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Price Discovery for Strategic Compensation of Toll Road Operators to Relieve State Maintenance Impacts

January 31, 2023

Prepared by:
J. Gifford, E. Miller-Hooks, S. McNeil, N. Lee,
S. Mamdoohi, B. Atolagbe, and T. Hurley

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J. Gifford, https://orcid.org/0000-0001-6216-2118, Elise Miller Hooks, https://orcid.org/0000-0002-6849-2916, S. McNeil, https://orcid.org/0000-0001-5983-8623, N. Lee, S. Mamdoohi, B. Atolagbe, and T. Hurley

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16. Abstract

The concept of compensating toll operators if tolls are suspended to encourage users of a parallel or nearby route to move to the toll facility during maintenance or reconstruction has not been widely used. However, closing a segment to traffic during maintenance or reconstruction has been shown to be efficient and offer significant benefits in terms of safety and the quality of the work. This research was undertaken to (1) document how state DOTs currently work with toll road operators, including public–private partnership (P3) concessionaires and public toll authorities, to mitigate the impacts of major maintenance and other planned and unplanned facility outages; (2) examine whether and how much states could further mitigate the adverse impacts of scheduled major maintenance and unanticipated facility closures by cooperating with the operators of nearby facilities operated by toll road operators; (3) examine how much states could benefit by designing major maintenance programs that, by using such mitigation measures, allow larger-scale and more efficient major maintenance strategies; (4) estimate the feasibility and cost of such cooperation to the state DOT and the toll road operators and devise potential strategies to enable such cooperation. A literature review, interviews, and modeling demonstrate that having a pre-existing strategy for compensating toll operators maximizes social welfare. A game theory model of the decision process showed that an ex-ante (as opposed to an ex-post) compensation arrangement is optimal. The model and solution method were applied on a case study associated with facilities along I-15 in California. The research demonstrated that the concept is promising and that respecting the perspective of the different actors is important. The federal government and many states have shifted significantly away from reliance on gas taxes and begun to rely much more heavily on general revenues and sales taxes. At the same time, interest in access to private capital markets, risk tolerance, and technological savviness has grown, and that often relies on toll-based delivery. As this shift unfolds over the decades ahead, this research has illustrated the potential benefits and challenges of a new type of collaboration and cooperation.

17. Key Words

Toll road operator, maintenance, reconstruction, public–private partnership, P3, concessionaire, facility closure, mitigation measure, social welfare

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Summary

The concept of compensating toll operators if tolls are suspended to encourage users of a parallel or nearby route to move to the toll facility during maintenance or reconstruction has not been widely used. However, closing a segment to traffic during maintenance or reconstruction has been shown to be efficient and offer significant benefits in terms of safety and the quality of the work.

A literature review, interviews, and modeling demonstrate that having a pre-existing strategy for compensating toll operators maximizes social welfare. The pre-existing strategy may be in the form of guidelines or a model that sets the level of compensation.

A game theory model of the decision process shows that an ex-ante (as opposed to an ex-post) compensation arrangement is optimal. Toll concessionaires are often willing to forego some claims for compensation for long-term gains such as preserving a relationship with the DOT and protecting business information. Such forbearance is certainly welcome from the DOT's perspective. However, DOTs cannot assume such forbearance in their maintenance planning. If the DOT wishes to incorporate toll suspensions systematically into its maintenance planning, then an ex-ante compensation provision is desirable.

A detailed model to set the level of compensation and schedule improvements is formulated, solved, and applied to a simple network. The potential benefits and costs of exploiting excess capacity along concurrent tolled roadway facilities during improvement action execution on a public roadway, where the tolled facilities are operated by a private concessionaire through a public-private partnership, are explored. Losses to the concessionaire due to reduced toll revenues are compensated.

The model uses a four-level mathematical conceptualization of this multi-stakeholder equilibrium problem that captures both public and private perspectives, and an iterative approach that exploits off-the-shelf software for its solution. In addition to identifying equilibrium reduced-toll prices and corresponding compensation to be paid to the P3 concessionaire, the technique produces the timing for executing the needed improvement actions to attain the lowest total costs to drivers and the public agency.

The model and solution method were applied on a case study associated with facilities along I-15 in California. The results of the case study demonstrated that the proposed model can be effectively used to determine optimal timing for improvement action execution while accounting for the needed compensation for the private concessionaire and network-wide impacts of activities to achieve a minimum total agency and user (A-U) cost. Results show that carefully scheduling the improvement activities and simultaneously agreeing to reduce toll prices can lead to a significant decrease in total travel time for travelers and total A-U cost. This is achieved with small costs to the state DOT and no reduction in total revenue for the concessionaire. As the solution methodology is heuristic, even lower cost solutions may exist, making this general concept more viable. Improved heuristics may reduce existing optimality gaps.

Based on interviews, there remain significant challenges to implementing this strategy. First, the agencies involved (toll authorities, P3 concessionaires, and state departments of transportation) are often reluctant to share the data needed to support the models. That is, the necessary transparency is absent. Second, federal regulations may not be supportive of the process. For example, managed lanes offer an opportunity to serve as alternative parallel routes, but these facilities must meet minimum speed requirements that are met by setting tolls at appropriate levels. Suspending the tolls and the increase in traffic may result in speeds below the required threshold. Another example is whether the compensation of toll revenue lost could be considered an eligible expense under federal aid. Third, toll authorities and concessionaires are answerable to their investors. Suspension of tolls will require reporting changes in revenue and may require approval of stakeholders such as a bond council or board of directors. Finally, at present, locations where parallel or near-parallel capacity is available for use as a relief route for a DOT maintenance project are not common. Indeed, managed lanes, which often parallel interstates and major arterials, are usually built only in places where capacity is highly constrained. However, off-peak excess capacity on managed lanes often is available. Also, managed lane projects have been proliferating in the U.S. market.

The research demonstrated that the concept is promising and that respecting the perspective of the different actors is important. The structure of funding, finance, and institutions involved in U.S. highway and other infrastructure delivery is in transition. The federal government and many states have shifted significantly away from reliance on gas taxes and begun to rely much more heavily on general revenues and sales taxes. At the same time, interest in access to private capital markets, risk tolerance, and technological savviness has grown, and that often relies on toll-based delivery. As this shift unfolds over the years and decades ahead, this research has illustrated the potential benefits and challenges of a new type of collaboration and cooperation.

CHAPTER 1

Introduction

BACKGROUND

One of the hardest constraints for states contemplating major maintenance events is the impact locally and across the state network of downtime for the facility. Often the cheapest and fastest way to rebuild a major facility is to shut it down completely and then work expeditiously to complete the repair and return it to service as soon as possible. Often, however, the impact of a wholesale facility closure on facility users and users of adjacent facilities is too great – or feared to be too great – to make wholesale closure publicly acceptable.

The recent experience of New York's MTA is instructive. MTA had worked for months to prepare the public for closure of the L Train Tunnel across the East River and within Manhattan so that it could be rebuilt quickly and efficiently. In the end, the state governor intervened at the last moment and blocked the closure, responding to public outcries about the impact it would have (New York City Department of Transportation, n.d.). In general, there is a large body of literature dealing with the travel implications of planned and unplanned closures or reduced capacity and alternatives for mitigating these impacts (for example, Brown et al., 2017; Zhu et al., 2010).

For state DOTs doing highway facility major maintenance, cooperating with toll road operators in the vicinity of a planned maintenance activity may provide an opportunity to mitigate impacts on the traveling public. State DOTs could "buy" excess capacity on the nearby toll facility during the downtime event. Such a strategy might also work for unanticipated closures or capacity losses due to weather, crashes, or other emergencies.

OBJECTIVES

The research objectives are to:

- Document how state DOTs currently work with toll road operators, including public–private partnership (P3) concessionaires and public toll authorities, to mitigate the impacts of major maintenance and other planned and unplanned facility outages.
- Examine whether and how much states could further mitigate the adverse impacts of scheduled major maintenance and unanticipated facility closures by cooperating with the operators of nearby facilities operated by toll road operators.
- Examine how much states could benefit by designing major maintenance programs that, by using such mitigation measures, allow larger scale and more efficient major maintenance strategies.
- Estimate the feasibility and cost of such cooperation to the state DOT and the toll road operators and devise potential strategies to enable such cooperation.

METHODOLOGY

The project involved the following tasks:

- **Document existing modes of cooperation between state DOTs and toll operators (P3s and toll roads).** The research team developed an interview protocol (with IRB approval) and canvassed contacts in state DOTs, toll authorities, P3 concessionaires, and professional organizations. Interviews were conducted by Zoom and the notes synthesized to document awareness of current practice and opportunities, and potential barriers and benefits to cooperation.
    - **Product**: An overview of current practice. (Chapter 2)
- **Develop simulation and supporting mathematical models to determine the value of excess capacity.** Two models were developed to understand the structure of the decision-making process that could lead to the suspension of tools and the process for setting the compensation paid to the toll operator. The first model is a game theory model. Rubinstein's repeated bargaining model for an economic non-cooperative game is used to model current P3 contract norms and capture ex-post staged bargaining. The second model is a mathematical model to support the discovery of optimal toll prices and concomitant compensation levels to P3 concessionaires for the use of their facilities during the maintenance of the public roadway. The mathematical model takes the form of a multi-level, mixed-integer program. The models recognize the constraints from the perspectives of the toll operator and the state DOT.
    - **Product**: Model descriptions. (Chapter 3 and Chapter 4)
- **Develop a case study.** A realistic case study was developed and provided an opportunity to explore how the mathematical model works.
    - **Product**: Documentation of case study and insights. (Chapter 4)
- **Structure a scenario analysis using the simulation and supporting mathematical model.** This work, aimed at a future project in which the mathematical model can be generalized, describes a sensitive analysis as well as a structure for exploring the threshold levels of demand, capacity reduction, and differential costs between daytime and nightwork to understand the situations in which compensation should be sought.
    - **Product**: Plan for future analysis. (Chapter 5)

REPORT OUTLINE

The report is organized as follows.

- Chapter 1: Introduction (this chapter). This chapter presents background, objectives, and an overview of the methodology.
- Chapter 2: State of the Art and State of the Practice. The chapter includes a brief literature review and documents the process used for interviews and the findings from the interviews of toll authorities, concessionaires, state DOTs, and other experts. The section describing the interviews and findings was presented in a poster at the CIAMTIS Transportation Asset and Infrastructure Management Conference in October 2022. The citation is:
    - Atolagbe, Babatunde, Narae Lee, Jonathan Gifford, and Sue McNeil, "Price discovery for strategic compensation of toll road operators to relieve state maintenance impacts: Insights from interviews of operators, states, and experts," CIAMTIS Transportation Asset and Infrastructure Management Conference, Boalsburg, PA, October 2022
- Chapter 3: Managed Lane Downtime Usage to Relieve Maintenance Impacts of Adjacent Facilities: A Repeated Game for P3 Cost Sharing. The chapter described the game theory model used to structure the negotiation between a state DOT and a concessionaire. This

chapter was prepared as a paper and poster presented at the Transportation Research Board Annual Meeting. The citation is:

  - Lee, Narae, and Jonathan Gifford, "On the Optimal Contract for Emergency Maintenance Project: A Repeated Game Analysis of the U.S. Department of Transportation and Private Toll Operator Cost Sharing," 102nd Annual Meeting Transportation Research Board, Washington D.C., January 2023.

- Chapter 4: An Equilibrium Approach for Compensating Public-Private Partnership Concessionaires for Reduced Tolls During Roadway Maintenance. The chapter formulates and solves a multi-level, mixed-integer program to determine both the optimal timing of maintenance (by day of the week and time of day) and the optimal toll. The chapter includes a case study. This chapter was also prepared as a paper that has been submitted to *Transportation Research Part A: Policy and Practice* for review.
- Chapter 5: Making Decisions. This chapter explores the opportunities and challenges associated with suspending tolls while an untolled facility is undergoing maintenance, resurfacing, or rehabilitation. This chapter serves as a foundation for future work.
- Chapter 6: Conclusions, Recommendation and Future Research. This chapter summaries the project. The conclusion is that the research is promising but the perspectives of the different actors is important. Areas for future research are presented.
- References are included at the end of each chapter. In addition, appendices provide supporting data. Appendix A is a list of acronyms. Appendix B includes the IRB documents required for the interview's discussion in Chapter 2. Appendix C provides supporting details for the models and case studies in Chapter 4.

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CHAPTER 2

State of the Art and State of the Practice

INTRODUCTION

Full road closure during roadway rehabilitation, maintenance, and repair have demonstrated gains in efficiencies, in particular reduced duration and cost, improved safety, better quality end products, and reduced short- and long-term user costs. These benefits are documented in a series of case studies (FHWA, 2003; FHWA, 2004a; FHWA, 2004b; FHWA, 2004c). Despite the potential benefits, and the often-favorable public perception of such projects, orchestrating full closure can be challenging. Public support is not always forthcoming, and the closure requires careful planning and communicating potential alternative routes to the users (Brown et al., 2017). Corridors in which a private road closely parallels a public road offer opportunities to realize the benefits of full closure, particularly if the public facility is closed and the tolls are reduced or eliminated during the closure. This presents a new challenge involving understanding the amount of compensation to the toll operator for the lost revenue.

This chapter documents the relevant literature, and findings from interviews with relevant stakeholders. The chapter also documents the methodology used to structure the interviews, recruit interviewees, and analyze the information collected during the interviews. The chapter concludes with a summary of the state of the art and state of the practice based on the literature review and interviews.

LITERATURE REVIEW

The concept of lane rentals, compensating toll authorities for reducing tolls to accommodate traffic while parallel and nearby facilities are maintained, is not commonly addressed in the literature. This literature review covers three areas:

- An overview of the landscape in which toll roads and public–private partnerships are operating.
- A review of 10 concessionaires and toll authorities focusing on their perceptions of opportunities to suspend tools.
- The motivation for this work; specifically, the challenges of implementing asset management processes.

Toll Roads and Public Private Partnerships

Public–private partnerships have emerged over the last four decades in response to the challenges presented to state DOTs with limited public funding. A P3 is a long-term contract between a private company and the government to deliver transportation infrastructure involving design-build-finance-operate-maintain (DBFOM) phases of the lifecycle. This structure supports sharing of risk and allocating risks to the sector best able to manage the specific type of risk. Furthermore, government agencies are motivated to pursue P3s to be able to address congestion and aging infrastructure, overcoming budget constraints, accelerating project delivery schedules, pursuing innovative methods, and incentivizing lifecycle management. There are also challenges and limitations related to P3s. These include statutory authority, lack of familiarity and transparency, and concerns with tolling and political risk (Gifford, 2019; Bolaños et al., 2017).

P3s have been used in California, Colorado, Florida, Maryland, Pennsylvania, Texas, and Virginia, as well as bi-state projects such as New York–New Jersey and Ohio–Kentucky. Projects include bridges, tunnels, commuter rail, and road segments. Several projects also include managed lanes (Gifford, 2019). Managed lanes are “highway facilities or a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions” (FHWA, 2022).

Contracts – Case Analysis

Gifford et al. (2021) reviewed eight P3 contracts to understand how concessionaires and government owners might support toll reductions if public entities choose to shift demand from publicly owned facilities to privately owned facilities during downtime events. While all contracts permit state departments of transportation to suspend tolls under certain circumstances, no contract supported non-emergency down-time management, and P3s are reluctant to use this mechanism.

The Challenges of Implementing Effective Asset Management Processes

Transportation asset management frameworks, tools, and processes have evolved over the last three decades to facilitate effective data-driven decision making related to maintenance and improvement of transportation assets recognizing constrained resources, risk, lifecycle costs, and the impacts on users (Shah et al., 2017). Asset management is not undertaken in isolation but works together with planning and operations. The emergence of new organizational structures, particularly P3s and concessionaires, means that state departments of transportation do not necessarily control all facilities, and asset management decision-making needs to consider institutional constraints. Estimating the costs of an action is difficult, as such costs vary with the duration of the project and the arrangements made to accommodate existing traffic.

INTERVIEWS

Planned and emergency maintenance disrupts traffic and imposes additional costs on both agencies and users. Often the cheapest and fastest way to rebuild or repair a major facility is to shut it down completely and then work expeditiously to complete the repair and return it to service as soon as possible. Often, however, the impact of a wholesale facility closure on facility users and users of adjacent facilities is too great – or feared to be too great – to make wholesale closure publicly acceptable. For state DOTs doing highway facility major maintenance, cooperating with toll road operators in the vicinity of a planned maintenance activity may provide an opportunity to mitigate impacts on the traveling public. State DOTs could “buy” excess capacity on the nearby toll facility during the downtime event. Such a strategy might also work for unanticipated closures or capacity losses due to weather, crashes, or other emergencies.

We explored opportunities for toll suspension with compensation to the toll operators when parallel state-owned routes are closed. This included modeling the decision-making process for setting the compensation and interviewing stakeholders to capture the state of the practice and to understand if relevant stakeholders were amenable to the concept. This chapter documents the results of the interviews. The interviews address the following research questions:

- What is the toll suspension mechanism, who has decision power and to what degree, who are stakeholders?
- What are the compensation criteria and procedures?
- What is the experience in toll suspension cases?

The chapter is organized as follows. The following section reviews the methodology and interview design. The subsequent section summarizes the findings, and the conclusion describes the contributions, future directions, and implications.

INTERVIEW METHODOLOGY

Interviews with state government officials (i.e., toll authorities and state DOTs), coalitions and advocacy organizations, and private development stakeholders as well as academic communities were conducted to capture the state of the practice and to understand if relevant stakeholders were amenable to the concept. Table 2-1 summarizes the different types of interviewees, the targeted number of each type and the number of interviews completed. The targeted interviewees were based on potential parallel facilities we were able to identify. The targeted interviewees represented seven different states, and the interviews completed represented facilities in four different states.

As no personal information was collected, the interviews were considered exempt from Institutional Review Board (IRB) approval. The exemption letters from the IRBs at George Mason University and University of Delaware are included in Appendix B. Appendix B also includes the script used to recruit interviewees, the background information provided to interviewees, and the interview script for the semi-structured interviews. However, some potential interviewees were reluctant or refused to be interviewed as this was a topic that they were not comfortable with. Interviewees were identified through personal contacts and recruited by email. The initial contact included a brief description of the project and a request to schedule the interview. Once a time and date were agreed upon, the following interview protocol was used:

- The interviewees were sent a Zoom invitation and brief project summary, a glossary of terms, and the interview questions.
- At the beginning of the interview, the interviewees were reminded that no personal information would be collected and asked if they would verbally consent to the interview.
- The project team proceeded with the interview and wrote notes.
- After the interview, the notes were shared with each interviewee.

Table 2-1. Interviewees.

Type of Interviewee	Target Number	Number Completed	Interviewee Labels
State DOT – Operates Toll Facility	5	1	A
State DOT – Operates Private Toll Facilities	2	3*	B, C, D
Toll Authorities	6	1	E
Coalition and Advocacy Organizations	2	1**	F
Private Toll Road Developers and Operators	3	1	G
Experts and Professional Organizations	3	2	H, I

*Includes two different interviews with the same state, but different divisions.

**Four participants from one organization.

The project summary and glossary, shared with interviewees, are shown in Figure 2-1. The interview questions were divided into eight categories. Categories and questions are shown in Figure 2-2. Not all interview questions applied to all interviewees. For example, some interviewees were not responsible for facilities, and some state DOTs interviewed did not have private toll roads.

Our findings and observations are summarized by categories following the same categorization for the questions shown in Figure 2-2. The responses varied depending on the type of organization and their role.

Project

This project is exploring how toll road operators (P3 concessionaires and toll authorities) collaborate with state highway officials when tolls must be suspended or reduced to accommodate maintenance or emergencies on parallel or nearby state highway facilities. In such cases, public use of toll roads may require the state to compensate the toll road operator for foregone revenue under various types of toll operating contracts, including P3s.

The interviews will focus on assembling information to support a qualitative analysis of these agreements, including a history of any downtime events and the level of cooperation between both parties.

Glossary

Bond covenant – a legally binding term of agreement between a **bond** issuer and a bondholder.... Negative or restrictive **covenants** forbid the issuer from undertaking certain activities; positive or affirmative **covenants** require the issuer to meet specific requirements. (https://www.investopedia.com/terms/b/bond-covenant.asp)

Concessionaire – in a public-private partnership, the concessionaire is the private entity that enters into a long-term concession for the design, construction, finance, operation, and/or maintenance of an infrastructure asset owned by a state DOT or other governmental body.

Constraints – include limitations imposed by the bond covenant or operating agreement.

Operating or concession agreement – the contract between the asset owner and the concessionaire in a public-private partnership.

Public-private partnership (P3) – a long-term (usually multi-decade) agreement between a public infrastructure asset owner and a concessionaire for the design, construction, finance, operation, and/or maintenance of that asset.

Stakeholder – Individuals or groups who have an interest or role in the project, program, or portfolio or are impacted by it. (https://www.apm.org.uk/resources/glossary/)

Toll authority – governing body that is legally empowered to review and adjust **toll** rates and design, construct, finance, operate, and maintain a toll road, bridge, or other facility. Unless otherwise delegated, the transportation commission is the **tolling authority** for all state highways. (https://www.lawinsider.com/dictionary/tolling-authority#:~:text=Tolling%20authority%20means%20the%20governing%20body%20that%20is%20legally%20empowered,authority%20for%20all%20state%20highways)

Toll suspension – the act of not requiring payment of a toll for the use of a road.

Figure 2-1. Project summary and glossary shared with interviewees.

