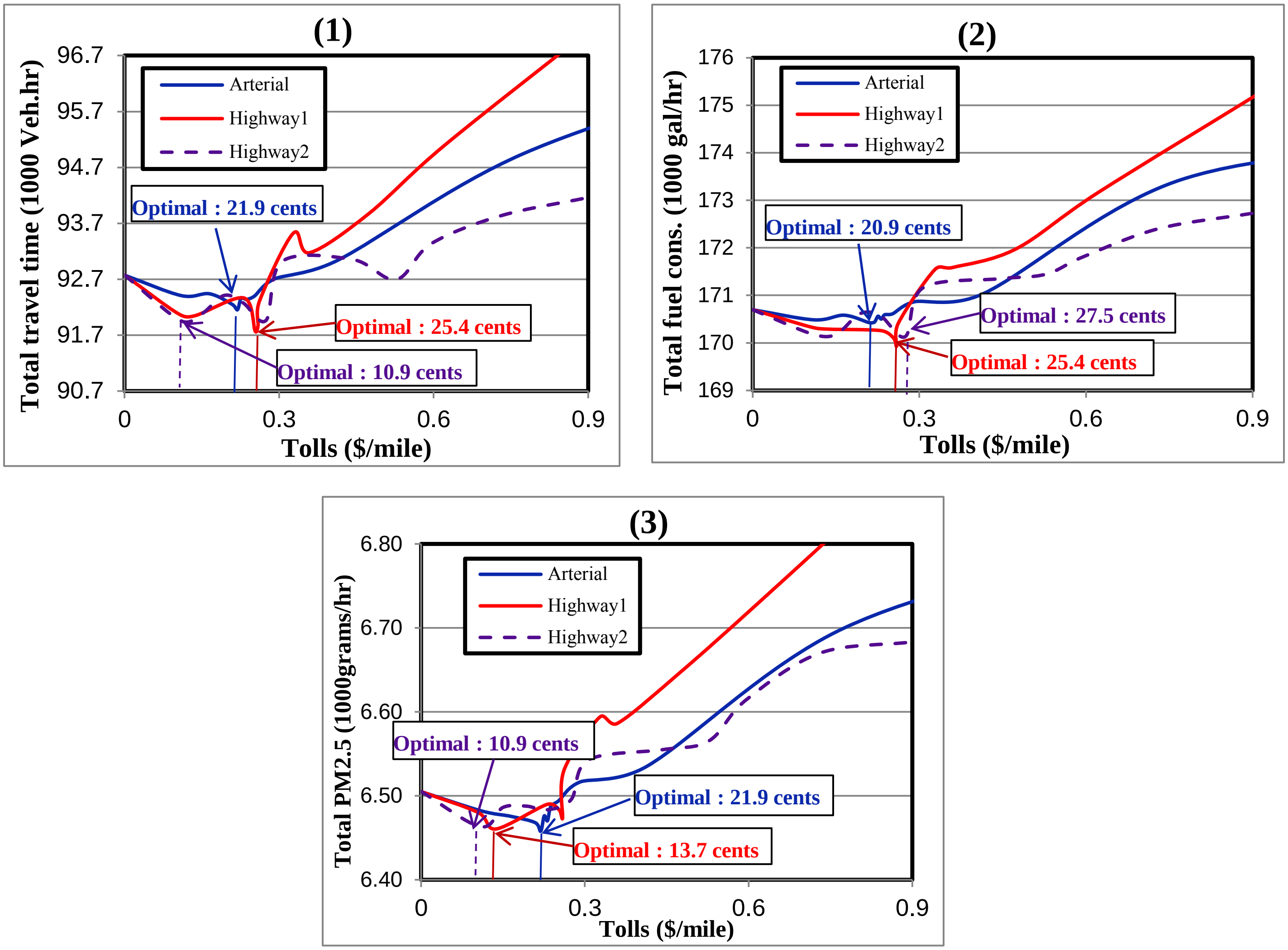


Figure 4. System-wide cost of (1) travel time (2) fuel consumption, and (3) $PM_{2.5}$ when pricing Highway No.1 and Arterial No.1 during peak hours.

The difference in the optimal rates will shrink further if weights (monetary costs) of the cost components are added since travel time is the dominant monetary factor. However, the toll rate that minimizes total travel time is not necessary the same as the toll rate that minimizes total system travel costs. For example, the corresponding system-optimal rate for Highway No.2 is 21.7 cents per mile (the rate that minimizes the combination of time, fuel, and emissions costs) while the rate that minimizes total travel time is 10.9 cents/mi. Particularly, when a city or region in a non-attainment area is required to conform to a specific level of emissions to be eligible for receiving a budget (Gauna, 1995), a separate analysis on optimal toll rates for emissions would be beneficial, and the health-related emissions costs would not be the only factor that should be taken into account.

For off-peak hours, Figure 5 shows that system cost trends are fundamentally different from those of peak hours (Figure 4). Almost all toll rates considered for off-peak periods would improve system performance (decrease travel costs) relative to the do nothing case (where tolls equal zero), opposite to what we found for peak periods. System performance is improved mainly by decreasing fuel consumption (also in Figure 3) because of lower travel demand.

