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Highway Reservation System Design and Its Application to Freight Transportation

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TECHNICAL SUMMARY

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Title

Highway Reservation System Design and Its Application to Freight Transportation

Introduction

Congestion and safety associated with freight trucks are key issues that arise in the context of highway transportation, especially in the heavily-traveled commercial corridors. To address these issues, truck-only lanes for freight trucks have been proposed as a solution to improve the productivity and reduce congestion, safety hazards and emissions. Truck-only lanes combined with a reservation system can potentially enable efficient operations and reliable demand management to guarantee high quality of service. In this regard, a reservation system with a real options approach can address key issues associated with the user-pays principle (i.e., the beneficiaries of truck-only lanes pay the toll) and fair reservation fees for both highway operators and the users for truck-only lanes. This research seeks to develop an option-pricing mechanism consistent with the highway system's operation and to formulate a closed-form pricing-function on reservation options on truck-only lanes to guarantee a threshold level of service, given the vulnerability associated with system management failure.

Findings

Based on the Black-Scholes framework in finance, we obtain several important findings. First, it is theoretically possible to make travel time on highway a tradable asset that has monetary value as the product of travel time on highway and value of travel time. The observation that travel time on highway has a log-normality property helps to formulate the dynamics of the price of travel time as a geometric Brownian motion and derive a closed-form equation for an easy implementation in practice. Finding a potential underlying asset in a reservation system is an innovative concept since the notion of travel time on highway as a tradable asset implies the feasibility of developing derivative contracts in the context of a reservation system for truck-only lanes. Second, reservation options on truck-only lanes differ from those of the financial market in the sense that unhedgeable risks exist for highway operators in terms of failing to guarantee the promised speed. This implies that the reservation options are subject to the risk of failing to guarantee travel time savings on truck-only lanes due to traffic incidents (e.g., accidents) and externalities (e.g., adverse weather events). The pricing-process considering no default situations causes reservation options to be over-priced unintentionally with respect to option period, which implies a biased price for highway operators in terms of the fairness. Finally, the reservation options must be honored since derivative contracts entail legal responsibilities of fulfilling obligations as the option supplier (i.e., highway operators).

Recommendations

This study suggests that an option-based approach for a reservation system on truck-only lanes is able to represent an efficient and feasible scheme for pricing reservation fees in terms of the user-pays principle and the fairness of pricing. In addition, this study will help highway operators meet demand and supply of a highway system and government agencies finance highway infrastructures. Finally, it provides useful insights for exploring an option-pricing scheme for other dedicated facilities.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background and motivation

Empirical data illustrates that the freight volume on transportation systems in the U.S. has sharply increased over the past few decades and will continue to increase (USDOT FHWA, 2004). It leads to increased focus on issues related to congestion and safety in the context of highway transportation. According to the Freight Analysis Framework (USDOT FHWA, 2002), between 1980 and 2002, the volume-miles of freight trucks on highway almost doubled. By comparison, the lane-miles of public roads increased by only 5 percent leading to significant pressure on the already congested highway systems. In addition, the Freight Analysis Framework (FAF) projects that 46 percent of highway systems in the U.S. will reach or exceed the capacity during peak hours in 2020 in comparison to 28 percent in 1998.

The congestion issue on highway systems in the U.S. is further exacerbated by the current gaps in capital investments for transportation infrastructure. Congestion on highway contributes to increased transportation costs of freight transportation in terms of increased fuel costs and transit time. Specifically, the trucking industry in the U.S. has experienced productivity losses due to traffic congestion. For example, the Federal Highway Administration (FHWA) in 2008 estimated that delays resulting from congestion at highway bottlenecks lead to more than $8 billion in costs incurred by the trucking industry annually (U.S. Chamber of Commerce, 2008).

Massive freight movement on highways using trucks tends to cause serious safety problems in highway operations. Past studies (e.g., Vaughan, 1975 and Mannering et al., 1993) suggest that accidents involving heavy trucks have more severe injuries and increased number of fatalities in comparison with those between passenger cars. A large body of research on freight transportation on highways has been devoted to address these problems. For example, Oberstar and DeFazio (2008) briefly summarize possible solutions to mitigate negative effects on the movement of freight, including those for trucks on highways.