Category	Questions
Context	• Please describe the facilities you operate and the structure of your organization.
Prior Experience	• Does your organization have any experience with toll reduction or suspension as a means of fostering relief for maintenance events on untolled adjacent or parallel facilities? • What was the process for deciding to suspend/reduce tolls? • Were toll road operators compensated for associated revenue losses? If so, at what rates? • What was the process for determining any compensation?
Toll Suspension Authority and Process	• Who has the authority to suspend the toll? • What is the suspension process? • Do DOTs tell the toll authorities to suspend, or do both parties form a consent agreement? • Some toll roads are limited by their bond covenants in reducing or waiving tolls. Are you aware of any such restrictions related to toll roads in your jurisdiction? • What are the major channels of communication between the state DOTs and the toll authorities?
Standard Practices	• What is the history of cooperation during downtime events? Are there standard practices? • Do you have any written protocols for operating practices? For instance, we recently found one protocol in Virginia.
Stakeholder Interests	• Who are the major stakeholders in deciding whether to waive or reduce tolls to accommodate maintenance on non-tolled facilities? • How do their interests vary? For example, how do their perceptions of cost, benefit, and barriers differ? • Are there any regulatory constraints on such cooperation? If so, what are they?
Potential for Expanded Use	• Do you believe there is potential for expanded use of toll reductions/suspensions to mitigate the impact of maintenance events on adjacent or parallel facilities? • What would the benefits be? • What are the barriers?
Opinions on the Research Concept	• Do the questions raised in this research have any relevance for or applicability to your organization? • Does such expanded cooperation seem practical? Does it seem relevant to your organization's operations? • Would you envision the results of this research leading to any changes to your organization's practices? If so, how? • Can you suggest any relevant examples of cooperation, publications, articles, or potential interviewees that might help us pursue our research?
Open Discussion	• Is there anything else you would like to share with us?

Figure 2-2. Interview categories and questions.

INTERVIEW FINDINGS AND OBSERVATIONS

Context

The owner/operators that we interviewed varied from states in which the toll road is an integral part of the state DOT, to toll authorities that are public organizations but have autonomy from the state DOT, to private toll operators.

Based on the interviews, toll authorities fall into classes as follows:

- Separate authority – Trust Agreements where the authority has some independence; reports to the DOT or Governor. Examples are Florida, Maryland, North Carolina, and Pennsylvania.
- Within the DOT – All activities handled by a unit within the DOT. Examples are Delaware, Maine, and Massachusetts.
- Autonomous, independent authority – Money is not appropriated from the budget and the DOT does not have a direct role. Examples are Illinois and New York.
- The P3 interviewed manages the entire right-of-way including untolled access roads and parallel routes.

Prior Experience

All owners/operators interviewed have some experience with suspension of tolls for emergencies, such as crashes or other major incidents. These are unplanned and short-term. There are also examples of toll suspensions given grandfathered agreements with communities or negotiations with communities. In one case, the state DOT paid an up-front amount to the private toll operator; in another, residents were able to purchase a reduced toll. Other examples include toll suspensions for presidential inaugurations and motorcades, work on toll plazas that has made collection infeasible, military convoys, funerals (where the funeral home has paid the tolls after the event), and inclement weather events such as snow. Interviewees C and E noted that state DOTs work to avoid full closure of major roads. However, partial closure can push traffic to other facilities. Interviewee E provided an example. Work on a tolled bridge reduced the number of lanes from four to two (one in each direction) and 40% of the traffic diverted to a nearby untolled facility.

Several interviewees alluded to the lack of trust between toll operators and state DOTs, or the reluctance to share data and information (Interviewees B, C, G, H, and I). This concept requires "commonality of purpose" (Interviewee H).

Some examples of compensation claims that have been submitted include:

- Revenue losses related to no access to a toll road due to ramp closure due to lack of drainage maintenance by the state. The claim was denied. (Interviewee C)
- Up-front payment by the state to provide community access to a toll facility. (Interviewee H)

Toll Suspension Authority and Process

All state DOTs have the authority to suspend tolls. The Bond Covenant/Comprehensive Development Agreement (CDA)/Trust Agreement typically spells out the circumstances under which tolls may be suspended and the toll operator has the right to seek compensation. No interviewee could identify a detailed process for determining the compensation and none had experience with toll authorities or private operators seeking compensation. The burden of documentation is on the concessionaire. Interviewees B and C suggested that neither party (the state nor the toll authority) wished to disclose too much information. We noted that disclosure can result in a fairer, more equitable process, but that is not the objective. There are also transaction costs.

In addition, the following observations were made:

- Interviewee D described an informal process requiring a lot of coordination of activities, particularly when tolled and untolled facilities are interconnected. Interviewee D also emphasized that such coordination could take advantage of off-peak traffic such as night-time work.
- Interviewee F recognized that how decisions are made depends on the structure of the organization and the role of the governor, secretary of transportation, or commissioner. Interviewee F also noted that there is a political cost, good will, and public relations associated with closing roads and charging tolls.
- Interviewee I noted: (1) DOTs prefer certainty, so would prefer to know what they are paying upfront; (2) the negotiation is simpler if there is no debt, as the toll operator does not have to report to the lenders.
- Interviewees B, D, and G would prefer to avoid a formal process for toll suspension.

Standard Practices

While no specific practices were identified, several interviewees (Interviewees A, B, and G) referred to the use of historical data on usage to determine the appropriate compensation or estimated lost revenue.

Stakeholder Interests

Concessionaires and toll authorities have a duty to be fiscally responsible. Lost revenue would typically be calculated based on historical usage and reported to the agency and the bond counsel. Investors, as stakeholders, play an important role here. This is closely tied to performance metrics that could change the terms of loans.

Users are interested in minimizing their disruptions. This concept is intended to benefit the road users. However, depending on the toll road and the toll collection points, in some systems there may be opportunities to avoid the toll (Interviewee A and E). In other cases, there are no parallel or nearby facilities. For example (Interviewee H), there are few alternatives to bridges over major rivers, such as the Mississippi.

There may also be regulatory issues and US DOT, as the regulator is a stakeholder. Specifically, managed lanes require a guaranteed minimum speed (45 mph), and federal regulations may influence the ability to suspend tolls (Interviewee I).

State DOTs do not want to pay compensation claims unless they really have to (Interviewee B), and minimize disruptions to the public, consistent with their commitments to deliver service (Interviewees B and D). DOTs also have limited resources for analysis (Interviewee I)

Potential for Expanded Use

It is challenging to include all possible scenarios in the contracts (Interviewee C).

Opinions on the Research Concept

The tools were perceived as good in a hypothetical situation (Interviewees B and E). However, some interviewees expressed a preference for negotiating (Interviewees B and C) or avoiding closure (Interviewee E).

Interviewee F asked for clarification on the objective of the research. Is the outcome a decision tree to determine when the toll should be lifted? The researchers responded that we are seeking to explore a range of practices related to planned and unplanned events. Long-term events require education and in some cases substitution (for example, extra transit service), particularly when the closure impacts commuters. Furthermore, our analysis may highlight when this is not an appropriate solution.

Interviewee H likes the concept but observed that "the devil is in the details." If states had hard data upfront, then they would be better able to explore different structures (work hours, duration, construction methods) for repair and reconstruction projects. In essence, one is balancing reliability and flexibility for the users, operators, and agencies.

The idea of a demonstration project was raised (Interviewee H). We have been unable to determine if toll compensation would be an eligible federal aid project cost. Interviewee I indicated that it would be difficult to generalize the conclusions on the basis of one example.

Open Discussion

In response to the questions "Is there anything else you would like to share with us?" several interesting topics came up for discussion:

- Differences in the proposed process if the operator is responsible only for managed lanes, or managed lanes and general-purpose lanes. Interviewee B and Interviewee G noted that operators with both managed and general-purpose lanes have more flexibility.
- Interviewee B noted that there is a constant negotiation process, and that process is influenced by external events such as a pandemic or the economy, not just the suspension of tolls.
- The idea of including in the agreement a fixed number of days over a fixed period of time for toll suspension might be interesting (Interviewee B and Interviewee F).
- Most states have a system for coordinating lane closures to avoid conflicts, and traffic modelers who explore closure scenarios. However, these data on closures are not tracked and the closure scenarios not shared (Interviewee C). Interviewee E indicated that the state computes user costs per vehicle hour for cars and trucks on an annual basis and publishes that data. These rates are useful for assessing the value of compensation.
- Most operators (states, authorities, and concessionaires) have too much going on to be able to explore new ideas (Interviewee C and Interviewee I).

Observations

In planning the interviews, we had attempted to recruit interviewees where there were potential parallel routes where toll suspension would benefit users of the untolled facility if there were major disruptions on the untolled facility due to maintenance. Over the course of the interviews, some of the interviewees identified other facilities to which the concept could be applied. Table 2-2 summarizes these facilities.

CONCLUSIONS FROM THE INTERVIEWS

In summary, there was little experience with toll suspensions other than for emergencies and events. Current P3 agreements always have toll suspension provisions and point to a negotiated process. Toll authorities are a mixed bag, with some authorities having power but rarely exercising it and others unsure or reluctant to consider it. Nevertheless, interviewees showed tentative interest in the concept of collaborative suspension. The interviews also provided insights into the processes and underscored the complexities.

Contributions

The contributions of this work include:

- Documentation of the variety of experiences and level of interest.
- Listing of locations where toll suspensions might work.
- Identification of areas of concern such as minimum speeds on managed lanes, and disclosure of information on the part of both states and concessionaires.

- Recognition of the limited number of opportunities with excess capacity for extended closure periods.
- Recognition that calculations could provide insights to agencies.

Future Directions

Opportunities for future research include:

- Development of a potential demonstration project.
- Further exploration of the role of models in making decisions about traffic disruptions.
- Research to fill gaps with respect to unknown information such as FHWA's regulations related to speeds on managed lanes, the decision-making structures of other authorities, and more experiences of P3s.
- Additional clarification of internal practices where the same authority manages multiple practices in the right-of-way.
- Better understanding and documentation of transaction costs.
- Additional examples.

Implications of the Research

The research provided:

- Insights into the role of institutional and organizational structure and infrastructure delivery, including understanding decision-making, and tangible and less tangible transaction costs.
- New information to inform discussion of make/ buy decisions for transportation agencies.
- Recognition of the importance of coordination across boundaries.
- Information sharing (presumption that transparency is in the public interest, but competition can be helpful) - concerns with setting binding precedence.
- Insights into the role debt plays in decision-making the need to report disruption to revenue streams to lenders, which introduces a new set of interests into the equation.
- Recognition that the decision to suspend tolls occurs within the large context that recognizes the status of the economy and changes in commuting patterns.

Table 2-2. Parallel facilities that may be candidates for toll suspension.

Location	Owners	Type(s) of Organization(s)	Roads/Bridges
DE	Delaware Department of Transportation/ Delaware Turnpike	State DOT/ Toll Authority	US 1 (tolled) and US 13 (untolled) I-95 (tolled) and US40 (untolled)
DE/NJ/ PA	Delaware River and Bay Authority/ Delaware River Port Authority	Toll Authority	Delaware Memorial Bridge/ Commodore Barry Bridge
FL	Florida DOT/ Florida Turnpike	State DOT/ Toll Authority	I-95 parallel to FL turnpike
MD	Maryland Department of Transportation (MDOT)/ Maryland Transportation Authority (MDTA)	State DOT/ Toll Authority	Beltway and harbor tunnels Bridge over Susquehanna – I95/ US40
NJ	New Jersey DOT and New Jersey Turnpike	State DOT/ Toll Authority	I-295 and New Jersey Turnpike
PA	PennDOT/ PA Turnpike	State DOT/ Toll Authority	I-476 (tolled) and I-81 (untolled)
TX	TXDOT/ Cintra	State DOT / Private Toll Facilities	Dallas/Ft. Worth managed lanes (LBJ, North Tarrant Expressway, SH 288)
VA	VDOT /Transurban (I-495/95/395) Cintra (I-66 outside the beltway)	State DOT / Private Toll Facilities	I-495/95/395 express lanes, I-66 outside the beltway (Washington Metro area)

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CHAPTER 3

Managed Lane Downtime Usage to Relieve Maintenance Impacts of Adjacent Facilities: A Repeated Game for P3 Cost Sharing

INTRODUCTION

As the preceding chapter elaborates, the users of road facilities with an outage and adjacent roads are heavily affected. Justifiably, these experiences, also called road user costs (RUCs) (Daniels et al., 2000), are often one of the primary constraints when a state DOT schedules a maintenance event. RUCs may deter state DOTs from implementing the complete blockage although a full closure of a road facility could achieve the most effective and efficient maintenance outcome.

A large body of literature discusses facility outages and RUCs, suggesting several mitigation strategies. For example, expanding nearby facilities by converting shoulders to lanes also lessens users' impact (Zhu et al., 2010). Increasing users' awareness also helps change user behaviors in the face of facility outages (Brownset al., 2017). A recent research report by one of the authors examines the borrowing of adjacent toll facilities during downtime. State DOTs could cooperate with adjacent toll operators to use some capacity of toll roads. Increasing access to the toll lanes allows the government to mitigate potential user impacts caused by maintenance events on general-purpose lanes (Gifford et al., 2021).

Suspending or reducing tolls necessarily incurs revenue losses for a toll operator. Since the toll suspension happens at the behest of the state government, the toll operator has a right to claim compensation for the profit loss. Despite long-term benefits for both parties, the suggested policy will entail bargaining between state DOTs and toll operators.

Existing practices allow various bargaining process forms, depending on the entity type of a toll operator and the government and toll operator relationship. For example, some toll roads are operated directly by state DOTs, easing the bargaining process into the internal organization. When looking into the most revenue-sensitive cases of public–private partnerships, however, the public and private entities need to negotiate directly. In current P3 practices, CDAs between DOTs and private toll concessionaires can include terms like "department changes," "significant force majeure events," and "unavailability events with pre-determined price," under which toll concessionaires can claim compensation for the lost profit from state governments (Gifford et al., 2021). However, most terms suggest the post-contract bargaining of unplanned events rather than ex-ante clarification by terms. The post-contract bargaining, if not agreed easily, will incur unnecessary administrative and time burdens.

Can owners and concessionaires avoid such after-contract bargaining by having ex-ante contingency compensation terms on the public use of toll facilities? Contract theory suggests the pros and cons, or fundamentally, the feasibility of both complete and incomplete contracts (Javed et al., 2014). The theory of incomplete contracting asserts that it is impossible to comprehensively develop contracts that cover all potential boundaries (Grossman and Hart, 1986; Hart and Moore, 1990; Hart, 2017). Efforts to address all future uncertainties within an initial contract not only make the initial agreement more complex but will also likely fail eventually, resulting in differing commitment problems from the associated parties.

However, scholars also suggest that ex-ante probabilistic uncertainty considerations can mitigate some of those problems (Maskin and Tirole, 1999). Despite accounting for all contingencies being theoretically impossible, well-structured contracts encompassing expected risks will reduce the transaction costs of future negotiations.

Motivated by the economic contract theory, this chapter aims to comparatively analyze the current practices of ex-post maintenance compensation and potential ex-ante provision of contract terms. Studying the different bargaining incidences with Rubinstein's repeated game framework, the authors derive a Subgame Perfect Nash Equilibrium (SPNE) and a Pareto optimal compensation type. The model choice reflects the indefinite states of an ex-post compensation process that the current practice suggests. The following sections elaborate on our model developed: players and their incentives, underlying assumptions of the game, three different circumstance scenarios, and anticipated Nash equilibriums.

EXISTING POLICY PRACTICES

By opening the toll facilities, the RUC can be directly transferred to toll concessionaires and DOTs. The user inconveniences from the maintenance are at least partially resolved through use of the additional capacity of the toll facilities (Gifford et al., 2021). Instead, the toll concessionaires will lose the lent capacity of the toll facility or the enforced price discount during the toll road borrowing as facilities are open to the public. The DOTs will need to compensate for the loss of the toll operators, which is also a direct loss of DOTs. (Here, the social cost can be part of indirect and large loss for DOTs considering the government objective and potential political and long-term risks. We address this later in the third contextual scenario.)

The direct loss of the two parties may not be independent depending on contract types. However, from a narrow perspective of compensation, the two losses offset each other, causing a sort of cost-bargaining situation. If such bargaining happens, what kind of conventions do the current agreements point to?

Existing practices vary depending on whether the toll operator is a public entity, especially a part of DOTs, or a private concessionaire. For some states, contracts have a detailed protocol because most toll operators are private concessionaires. In others, where most toll roads are operated by the government, internal documentation does not elaborate on compensation. Instead, the budgetary system is consolidated and executed at the department level. In some unique cases, a combined case of government operation and the use of private concession, the state DOT annually calculates RUC for associated closures and the private concessionaires possess toll profiles for all past price changes.

Among the different operation structures, the P3 case is most probable with the bargaining issue, as the DOT and the concessionaire's calculation of cost varies, with the private concessionaire being most sensitive to profit maximization. The P3 case of Comprehensive Development Agreements contains terms for the DOT to suspend toll roads if deemed necessary during emergencies. For example, an unexpected winter storm may result in road clearing issues, and the DOT can suspend managed lanes operated by private concessionaires to clear them. In such cases, the toll concessionaire has a right to claim lost profits. Included contractual terms, such as "department changes," "significant force majeure events," or "unavailability events with pre-determined price," justify such compensation claims.

In other words, the terms of the P3 CDA suggest the implementation of post-contract bargaining, rather than ex-ante clarification, by terms when roads need to suspend due to DOT-deemed emergencies. If our policy suggestion of borrowing managed lanes to mitigate RUC for general lane maintenance is implemented, this term would be most applicable under these current practices.

LITERATURE: THEORIES OF ECONOMIC CONTRACT

Economic contract theory has explored the most effective contract terms for such unexpected cost dealing. Hart et al. (1997) suggested that a government-funded private supply for public goods can use significantly incomplete contracts (Hart et al., 1997) when the non-contractable qualities of the goods and services are controlled by, for instance, the public institution or competition. Even if there are no tight complete terms, a private party will do their best diligence for the best service on the contractable qualities, as it is bound to contractual monitoring.

In the transportation P3 case, non-contractable qualities seem to be well under the control of the state DOTs with the procurement competitions. Also, private concessionaires generally have long-term operational relationships. If non-contractable service quality causes severe fallout, the likely punishment that private partners would face, such as opting out from future contract opportunities, could be catastrophic.

However, at the same time, the long and overlapping durations of the transportation contract and evaluation can also easily cause principal-agent problems, making the non-contractable quality controls ineffective. A concessionaire with multiple contracts can seek rents from different projects to cover the loss when not fully compensated. In such a case, Hart (2017) suggests that in-house services are better not to have deleterious effects on the quality (Hart et al., 1997). In reality, the private involvement for transportation projects benefits in many aspects. Therefore, it is still valuable to study the ex-ante specification possibilities of the compensation terms in the transportation policy domain.

A near-complete contingency plan for future managed lane projects would be difficult to draft ex-ante, as it necessarily involves all potential safety, weather emergency, and other issues (Grossman and Hart, 1988; Hart and Moore, 1990). Despite this, several scholars suggest that ex-ante specification of certain terms would reduce post-dealing costs significantly (Maskin and Tirole, 1999; Javed et al., 2014). While counting the unrealized contingencies is impossible, probabilistic uncertainty considerations would evolve a contract to its complete form. From the policy perspective, the ex-ante specification will enhance the transparency in the policy process.

Potential cooperation, such as through collusion or the integration of public and private parties, would also be beneficial in aligning mutual incentives and reducing the scope of future conflicts (Hart, 2017). Indeed, in cases of state toll operators, the management issue dealing with DOT was easier–however, the P3 was near-impossible to integrate.

Considering that cooperation evidence is more readily extrapolated from non-private involvement cases, the analysis in this study primarily focused on non-cooperative bargaining.

MODEL APPLICATION: RUBINSTEIN REPEATED BARGAINING GAME

To reflect the current P3 contract norms of ex-post indefinite-staged bargaining, this chapter employed Rubinstein's repeated bargaining model from economic non-cooperative game theory (Rubinstein, 1982). Rubinstein's repeated bargaining game is a frequently revisited model in the scholarly world of economic game theory to elaborate the bargaining process of cost (loss) or surplus (pie) among players through defined periods. If it analyzes only one shot of players for the time period of a number of players, we call it an "Ultimatum Game." The analyzed time can be expanded up to an infinite time horizon, and the infinitely repeated game was used in our analysis to reflect the indefinite stages of the ex-post cost bargaining within the current CDA practices.

Our model has an unbounded time horizon to make the negotiation process repeatable but imposes the cost of each time delay (time discount factors). The cost of time delay is an important, yet often unaddressed, component in the domain of transportation policy. Not only is it a common problem of state DOTs and DBFOM toll concessionaire conflicts, but the time delay is also a traditionally unveiled aspect of inefficiency in transportation contract literature. The management burdens of time delay for state DOTs and toll concessionaires are eventually a cost to citizens in the form of tax and user inconveniences. With the repeated game model, we could include the time delay in our analysis. Lastly, the non-cooperative structure allows for analyses of the most trivial P3 case, where government actors and toll operators are completely different and seek their own interests with minimum administrative cooperation. However, our current model can be expanded to cooperative bargaining for joint cost minimization. Lastly, note that we are dealing with cost rather than surplus. Therefore, the aim of two players is to minimize the negative payoff (the cost burden for each player), not positive share from a pie or surplus.

The Two Cases of Ex-ante and Ex-post

For simplicity and clarity of the model, we structured the cases and the game steps as below. The game divided the ex-ante and ex-post compensation cases into two subgames. The two-subgame structure allows a comparative analysis of the optimal strategies, payoffs, and the probable examples of Nash Equilibrium. In reality, however, players can move at any time during the bargaining process.

Case 1: Ex-ante Compensation Term Exists

If there is an ex-ante compensation guideline, both players follow the guideline (only one action) and the game finishes.

Case 2: Suspend First, Claim Later, Ex-post Cost Distribution

The DOT's suspension triggers the concessionaire's decision to forgo the compensation or claim the cost. If the concessionaire decides to claim the cost, then bargaining begins through iteration of the following steps:
Step 1: Concessionaire decides to bid the claim amount.
Step 2: If DOT accepts the bid, the game ends.
Step 3: If DOT rejects the bid, concessionaire must decide to forgo or re-claim.
Step 4: If the concessionaire decides to forgo, the game ends.
Step 5: If the concessionaire decides to re-claim, goes back to Step 1 (Stage T = t+1).

The Game Structure

The game structure shown in Figure 3-1**.** Figure 3-2 delineates Case 1 and Case 2 and identifies the steps for Case 2. The notation is summarized in Table 3-1.

In Figure 3-1 and Figure 3-2, x indicates the amount of compensation the state DOT gives to the toll concessionaire. In Case 1, in which the ex-ante compensation terms exists, the amount $\overline{x_{DOT}}$ is pre-negotiated by the two players as the expected per-user compensation price (*p*) multiplied by the user volume (*user*) and given to the toll concessionaire when the toll road borrowing happens.