In addition, the hockey shape curves observed for peak hours transform into sine-shape curves, especially for highways, where travel costs rise and fall with increasing toll rates (Figure 5). These changes result from the cumulative effects of travel demand reduction and spillover. Although travel demand reduction is the prevalent factor, the spillover effects can increase travel costs for a short range of toll rates. Note that the irregularity in some of the functions in Figure 5 (for off-peak) results from the fact that the model is sensitive to very small changes in travel costs. These small changes can shift users' route choices, and consequently alter the resulting system travel costs, significantly. On the other hand, travel costs in off-peak hours are generally lower than those of peak hours. Therefore, even small changes in toll rates lead to greater impacts on users' travel cost estimations. However, these small changes might not be fully perceived by users in practice since users do not have complete information about travel costs.

In general, taking fuel consumption and emissions costs into account might have small effects on system-optimal toll rates. However, the magnitude of travel costs and the relevant system-wide benefits or costs of employing P3 projects could be greatly affected by considering those additional cost terms.

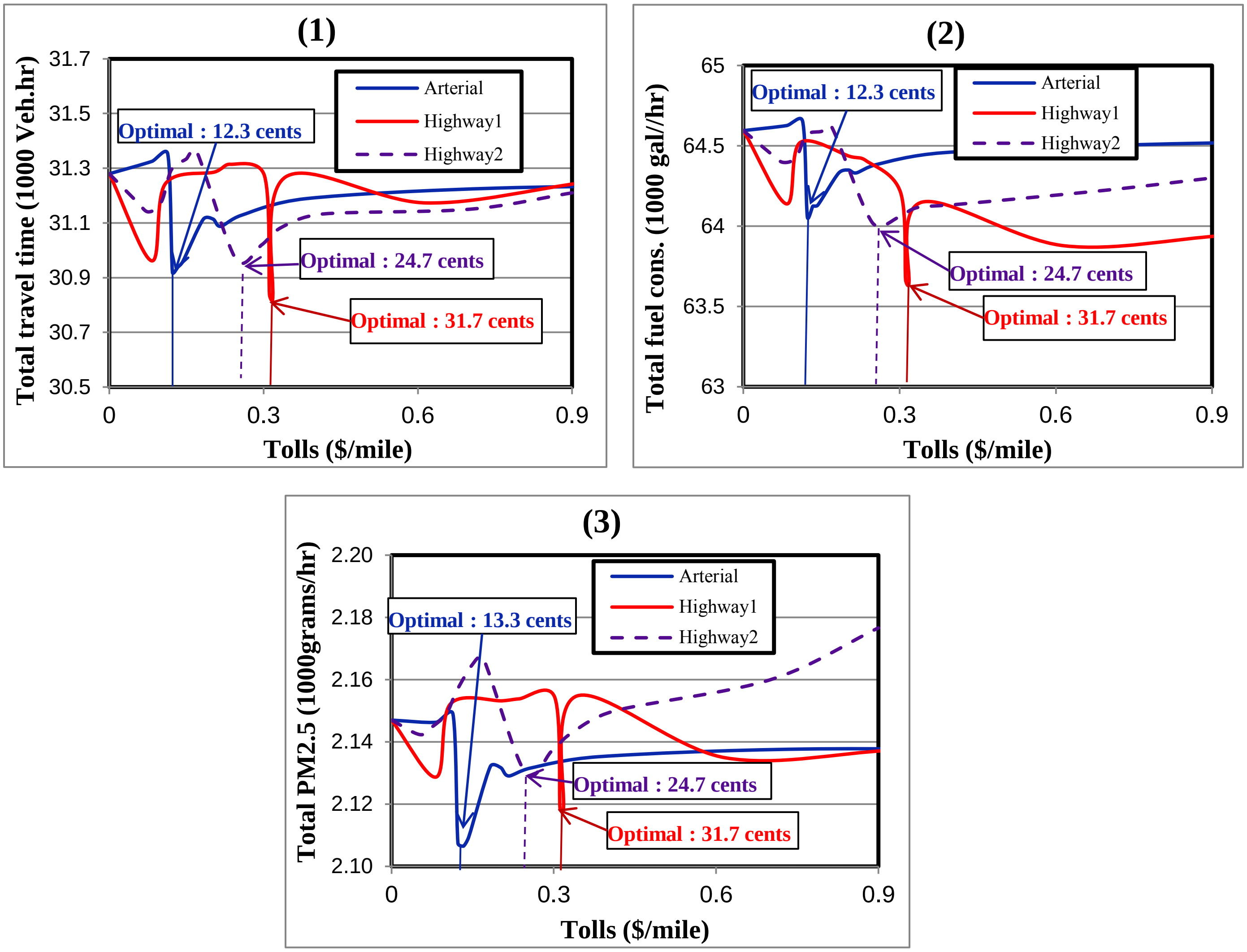


Figure 5. Off-peak total system-wide cost of (1) travel time (2) fuel consumption, and (3) emissions when pricing Highway No.1 and Arterial No.1.

3.2. Spatially and temporally varying tolls

Several studies have shown the effectiveness of temporally variable tolls (somtimes called value pricing) in improving the transportation system performance, especially for reducing congestion (Burris and Sullivan, 2006; Lou et al., 2011). Figure 6 shows the difference in system-optimal prices between peak and off-peak periods for candidate roads. This significant difference suggests that in order to reach system/profit-oriented optimal flow patterns, a temporally variable pricing scheme should be formulated in P3 contracts, i.e., rates should be flexible in P3 contracts and should allow variations over time. Temporally variable tolling is more effective in peak hours than in off-peak hours since congestion is the main factor driving the difference.