It has been proposed that introducing congestion pricing schemes, enhancing intermodal transport with rail lines, constructing truck-only lanes, etc. can be viable options to address these problems, in addition to traditional approaches such as constructing new highway infrastructure or adding new additional capacity to existing highway infrastructure. Solutions such as truck-only lanes can improve safety as well as provide potential operational gains for trucking companies. Compared to other solutions, truck-only lanes on highway have been proposed as a practical solution and actually tested at a few locations worldwide. For instance, there exist truck-only lanes on I-5 in Los Angeles County, I-15 in San Bernardino County in California, and the New Jersey Turnpike in New Jersey. Also, truck-only road networks have been studied in Britain, Italy, and the Netherlands (Lindsey, 2009). The truck-only lanes are expected to decrease traffic conflicts, congestion and safety hazards to other passenger vehicles and offset maintenance costs on regular lanes as well in a sense that exclusive right-of-way on specially-dedicated lanes for freight trucks enables the efficient and reliable movement of freight trucks through physical separation unlike regular mixed traffic flows. There are additional benefits in terms of substantial savings in terms of fuel costs and emission reductions.

The literature illustrates several potential benefits from exclusive truck-only facilities for freight transportation: (1) Truck-only lanes can mitigate congestion for trucks and other vehicles in that trucks traveling on truck-only lanes will have less need for braking, accelerating or decelerating, and overtaking. Other vehicles (e.g., passenger cars) can benefit from the reduction of trucks moving on regular lanes at lower speeds, less interference due to blind spots, and the ease of changing lanes; (2) Physical separation of trucks and regular vehicles leads traffic flows to be more homogeneous and improves safety in terms of rates and the severity of injuries and fatalities in accidents.

Regardless of these advantages, the feasibility of truck-only lanes still remains restricted because it is effective only under the scenario that traffic volumes include a relatively high level of heavy trucks. Besides, truck-only lanes entail significant construction costs, which is problematic under limited available budgets for highway infrastructure. Past studies (e.g., Rodier and Johnston, 1999 and Meyer et al., 2006) have proposed solutions to finance the construction of truck-only lanes in terms of collecting tolls from truck users to bridge the gap between the funding needs to construct them and the ability of the government to pay for it. At the same time, a toll system on a highway leads to important issues in terms of who would pay for it and who benefits from the facility. To address these issues, the user-pays principle is a possibility in that the beneficiaries of truck-only lanes (e.g., trucking companies or its truck users) pay for the necessary costs for the construction and maintenance of the facility.

In addition to the financial aspects associated with truck-only lanes, charging tolls to the users leads to operational issues for highway operators in terms of whether the highway operators are able to provide improved service to the facility users. As users pay for the service, highway operators need to ensure that the tolled facility performs at an acceptable level, as well as reduce the uncertainty in service quality (e.g., travel time or safety). This requires the highway operators to manage the demand on truck-only lanes.

Akin to a “reservation” in other transportation modes (e.g., rail or airline), reservation on a highway as a strategy of demand management is a powerful instrument to control traffic flow and manage the performance at the optimal level. Hence, reservations of truck-only lanes are expected to control potential demand for this facility and maintain improved performance by reducing uncertainty related to travel time and congestion. Therefore, truck-only lanes combined with a reservation system can potentially provide highway operators benefits in terms of more reliable and accurate information on the demand for truck-only lanes. Further, the reservation system leads to more efficient operations through timely demand management. Nevertheless, important issues need to be addressed such as how the appropriate levels of reservation rates on truck-only lanes can be determined and how potential benefits (such as savings in terms of travel time and accrued safety) can be distributed equitably.

To address these problems, this study proposes a highway reservation system using a real options approach. Real options have the potential to address the aforementioned issues by charging reservation fees equal to the expected monetary gains that freight truckers can obtain from traveling on truck-only lanes. In addition, it can enable a solution that is beneficial to all relevant stakeholders including freight companies, road users and highway operators. Specifically, it enables freight companies to plan more reliable and efficient delivery schedules and to charge higher premium for the savings on delivery time through just-in-time transport services. At the same time, it can provide road users an improved quality of travel experience and accrued safety (e.g., psychological comfort) due to the physical separation from heavy freight trucks. Finally, highway operators benefit from the reliable estimation of potential demand for truck-only lanes in advance in terms of developing better traffic management strategies, and the availability of a new financing source for the maintenance and construction of highway infrastructure. In turn, the operating agencies are strongly motivated to provide improved-quality service to generate additional revenues from the increased demand.