If the game moves to ex-post bargaining, the existing CDAs allow theoretically unbounded compensation claims and DOT responses. Therefore, the information set of compensation amount x_{DOT}^{t} will be continuous and unbounded in our game structure. The time discount factor γ_1, γ_2 in the model increases the time cost at a fixed rate. The time cost can vary for each player. However, the frequent reality is that the bargaining does not go more than t = 1 to 3 periods.

Players

For simplicity, we define the two players of our game as the state DOT and the toll concessionaire. In real situations, the two parties can also be independent units of the state DOT engaging in the cooperative game. However, instances where two separate parties are engaging in the game allow for an analysis of the simplest but most generalizable cases.

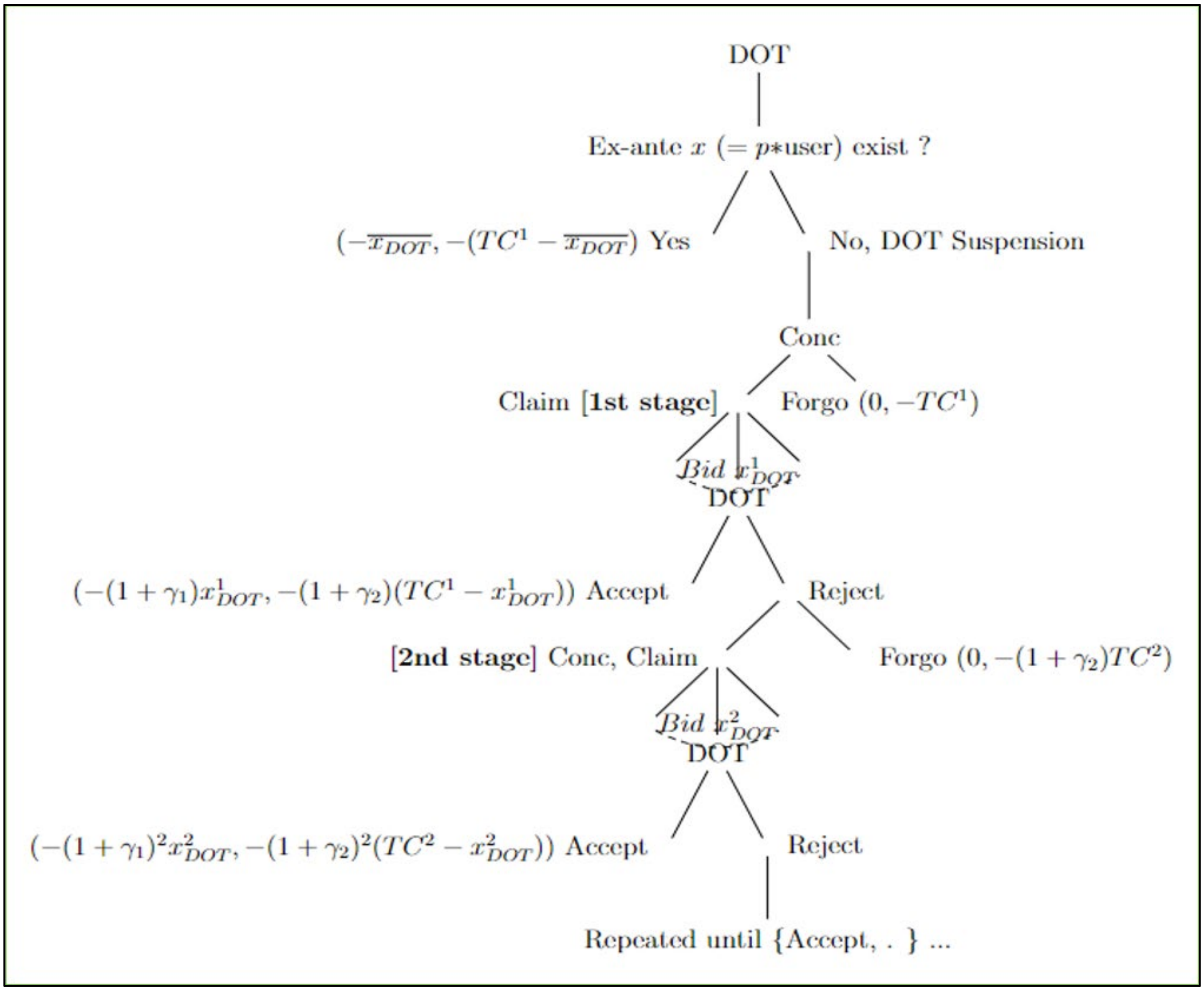

Figure 3-1. The repeated game design for the maintenance cost bargaining.

Incentives

Looking into the incentives, the economic cost is still a primary consideration of the players. However, state DOTs will potentially be concerned with social costs (that is, RUCs and civic utility) and induced political costs as well. The model counts the calculable cost first but also considers the scenario where social cost is important.

The concessionaire will primarily consider the direct loss of suspending or reducing the toll fare and the transaction cost of proceeding with various negotiation processes, including consulting and accounting fees and the human resources devoted to the bargaining processes. However, the long-term relationship with state DOTs and the sensitivity in disclosing information to file a claim will be a major consideration. Specifically, the concessionaire will face a conflict of interest between claiming the direct loss and preserving a long-term relationship with the DOT and business information. We analyzed a scenario where the latter is more important than the loss claim.

The transaction cost of consulting, accounting, and workforce utilization for claim processing contributes to the time discount factor, largely to the concessionaire but to the DOT as well. Both parties will prefer to end the compensation bargaining earlier.

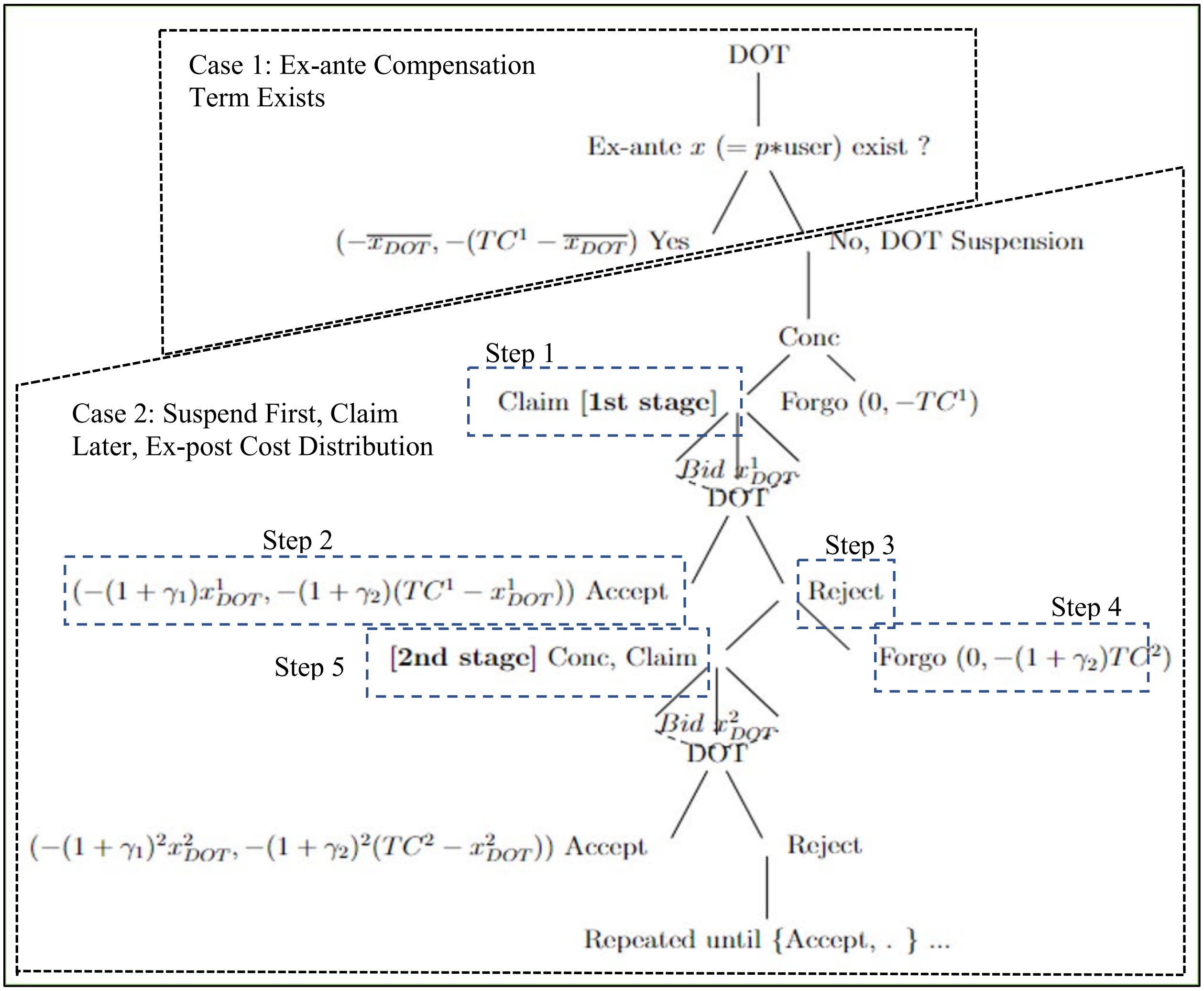

Figure 3-2. Game design showing cases and steps.

Stages

The game involves multiple stages, T = {1,2,3, ...}, until an offer *x* is accepted or the concessionaire forgoes the claim (the case of accepting *x* = 0).

Action Sets

For Case 1, an ex-ante term either exists or does not exist. The action for the DOT is to either make the ex-ante determined payment to the concessionaire or suspend tolls without an agreement. The action for the concessionaire is to accept the payment or to suspend tolls at the direction of the DOT and make a claim. The action set is represented as:

$\text{DOT}_{\text{Case1}}$ = {*Payment*, *Suspend*}
$\text{Concessionaire}_{\text{Case1}}$ = {Accept, No action proceed to Case 2}

For Case 2, an action set is defined for each player (DOT and concessionaire) as pairs of options at each stage. For the DOT, at each stage the decision is to accept or reject the claim. For the concessionaire,

the decision at stage *t* is to make a claim, x_{DOT}^{t}, or to forgo compensation. The action set is represented as:
$\text{DOT}_{\text{Case2}} = \{\{\text{Accept, Reject}\}, \{\text{Accept, Reject}\}, ...\}$

Table 3-1. Notation used in Rubinstein repeated bargaining game.

Indices	Description
I	Player i (DOT, or Concessionaire)
T	Stage *t* (1, 2, 3, … until game ends)
Sets	
DOT	Set of actions at each stage for the DOT
Concessionaire	Set of actions at each stage for the concessionaire
Equilibrium	DOT, Concessionaire optimal action (set) sequences of Subgame Perfect Nash Equilibrium
T	Set of stages
Action Type	
Case 1: DOT	
Payment	Pay amount in ex-ante agreement
Suspend	Suspend toll in absence of ex-ante agreement
	Case 1: Concessionaire
Accept	Accept payment in ex-ante agreement
No action	If there is no ex-ante agreement and DOT suspends tolls, then concessionaire proceeds to Case 2
Case 2: DOT	
Accept	Accept the claim submitted by the concessionaire
Reject	Reject the claim submitted by the concessionaire
	Case 2: Concessionaire
$Claim\ x_{DOT}^{\mathrm{t}}$	Concessionaire claims x_{DOT}^{t}
Forgo	Concessionaire forgoes claim
Variables	
p	Per-user price of compensation for borrowed toll road
TC^{t}, z^{t}	Total cost in stage *t*
users	Predicted number of users of borrowed toll road
x	Compensation the state DOT gives to the toll concessionaire
$\overline{x_{DOT}}$	Compensation the state DOT gives to the toll concessionaire when ex-ante compensation term exists
x_{DOT}^{t}	Amount claimed by the toll concessionaire in stage *t*
	Parameters
C	Total cost
γ_{i}	Discount factor for player i
η_{t}	Random shock
ρ	Common discount factor for the total cost
S	Social cost

Concessionaire$_{\text{Case2}}$
$= \{\{\, Claim\ x_{DOT}^{1}, \text{Forgo}\}, \{Claim\ x_{DOT}^{2}, \text{ Forgo}\}, \{Claim\ x_{DOT}^{3}, \text{Forgo}\}, \ldots\}$

The Total Cost for Bargaining

For the simplest case, we assume that the cost increments stochastically with a random shock, η_t. The stochastic incremental function with the zero conditional mean interprets to stationary maintenance costs with minor fluctuations. The fluctuation, even if it happened, is in manageable boundary and considered seasonal (The distributional assumption can be changed further.) A common time burden for both players $(1+\rho)$ is increasing over time (that is, inflation):

$$TC^{t+1} = z^{t+1} = (1+\rho)z^t + \eta_{t+1}$$
$$\text{where } \rho\epsilon\ (0,1), E(\eta_{t+1}|z^t) = 0, Prob(\eta_{t+1} \leq -(1+\rho)z^t||z^t) = 0 \tag{3-1}$$

Game Rules

The game rules for case 2 are as follows:

- At the beginning of stage *t*, the players observe z^t but not z^{t+1}.
- In each stage, concessionaires *Claim* or *Forgo* compensation, and DOTs *Accept* or *Reject* the claim.
- The game ends the first time DOT *Accepts* or the concessionaire *Forgoes*.
- Players have different discount factors γ_1, γ_2 in (0,1) and perceived costs increase at $(1+\gamma_1)$, $(1+\gamma_2)$ each.

Payoffs

If an offer is accepted at *t*, the state DOT pays the eventual cost of $-(1+\gamma_2)^t\ (x_{DOT}^t)$, and the concessionaire pays the rest, $-(1+\gamma_2)^t\ (z^t - x_{DOT})$.

EQUILIBRIUM UNDER DIFFERENT CIRCUMSTANCES

In this section, we explore three different contextual scenarios in which the outcome of the game represents a stationary equilibrium or stable solution. The first scenario is the baseline model without imposing any additional conditions. The second scenario assumes the claim is costly for a concessionaire in the long run. The concessionaire's decision in the second scenario is frequently observed in the real world. The third scenario considers social cost when the second scenario happens and counts the social cost minimization as part of the DOT incentives.

In each scenario, the equilibrium is represented by the action sequence pairs for the DOT and concessionaire as follows:

- {DOT, Concessionaire}
- = {{DOT Decision$_1$, Concessionaire Decision $_1$}; {DOT Decision$_2$, Concessionaire Decision $_2$};….}

With a cost to the DOT and concessionaire at equilibrium of:

- {CostDOT, CostConcessionaire} = $\{x_{DOT}^t, z^t - x_{DOT}^t\}$

Scenario 1. A Stationary Equilibrium from the Baseline Model

We start by deriving the equilibrium from the baseline model. The Rubinstein game has many possible Subgame Perfect Nash Equilibriums. Here, however, we are utilizing a stationary case to reflect that it is a rare case for an organization to make largely different decisions every time. To be specific, each different time can have potentially different offers that the state DOT may accept. However, suggesting and evaluating a different offer in each stage will incur large administrative costs to both parties, which are unlikely to happen. (The non-stationary cases can be explored further.)

In our stochastic case, the total cost can be reduced to (1+ρ) z^t, conditional on the expected random shock being zero.

$$E(z^{t+1}|z^t) = (1+\rho)z^t + E(\eta^{t+1}|z^t) = (1+\rho)z^t, \qquad where\ E\big((\eta^{t+1}|z^t)\big) = 0 \tag{3-2}$$

For the stationary solution to be internal, the solution of all accepted offers should be within a feasibility set. The feasibility condition is satisfied as follows:

$$z^t \leq (1+\gamma_i)E(z^{t+1}) = (1+\gamma_i)(1+\rho)z^t \tag{3-3}$$

In a stage *t* of case 2, if the concessionaire *Forgoes*, the expected payoff is $-z^t$. Therefore, the best response of the concessionaire is to claim x_{DOT}^t. If DOT rejects the offer x_{DOT}^t, the expected payoff in *t*+1 is $-(1+\gamma_1)^{t+1}\, x_{DOT}^{tt+1}$. Note that a concessionaire will never *Forgo*. Therefore, DOT's best response is to accept if $(1+\gamma_1)^t x_{DOT}^t \ \leq \ (1+\gamma_1)^{t+1}\, x_{DOT}^{t+1}$, for all values under z^t. Again, for a concessionaire knowing the DOT will accept an offer, it is ideal to claim x_{DOT}^t slightly lower than z^t.

Therefore, the stationary equilibrium for repeated bargaining in case 2 is,

{DOT, Concessionaire} = {Accept, Claim x_{DOT}^1 near $z^1(TC_1)$}

By comparing with the case 1 equilibrium, any $\overline{x_{DOT}} < x_{DOT}^1 \leq$ TC$_1$ will make the ex-ante compensation of case 1 superior to the ex-post cost compensation scenario for the DOT. For the concessionaire, pursuing the ex-post compensation yields larger compensation ($TC^1 - x_{DOT}^1 < TC^1 - \overline{x_{DOT}}$). However, at the beginning of a contract, the DOT likely has stronger power to choose as a government buyer for the contract. Therefore, the cost to the DOT and concessionaire at equilibrium is:

{Cost$_{\text{DOT}}$, Cost$_{\text{Concessionaire}}$} = {$\overline{x_{DOT}}, TC^1 - \overline{x_{DOT}}$}

Scenario 2. High Cost Attached to Concessionaire's Claiming ($z^t \leq C$)

In reality, however, ex-post bargaining frequently results in zero compensation from the state DOT and the concessionaire forgoes making a claim. This is because claiming the short-term toll operating loss incurs a high potential cost to the long-term business of the concessionaire. For example, the concessionaire will not want to disclose confidential business information such as material costs, the organization and management of crews, etc. Also, pursuing short-term compensation can make the bargaining complex, harming the long-term business relationship with the state DOT.

Assuming that such long-term cost, *C*, is larger than the immediate total cost of the toll suspension for a concessionaire, our game model derives the forgo equilibrium. Because $C > z^t$, a concessionaire's best response is to forgo at some point when time subsequently passes (zero amount claim). If the DOT knows that the concessionaire will forgo, its best response in time *t* is to reject any previous claim. Again, if the concessionaire knows the DOT's best response of rejecting all offers, it will not waste administrative costs by forgoing from the beginning.

In such a case, the equilibrium set for our bargaining game in case 2 is

{DOT, Concessionaire} = {Forgo, Reject}.

Compared with case 1 of the ex-ante compensation term, any $\overline{x_{DOT}} \geq 0$ will make the ex-ante compensation terms inferior to the current practice of ex-post cost claiming for the DOT. It would be better for the state DOT to maintain current practices and compensate zero amounts to the concessionaire rather than prefixing the compensation for the toll borrowing.

Scenario 3. High Social Cost, Potentially Returning to DOT ($z^t \leq C$, $z^t \leq S$)

In the situation of scenario 2, however, we note that the concessionaire, at least in the P3 case, is a profit-maximizing (and consequently cost-minimizing) firm. Therefore, it will necessarily supplement the operational loss from other business areas, like unnecessary but user-friendly services. Or it can seek rent from different projects when it involves multiple projects. Such loss transfer to social cost, if accumulated and becomes a business custom, can pose political and social burdens on the DOT. It is not significantly different for a public-sector toll operator if it faces tight budgets or any push toward operational efficiency.

If the social cost, S, is equal to or larger than the short-term compensation to the concessionaire z^t and incomparable to the concessionaire's long-term cost of compensation claiming, the DOT's best response is to accept any offer and pay $x^*_{DOT} \leq S$. The best response of the concessionaire is still to forgo. Therefore, the equilibrium set for the scenario with high social costs is *{{Forgo, Accept}, ...}*, which results in incurring the social cost. Therefore, any $\overline{x_{DOT}} \leq S$ will again make the ex-ante compensation terms superior to current practices, resulting in welfare loss.

CONCLUSION: THE IMPLICATIONS FOR OPTIMAL TOLL PRICES

This chapter analyzed the equilibrium cost bargaining for the suggested policy circumstance of state DOTs borrowing downtime toll facilities in the preceding research. The current contract terms, in the most independent government-operator case of P3, allow the toll suspension by state DOTs and the ex-post compensation claim of the toll operators. Within the contract theoretical framework of the economic analysis of ex-post and ex-ante compensation dealing, this chapter employs the Rubinstein repeated game model for the equilibrium cost derivation for public and private entities.

The findings in this chapter suggest that the ex-ante compensation arrangement is optimal. However, in the scenario of a toll concessionaire having higher priority on the long-run incentives (i.e., the relationship with DOT, the internal business information protection) than short-term loss, the newly derived equilibrium suggests that the frequently observed current practices of concessionaires forgoing the loss are optimal. Nevertheless, if we think of the loss as transferable to social costs, the optimal equilibrium again points to the ex-ante compensation arrangement.

The chapter's second scenario analysis is widely supported by several states' P3 cases. Most of the private concessionaires do not claim compensation in the case of DOT suspension. Some request compensation, but mostly cease to pursue it after one to two times of trials and rejections. However, our findings suggest that policymakers consider the third scenario where the forgone claim leads to social costs or higher future project costs. Establishing ex-ante compensation terms in the circumstance of unexpected managed lane usage will contribute to the cost efficiency of the state DOT, a toll-operating entity, and, most importantly, road users and civil society.

A limitation of our chapter is the simplified model not fully elaborating on qualitative aspects of cost bargaining (i.e., an optimal micro-level process of compensation bargaining). Also, the developing model does not fully detail the cost in terms of numerical measures. Empirical estimations on how the compensation pre-arrangement changes the project indicators such as road safety, operation staffing, etc., will be useful for future analyses and conceptualizing social costs. Also, generalizing our model to a cooperative case will widen the understanding of different toll-operating entities.