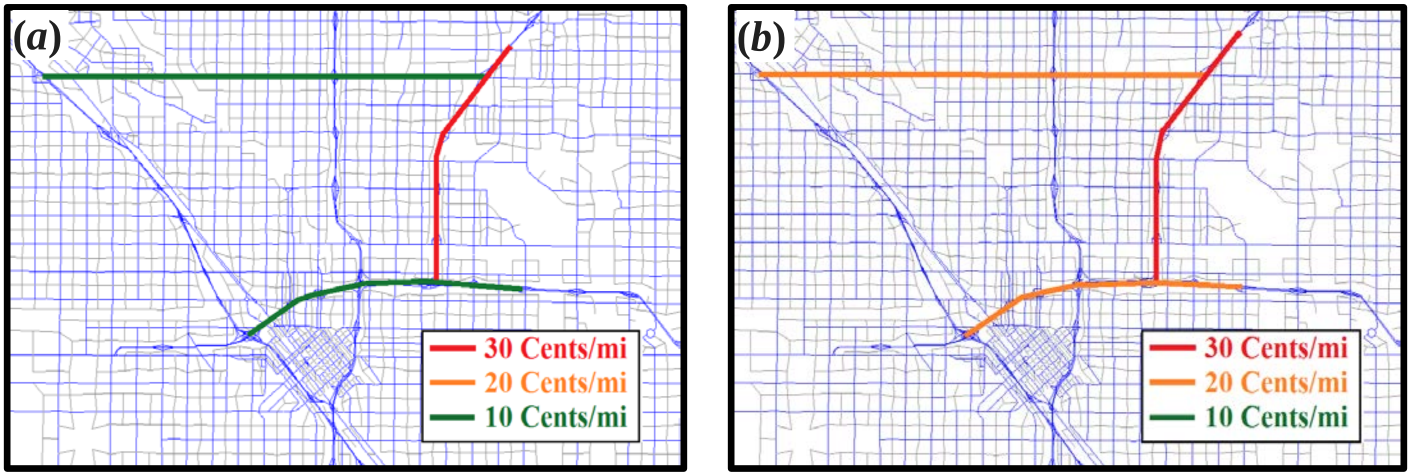


Figure 6. System-optimal prices for (a) off-peak; (b) AM peak.

In addition to temporal variation, road owners or public officials could distort traffic flows along a corridor by setting different toll rates for different road segments (spatial variation) in order to reduce congestion, raise more revenue, or to satisfy a combination of the two goals. Figure 7 shows optimal spatial variation in toll rates along Highway No. 2. As can be seen, tolling pattern in off-peak (dotted lines) is different from those of peak hours (solid lines), and tolling pattern for profit maximization (Figure 7–a) is different from the system optimal pattern (Figure 7–b). Irregular variations of optimal toll rates on different road segments indicate how complex setting optimal variable tolls could be.

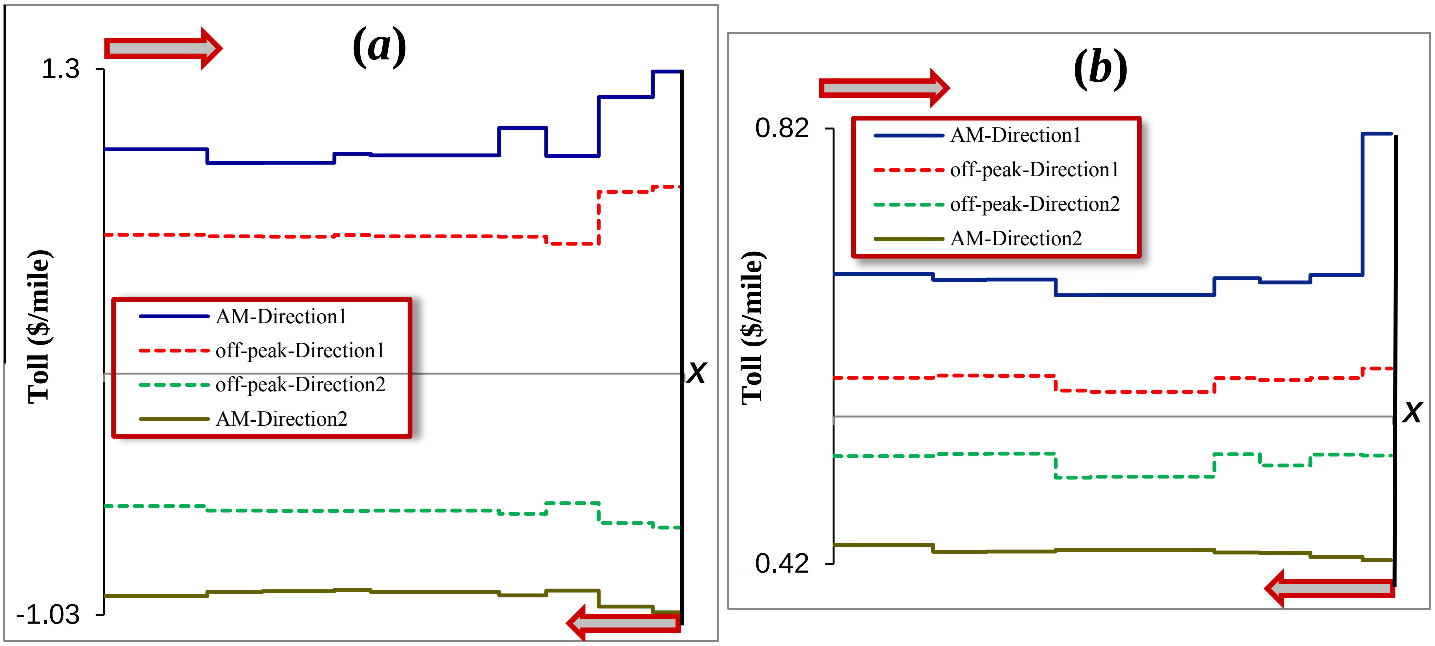


Figure 7. Toll patterns along Highway No. 2 for (a) profit maximization and (b) system–optimal problems.

Exploring overall impacts of applying temporally and spatially variable tolls, we found that the impacts are significant. For the profit maximization cases, temporal variations in tolls increase total revenues by 10% for the arterial and 1.5% for the highway, over the counterpart flat tolls. For system cost minimization cases, temporally-variable tolls increase, compared to flat tolls, the average total travel time saved by 19.5% and 131.1% for the studied arterial and highway, respectively. In addition to temporally variable tolling, spatial variation increases total revenues further by 23.4% for the arterial and by 5.9% for the highway, and it reduces total travel time of the whole system further by 65.7% for tolling the arterial and 167% for tolling the highway, over corresponding flat tolls (compared to what temporal variation offers). The result has extremely important policy implications: variable tolling on highways is more effective in improving system-wide travel time (system-optimal cases) than in raising revenues. This policy insight explains why private sponsors might not be interested in variations in tolls while the variations could offer huge social welfare improvements.

3.3. Sensitivity analysis

To examine robustness of the results under different parameters, we run a sensitivity analysis on several key parameters of our model. The sensitivity analysis determines the changes in results when a parameter deviates from its base level. Figure 8 displays changes in profit-optimal tolls and optimal profits as the operating cost of toll collection increases, for Highway No.1 (Figures 8–a) and Arterial No.1 (Figures 8–b), and for peak (Figures 8–1) and off-peak (Figures 8–2) periods. For all cases, as operating cost increases, optimal toll increases and optimal profit decreases. The latter is an intuitive result. The increase in profit-optimal toll is also expected. In fact, high operating cost incentivizes road owners (operators) to transfer their toll collection cost burden to road users; road owners would raise toll rates to reduce travel demand and consequently to reduce their operating costs.