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CHAPTER 4

An Equilibrium Approach for Compensating Public-Private Partnership Concessionaires for Reduced Tolls During Roadway Maintenance

INTRODUCTION AND BACKGROUND

Planned activities such as maintenance, rehabilitation, and restoration (together improvement actions) of roadways aim to preserve or increase serviceability and, ultimately, improve safety and travel time reliability for future operations. However, execution of such activities can considerably reduce roadway capacity due to blocked traffic lanes. The impact is oftentimes increased traffic congestion and travel times as well as social and other travel costs. These negative impacts due to improvement actions can be diminished through demand-side actions, such as affecting route change behaviors through supply-side actions that encourage new behavior (e.g., congestion pricing, adjusting tolls on adjacent tolled routes, or careful activity scheduling). As an alternative, this study considers the possibility of exploiting excess capacity along concurrent tolled roadway facilities operating in a public-private partnership (P3) during improvement action execution on a public roadway facility by appropriately compensating the tolled facility concessionaires for reducing or suspending tolls during these periods.

The idea of exploiting excess capacity of designated or managed lanes or alternative privately run facilities to benefit the public is not new, as several works have suggested sending additional traffic onto these facilities in bad weather (Hoppers, 1999), during an evacuation (Ballard and Borchardt, 2006), and during traffic incidents (Carson, 2005; Chou and Miller-Hooks, 2011; Yin et al., 2013). But the idea of using such lanes to reduce the negative effects of roadway improvement projects is novel. To this end, this chapter presents a mathematical model to support the discovery of optimal toll prices and concomitant compensation levels to offer P3 concessionaires for instituting artificially low prices for the use of their facilities toward reducing capacity and costs for maintaining the public roadway. User costs include a monetary value of travel time and tolls paid. Compensation to the P3 concessionaire aids in overcoming lost opportunities for increasing revenue due to lower than agreed-upon toll prices or by refraining from increasing toll prices. Compensation is presumed to be paid by a governing agency within the United States, and the suggested pricing-compensation scheme is presumed to be acceptable to both the concessionaire and the agency. As toll prices often depend on traffic levels, the model also determines the optimal timing and time-of-day for executing a set of required improvement actions over a short planning horizon to ensure the lowest total cost to the public.

The mathematical model takes the form of a multi-level (i.e., four-level), mixed-integer program. The agency, presumed herein to be a state DOT, acts as the leader in an upper-level, bilevel problem by seeking an optimal schedule for executing a set of improvement actions and toll prices to support increased access to the tolled facility, given the response of the concessionaire in a lower-level bilevel program. The optimal solution has the minimum total cost and is obtained from its own lower-level, link-based, tolled user equilibrium (UE) (Beckmann et al., 1956) program, assuming reduced toll price settings.

The concessionaire acts as the follower in the lower-level, bilevel program, calculating its expected profits that would be obtained by setting toll prices that take advantage of the DOT's improvement action schedule, as some drivers may be willing to pay more for use of the P3 facility during these activities. Within the concessionaire's bilevel problem, the response of the drivers to reduced capacity and potential toll increases proposed in the upper level of this lower bilevel program is obtained from solution of a tolled UE formulation in its own lower level. That is, each level of the overall problem is itself a bilevel program, each with a tolled UE lower level. The DOT's tolled UE uses reduced toll prices, while the concessionaire's tolled UE uses inflated toll prices based on expectations for profiting during periods of reduced capacity on competing general-purpose lanes or the untolled facility. Under a typical contract, the concessionaire would expect that if tolls are set to an artificially low price, it will be compensated for its lost opportunity for increasing revenue.

This problem of discovering best toll prices and needed compensation to pay for added capacity through the use of privately tolled lanes is referred to as the maintenance timing and price discovery (MTPD) problem herein. The problem seeks the optimal start time for maintenance actions or sets of actions to be executed within the untolled facility in a given time horizon (e.g., a month). The timing decisions, including the effects of the order in which they are undertaken and whether they are undertaken simultaneously, impact total network-wide travel time. The MTPD problem is bilevel with nonlinear upper and lower levels. The solution procedure iterates between solution of upper- and lower-level programs and calls an off-the-shelf nonlinear optimization solver for each level separately.

In the next section, a review of related literature is presented. This is followed by details of the mathematical formulation of the MTPD problem and an iterative approach proposed for its solution. In the subsequent section, the proposed formulation and general solution methodology are applied on an illustrative example from which computational results are obtained. Insights from the results of the case study are given that can inform state DOTs on the potential gains for the public of exploiting excess capacity of P3 facilities to reduce the impacts of roadway improvement activities. The final section presents the conclusions.

LITERATURE REVIEW ON CONGESTION PRICING

Charging for the use of roadway capacity has been an effective strategy for alleviating traffic congestion (e.g., Zhong et al., 2021; Aboudina et al., 2016; Tan et al., 2015; Zhou et al., 2015; Xu et al., 2013). Dynamic and congestion-based pricing approaches have been proposed in the literature and deployed across many cities throughout the world, including London, Singapore, Toronto, and Tehran, to name a few, with the aim of luring drivers to move their trips to times of day when the roadways are less congested. This has the effect of distributing traffic demand more evenly over the day and away from the peak periods, as well as over space and away from congested facilities (Aboudina et al., 2016).

Numerous works have explored the role of dynamic and/or congestion pricing schemes for optimizing traffic performance metrics, such as expected throughput (Chen et al., 2016) and total travel time (Yan and Lam, 1996; Yang, 2004; Tan et al., 2015; Triantafyllos et al., 2019), enhancing sustainability by reducing congestion and improving air quality (e.g., Chen and Bernstein, 2004; Chen et al., 2015, Vosough et al., 2020), minimizing adverse health effects (Wang et al., 2014), maximizing toll revenue (Chen et al., 2016; He et al., 2017; Triantafyllos et al., 2019), and minimizing the impacts for retailers and local residents (Amirgholy et al., 2015). Dynamic models price by time-of-day rather than by realized congestion levels. These works generally focus on recurrent traffic conditions.

In recent years, government agencies have partnered with private parties (P3s), wherein the private firm is permitted to charge tolls, often without bounds (Shi et al., 2016), in exchange for improving, operating, and maintaining the roadway. These firms seek return on their investments. They set tolls for their facilities to maximize their profits while competing against free alternative facilities (Guo and Xu, 2016). As demand is elastic, their revenue depends on the response of the potential users to the prices.

Quite a few works develop models to support profit maximization of these tolled private facilities (e.g., Chen et al., 1999; Xiao and Yang, 2007; Guo and Xu, 2016). To maximize profits, the firms must attract users away from congested, alternative facilities, and thus these works are similar to those that consider congestion-based pricing.

A vast literature exists for determining an optimal maintenance activity schedule that alleviates disruptions caused by roadway maintenance activities, such as pothole patching, crack sealing, and resurfacing. These works prioritize activities, pushing some off to future years. Fewer works, however, focus on reducing the impacts of already selected activities based on their specific timing within shorter periods and through bundling activities together (e.g., Lee, 2009; Gong and Fan, 2016). There are tradeoffs between executing activities concurrently, including reduced disruption times due to synergies between the activities, but at a cost of fewer alternate pathways around work zones. With this in mind, Lee (2009) proposed a model to determine the optimal timing of a given number of activities over a set of days while considering traveler behavior. Their model determines whether to execute any activities simultaneously. They use the objective of minimizing total traffic delay over a network, where these delays are computed through microscopic simulation using VISSIM. Ant colony optimization is proposed to search for an optimal combination of activity timing.

More recently, and of greater relevance, Gong and Fan (2016) optimized the timing of chosen highway work zone projects from the perspective of traffic agencies and jurisdictions using a bilevel formulation and genetic algorithm-based solution method. The upper-level model minimizes total travel delay over a long-term planning horizon, and followers in the lower-level seek the shortest travel time paths that achieve a UE on a daily basis. Herein, a similar bilevel approach for determining the optimal timing and simultaneity of action is employed. This chapter expands on these earlier concepts where the timing, as well as synergies or super additive negative effects that arise from executing more than one activity simultaneously, are incorporated in determining the remuneration for the use of a concurrent, tolled facility at reduced toll prices.

While a few works have proposed models with two objectives, minimizing social cost and maximizing toll revenue, these works take only a public agency's perspective wherein the agency owns and operates all facilities (e.g., Chen et al., 2016; He et al., 2017). It appears that no prior work has considered the possibility of remunerating privately run concurrent tolled facilities for the use of their capacity during improvement activity execution at reduced toll prices or the effects of chosen timing given the right to congestion-based pricing schemes of the P3s. Nor has any work sought to set optimal pricing and remuneration values appropriate for the cost savings that would be obtained for users for this setting. The proposed multi-level mathematical conceptualization of the MTPD problem is presented here to fill this gap.

FORMULATION OF THE MTPD

The MTPD is formulated in this section. The problem involves the perspectives of two stakeholders: the state DOT or other entity that represents the users' interests that wishes to minimize total agency and user (A-U) cost and the concessionaire that seeks a maximum profit.

From a State DOT's Perspective

The state DOT seeks an agreement with the concessionaire to minimize total A-U cost associated with executing roadway improvement projects by allowing the users to take advantage of excess capacity on a concurrent, tolled facility that operates under a P3 structure at artificially reduced prices. Since the P3 could incur diminished revenues by offering reduced tolls, and this revenue loss could be sizeable due to the potential for increased congestion on the main facility arising from the improvement activity execution, the state DOT will need to remunerate the P3 for its potential losses. Thus, there is a trade-off between reducing tolls for users and compensation expenses.

From a P3 Concessionaire’s Perspective

The P3 concessionaire views the roadway improvement activities as an opportunity to increase tolls and overall toll revenue, as road users will be willing to pay more for use of the tolled facility when one or more of the lanes of the main facility are closed due to planned improvement activities. Thus, if they are asked to reduce their tolls at a time when they would have increased tolls, they will ask for compensation commensurate with their expected losses. As typically implemented, tolls are set by an algorithm that is proprietary to the concessionaire. The tolls are set to maintain a required minimum speed. It is reasonable to assume that concessionaires will seek to maximize revenue given their obligations to their lenders and equity investors. In some cases, concessionaires may moderate toll increases for limited periods for a variety of reasons, such as to engender public good will or to maintain a positive relationship with the state DOT. Such moderation in increases would not be obligatory and thus cannot be assumed by the DOT in advance.

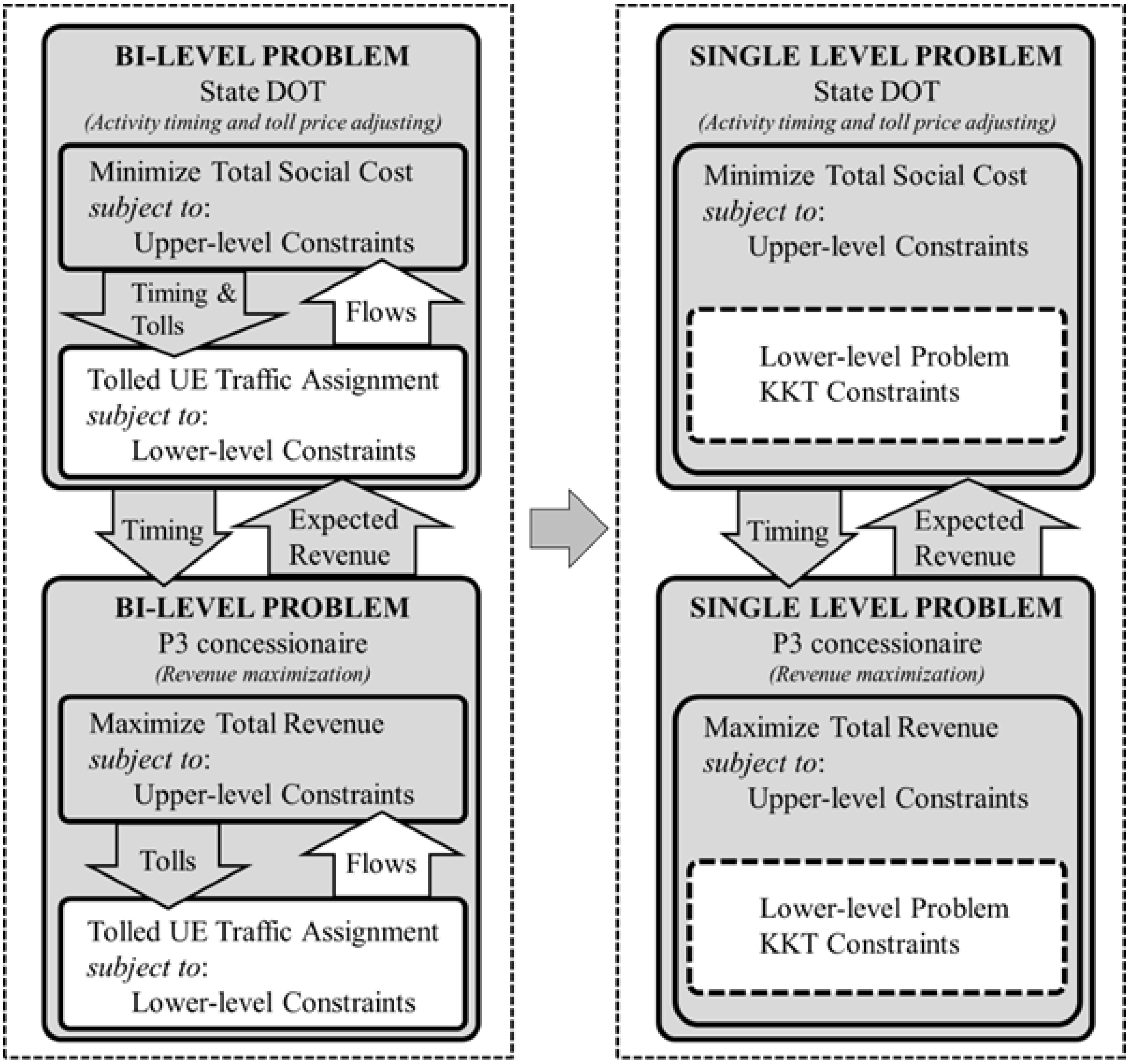
Combining Perspectives – the MTPD

The MTPD problem simultaneously considers perspectives of both stakeholders within a single mathematical framework of multiple levels. The general structure of the MTDP problem is founded on the following key concepts: (1) the state DOT seeks to settle the maintenance schedule and toll prices and (2) the concessionaire seeks compensation for its lost opportunity to profit. Both entities are beholden to the users who have autonomy in their route (i.e., tolled or untolled) selection. The conceptualization is built on an overarching bilevel structure wherein the solution is obtained at a Stackelberg equilibrium between the leader (e.g., a state DOT) in the top level and the follower (concessionaire) in the lower level. Each level is itself a bilevel program.

The upper-level state DOT bilevel program seeks a toll price reduction aligned with an improvement action timing plan for which the travel delays incurred by users as a consequence of improvement action execution are minimized. Thus, the upper level of this state DOT problem sets the tolls and timing plan, along with compensation to the concessionaire for revenue losses due to reducing its tolls, while its lower level gives feedback on the response of users to the updated tolls and reduced capacity from improvement action execution through solution of a link-based, tolled UE. A disutility function that captures the tolls along with other travel costs (e.g., time) is employed in this UE. Demand is presumed to respond to price, whereby users move to the reduced-cost toll lanes in proportion to the reduction. Solution of the upper-level occurs at a Stackelberg equilibrium between upper- and lower-levels of this upper level, state DOT problem.

Similarly, the lower-level concessionaire’s bilevel program seeks an optimal toll setting to maximize revenue, taking advantage of reduced capacities on the untolled facility due to execution of the improvement action timing plan from solution of the state DOT’s bilevel program. That is, capacity reduction from improvement action execution creates an opportunity for the concessionaire to raise its tolls and increase its revenue. How much to raise the tolls depends on the demand function. The concessionaire’s lower-level, link-based, tolled UE thus returns an estimate of the potential revenue resulting from increased toll settings and estimated demand under newly set, inflated tolls. Solution of this concessionaire’s bilevel program also occurs at a Stackelberg equilibrium between its own upper and lower levels.

The difference between upper- and lower-level toll settings informs the calculation of needed compensation for toll setting reductions desired by the state DOT. Thus, work zone timing, toll settings, and remuneration to the concessionaire for anticipated losses are set in the state DOT’s program, given an expectation of how users will respond to the delays and reduced prices, and their optimal setting is a function of the response of the concessionaire, which is determined through their estimates of the response of its users as would be expected if the state DOT did not intervene.



(a) (b)

Figure 4-1 Overview of the MTPD

The link-based tolled UE in both upper-level state DOT and lower-level concessionaire programs is formulated as a second-best toll pricing problem, wherein tolls are charged only on a subset of links (Verhoef, 2002). Tolls contribute to the disutility of the tolled links, a concept that has been widely used (e.g., Chen et al., 1999; Chen and Bernstein, 2004; and Amirgholy et al., 2015). Rather than imposing the tolls on road users by treating them as added link travel time, as is used in some of these works, here, the travel times are monetized through a value of time conversion factor. Thus, a monetized disutility function of travel time and tolls is associated with each link.

Ultimately, a four-level program is constructed but is thought of as a bilevel program, wherein each level contains a bilevel program. This structure is presented in Figure 4-1-a. To avoid confusion, each bilevel program of Figure 4-1-a is transformed to a single-level program as in Figure 4-1-b. To this end, each bilevel program is replaced by an equivalent single-level program, wherein the Karush Kuhn Tucker (KKT) conditions of each link-based tolled UE traffic assignment lower-level program are incorporated into the upper level as complementarity constraints and the lower level is dropped. Similar transformation has been used widely, including in link-based pricing studies (e.g., Yin and Lawphongpanich, 2006; Zangui et al., 2015). That the KKT conditions are necessary and sufficient for optimality in a bilevel program with a link-based tolled UE formulation at its lower-level has been previously shown (Yang and Huang, 2004; Chen and Yang, 2012).

The Upper-Level State DOT Program

The state DOT's problem of determining the optimal timing for improvement action execution, adjusted toll prices, and needed compensation for the concessionaire to achieve a minimum total A-U cost is formulated in this section. For simplicity, the type of activity is not distinguished. Activity durations are a function of the link to which they are applied, capturing length, grade, number of lanes, and other characteristics. Further, maintenance costs vary by time-of-day and day-of-week, reflecting the role of timing in labor costs. The notation used in formulating this problem is given in Table 4-1.

Table 4-1. Notation Used in the Upper-level State DOT Timing and Toll Price Adjustment Problem

Sets		**Subsets**		**Indices**	
A	Links	$A^+ \subseteq A$	Tolled links	a	Links
T	Time increments	$A^- \subseteq A$	Untolled links	t	Time increments
R	Routes			r	Routes
Parameters	**Description**				
γ_a^t	Capacity reduction factor of activity on link a in time increment t, $0 \le \gamma_a^t \le 1$				
M_a^t	Variable cost of completing an improvement action on link a in time increment t				
L_a	Duration of activity on link a				
D^t	Traffic demand of a single O-D pair in time increment t				
$\delta_{a,r}$	=1 if link a belongs to route r, 0 otherwise				
$x_{a,P3}^t \vert [y_a^t]$	Total traffic flow on link a in time increment t obtained from lower-level (P3) UE given y_a^t				
$c_{a,P3}^t$	Monetary cost of travel on link a in time increment t obtained from lower-level (P3) UE				
$p_{a,P3}^t \vert [y_a^t]$	Toll price of link a in time increment t obtained from lower-level (P3) UE, a constant in the upper-level program given y_a^t				
Q_a	Base capacity of link a, fixed in all time increments				
t_a^0	Free flow travel time for link a, fixed in all time increments				
Decision Variables	**Description**				
$x_{a,DOT}^t$	Total traffic flow on link a in time increment t in the state DOT's problem				
$c_{a,DOT}^t$	Monetary cost of travel along link a in time increment t in the state DOT's problem				
p_a^t	Effective toll price of link $a \in A^+$ in time increment t (price paid by users)				
$p_{a,DOT}^t$	Adjusted toll price of link $a \in A^+$ in time increment t in the state DOT's problem				
y_a^t	=1 if link $a \in A^-$ is under maintenance in time increment t, 0 otherwise				
$f_{r,DOT}^t$	Total traffic flow on route r in time increment t in the state DOT's problem				
$u_{r,DOT}^t$	Monetary cost of travel along route r in time increment t in the state DOT's problem				
$\lambda^t{}_{DOT}$	Monetary cost of the UE route (tolled/untolled route) in time increment t in the state DOT's problem				

With this nomenclature, the formulation is presented.

$$Min \sum_{t\in T}\sum_{a\in A} x^t_{a,DOT} \cdot c^t_{a,DOT} + \sum_{t\in T}\sum_{a\in A^-} y^t_a \cdot M^t_a + \sum_{t\in T}\sum_{a\in A^+} x^t_{a,P3}|[y^t_a] \cdot p^t_{a,P3}|[y^t_a] - \sum_{t\in T}\sum_{a\in A^+} x^t_{a,DOT} \cdot p^t_a \tag{4-1}$$

Objective function (4-1) seeks a minimum total A-U cost. This cost is captured through three terms: (i) total monetary cost of travel for the network users over a time horizon; (ii) cost of activity execution on the untolled roadway links; and (iii) compensation to the P3 concessionaire for reducing the tolls during the chosen time of activity execution as estimated by the state DOT. This last cost factor is constructed from two terms, where the first portion computes the revenue that the P3 concessionaire expects can be obtained and the last term calculates the revenue the concessionaire can expect with the adjusted toll settings set by the DOT. Thus, together these terms determine the compensation owed to the P3 concessionaire to overcome lost opportunities for increasing revenue due to refraining from increasing toll prices. The lower the toll prices are set, the more compensation to the concessionaire will be needed. This compensation can be paid by the state DOT in the form of a lump-sum payment to the concessionaire or through alternative mechanisms.

The objective is subject to constraints associated with improvement activity duration, roadway toll price adjustments, link flows, link capacities, monetary cost of travel conversion, and the KKT conditions associated with the lower level. These constraints are given next.