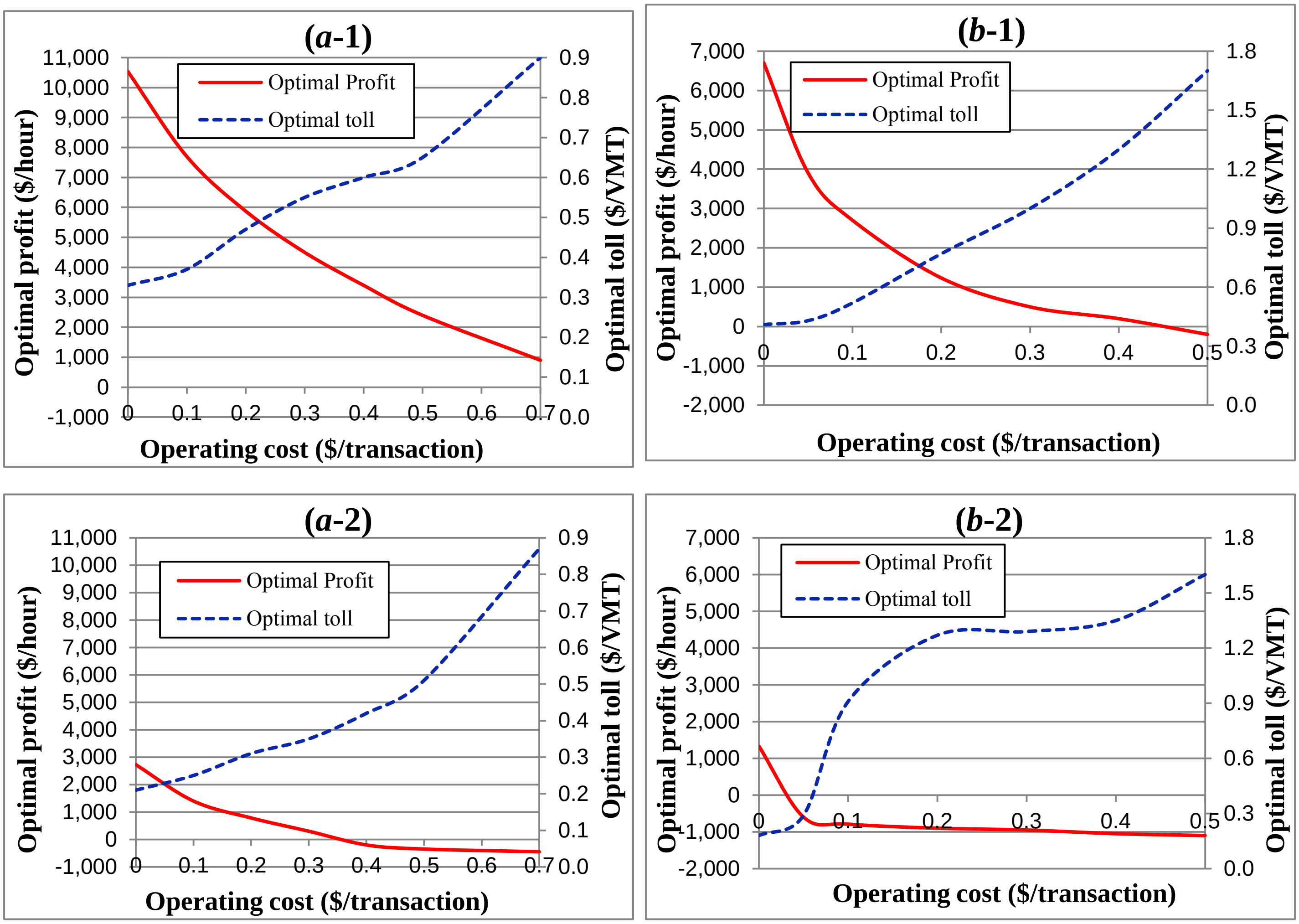


Figure 8. Sensitivity of the profit and toll with respect to operating cost for (a) Highway No.1 and (b) Arterial No.1 and for (1) peak vs. (2) off–peak.

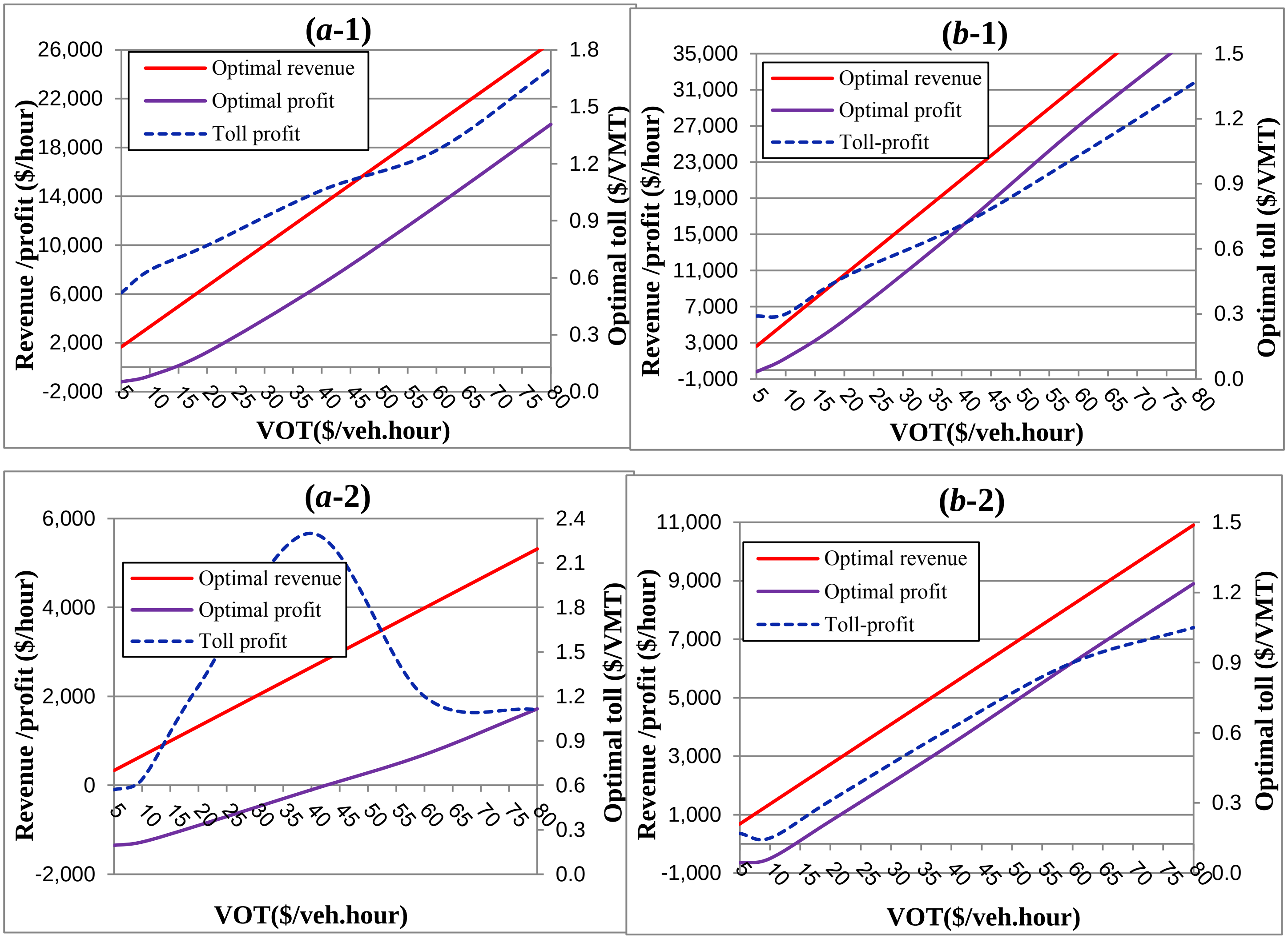


Figure 9. Sensitivity of the revenue, profit, and toll with respect to average VOT for (a) Highway No.1, (b) Arterial No.1, and for (1) peak vs. (2) off-peak periods**.**

Value of time (VOT) is one of the major elements in analyzing P3 projects. By changing VOT, a specific time-equivalent cost of tolling will be translated into different monetary costs of tolls, i.e., a 10 minute-equivalent toll equals to $5 using a $30/hour VOT and equals to $10 using a $60/hour[3]. Under the revenue-optimal flow patterns (holding time costs constant), a higher average VOT will result in a higher toll rate (monetary) and consequently a higher revenue by a constant ratio.

---

[3] The time cost of tolls is the major driver of users' travel behavior and consequently travel demand and traffic flow patterns.

Figure 9 shows the linear relationship between optimal revenue and VOT, as explained above. However, the effects of VOT on profit-optimal tolls and optimal profits are more complicated. Optimal toll might even decrease with VOT (Figure 9–a–2) since private owners might find it more profitable to decrease tolls and attract more demand. This counterintuitive result has higher chances of occurrence in off-peak hours, due to more elastic travel demand during off-peak periods. However, the addition of heterogeneous users in terms of VOT (using a multi-user equilibrium) could dramatically impact the results.

Policy Recommendations

Based on our discussions in the results section, we provide policy makers with several new insights about how to design P3 contracts and how to evaluate P3 projects. To this end, we offer specific recommendations to which the public sector can refer in order to promote successful P3 projects.

Recommendation #1: To promote a profitable and more efficient transportation system, toll rates should be set within a range between profit-maximizing rates and system-optimal rates, carefully considering their potential effects.

System optimization and profit maximization solutions usually fall short of the contradictory goals of raising profits and improving system performance, respectively. A successful P3 project both raises a significant amount of profits and simultaneously reduces transportation system travel costs. Therefore, neither profit maximization nor system cost minimization should be the sole target of policy makers. Rather, a combination of congestion reduction and profit-making goals should be the criteria for choosing among P3 projects and setting the toll rates.

Recommendation #2: Tolls (higher travel costs) on a few roads do not lead to lower total travel costs for a transportation system as a whole. The opposite could be simply true for unlimited profit-maximizing tolls.

As shown in Figures 2–a–1 and 3–a–1, for peak hours, total system travel cost decreases with tolls at first and then generally increases with tolls. The increasing system cost with tolls is specific to high toll rates in peak periods since spillover effects to other congested roads could diminish system performance. As an extreme case in Table 5, the profit-optimal rate on (only)

Highway No.1 would increase the total system travel cost by 2% leading to an immense $75 million dollar increase in travel costs (time and fuel) annually, excluding the toll costs. As many congestion pricing studies assume, the simple assumption that tolls would reduce congestion is wrong. Instead, the public sector should deliberately search for the toll roads and toll rates that could reduce system-wide congestion, not the congestion on P3 (toll) roads only. However, existence of alternative modes to private cars can justify implementing high profit-maximizing toll rates. User choice is less restricted in an urban system than in a rural system. Incentivizing the use of less-costly public transportation would promote a more efficient and sustainable transportation system (e.g., increase in share of public transports in London, Leape, 2006).

Recommendation #3: A lower limit(s) along with an upper limit(s) might be required for enforcing the application of system-optimal or any system-improving toll rates by the private sector.

As we discussed in the results section, system-optimal rates are not related to elasticities (they are mostly determined by the network effects), therefore, they could be either lower or higher than profit-optimal rates, which are mainly determined by elasticity. Particularly in an urban environment with many alternatives to toll roads, system optimal rates could be associated with elastic demand. Not only should policy makers put a cap on toll rates based on system-optimal rates, they should also set a lower limit on toll rates in P3 contracts, which prevents road operators from undercutting the applied upper toll limit(s).

Recommendation #4: To increase profits and reduce travel costs, policy makers could provide a flexible (temporal and spatial) tolling scheme for the private sector.

Spatially and temporally varying tolls could be significantly effective in increasing profits, and specifically in improving system performance (Table 3). Rules #3 and #4 are not contradictory, rather these rules should be considered together. Although we recommend setting a limited range in which toll rates could change, this range should vary for different time periods (peak versus off-peak) and for different segments of the road. However, applying variable tolls might favor a publicly-run tolling scheme where tolls could be set with more flexibility.

Recommendation #5: A detailed system-wide impact analysis of P3 projects is a must.

Many lessons can be learned from a system analysis of P3 projects. Examining a toll road only, or even a toll road and its major competing roads, is not sufficient. The possible spillover effects could lead to millions of dollars of travel costs, as is the case with some unlimited pricing scenarios in our study. In fact, without a systems analysis, a policy maker tends to use those cases that can bring more money to the table while these more profitable cases could be disastrous for transportation system performance. On the other hand, running a pure congestion pricing scheme (only to improve system performance) could become an economic failure (Prud’homme and Bocarejo, 2005).

Table 3. Results of applying temporally- and spatially-variable tolls.

	Case No.	**Cases**	**Type of variation**	**Optimum Toll (cents/mi)**				**Improved travel time (pc equ-hour)**	**Total Revenue ($)**	**Throughput (VMT)**
				Flat	Ave. Var	Max Var	Min Var	% decrease from Flat to Var	% change from Flat to Var	% change from Flat to Var
Profit Max	1	Art. No.1	Temporal	25	26	41*	17*	-	10.0%	-1%
	2	HW No.1	Temporal	32	26	33*	21*	-	1.5%	25%
	3	Art. No.1	Spatial & temporal	25	29	183	18	-	23.4%	0%
	4	HW No.1	Spatial & temporal	32	34	65	23	-	5.9%	15%
System Optimal	5	Art. No.1	Temporal	13	17	22*	14*	19.5%	-	-6%
	6	HW No.1	Temporal	11	16	26*	8*	131.1%	-	-4%
	7	Art. No.1	Spatial & temporal	13	10	120	0	65.7%	-	-8%
	8	HW No.1	Spatial & temporal	11	14	34	10	167.0%	-	2%

* For temporal variation, only two toll values have been used in peak and off-peak periods.