Improvement Activity Duration and Toll Price Adjustments

The duration of the activities is enforced through constraint (4-2), where L_a= 0 for all links for which no improvement action is required. Continuity in activity execution over time is enforced in constraint (4-3). Constraint (4-4) ensures that the state DOT can only affect the price of tolled links $a \in A^+$ while activities are ongoing. Constraint (4-5) ensures that the toll price does not exceed a maximum value if such a limit was agreed upon in the contract.

$$\sum_{t\in T} y^t_a = L_a \qquad \forall a \in A^- \tag{4-2}$$

$$(1\text{-}y^t_a) + y^{t-1}_a + y^{t+1}_a \geq 1 \text{ for } L_a > 1 \qquad \forall a \in A^-, \forall t \in T \tag{4-3}$$

$$p^t_a = y^t_{a\in A^-} \cdot p^t_{a,DOT} + (1 - y^t_{a\in A^-})p^t_{a,P3} \qquad \forall a \in A^+, \forall t \in T \tag{4-4}$$

$$p^t_a \leq P_{max} \qquad \forall a \in A^+, \forall t \in T \tag{4-5}$$

Traffic Flow and Link Capacities

Constraints (4-6) through (4-8) determine network-wide path flows and travel costs for a single origin-destination (O-D) pair. Constraint (4-9) computes the updated capacity of link a at time increment t given the improvement activities scheduled for that link. It is assumed that at most one improvement activity will be executed on any link in the planning horizon and only on untolled links of $\{A^-\}$. This calculation presumes a reduction in the base capacity of link a (Q_a) by a given factor, leaving, for example, 25% or 50% of the base capacity. For simplicity, any improvement action is presumed to reduce the capacity of each link by half. Additional capacity reduction settings can be readily incorporated. Link flows are assumed to be continuous variables with no preset upper limit.

$$x^t_{a,DOT} = \sum_{r\in R} f^t_{r,DOT} \cdot \delta_{a,r} \qquad \forall a \in A, \forall t \in T \tag{4-6}$$

$$u^t_{r,DOT} = \sum_{r\in R} c^t_{a,DOT} \cdot \delta_{a,r} \qquad \forall a \in A, \forall t \in T \tag{4-7}$$

$$D^t - \sum_{r \in R} f^t_{r,DOT} = 0 \qquad \forall t \in T \qquad (4\text{-}8)$$

$$Q^t_a = Q_a \cdot (1 - \gamma^t_a \cdot y^t_a) \qquad \forall a \in A^-, \forall t \in T \qquad (4\text{-}9)$$

Monetary Cost of Travel Conversion

The monetary cost of travel along each link for each time increment within the planning horizon is computed through constraints (4-10) and (4-11). The use of these equations insinuates that travelers have perfect information of travel times. The conversion involves a value-of-time (VOT) factor, presumed to be identical for all users. The VOT may be set according to average hourly wages in an area. The Bureau of Public Roads (BPR) (BPR, 1964) function is applied to calculate the link travel times from traffic flows presuming recurrent conditions. Since execution of an improvement activity affects the link's capacity, travel costs along the untolled links depend on both traffic flow and capacity at each time increment (constraint (4-10)). Travel costs of tolled links depend on the traffic flow and effective toll prices at each time increment; their capacities are fixed to their base (or nominal) values (constraint (4-11)); α_a and β_a are coefficients that are obtained from model calibration using empirical data. In the case where traffic volume exceeds capacity, the higher the value of β_a, the quicker congestion forms (Huntsinger and Rouphail, 2011).

$$c^t_{a,DOT} = t^0_a \left[1 + \alpha_a \left(\frac{x^t_{a,DOT}}{Q^t_a} \right)^{\beta_a} \right] \cdot VOT \qquad \forall a \in A^- \qquad (4\text{-}10)$$

$$c^t_{a,DOT} = t^0_a \left[1 + \alpha_a \left(\frac{x^t_{a,DOT}}{Q_a} \right)^{\beta_a} \right] \cdot VOT + p^t_a \qquad \forall a \in A^+ \qquad (4\text{-}11)$$

KKT Conditions

The KKT conditions associated with the link-based, tolled UE traffic assignment in the lower-level of the state DOT bilevel problem are given by constraints (4-12)-(4-14) (Yang and Huang, 2004; Chen and Yang, 2012). Similar constraints are required for the P3 concessionaire's lower level, where variables with index DOT are indexed by P3.

$$f^t_{r,DOT} \cdot (u^t_{r,DOT} - \lambda^t{}_{DOT}) = 0 \qquad \forall r \in R, \forall t \in T \qquad (4\text{-}12)$$

$$u^t_{r,DOT} - \lambda^t{}_{DOT} \geq 0 \qquad \forall r \in R, \forall t \in T \qquad (4\text{-}13)$$

$$f^t_{r,DOT} \geq 0 \qquad \forall r \in R, \forall t \in T \qquad (4\text{-}14)$$

Binary integrality of activity timing variables and nonnegativity of toll prices are enforced through constraints (4-15) and (4-16), respectively.

$$y^t_a \in \{0,1\} \qquad \forall a \in A^-, \forall t \in T \qquad (4\text{-}15)$$

$$p^t_a \geq 0 \qquad \forall a \in A^+, \forall t \in T \qquad (4\text{-}16)$$

Lower Level: P3 Concessionaire Revenue Maximization

The state DOT makes an offer of compensation in exchange for lower toll prices (or by refraining from toll increases) in the requested maintenance period. The P3 concessionaire can accept or reject the offer. It is presumed in the model that they will accept any offer that provides equal or larger total revenue from the lower tolls plus the compensation to that which they expect using their tolling strategy for high congestion settings as found under maintenance conditions. The P3 concessionaire's problem of determining a toll price appropriate for traffic conditions as affected by execution of maintenance activities and their timing determined by the state DOT in the upper level ($[y_a^t]$) to maximize revenue and argue for concessions if prices are artificially deflated is formulated through constraints (4-5) to (4-14) and (4-16), where y_a^t is a parameter (not a decision variable) obtained from solution of the state DOT's problem at the upper level of the overall framework. Additional notation needed to formulate this problem is given in Table 4-2.

Table 4-2. Notation used in the lower-level problem: P3 concessionaire revenue maximization.

Parameters	**Description**
y_a^t	Activity timing decision as determined from upper-level (state DOT's problem)
P_{max}	Maximum toll that can be charged
Decision Variables	**Description**
$x_{a,P3}^t$	Total traffic flow on link a in time increment t in the P3's problem
$c_{a,P3}^t$	Travel monetary cost of link a in time increment t in the P3's problem
$f_{r,P3}^t$	Total traffic flow on route r in time increment t in the P3's problem
$u_{r,P3}^t$	Travel monetary cost of route r in time increment t in the P3's problem
$\lambda^t{}_{P3}$	The least travel monetary cost of all routes in time increment t in the P3's problem

$$Max \sum_{t\in T} \sum_{a\in A^+} \left(x_{a,P3}^t \cdot p_{a,P3}^t \middle| [y_a^t] \right) \tag{4-17}$$

Objective (4-17) seeks to maximize revenue given the activity timing determined by the state DOT in the upper level ($[y_a^t]$). The P3 concessionaire discovers their potential maximum revenue from toll collection under traffic congestion conditions associated with maintenance execution through objective (4-17). The problem is subject to constraints on maximum allowed toll prices, link capacities, link flows, and the KKT conditions associated with the lower-level tolled UE problem.

Solution of the MTPD problem is obtained at a Stackelberg equilibrium between the leader (state DOT) in the upper level and the follower (P3 concessionaire) in the lower level. At equilibrium, the state DOT identifies an activity timing plan for maintaining its roadway links in the considered corridor, toll prices for the periods in which maintenance is executed and the amount of compensation to pay the P3 concessionaire, given an expectation of the P3 concessionaire's reaction, to achieve the least total A-U cost.

Solution Method

An iterative solution methodology is proposed for solving the MTPD problem. The methodology is composed of four sequential steps, as depicted in Figure 4-2.

Step 1 is an initialization step wherein the initial toll prices and UE link traffic flows for the time horizon are determined through creation of an initial improvement activity plan. Revenue obtained by the P3 concessionaire under this tolled UE assignment is computed based on the usage of the tolled links. This value provides an initial expectation of the concessionaire's potential claim, creating a starting point for the state DOT. For simplicity, an initial improvement activity plan could include the scheduling of no activities, i.e., $y_{a\in A^-}^t = 0, \forall a \in A^-, \forall t \in T$. The equilibrium solution to the tolled UE problem may not be unique. Thus, the problem can be solved with different initial solutions, and the one with the minimum total A-U cost may be selected.

Step 2 solves the state DOT's problem (the upper-level problem) given the P3 concessionaire's revenue. Adjusted toll prices, activity timing, and compensation expenses are determined. Off-the-shelf software can be applied to solve this nonconvex, mixed-integer nonlinear program (MINLP).

Step 3 then solves the P3 concessionaire's problem (the lower-level problem) given the activity timing determined in Step 2. The P3 concessionaire's revenue expectation is updated. Again, off-the-shelf software can be used to obtain the solution of this nonconvex nonlinear program (NLP).

Finally, in Step 4, the state DOT's objective function value is reassessed with the outcomes of Step 3 on the updated P3 concessionaire's expected revenue. Convergence is achieved when the difference between the state DOT's objective function value of two consecutive iterations is less than a predefined threshold value. If convergence is achieved, the procedure terminates; otherwise, the procedure returns to Step 2 with an updated expectation of the concessionaire's revenue. In this solution approach, both state DOT and P3 concessionaire problems solved in Steps 2 and 3 account for the traffic's response to toll prices and capacity reduction due to maintenance actions.

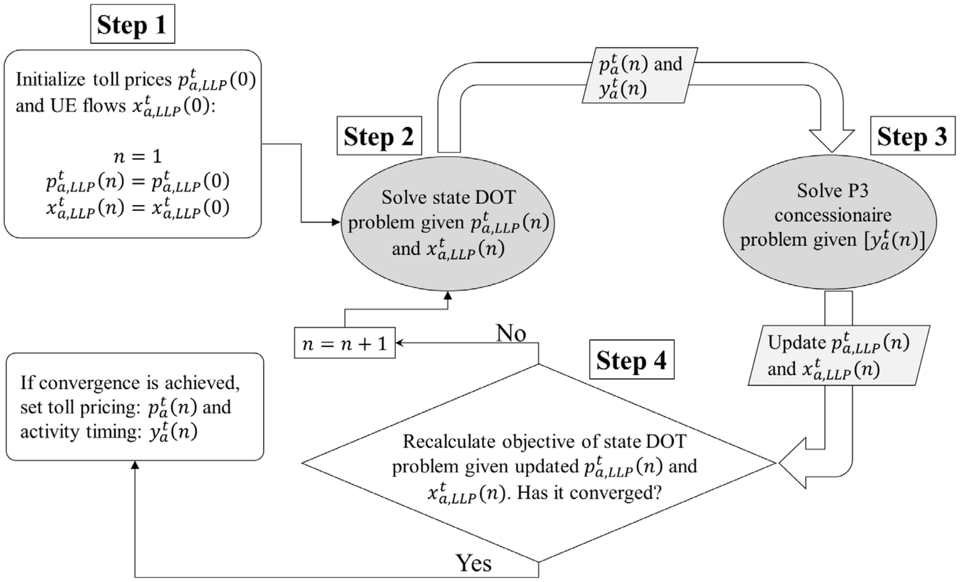


Figure 4-2. Solution of the MTPD through the proposed interactive technique.

Solution of the MINLP and NLP programs in Steps 2 and 3, respectively, is obtained using a robust nonlinear optimization solver, KNITRO (Byrd et al., 2006). KNITRO is specialized in solving nonlinear programs and has been used in transportation network studies in recent years (e.g., Durango-Cohen and Sarutipand, 2009; George and Xia, 2011; Lindsey and Mahmassani, 2017; Angelelli et al., 2020; Pinto et al., 2020; Wang et al., 2021). For the MINLP in Step 2, a modified sequential quadratic programming (SQP) method is used, where the key problem function is evaluated only at integer points. It also uses a traditional SQP method to solve the NLP of Step 3. KNITRO is known to be effective in solving nonlinear problems (e.g., Kronqvist et al., 2019).

For a network with $M \subseteq A$ links requiring maintenance over a time horizon of $|T|$ increments, assuming each improvement activity takes only one time unit, there will be a finite number of $|T|^{|M|}$ activity-timing combinations. Thus, the P3 concessionaire's expected revenue could be computed for all combinations in a pre-processing step, and the state DOT's problem can be solved directly with this input. Thus, convergence of the MTPD can be guaranteed for problem instances with a manageable number of such combinations.

CASE STUDY

The model and solution method are illustrated on a case study on an 8-mile stretch of I-15 southbound between the exit at West 9th Avenue and the exit at Camino del Norte in San Diego County's North County. The lane configuration of this corridor is shown in Figure 4-3-a. The corridor details are given schematically in Figure 4-3-b through a network representation with three nodes and four links, half of which are tolled (doubled arrows) and the other half of which are untolled (solid arrows). A time horizon of 7 days was used. This time period was broken into four 6-hour blocks in each 24-hour period, resulting in a total of 28 time increments: $T = \{1, 2, \dots 28\}$. The value of time was presumed to be \$35/hour, set slightly higher than the \$31.22 in (Zhou et al., 2022). The average travel demand at each time increment t, D^t, as reported in Table 4-3, was obtained from the Performance Measurement System (PeMS, 2022) of the California Department of Transportation.

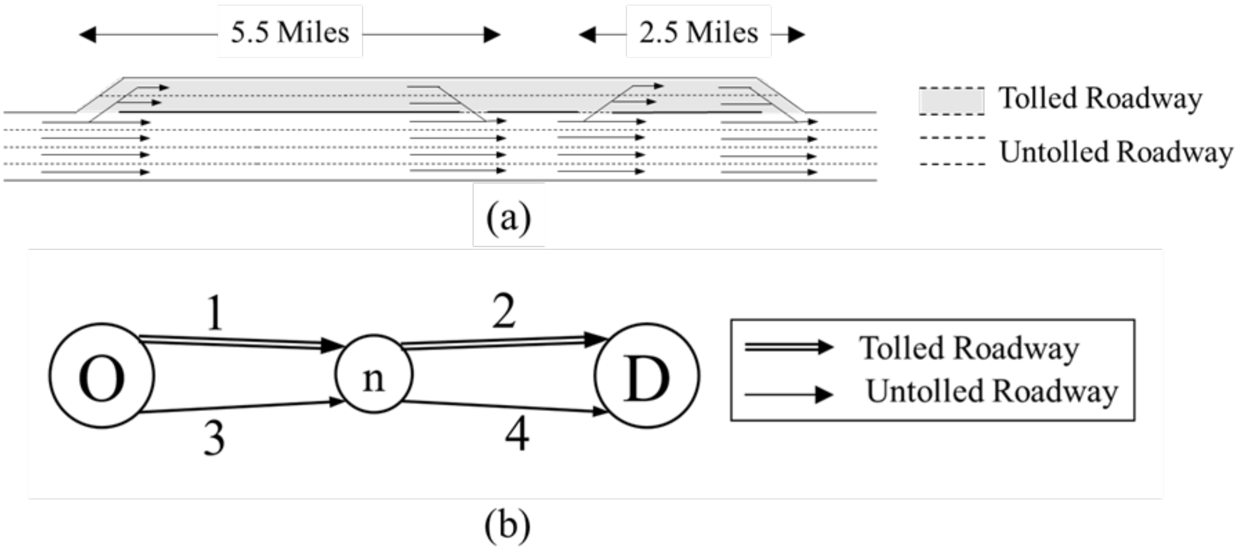


Figure 4-3. Case study (a) lane configuration and (b) network schematic.

Table 4-3. Total traffic counts at entry to study location over one week.

Time Increment (t)	Time Block	Demand (D^t) (vph)		Time Increment (t)	Time Block	Demand (D^t) (vph)
1	10/7/2019, 0-6 AM	2,585		15	10/10/2019, 12-6 PM	7,732
2	10/7/2019, 6-12 PM	9,298		16	10/10/2019, 6-0 AM	3,580
3	10/7/2019, 12-6 PM	7,024		17	10/11/2019, 0-6 AM	2,524
4	10/7/2019, 6-0 AM	3,033		18	10/11/2019, 6-12 PM	9,261
5	10/8/2019, 0-6 AM	2,576		19	10/11/2019, 12-6 PM	8,574
6	10/8/2019, 6-12 PM	9,459		20	10/11/2019, 6-0 AM	4,536
7	10/8/2019, 12-6 PM	7,236		21	10/12/2019, 0-6 AM	1,182
8	10/8/2019, 6-0 AM	3,289		22	10/12/2019, 6-12 PM	7,326
9	10/9/2019, 0-6 AM	2,586		23	10/12/2019, 12-6 PM	8,621
10	10/9/2019, 6-12 PM	9,401		24	10/12/2019, 6-0 AM	4,420
11	10/9/2019, 12-6 PM	7,294		25	10/13/2019, 0-6 AM	979
12	10/9/2019, 6-0 AM	3,278		26	10/13/2019, 6-12 PM	4,846
13	10/10/2019, 0-6 AM	2,593		27	10/13/2019, 12-6 PM	7,039
14	10/10/2019, 6-12 PM	9,537		28	10/13/2019, 6-0 AM	3,957

Routes between the considered O-D pair are in terms of entry/exit and lane choice. Interior node n provides mid-trip entry to and exit from tolled links, enabling users to switch between facilities.
The network data, including the values of the link travel time function parameters and routes, are given in Table 4-4. Details of the methodology used in, and results of, the calibration of the parameters of the link performance function based on the collected loop detector data for both tolled and untolled lanes are

provided in Appendix C. A cap on the maximum allowable toll price was set to \$8.00 (i.e., P_{max}= \$8) as is consistent with prices on this facility. Toll collection costs are assumed to be zero but can be readily incorporated within the model.

Table 4-4. Network data (values of link travel time function parameters and routes of O-D pair).

Link (a)	Link Type	t_a^0(min)	$\propto_a$	β_a	Q_a(veh/hr)		Route (r)	Links Contained
1	Tolled	5.1	0.56	2.55	4,228		1	1-2
2	Tolled	2.3	0.56	2.55	4,228		2	1-4
3	Untolled	4.9	9.07	13.27	7,261		3	3-2
4	Untolled	2.2	9.07	13.27	7,261		4	3-4

Two maintenance activities, one on link 3 and the other on link 4 (blocking two lanes), each with a duration of 18 hours (or 3 time increments, i.e., $L_3 = L_4 = 3$) and an impact that reduces facility capacity by half (i.e., $\gamma_3^t = \gamma_4^t = 0.5$) for the chosen time increments $t \in T$, must be executed. Based on estimates in (Tang and Chien, 2008), maintenance/improvement costs were set at \$50,000 per 6-hour block when executed during daytime hours (6:00 a.m. to 6:00 p.m.) and \$76,000 per 6-hour block when executed at night (6:00 p.m. to 6:00 a.m.).

Solution of the MTPD problem was obtained using the iterative algorithm described in subsection 3.2. The algorithm was implemented in R 3.6.1 (R Core Team, 2019) and solved using KNITRO 12.3.0 solver (Hours, 2018). Computation times were on the order of an hour using a personal computer with Intel Core i7-6820HQ 2.70 GHz CPU and 16.0 GB RAM running Windows 10 Enterprise edition. Link travel times at equilibrium when no activity is executed provide a baseline on performance and are given in Appendix D. These values were used to obtain an initial estimate of baseline toll revenue, which was found to be \$503,293 (i.e., $\sum_{t\in T}\sum_{a\in A^+}\left((x_{a,LLP}^t \cdot p_{a,LLP}^t)\middle|[y_a^t]\right)$ = \$503,293) in upper-level objective (4-1) of the state DOT level problem and were used to initiate the algorithm.

Total A-U cost, objective (4-1), was calculated in the upper level of each iteration (Step 2). At the end of each iteration, total A-U cost was updated after the expected revenue of the P3 concessionaire was updated in the lower level (Step 4) in response to updated maintenance timing plans from the upper level. The algorithm converged, terminating at the 16th iteration and producing the optimal improvement activity timing plan, toll price adjustments, and compensation expenses. Figure 4-4 shows the convergence between objective function values obtained from solution of upper- and lower-level problems. The minimum total A-U cost was found to be \$7.6 million.

As shown through Table 4-5, the optimal improvement activity timing plan suggests that maintenance along link 3 should be undertaken in time increments 11 to 13 (i.e., $y_3^t = 1, \forall t \in \{11, 12, 13\}$), while similar activities along link 4 should be executed in time increments 25 to 27 (i.e., $y_4^t = 1, \forall t \in$ {25, 26, 27}). The final toll prices are similar to baseline values by design and result in total required compensation of \$347,392 to be paid to the concessionaire by the state DOT. Table 4-6 shows the increase in toll prices for these time increments that would have been incurred if these activities were undertaken and no additional agreement between entities were made. The total added A-U cost in this case would have increased to \$8.12 million from \$7.56 million for a 7.5% increase. Thus, a reduction of \$560,000 in total A-U cost, including a reduction by 16,012 hours of added travel time, can be achieved through compensating the P3 concessionaire with \$347,393 as shown in Table 4-5.

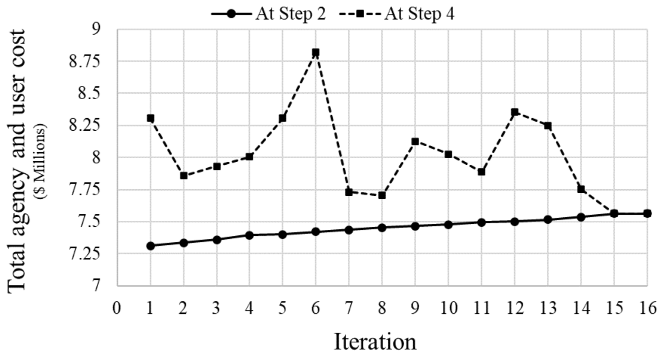


Figure 4-4. Convergence of the iterative solution algorithm.

Ultimately, the state DOT pays $21.70/hour ($347,393 for 16,012 hours) to buy time as a commodity for the public. In comparison to the VOT set at $35/hour, this is a rate of 62% of the VOT. At higher VOTs, this mechanism is expected to be even more effective. The state, thus, acts in the interest of the drivers more effectively than the drivers can for themselves. That is, intervening to bring the toll price down creates a cross-price elasticity effect. As demand is attracted to the tolled lanes, traffic conditions improve on the untolled lanes and user costs on these lanes decrease.