Caveat

The transportation planning model used in this study was employed only for research purposes, and not for developing regional transportation plans or transportation improvement programs.

References

AEA Technology Environment, 2005. Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 member state and surrounding seas, Clean Air for Europe (CAFE) Programme. European Commission. Available from: http://www.cafe-cba.org/assets/marginal_damage_03-05.pdf , Accessed October 2012.

American Society of Civil Engineers, ASCE, 2013. Report Card for America's infrastructure, available at: http://www.infrastructurereportcard.org/ , Accessed April 2013.

Balducci, P., Shao, G., Amos, A., Rufolo, A., 2011. Costs of alternative revenue-generation systems. National Cooperative Highway Research Program-NCHRP REPORT 689, ISBN 978-0-309-21316-5.

Burris, M., Sullivan, E., 2006. Benefit-cost analysis of variable pricing projects: QuickRide HOT lanes. *Journal of Transportation Engineering*, 132 (3), 183–190.

Chen, A., Subprasom, K., 2007. Analysis of regulation and policy of private toll roads in a Build-Operate-Transfer scheme under demand uncertainty. *Transportation Research Part A*, 41 (6), 537–558.

Chung, D., Hensher, D.A., Rose, J. M., 2010. Toward the betterment of risk allocation: Investigating risk perceptions of Australian stakeholder groups to public-private-partnership toll road projects. *Research in Transportation Economics*, 30 (1), 43–58.

De Bettignies, J. E., Ross, T. W. 2004.The economics of public-private partnerships. *Canadian Public Policy/Analyse de Politiques*. (2004), 135-154.

de Jong, M., Mu, R., Stead, D., Ma, Y., Xi, B., 2010. Introducing public–private partnerships for metropolitan subways in China: what is the evidence? *Journal of Transport Geography*, 18 (2), 301–313.

Dimitriou, L.,Tsekeris, T., Stathopoulos, A., 2009. Joint pricing and design of urban highways with spatial and user group heterogeneity. *NETNOMICS*, 10(1), 141–160.

Dulles Greenway, 2012. Toll Rates-January 2012, Available at: http://dullesgreenway.com/toll-rates-2/ (Accessed June 8, 2012).

EMFAC, 2011, Available from: http://www.arb.ca.gov/jpub/webapp//EMFAC2011WebApp/MainPageServlet?b_action=view , Accessed October 2012.

Evenhuis E., Vickerman R., 2010. Transport pricing and Public Private Partnerships in theory: Issues and suggestions. *Research in Transportation Economics*, 30(1), 6–14.

FHWA, 2011. Toll facilities in the United States. Web publication# FHWA-PL-11-032, Available from: http://www.fhwa.dot.gov/policyinformation/tollpage/t1part3.cfm Accessed April 2013.

Gauna, E., 1995. Major sources of criteria pollutants in nonattainment areas: Balancing the goals of clean air, environmental justice, and industrial development. *Hastings West-Northwest Journal of Environmental Law and Policy*, 3, 379–404.

Geddes, R. R., Nentchev, D. N., 2013, Private investment and road pricing: The investment public-private partnership. *PERC Research Paper* No. 12-16. Available at SSRN: http://ssrn.com/abstract=2139463 or http://dx.doi.org/10.2139/ssrn.2139463.

Kim, D. S., Porter, J. D., Whitty, J., Svadlenak, J., Larsen, N. C., Capps, D. F., Imholt, B., Pearson, J.L., and Hall, D. D., 2008. Technology evaluation of Oregon's vehicle-miles traveled revenue collection system- Lessons learned. *Transportation Research Record*, 2079, 37-44.

Leape, J., 2006. The London congestion charge. *The Journal of Economic Perspectives*, 20(4), 157-176.

Lou, Y., Yin, Y., Laval, J. A., 2011. Optimal dynamic pricing strategies for high-occupancy/toll lanes. *Transportation Research Part C*, 19(1), 64–74.

Mallozzi, L., 2007. Noncooperative facility location games. *Operations Research Letters*, 35 (2), 151–154.

McCubbin, D.R., Delucchi, M.A., 1999. The health costs of motor-vehicle related air pollution. *Journal of Transport Economics and Policy*, 33 (3), 253–286.

Nagurney, A. 2000. *Sustainable Transportation Network*. Edward Elgar Publishing Inc., Northampton, MA, USA.

Poole, R., 2011. Rebuilding and modernizing Wisconsin's interstates with toll financing. Wisconsin Policy Research Institute, (September 2011), 18–25.

Poorzahedy, H., Rouhani, O.M., 2007. Hybrid meta-heuristic algorithms for solving transportation network design. *European Journal of Operational Research*, 182 (2), 578–596.

Prud'homme, R., Bocarejo, J.P., 2005. The London congestion charge: A tentative economic appraisal. *Transport Policy*, 12, 279–287.

Reason Foundation, 2009. Annual privatization report, edited by L. C. Gilroy.

Rouhani, O.M., Niemeier, D., 2011. Urban network privatization: A small network example. *Transportation Research Record*, 2221, 46–56.

Rouhani, O.M., Niemeier, D., Knittel, C., Madani, K., 2013. Integrated modeling framework for leasing urban roads: A case study of Fresno, California. *Transportation Research Part B*, 48 (1), 17–30.

Rouhani, O.M., Niemeier, D., 2013. Flat versus spatially variable tolling: A case study of Fresno, California, Working Paper.

Sheffi, Y., 1984. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Englewood Cliffs, N.J., Prentice-Hall.

The Road Information Project (TRIP), 2011. Key facts about America's surface transportation system and federal funding, available at: http://www.tripnet.org/docs/TRIP%20National%20fact%20sheet%20Sept%202011.pdf. Accessed December 2012.

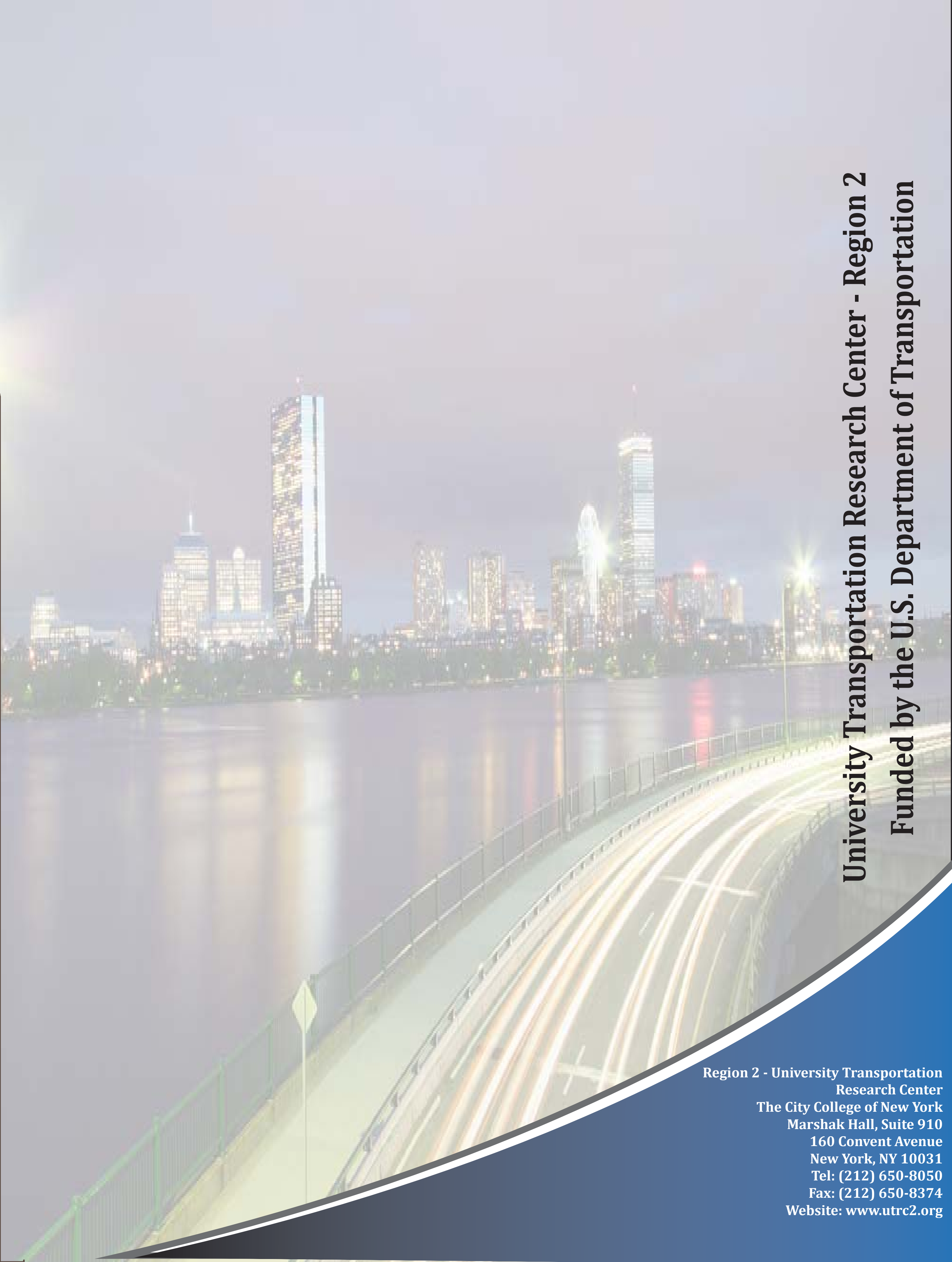
Wardrop, J.G., 1952. Some theoretical aspects of road traffic research. Proceedings of the Institute of Civil Engineers, Part II, 325–378.

Wang, M.Q., Santini, D.J., Warinner, S.A., 1994. Methods of valuing air pollution and estimated monetary values of air pollutants in various US regions. Technical report, Argonne National Lab.

Zhang, X.Q., 2005. Critical success factors for public–private partnerships in infrastructure development. *Journal of Construction Engineering and Management*, 131 (1), 3–14.

Zhang, L., 2008. Welfare and financial implications of unleashing private-sector investment resources on transportation networks. *Transportation Research Record*, 2079, 96–108.

Zhang, L., Levinson, D., 2009. The economics of road network ownership: An agent-based approach. *International Journal of Sustainable Transportation*, 3 (5-6), 339–359.



University Transportation Research Center - Region 2
Funded by the U.S. Department of Transportation

**Region 2 - University Transportation
Research Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: (212) 650-8050
Fax: (212) 650-8374
Website: www.utrc2.org**