Consistent with common practice, the results indicate that there are advantages to execution of maintenance activities in off-peak hours when the costs to the public in terms of congestion offset the added costs of labor.

Table 4-5. Results under different scenarios.

Metrics	Scenario Baseline	Scenario Adjusted agreement	Scenario Original agreement
Optimum schedule	No maintenance activities	$y_3^t = 1, \forall t \in \{11, 12, 13\}$ $y_4^t = 1, \forall t \in \{25, 26, 27\}$	$y_3^t = 1, \forall t \in \{11, 12, 13\}$ $y_4^t = 1, \forall t \in \{25, 26, 27\}$
Total toll revenue	$503,293	$495,590	$842,982
Compensation	$0	$347,392	$0
P3 concessionaire total revenue	$503,293	$842,982	$842,982
Total travel time (hours)	179,193	181,109	197,121
Activity execution costs	$0	$378,000	$378,000
Total monetary cost of travel*	$6,271,767	$6,839,036	$7,746,843
Total A-U cost**	$6,779,100	$7,564,428	$8,124,843

*Assumes average value of time of $35/hour and 1.67 person per vehicle and includes total toll revenue.
**A-U cost is taken as the sum of agency costs (including activity execution cost and compensation) and user costs (monetary cost of travel and toll).

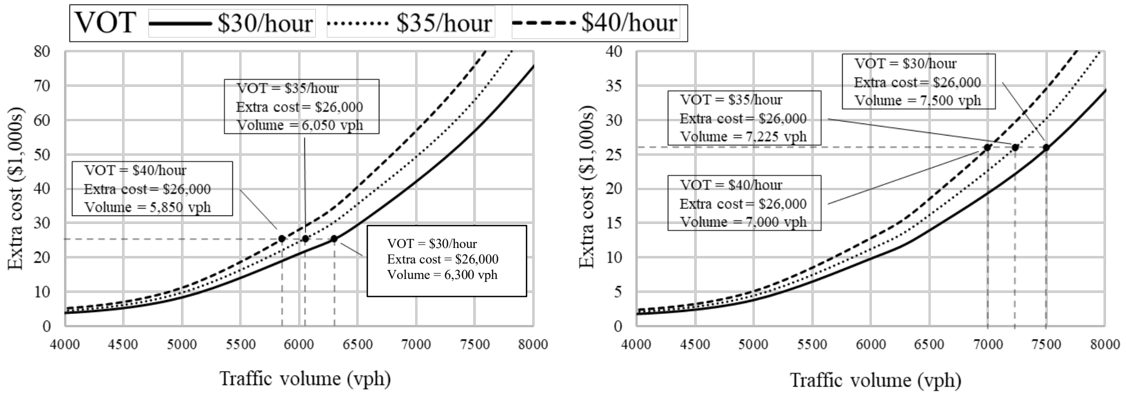
Additional insights can be gleaned from deeper study of the model outcomes. Consider links 3 and 4. For link 3, maintenance is scheduled to be executed between noon and 6:00 p.m. (6 hours of the daytime) and 6:00 p.m. to 6:00 a.m. (12 hours in the nighttime). Of interest is that a greater number of hours are scheduled at night, despite the significantly greater labor costs. That is, the costs to the public in terms of congestion during daytime hours and total compensation paid to the concessionaire outweigh the added costs of nighttime labor. For link 4, a greater portion of the maintenance hours of execution is scheduled for daytime hours, with 12 hours of daytime execution and only 6 hours of nighttime execution. These hours, however, are scheduled for a Sunday with lower daytime maintenance costs and lower traffic volumes. That is, the difference between costs to the public in terms of congestion in nighttime and daytime hours will not be great enough to overcome related differences in labor costs.

Additional experiments were run to determine at what traffic volume level the cost to execute a maintenance activity at night can be justified given the higher nighttime labor costs. Figure 4-5 plots the extra costs due to delays and compensation arising from capacity reduction in links 3 and 4 against traffic volume for a chosen 6-hour block. Break-even points, where the extra costs are equal to the difference between labor costs associated with daytime and nighttime (here, $26,000), are marked. For link 3 (Figure 4-5-a), the results indicate thresholds of 5,850, 6,050, and 6,300 vehicles per hour associated with VOTs of $40, $35, and $30 per hour, respectively, where the capacity reduction factor, labor costs, and maximum allowed toll price remain constant. For the shorter link 4 (Figure 4-5-b), these thresholds are a bit higher at 7,000, 7,225, and 7,500 vehicles per hour with VOTs of $40, $35, and $30 per hour, respectively.

Table 4-6. Toll prices ($) under different scenarios.

Time Increment (t)	Baseline* p_1^t	Baseline* p_2^t	Adjusted Agreement p_1^t	Adjusted Agreement p_2^t	Original Agreement p_1^t	Original Agreement p_2^t
1	0	0	0	0	0	0
2	0.06	0.55	0.06	0.55	0.06	0.55
3	7.98	7.16	7.98	7.16	7.98	7.16
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0.98	1.34	0.98	1.34	0.98	1.34
7	0.04	0.01	0.04	0.01	0.04	0.01
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0.23	7.99	0.23	7.99	0.23	7.99
11	**0.05**	**0.01**	**0**	**0**	**8.00**	**0.89**
12	**0**	**0**	**0**	**0**	**5.38**	**0**
13	**0**	**0**	**0**	**0**	**0.2**	**0.00**
14	0.11	2.93	0.11	2.93	0.11	2.93
15	0.12	0.15	0.12	0.15	0.12	0.15
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	7.95	6.55	7.95	6.55	7.95	6.55
19	0.15	0.14	0.15	0.14	0.15	0.14
20	0	0.03	0	0.03	0	0.03
21	0	0	0	0	0	0
22	0.15	0.05	0.15	0.05	0.15	0.05
23	0.18	0.14	0.18	0.14	0.18	0.14
24	0	0.01	0	0.01	0	0.01
25	**0.02**	**0**	**0.02**	**0**	**0**	**0.**
26	**0**	**0**	**0.01**	**0**	**0.01**	**7.43**
27	**0.88**	**0.01**	**0.0**	**0.02**	**1.91**	**3.16**
28	0.01	0	0.01	0	0.01	0

*Baseline values presented in Appendix D.



(a) (b)

Figure 4-5. Extra costs arising from capacity reductions due to maintenance execution in (a) link 3 and (b) link 4.

The savings derived from this toll-adjustment strategy were assessed under varying traffic conditions. Results are summarized in Table 4-7. In Table 4-7, actual traffic demand over the day, in peak and non-peak hours, from the case study location (Table 4-4) is multiplied by a traffic factor, as shown in the first column. The results indicate savings at all traffic regimes, but with diminishing returns under higher levels of traffic. The toll-adjustment strategy would not be effective (beneficial) under very low levels of traffic (traffic factor ≤ 0.25).

Table 4-7. Savings under different traffic conditions.

Traffic Factor	Return in User Costs* ($)	Compensation ($)	Return in A-U Costs** ($)	Return Ratio***
2	2,941,140	1,883,100	1,058,040	1.56
1.75	2,002,613	1,134,749	867,863	1.76
1.5	1,499,672	863,081	636,591	1.74
1.25	1,218,623	603,969	614,653	2.02
1	907,806	347,392	560,413	2.61
0.75	255,942	59,379	196,563	4.31
0.5	73,519	11,570	61,949	6.35
0.25	0	0	0	NA

* Users costs include monetized cost of travel and toll.
* Return in A-U costs = Return in user costs minus compensation.
*** Return ratio = Return in user costs to compensation.

CONCLUSIONS AND EXTENSIONS

This study investigates the potential benefits and costs of exploiting excess capacity along concurrent tolled roadway facilities during improvement action execution on a public roadway, where the tolled facilities are operated by a private concessionaire through a public-private partnership. The public agency is given the opportunity to purchase excess capacity from the concessionaire by asking the concessionaire to offer the use of its facilities at artificially low prices. Losses to the concessionaire due to reduced toll revenues are compensated. The compensation addresses lost profits by refraining from increasing toll prices and also accounts for opportunity losses due to the potential for greater facility usage during improvement activities on the general-purpose lanes. The idea of managing the impacts of roadway improvement activities through "purchasing" excess capacity from an alternative tolled facility is novel. To this end, a four-level mathematical conceptualization of this multi-stakeholder equilibrium problem is proposed that captures both public and private perspectives, and an iterative approach that exploits off-the-shelf software is presented for its solution. In addition to identifying equilibrium reduced-toll prices and corresponding compensation to be paid to the P3 concessionaire, the technique produces the timing for executing the needed improvement actions to attain the lowest total costs to drivers and the public agency.

The model and solution method were applied on a case study associated with facilities along I-15 in California. The results of the case study demonstrated that the proposed model can be effectively used to determine optimal timing for improvement action execution while accounting for the needed compensation for the private concessionaire and network-wide impacts of activities to achieve a minimum total A-U cost. Results show that carefully scheduling the improvement activities and simultaneously agreeing to reduce toll prices can lead to significant decrease in total travel time for travelers and total A-U cost. This is achieved with small costs to the state DOT and no reduction in total revenue for the concessionaire. As the solution methodology is heuristic, even lower cost solutions may exist, making this general concept more viable. Improved heuristics may reduce existing optimality gaps. In this study, it was assumed that all travelers have perfect knowledge of the network, depart at the same time, and seek to minimize the monetary cost of their travel. It was also assumed that the value of time is equal for all travelers. Such assumptions have been adopted by numerous researchers for the sake of convenience. In reality, however, it is less likely that all travelers share the same value of time and stick to the route that has the least monetary cost. Thus, in future studies, addressing heterogeneity in traveler behavior, departure time dynamics, and uncertainty about traffic conditions could be considered but would require solution of more complex dynamic and stochastic extensions. Future studies might also test varying values of the capacity reduction factor and maintenance duration. The model might also require some changes to replicate additional terms of such P3 agreements that may exist. Additionally, the proposed model may have applicability in other infrastructure delivery arrangements, such as public toll road authorities, e.g., the Pennsylvania Turnpike Commission.

The proposed toll-adjustment strategy could apply in other circumstances, such as where unanticipated closures or periods of capacity reduction during traffic incidents arise during large events or, perhaps, in emergency circumstances.

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CHAPTER 5

Making Decisions

INTRODUCTION

This chapter explores the opportunities and challenges associated with suspending tolls while an untolled facility is undergoing maintenance, resurfacing, or rehabilitation. The focus is on the practical issues, constraints, and considerations required when deciding to suspend tolls to relieve congestion on another facility.

The interviews summarized in Chapter 2 suggest that most agencies, toll authorities, or concessionaires have not explored this concept and generally have no experience with the concept. The interviews also indicated that all organizations are reluctant to share information that would support such decisions, and many interviewees pointed out specific constraints. These constraints include the need to report reductions in revenue to investors or an oversight body such as a bond council as well as regulatory constraints such as the need to maintain minimum speeds on managed lanes.

The repeated game analysis in Chapter 3 demonstrated that the most efficient strategy from a social welfare point of view is to agree to compensate for lost revenue prior to the event. The MTPD optimization framework in Chapter 4 describes a formulation and heuristic solution method to determine the timing of the maintenance and setting the compensation rate. It may be in the interest of the DOT to pursue toll suspension or reduction, since literature on road closure has claimed that closures enhance construction quality and reduce costs (e.g., maintenance of traffic cost can be diverted to tolls). The application of the MTPD optimization framework to a case study demonstrated that this approach is both logical and feasible.

OBJECTIVES

The objective of this chapter is to design a more detailed case study that illustrates the use of the MTPD optimization framework and the repeated game analysis for strategic toll pricing. While the case study is not completed in this project, the chapter serves as a foundation for future work.

The objective of the case study is to show that it is beneficial for the DOT and concessionaire to have an ex-ante agreement and the circumstances that would trigger such an agreement. Questions addressed are:

- What are the perceived benefits of having an ex-ante toll agreement?
- What is the implication of not having one?
- When should DOTs agree to the concessionaire's toll recovery claim?

BACKGROUND

Repeated game analysis focuses on how to establish compensation strategies between DOTs and the concessionaire. Given estimated revenue losses to the concessionaire, the perceived costs and benefits to the DOT under different contract agreements can be calculated and used to suggest the best agreement. Figure 5-1 shows the repeated game analysis as described in Chapter 3. The repeated game analysis looks at three cases:

- Case 1. Stationary Subgame Perfect Nash Equilibrium: To calculate different but accepted offers each time is hard and incurs additional administrative costs for the players.
- Case 2. High Cost Attached to Claim for Concessionaire: In reality, concessionaires many times chose to forgo due to excessive costs of the compensation claim such as disclosing confidential business practices or harming its long-term relationship with the DOT.
- Case 3. High Social Cost for DOT: However, if the concessionaire burdens society by seeking rents from internal business operation, the situation changes.

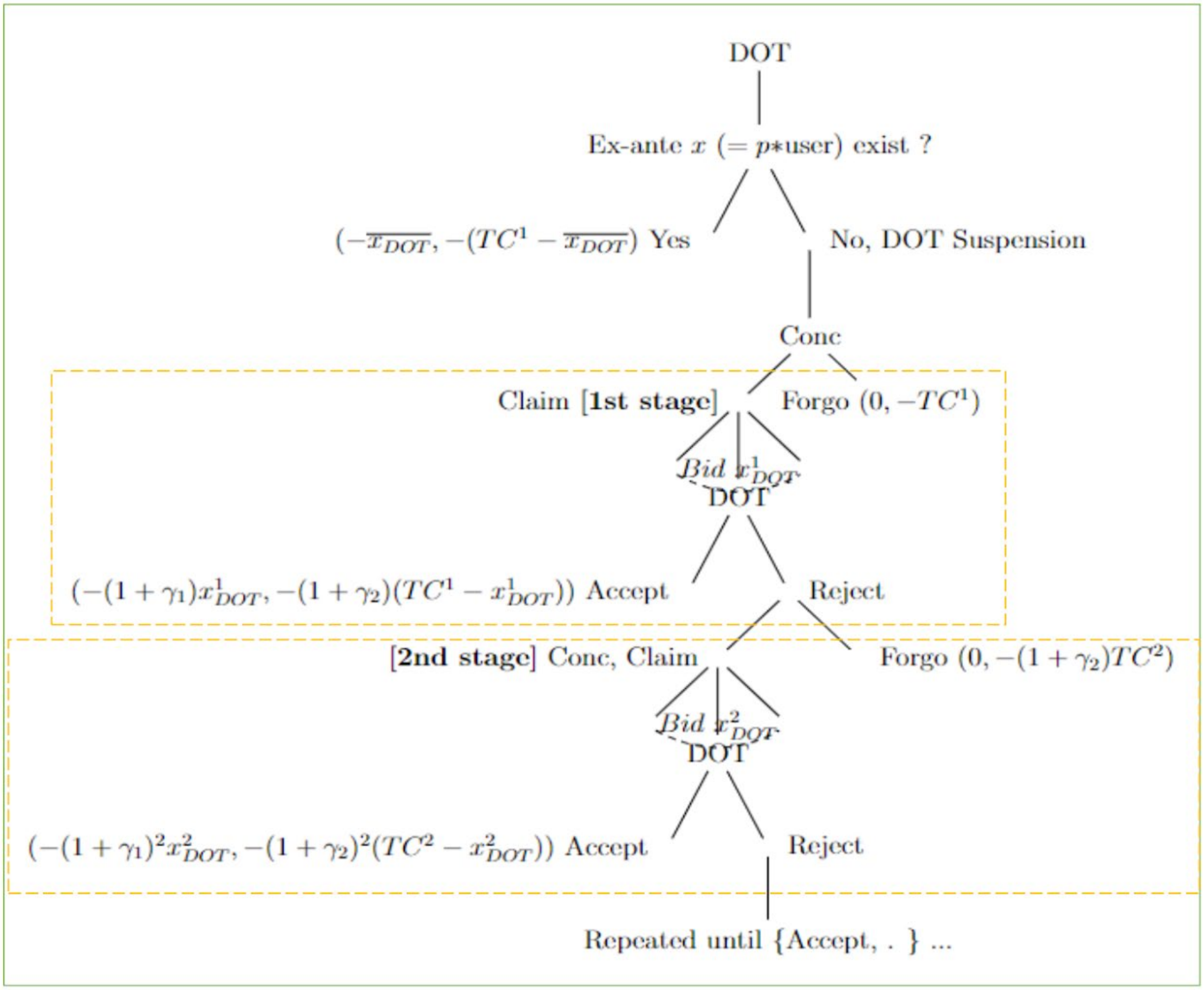

Figure 5-1. Repeated game analysis structure.

The MTPD focuses on how to set the compensation given a closure and the DOT asks the concessionaire to suspend tolls, as described in Chapter 4. The tool determines:

- Adjusted toll
- Compensation required to offset the toll adjustment
- Timing of the maintenance activity (schedule)

This is represented by the first branch on the left in Figure 5-1, where:
$\overline{x_{DOT}}$ is the compensation paid by the DOT and TC is the total cost to the concessionaire.
The MTPD uses two bi-level problems, as shown in Figure 5-2.

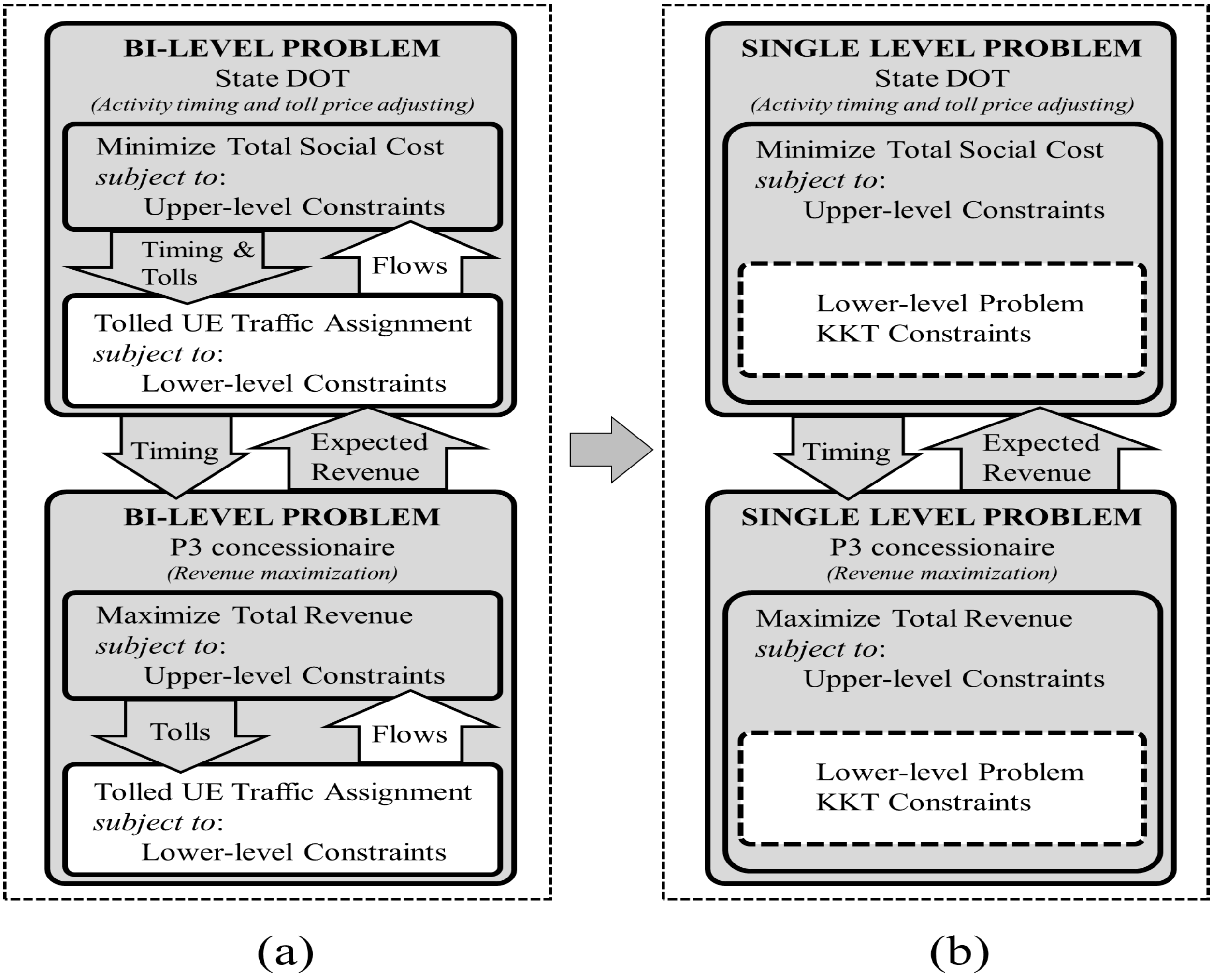

Figure 5-2. MTPD problem structure.

The case study presented in Chapter 4 indicates that:

- Actions are scheduled, when possible, during periods of low demand (nights and weekends) to minimize the need for compensation.
- Actions requiring longer time periods make use of the periods of low demand.

Further analysis showed the traffic levels, given three levels of the value of time, required to justify the increased costs associated with nighttime construction, and the impact of increases or reductions in the traffic volumes. The analyses suggested that shifting activities to nighttime construction is justified at modest traffic levels and that compensation is a desirable approach at all but free-flow conditions, with decreasing returns as the network becomes more congested.

These observations suggest that there are further opportunities to explore different situations reflecting the impact of other parameter values, reflecting the relative importance of disruption, along with different levels of demand (usage) in different time periods.

USING THE TOOLS TO MAKE DECISIONS: A PROPOSED CASE STUDY

Overview of the Proposed Methodology

Using the tools described in Chapter 3 (Game Theory) and Chapter 4 (MTPD), the case study will explore the outcomes (schedule, costs, and tolls) in a variety of situations. The proposed case study builds on the network used in Chapter 4. The network, toll structure, and potential actions for the case study are briefly reviewed. The case study involves two parts. The first part is an initial exploration of three scenarios representing situations that occur in practice. For each scenario, we identify relevant questions, hypothesize answers, and identify areas for further analysis. The second part is the proposed analysis, which is structured to provide the relevant insights. The proposed analysis involves a systematic sensitivity analysis that considers changes in individual parameters and interactions among parameters.

Case Study Description

Description – Network, Tolls, Actions

This analysis would use the case study described in Chapter 4. The case study is an 8-mile stretch of I-15 southbound between the exit at West 9th Avenue and the exit at Camino del Norte in San Diego County's North County. There are parallel tolled and untolled lanes with one crossover point. The case study used a time horizon of 7 days broken into four 6-hour blocks in each 24-hour period, resulting in a total of 28-time increments. Reported demand for each 6-hour block was used. Other parameters include the value of time ($35/hour), maximum toll, duration of repair activities, and costs for daytime versus night work.

Options: Scenarios, Questions and Speculative Answers

Scenario I: Ex-ante agreement exists, and DOT must compensate for concessionaire revenue loss.

- What is the benefit to DOT from a user cost perspective?
    - Can be inferred from the MTPD model as shown in Table 4-5, as reduction in social cost.
- What is the loss to the concessionaire?
    - None, since both parties are guided by a pre-defined agreement that accounts for the projected revenue loss.

Scenario II: Ex-ante agreement does not exist, and DOT does not want to compensate concessionaire for revenue loss.

- What is the social cost to DOT considering RUC (road user costs)?
    - Can be inferred from the MTPD model as shown in Table 4-5. (Worst case scenario and best-case scenario are sought.)
- What is the “actual” loss to the concessionaire?
    - DOT can always compel concessionaire to suspend toll, therefore some losses may be incurred.
    - Concessionaire is likely to increase the toll rate (worst case for DOT) as shown in Table 4-5.
    - Concessionaire may not increase toll rate (best case for DOT) as shown in Table 4-5.

Scenario III: When ex-ante agreement does not exist, and DOT is willing to compensate concessionaire for revenue loss.

- What is the benefit to DOT from a user cost perspective?
    - Concessionaire is discouraged from maximizing profit. Social cost reduces for DOT.

    - Cost can be inferred from the MTPD model as shown in Table 4-5.

- What is the loss to the concessionaire?
    - Depends on whether the offer is rejected or accepted.
    - Triggers repeated game process. Costly!

Proposed Analysis and Methods

Using the MPDT tool described in Chapter 4 or a similar tool, the following inputs can be modified:

- Demand (D_t), given that the situation in which all demand decreases or increases uniformly is explored in Chapter 4 (see Table 4-7), the following changes should be considered:
    - Peak only
    - Off-peak only
    - Weekends only
- Capacity reduction factor of maintenance activity g_t
- Duration of activity on link a
- Variable cost of maintenance activity on link a at time t, M_a^t
- Maximum toll, P_{max}

Although the plan is to conduct a sensitivity analysis to understand how each of the parameters impacts the decisions, the proposed analysis goes beyond a sensitivity analysis. Modifying the inputs list above would allow us to explore answers to a variety of questions. Examples of such questions and the strategy for answering the question are as follows:

- Does the schedule and compensation change if traffic levels are reduced or increased during: (1) peak periods only, (2) off-peaks periods only, and (3) weekends only?
- At what capacity reduction (trigger point) does it become imperative to consider suspension or compensation?
    - This involves understanding how much the capacity can be reduced while still accommodating the existing demand.
- How do the results change for short (say 1 period) versus long (say 4 periods) duration projects?
    - Running the MTDP with different activity durations is expected to demonstrate that the need for toll suspension is more critical for longer projects that cannot be accommodated outside peak hours.
- Can we make any generalizations about day of the week or time of day? Differences in daytime versus nighttime costs?
    - For example, scheduling projects for the lowest traffic periods while accounting for the nighttime penalty is a reasonable heuristic.
    - Isolate costs for days and nights for each activity plan and study the relationships.
    - Explore changes with changing O-D demands.
- What is the impact on existing users?
    - To explore equity issues among users, report changes in travel times and out-of-pocket costs for existing toll facility users and users of the untolled facilities.
- What happens if the cap on the maximum allowable toll price is changed?

        - To explore equity issues between the concessionaire and the DOT, changing the cap may shift the burden among different operators.

Other analysis could explore the impact of different definitions of periods of analysis. For example, the case study used four 6-hour periods for each day, which means that morning and evening peak periods are not distinguished from the middle of the day. Is this the appropriate level of granularity? Using eight 3-hour periods or three 8-hour periods would support the exploration of the impact of the hourly variability in the traffic. Furthermore, the interactions between the various parameters could be explored.

Expected Outcomes

In addition to a narrative describing the results of the sensitivity analysis, the exploration of the parameters will provide specific data related to the case study that includes:

- Thresholds at which compensation would not be offered varying with:
- Demand by period
- Volume/cCapacity ratio
- Duration
- Percentage increase in cost for nighttime construction
- Hypotheses related to how other networks might behave.
- Steps to develop a long-term plan for further analysis including generalizing the software so it can be used for other networks and parameters easily modified.

This analysis is intended to help answer the questions:

- What are the perceived benefits of having an ex-ante toll agreement?
- What is the implication of not having one?
- When should DOTs agree to the concessionaire’s toll recovery claim?

The case study in Chapter 4 showed that substantial travel time savings and reduced social costs are realized when an agreement is in place. The analysis will help to understand how the magnitude of these benefits vary. The thresholds will help to understand when an agreement is not necessary. The analysis will also help to demonstrate the value of transparency in terms of the basis for compensation.

Conclusions and Recommendations

The analysis and tools described in Chapters 3 and 4 serve as a foundation for understanding the limitations and challenges in implementing toll suspensions. This chapter outlined steps for additional analysis.

CHAPTER 6

Conclusions, Recommendations and Future Research

SUMMARY AND CONCLUSIONS

The concept of compensating toll operators if tolls are suspended to encourage users of a parallel or nearby route to move to the toll facility during maintenance or reconstruction has not been widely used. However, closing a segment to traffic during maintenance or reconstruction has been shown to be efficient and offer significant benefits in terms of safety and the quality of the work.

Our research, including a literature review, interviews and modeling, demonstrates that having a pre-existing strategy for compensating toll operators maximizes social welfare. The pre-existing strategy may be in the form of guidelines or a model that sets the level of compensation.

A game theory model of the decision process shows that an ex-ante (as opposed to an ex-post) compensation arrangement is optimal. Toll concessionaires are often willing to forego some claims for compensation for long term gains such as preserving a relationship with the DOT and protecting business information. Such forbearance is certainly welcome from the DOT's perspective. However, DOTs cannot assume such forbearance in their maintenance planning. If the DOT wishes to incorporate toll suspensions systematically into its maintenance planning, then an ex-ante compensation provision is desirable.

A detailed model to set the level of compensation and schedule improvement is formulated, solved and applied to a simple network. The potential benefits and costs of exploiting excess capacity along concurrent tolled roadway facilities during improvement action execution on a public roadway, where the tolled facilities are operated by a private concessionaire through a public-private partnership, are explored. Losses to the concessionaire due to reduced toll revenues are compensated.

The model uses a four-level mathematical conceptualization of this multi-stakeholder equilibrium problem that captures both public and private perspectives, and an iterative approach that exploits off-the-shelf software for its solution. In addition to identifying equilibrium reduced-toll prices and corresponding compensation to be paid to the P3 concessionaire, the technique produces the timing for executing the needed improvement actions to attain the lowest total costs to drivers and the public agency. The model and solution method were applied on a case study associated with facilities along I-15 in California. The results of the case study demonstrated that the proposed model can be effectively used to determine optimal timing for improvement action execution while accounting for the needed compensation for the private concessionaire and network-wide impacts of activities to achieve a minimum total agency and user (A-U) cost. Results show that carefully scheduling the improvement activities and simultaneously agreeing to reduce toll prices can lead to a significant decrease in total travel time for travelers and total A-U cost. This is achieved with small costs to the State DOT and no reduction in total revenue for the concessionaire. As the solution methodology is heuristic, even lower cost solutions may exist, making this general concept more viable. Improved heuristics may reduce existing optimality gaps.

There remain significant challenges to implementing this strategy. First, the agencies involved (tolls authorities, P3 concessionaires and state departments of transportation) are often reluctant to share the data needed to support the models. That is, the necessary transparency is absent. Second, federal regulations may not be supportive of the process. For example, managed lanes offer an opportunity to serve as alternative parallel routes, but these facilities must meet minimum speed requirements that are met by setting tolls at appropriate levels. Suspending the tolls and the increase in traffic may result in speeds below the required threshold. Another example is whether the compensation of toll revenue lost could be considered an eligible expense under federal aid. Third, toll authorities and concessionaires are answerable to their investors. Suspension of tolls will require reporting changes in revenue and may require approval of stakeholders such as a bond council or board of directors. Finally, at present, locations where parallel or near-parallel capacity is available for use as a relief route for a DOT maintenance project are not highly numerous. Indeed, managed lanes, which often parallel interstates and major arterials, are usually built only places where capacity is highly constrained. However, off-peak excess capacity on managed lanes often is available. Also, managed lane projects have been proliferating in the U.S. market.

The research demonstrated that the concept is promising and that respecting the perspective of the different actors is important. The structure of funding, finance and institutions involved in U.S. highway and other infrastructure delivery is in transition. The federal government and many states have shifted significantly away from reliance on gas taxes and begun to rely much more heavily on general revenues and sales taxes. At the same time, interest in access to private capital markets, risk tolerance, and technological savviness has grown, and that often relies on toll-based delivery. As this shift unfolds over the years and decades ahead, this research has illustrated the potential benefits and challenges of a new type of collaboration and cooperation.

OPPORTUNITIES FOR FUTURE RESEARCH

The limitations of the current research suggest opportunities for future research. These can be broadly categorized as three areas. The first area is to understand better the institutional context for suspensions of tolls. The second is to generalize the models for setting compensation. The third is to explore opportunities for a demonstration project.

Institutional Context

The nine interviews we conducted revealed a diversity of perspectives. This diversity underscores the need to capture different perspectives, organizational structures, and experiences. Getting potential interviewees to respond to requests for interviews proved challenging, but the experience to date should serve to demonstrate that no specific information will be revealed. The work could also be extended to include international experiences.

A broader survey would also seek to reveal additional examples of potential locations beyond the examples shown in Table 2, highlight data needs, and connect to existing work on models of traffic impacts of construction.

Generalization and Extension of Models

The model for setting compensation described in Chapter 4 was coded for a very specific example with just four links and three nodes. Generalizing this model will provide insight into the required data, the sensitivity of various model parameters and the impact of analyzing different temporal and spatial scales. These options were also discussed in Chapter 5.

Also, as discussed in Chapter 4, the model assumes that travelers have perfect knowledge of the network, all travelers depart uniformly over the period considered, seek to minimize travel the monetary cost of travel and have the same value of travel time. Considering heterogenous travelers, and travel dynamics and stochasticity have the potential to enhance the model. Finally, other delivery mechanisms could be considered, such as public toll authorities.

Heuristic Solutions

The model developed in Chapter 4 uses a heuristic solution. As with all heuristic solution methods, there is potential for more optimal solutions and more commutationally efficient solutions. Similarly, validation is challenging and the exploration of additional case studies and sensitivity provide insights into whether the results are logical and consistent.

Demonstration Project

Demonstration projects have been widely used by US DOT to demonstrate the application of innovative concepts. A demonstration project involving a collaboration between US DOT, a state department of transportation, and a concessionaire could help to identify implementation challenges, help to validate the models for setting compensation, explore the data needed to support the concept of toll suspensions, explore strategies for communicating the toll suspension to the public, and initiate the discussion of what it takes to generalize the experience from a demonstration project to a strategy.

Appendix A: List of Acronyms

A-U – Agency–user
CDA – Comprehensive Development Agreement
DBFOM – Design-build-finance-operate-maintain
DOT – Department of Transportation
IRB – Institutional Review Board
KKT – Karush Kuhn Tucker
MTPD – Maintenance timing and price discovery
PPP or P3 – Public–Private Partnership
RUC – Road User Cost
SPNE – Subgame Perfect Nash Equilibriums
UE – User equilibrium

Appendix B: Interview Protocols

OVERVIEW

The approval of the Institutional Review Board (IRB) at George Mason University and University of Delaware was obtained for this project. This appendix includes the IRB exemptions from George Mason and University of Delaware, an overview of potential interviewees, the script used to recruit participants, background information provided to interviewees, and the interview script for the semi-structured interviews.

The goal was to complete approximately 15 interviews. Nine interviews were conducted. The interviews were conducted by zoom between February 2022 and May 2022.

IRB EXEMPTION – GEORGE MASON

Dear …….

My name is Sue McNeil, and I am a Professor in the Department of Civil and Environmental Engineering at the University of Delaware. With colleagues at George Mason University led by Jonathan Gifford, a Professor in the Schar School of Policy and Government, I am conducting research on how toll road operators (concessionaires and toll authorities) collaborate with state highway officials for suspending or reducing tolls when parallel or nearby state facilities are out of service for maintenance or emergencies. This research is part of project funded through the Region 3 University Transportation Center led by Pennsylvania State University. I am hoping you might be able to help me with that research.

I am reaching out to you because I believe that you have that knowledge and expertise. We hope that you would be willing to share it with our research team. If you are willing, we would like to interview you and ask you some questions about your experiences, and perceptions related to opportunities, constraints, and legal implications. The purpose of this interview is to better understand the opportunities for state Departments of Transportation (DOT) and toll operators to cooperatively share facilities when parallel roadways are being maintained or rehabilitated to minimize the disruption to the users. This can include suspending tolls and remuneration of costs. The results of interviews with several state DOTs, toll operators and professionals will be summarized in our project report. No personal identifying information (name, position or affiliation) will be included in the project reports, and you can choose not to answer any question that you do not feel comfortable with.

We would like to conduct this interview via a video call (Zoom or Microsoft Teams), or over the phone, whichever works best for you. The interview should take approximately 45 minutes to 1 hour. Please let me know if you would be willing to do an interview. Your expertise and insights will be very helpful for our research, and I would greatly appreciate your taking the time to talk with our team. I can be reached via email (smcneil@udel.edu).

Thank you,

Sue McNeil
Professor
Department of Civil & Environmental Engineering
University of Delaware

Jonathan Gifford
Professor / Director
Center for Transportation Public-Private Partnership Policy
Schar School of Policy and Government
George Mason University

IRBNet Number: 1768792-1

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Project Number: 1768792-1

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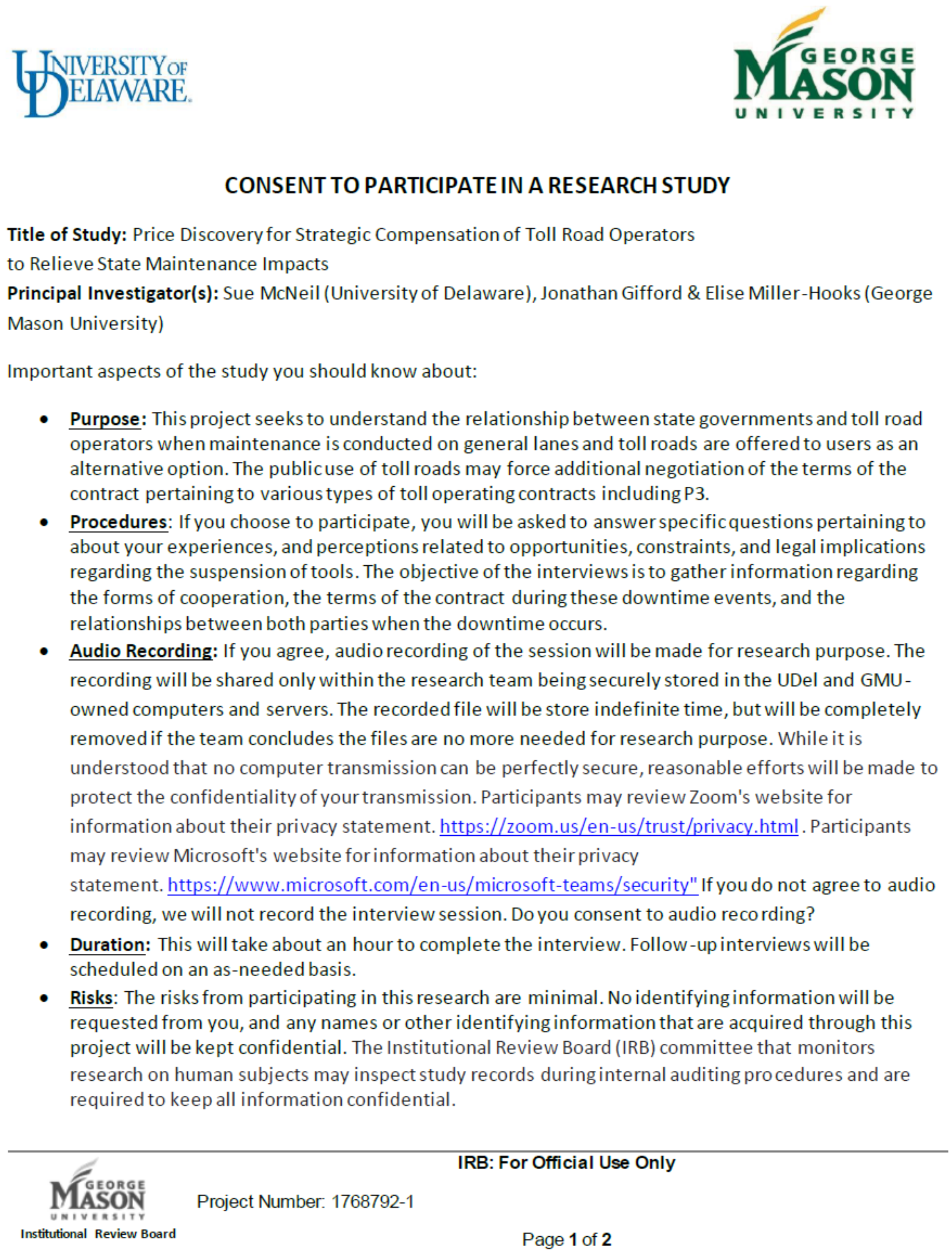

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

Title of Study: Price Discovery for Strategic Compensation of Toll Road Operators
to Relieve State Maintenance Impacts
Principal Investigator(s): Sue McNeil (University of Delaware), Jonathan Gifford & Elise Miller-Hooks (George Mason University)

Important aspects of the study you should know about:

- **Purpose:** This project seeks to understand the relationship between state governments and toll road operators when maintenance is conducted on general lanes and toll roads are offered to users as an alternative option. The public use of toll roads may force additional negotiation of the terms of the contract pertaining to various types of toll operating contracts including P3.
- **Procedures**: If you choose to participate, you will be asked to answer specific questions pertaining to about your experiences, and perceptions related to opportunities, constraints, and legal implications regarding the suspension of tools. The objective of the interviews is to gather information regarding the forms of cooperation, the terms of the contract during these downtime events, and the relationships between both parties when the downtime occurs.
- **Audio Recording:** If you agree, audio recording of the session will be made for research purpose. The recording will be shared only within the research team being securely stored in the UDel and GMU-owned computers and servers. The recorded file will be store indefinite time, but will be completely removed if the team concludes the files are no more needed for research purpose. While it is understood that no computer transmission can be perfectly secure, reasonable efforts will be made to protect the confidentiality of your transmission. Participants may review Zoom's website for information about their privacy statement. https://zoom.us/en-us/trust/privacy.html . Participants may review Microsoft's website for information about their privacy statement. https://www.microsoft.com/en-us/microsoft-teams/security" If you do not agree to audio recording, we will not record the interview session. Do you consent to audio recording?
- **Duration:** This will take about an hour to complete the interview. Follow-up interviews will be scheduled on an as-needed basis.
- **Risks**: The risks from participating in this research are minimal. No identifying information will be requested from you, and any names or other identifying information that are acquired through this project will be kept confidential. The Institutional Review Board (IRB) committee that monitors research on human subjects may inspect study records during internal auditing procedures and are required to keep all information confidential.

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Institutional Review Board

Project Number: 1768792-1

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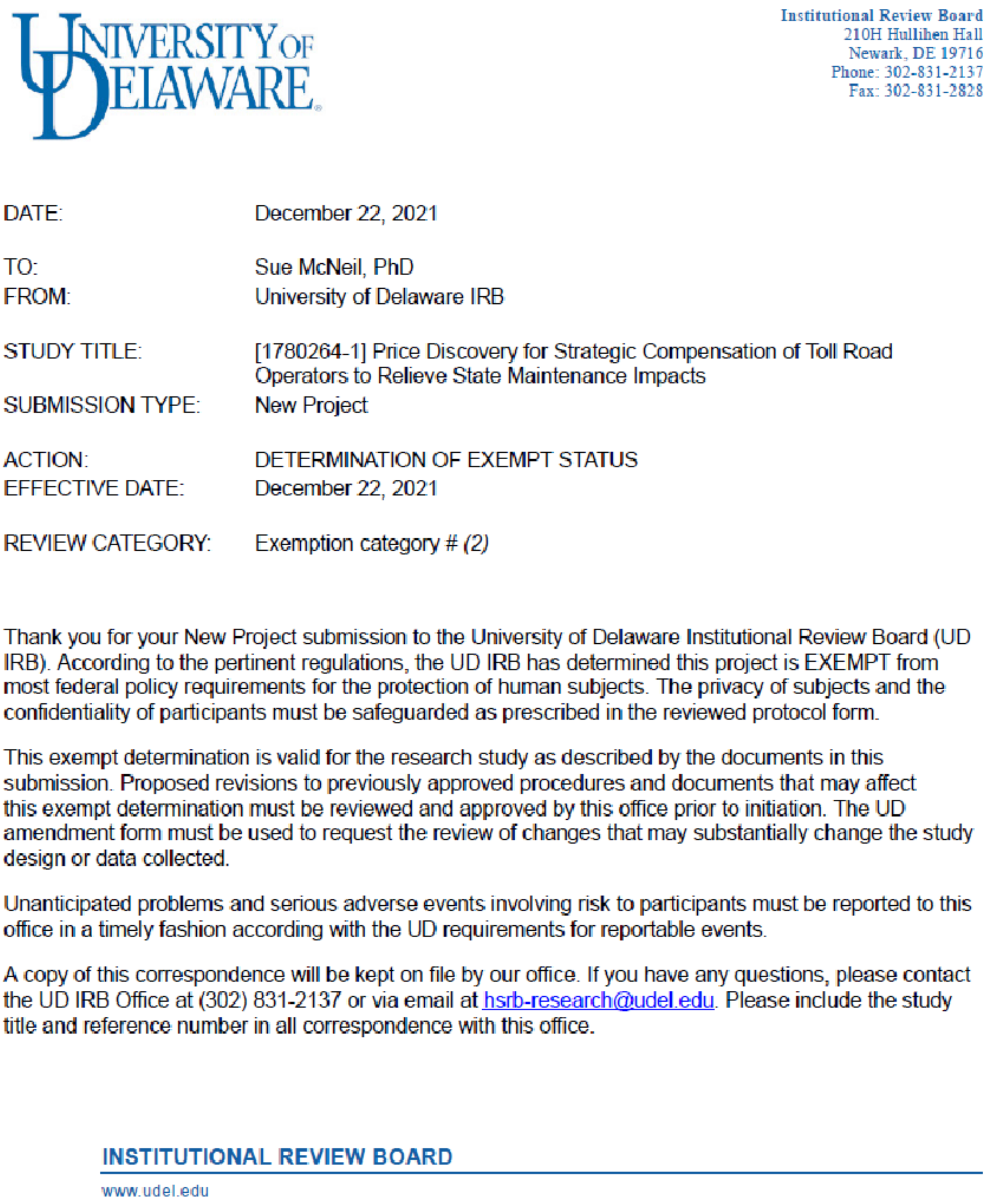
- **Benefits:** The main benefit to you from this research is that you may be inspired to consider these types of decisions when planning maintenance and repair.
- **Costs and Compensation:** e.g., If you decide to participate there will be no additional cost to you and there will be no compensation for participation.
- **Participation:** Taking part or not in this research study is your decision. You can decide to participate and then change your mind at any point.
- **Reference for Future Research:** The de-identified data could be used for future research without additional consent from participants.

Contact Information: If you have any questions about the purpose, procedures, or any other issues related to this research study you may contact the Principal Investigators, Sue McNeil at (302) 831-2422 or smcneil@udel.edu and Jonathan Gifford at (202) 669-9228 or jgifford@gmu.edu. You may also contact IRB directory at irb@gmu.edu or by phone, 703-993-4121

CONSENT TO PARTICIPATE IN THE RESEARCH STUDY:

I have read and understood the information in this form and I agree to participate in the study. I am 18 years of age or older. I have been given the opportunity to ask any questions I had, and those questions have been answered to my satisfaction. I understand that I will be given a copy of this form for my records upon my verbal consent.

IRB EXEMPTION – UNIVERSITY OF DELAWARE



UNIVERSITY OF DELAWARE

Institutional Review Board
210H Hullihen Hall
Newark, DE 19716
Phone: 302-831-2137
Fax: 302-831-2828

DATE:	December 22, 2021
TO:	Sue McNeil, PhD
FROM:	University of Delaware IRB
STUDY TITLE:	[1780264-1] Price Discovery for Strategic Compensation of Toll Road Operators to Relieve State Maintenance Impacts
SUBMISSION TYPE:	New Project
ACTION:	DETERMINATION OF EXEMPT STATUS
EFFECTIVE DATE:	December 22, 2021
REVIEW CATEGORY:	Exemption category # *(2)*

Thank you for your New Project submission to the University of Delaware Institutional Review Board (UD IRB). According to the pertinent regulations, the UD IRB has determined this project is EXEMPT from most federal policy requirements for the protection of human subjects. The privacy of subjects and the confidentiality of participants must be safeguarded as prescribed in the reviewed protocol form.

This exempt determination is valid for the research study as described by the documents in this submission. Proposed revisions to previously approved procedures and documents that may affect this exempt determination must be reviewed and approved by this office prior to initiation. The UD amendment form must be used to request the review of changes that may substantially change the study design or data collected.

Unanticipated problems and serious adverse events involving risk to participants must be reported to this office in a timely fashion according with the UD requirements for reportable events.

A copy of this correspondence will be kept on file by our office. If you have any questions, please contact the UD IRB Office at (302) 831-2137 or via email at hsrb-research@udel.edu. Please include the study title and reference number in all correspondence with this office.

INSTITUTIONAL REVIEW BOARD

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POTENTIAL INTERVIEWEES

The research for this project included a series of interviews with state government officials (i.e., toll authorities and state DOTs), coalitions and advocacy organizations (The Eastern Transportation Coalition, formerly the I-95 corridor coalition and the IBTTA), and private development stakeholders (Cintra, Transurban) as well as academic communities (e.g., TRB committee on regional transportation systems management and operations). Table B-6-1 describes the general categories.

Table B-1. Categories of potential interviewees.

Location	Interviewees	Roads/Bridges
California	Orange County Toll Authority	SR91
Delaware	Delaware Department of Transportation/ Delaware Turnpike	US 1 (tolled) and US 13 (untolled) I-95 (tolled) and US40 (untolled)
Delaware/ New Jersey Pennsylvania/ New Jersey	Delaware River and Bay Authority/Delaware River Port Authority	Delaware Memorial Bridge/ Commodore Barry Bridge
Florida	Florida DOT/ Florida Turnpike	I-95 parallel to FL turnpike
Maryland	Maryland Transportation Authority/MDTA (MDOT)	Bridge over Susquehanna – I95/ US40
New Jersey	New Jersey DOT and New Jersey Turnpike	I-295 and New Jersey Turnpike
Pennsylvania	PennDOT / PA Turnpike	I-476 (tolled) and I-81 (untolled)
Texas	Cintra concession companies	Dallas/Ft. Worth managed lanes (LBJ, North Tarrant Expressway, SH 288)
Virginia	VDOT Transurban (I-495/95/395) Cintra (I-66 outside the beltway)	I-495/95/395 express lanes, I-66 outside the beltway (Washington Metro area)
East coast	The Eastern Transportation Coalition	
National	TRB Committee members (Managed Lanes Committee)	
International	IBTTA	
	Other Expertise	

SCRIPT FOR RECRUITING PARTICIPANTS

My name is Sue McNeil, and I am a Professor in the Department of Civil and Environmental Engineering at the University of Delaware. With colleagues at George Mason University, I am conducting research on how toll road operators (concessionaires and toll authorities) collaborate with state highway officials when tolls must be suspended or reduced to accommodate maintenance or emergencies on parallel or nearby state highway facilities. This research is part of project funded through the Region 3 University Transportation Center led by Pennsylvania State University. I am hoping you might be able to help me with this research.

I am reaching out to you because I believe that you have the knowledge and expertise to support this study. We hope you will be willing to share it with our research team. If you are willing, we would like to interview you and ask you some questions about your experiences, and perceptions related to opportunities, constraints, and legal implications. The purpose of this interview is to better understand the opportunities for state Departments of Transportation (DOTs) and toll operators to cooperatively share facilities when parallel roadways are being maintained or rehabilitated to minimize disruption to end users. This can include suspending tolls and remuneration of costs. The results of interviews with several state DOTs, toll operators, and professionals will be summarized in our project report. No personal identifying information (name, position, or affiliation) will be included in the project reports, and you can choose not to answer any question that you do not feel comfortable with.

We can conduct this interview via a video call (Zoom or Microsoft Teams) or over the phone; whichever works best for you. The interview would take approximately 45 minutes to 1 hour. Please let me know if you would be willing to do an interview. Your expertise and insights will be very helpful for our research, and I would greatly appreciate your taking the time to talk with our team. I can be reached via email at smcneil@udel.edu.

BACKGROUND INFORMATION PROVIDED TO INTERVIEWEES

Project Summary (to be shared with interviewees)

This project is exploring how toll road operators (P3 concessionaires and toll authorities) collaborate with state highway officials when tolls must be suspended or reduced to accommodate maintenance or emergencies on parallel or nearby state highway facilities. In such cases, public use of toll roads may require the state to compensate the toll road operator for foregone revenue under various types of toll operating contracts, including P3s.

The interviews will focus on assembling information to support a qualitative analysis of these agreements, including a history of any downtime events and the level of cooperation between both parties.

Glossary (to be shared with interviewees)

Bond covenant - a legally binding term of agreement between a **bond** issuer and a bondholder.... Negative or restrictive **covenants** forbid the issuer from undertaking certain activities; positive or affirmative **covenants** require the issuer to meet specific requirements. (https://www.investopedia.com/terms/b/bond-covenant.asp)
Concessionaire – in a public-private partnership, the concessionaire is the private entity that enters into a long-term concession for the design, construction, finance, operation and/or maintenance of an infrastructure asset owned by a state DOT or other governmental body.
Constraints – include limitations imposed by the bond covenant or operating agreement.
Operating or concession agreement – the contract between the asset owner and the concessionaire in a public-private partnership.
Public-private partnership (P3) – a long-term (usually multi-decade) agreement between a public infrastructure asset owner and a concessionaire for the design, construction, finance, operation and/or maintenance of that asset.
Stakeholder - Individuals or groups who have an interest or role in the project, program or portfolio, or are impacted by it. (https://www.apm.org.uk/resources/glossary/)
Toll authority - governing body that is legally empowered to review and adjust **toll** rates and design, construct, finance, operate and maintain a toll road, bridge or other facility. Unless otherwise delegated, the transportation commission is the **tolling authority** for all state highways. (https://www.lawinsider.com/dictionary/tolling-authority#:~:text=Tolling%20authority%20means%20the%20governing%20body%20that%20is%20legally%20empowered,authority%20for%20all%20state%20highways.)
Toll suspension – the act of not requiring payment of a toll for the use of a road.

INTERVIEW SCRIPT

The following script was used for the semi-structured interviews.

The objective of the interviews is to gather information regarding the forms of cooperation, the terms of the contract during these downtime events, and the relationships between both parties when the downtime occurs. Below are the general and sub-questions drafted to date:

(Informed consent)

We sent you a disclosure and consent document. Did you receive it? Do you grant your consent for this interview?

(Context)

Please describe the facilities you operate and the structure of your organization.

(Prior Experience)

Does your organization have any experience with toll reduction or suspension as a means of fostering relief for maintenance events on untolled adjacent or parallel facilities?)

What was the process for deciding to suspend/reduce tolls?

Were toll road operators compensated for associated revenue losses? If so, at what rates?

What was the process for determining any compensation?

(Toll Suspension Authority and Process)

Who has the authority to suspend the toll? What is the suspension process?

Do DOTs tell the toll authorities to suspend, or do both parties form a consent agreement?

Some toll roads are limited by their bond covenants in reducing or waiving tolls. Are you aware of any such restrictions related to toll roads in your jurisdiction?

What are the major channels of communication between the state DOTs and the toll authorities?

(Standard Practices)

What is the history of cooperation during downtime events? Are there standard practices?

Do you have any written protocols for operating practices? For instance, we recently found one protocol in Virginia.

[Thorough desk research will be useful.]

(Stakeholder Interests)

Who are the major stakeholders in deciding whether to waive or reduce tolls to accommodate maintenance on non-tolled facilities?

How do their interests vary? For example, how do their perceptions of cost, benefit, and barriers differ?

Are there any regulatory constraints on such cooperation? If so, what are they?

[Some behavioral questions on suggested policy options will be helpful. We can give several imaginary scenarios and ask interviewees' opinions.]

(Potential for Expanded Use)

Do you believe there is potential for expanded use of toll reductions/suspensions to mitigate the impact of maintenance events on adjacent or parallel facilities?

What would the benefits be?

What are the barriers?

Opinions on the research concept

Do the questions raised in this research have any relevance for or applicability to your organization?

Does such expanded cooperation seem practical? Does it seem relevant to your organization's operations?

Would you envision the results of this research leading to any changes to your organization's practices? If so, how?

Can you suggest any relevant examples of cooperation, publications, articles, or potential interviewees that might help us pursue our research?

Open ended questions

Is there anything else you would like to share with us?

Appendix C: BPR Function Calibration

Calibration of BPR function parameters α and β and roadway parameters of free-flow speed and capacity for each facility type (tolled and untolled) was based on traffic data. Traffic volumes and average speeds for each 1-hour increment were obtained for a 2-week period at the location of the case study from detector data (PeMS, 2022). Equation (C-1) shows the speed-volume relation used for the calibration.

$$u_i = \frac{u^0}{1 + \alpha \left(\frac{x_i}{Q}\right)^{\beta}}, \tag{C-1}$$

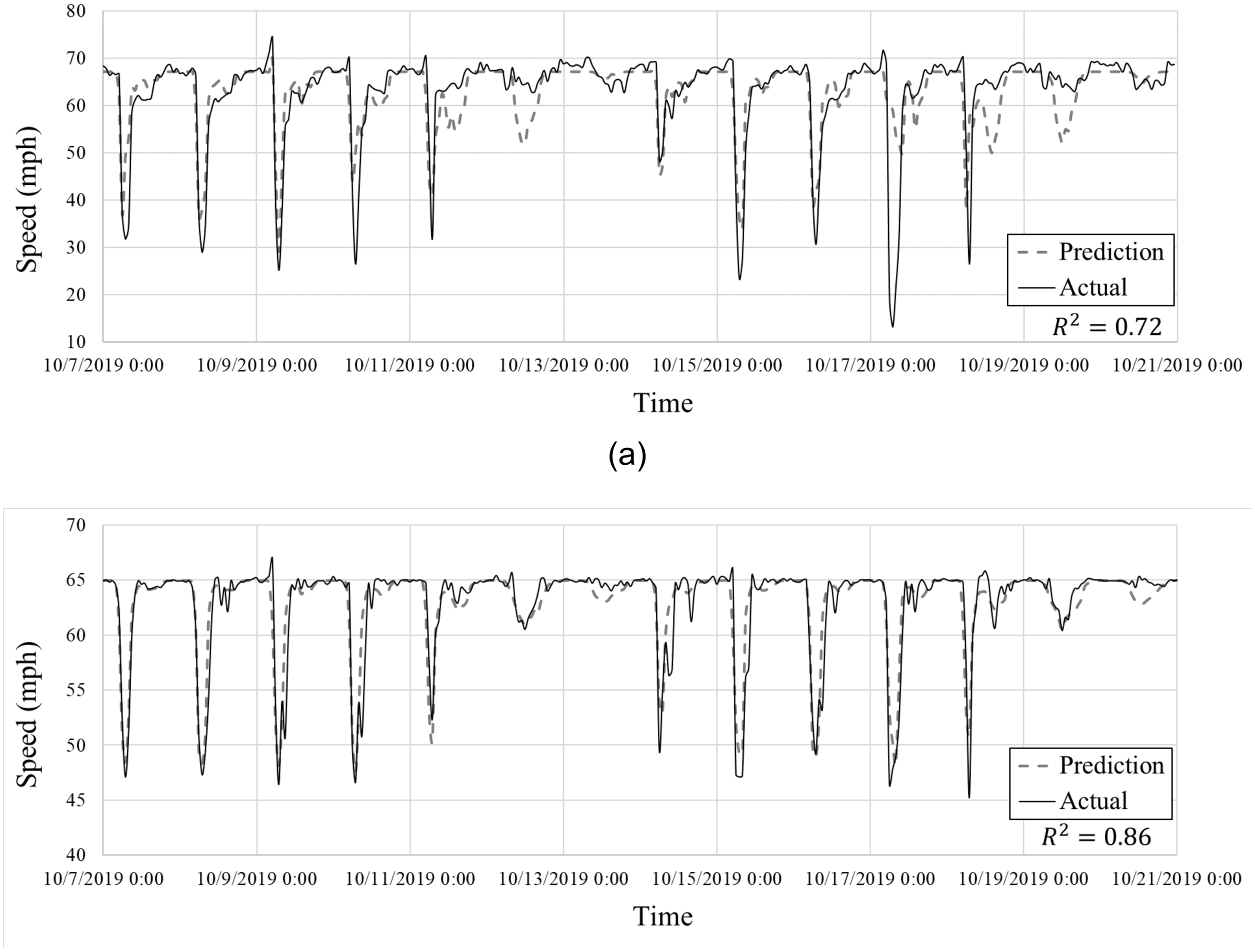
where u_i is the average speed in time increment i, x_i is the traffic volume in time increment i, u^0 and Q are roadway parameters representing free-flow speed and capacity, respectively.

To calibrate the parameters, the average speed of each 1-hour time increment is predicted ($\hat{u}_i$) given the traffic volume of the same time increment. The parameters in (C-1) were calibrated to minimize the residual sum of squares (RSS) of the prediction as in C-2.

$$min \sum_i (u_i - \hat{u}_i)^2, \tag{C-2}$$

where $\hat{u}_i$ is the predicted traffic speed in time increment i.

Results of the calibration are reported for each link and facility type in Table 4-4 in the main content. Note that the free-flow time t^0 in Table 4-4 was calculated using free-flow speed u^0. Speed values for both untolled and tolled lanes that were predicted using the calibrated parameters were plotted against the actual speed values collected from the data in Figure C-1. The figure includes the R^2 values indicating acceptable goodness of fit.



(a)

(b)

Figure C-1. Predicted calibrated versus actual speed values in (a): untolled lanes and (b): tolled lanes.

Appendix D: Case Study Baseline Conditions

Table D-1. Baseline condition of case study network.

Increment (t)	**Average flow of link a over time increment t (x_a^t) (veh/hour)**					**Travel time of link a over t (t_a^t) (min)**					**Price of a over t (p_a^t) (USD)**			**Travel cost of link a over time increment t (c_a^t) (USD)**					**Travel time at t ($6 \times \sum_{a \in A} x_a^t \cdot t_a^t$)**	**Total revenue at t ($6 \times \sum_{a \in A^+} x_a^t \cdot p_a^t$)**	**Total travel cost at t ($6 \times \sum_{a \in A} x_a^t \cdot c_a^t$)**
	***a*=1**	***a*=2**	***a*=3**	***a*=4**		***a*=1**	***a*=2**	***a*=3**	***a*=4**		***a*=1**	***a*=2**		***a*=1**	***a*=2**	***a*=3**	***a*=4**				
1	0	0	2585	2585		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.11E+05	0	6.46E+04
2	3607	3338	5691	5960		6.77	2.94	6.87	3.88		0.06	0.55		4.01	2.26	4.01	2.26		5.79E+05	12308.3	3.50E+05
3	430	86	6594	6938		5.09	2.31	18.77	14.59		7.98	7.16		10.95	8.51	10.95	8.51		1.36E+06	24268.29	8.20E+05
4	0	0	3033	3033		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.30E+05	0	7.58E+04
5	0	0	2576	2576		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.10E+05	0	6.44E+04
6	3523	3230	5936	6229		6.67	2.89	8.35	5.19		0.98	1.34		4.87	3.03	4.87	3.03		6.88E+05	46684.72	4.48E+05
7	2018	2033	5218	5203		5.46	2.49	5.53	2.5		0.04	0		3.23	1.46	3.23	1.46		3.48E+05	581.84	2.03E+05
8	0	0	3289	3289		5.08	2.31	4.91	2.23		0	0		2.97	1.35	2.86	1.3		1.41E+05	0	8.22E+04
9	0	0	2586	2586		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.11E+05	0	6.46E+04
10	3643	2396	5758	7005		6.81	2.58	7.21	16.28		0.23	7.99		4.2	9.5	4.2	9.5		1.12E+06	119990.2	7.73E+05
11	2053	2075	5241	5220		5.48	2.5	5.57	2.51		0.05	0.02		3.25	1.47	3.25	1.47		3.52E+05	743.8	2.06E+05
12	0	0	3278	3278		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.40E+05	0	8.19E+04
13	0	0	2593	2593		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.11E+05	0	6.48E+04
14	3784	3002	5753	6534		6.98	2.79	7.18	7.81		0.11	2.93		4.19	4.56	4.19	4.56		7.63E+05	55322.78	5.00E+05
15	2347	2231	5385	5501		5.64	2.54	5.85	2.8		0.12	0.15		3.41	1.63	3.41	1.63		3.95E+05	3785.68	2.34E+05
16	0	0	3580	3580		5.08	2.31	4.91	2.23		0	0		2.97	1.35	2.87	1.3		1.54E+05	0	8.95E+04
17	0	0	2524	2524		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		1.08E+05	0	6.31E+04
18	2642	2357	6618	6903		5.84	2.57	19.47	13.8		7.95	6.55		11.36	8.05	11.36	8.05		1.47E+06	218644.7	1.08E+06
19	3003	2940	5571	5635		6.14	2.77	6.39	3.01		0.15	0.14		3.73	1.76	3.73	1.76		4.75E+05	5226.49	2.82E+05
20	0	0	4536	4536		5.08	2.31	5.01	2.27		0	0		2.96	1.38	2.92	1.33		1.98E+05	0	1.16E+05
21	0	0	1182	1182		5.08	2.31	4.91	2.23		0	0		2.96	1.35	2.86	1.3		5.06E+04	0	2.95E+04
22	2006	2025	5320	5301		5.46	2.49	5.71	2.58		0.15	0.05		3.33	1.5	3.33	1.5		3.60E+05	2443.58	2.13E+05
23	3028	2979	5593	5642		6.16	2.78	6.47	3.03		0.18	0.14		3.77	1.76	3.77	1.76		4.81E+05	5836.7	2.86E+05
24	0	0	4420	4420		5.08	2.31	4.98	2.26		0	0		2.96	1.36	2.9	1.32		1.92E+05	0	1.12E+05
25	0	0	979	979		5.08	2.31	4.91	2.23		0	0		2.99	1.35	2.86	1.3		4.20E+04	0	2.45E+04
26	111	94	4736	4753		5.08	2.31	5.08	2.31		0	0		2.96	1.35	2.96	1.35		2.15E+05	0	1.25E+05
27	1378	1875	5661	5164		5.23	2.45	6.74	2.48		0.88	0		3.93	1.44	3.93	1.44		3.77E+05	7454.6	2.27E+05
28	0	0	3957	3957		5.08	2.31	4.93	2.24		0	0		2.97	1.35	2.87	1.31		1.70E+05	0	9.92E+04
																			Sum=1.08E+07	**Sum = $503,293**	**Sum = $6.78E+06**