The consideration of travel time on highway as a tradable asset is an innovative idea from a financial perspective. In addition, from the perspective of highway operators, the securitization of travel time on highway as derivative contracts is intrinsically needed to account for the possibility that highway operators may fail to manage traffic conditions at a promised threshold due to unexpected traffic incidents (e.g., accidents) and externalities (e.g., weather events). This aspect, which is different from that of financial markets, enables the highway reservation system using a real options approach to represent a viable solution to the unhedgeable risks for highway operators in terms of failing to guarantee the promised level of service (for example, in terms of speed). In this study, this risk for highway operators in failing to meet the promised speed is labeled as a default risk of reservation options hereafter to be consistent with the definition of the default used in finance which refers to the failure of promised obligations (e.g., repaying debts). Generally, since an option-pricing framework used in financial derivatives market does not consider this issue, ordinary options traded on the exchange or over-the-counter have no default risks of fulfilling obligations (i.e., promised transactions) written in the contract.

By contrast, the highway reservation options on truck-only lanes have the likelihood that highway operators may fail to guarantee a certain traffic service level (e.g., LOS A in this study) on truck-only lanes due to traffic management challenges associated with unexpected incidents and weather events. Accordingly, the frequent generation of these default situations may lead to reduced trust in a reservation system for truck-only lanes. Unless these default risks are fully considered in developing the reservation options at a fundamental level, the options remain over-priced in terms of the fair price for the users, and then the resulting default situations may lead to legal and credibility issues for highway operators. This type of derivative contract is labeled a “vulnerable option” in finance in that the options are subject to default risk.

In this study, we seek to find an appropriate option pricing mechanism in association with the operational limitations of managing highways under uncertainty. Besides, the introduction of the reservation options by factoring default risks will ease the operational burden of highway operators, increase the credibility of the reservation system for users, and reduce the likelihood of legal and trust issues for highway operators.

1.2 Organization of the research

The remainder of the report is structured as follows. Chapter 2 reviews the literature on truck-only lanes and reservation systems, and discusses the potential of introducing derivatives to manage truck-only lanes. Chapter 3 models the dynamics of travel time on a highway and identifies a tradable asset of reservation options on truck-only lanes. The Black-Scholes framework will be applied to construct a pricing-function of reservation options on truck-only lanes with a closed-form formulation. The default situations of highway operators will be considered in the formulation in order to reflect distinct properties of the highway system's management into derivative contracts. Chapter 4 presents numerical results that illustrate in detail the influence of default risk on the price of reservation options, depending on the historical volatility of travel time on highway. Chapter 5 summarizes insights and contributions, and provides potential venues for further research.

CHAPTER 2. HIGHWAY RESERVATION SYSTEM WITH A REAL OPTIONS APPROACH FOR TRUCK-ONLY LANES

This chapter presents a brief review of highway reservation systems for truck-only lanes. Truck-only lanes contribute to the mitigation of the negative effects associated with the movement of freight trucks in heavily-traveled commercial corridors through an exclusive right-of-way for truck users.

2.1 Literature review

Fischer et al. (2003) indicate that truck-only lanes enable the improvement of freight mobility and delivery reliability within congested areas through exclusively dedicated lanes. They illustrate potential benefits in terms of social benefits that include reducing congestion and enhancing safety. Middleton and Lord (2005) indicate that the separation of trucks from other mixed traffic flows decreases crashes on freeway. They suggest the introduction of exclusive lanes on highways with high traffic volume whose limited access can lead to improvement of mobility and safety. Adelakun and Cherry (2009) implement a survey to study truck driver perceptions on congestion and safety and preferences on potential geometric or operational schemes on highways. They suggest that some truck drivers are willing to pay for the operation of truck-only lanes to avoid traffic congestion and safety hazards.

However, the efficient usage of truck-only lanes requires systematic planning and operational strategies such as a reservation system and a pricing mechanism to control the demand for truck-only lane and to maintain high quality of service. In this context, Wong (1997) studied a highway booking system which leverages the logic of the trip-planning process. The booking system collects travel patterns of individuals, such as departure times and routes, and the highway authority can manage traffic flows on roads to mitigate congestion. Edara and Teodorović (2008) propose a travel demand management system labeled as the Highway Space Inventory Control System (HSICS) in which all road users have to make reservations in advance to enter the highway. This system assists highway operators to make real-time decisions on whether to accept or reject requests of road users. Zhao et al. (2010) propose a travel demand management strategy called Downtown Space Reservation System (DSRS) in which travelers seeking to enter a downtown area have to make reservations in advance for obtaining access. The system controls the traffic volume entering this area to mitigate congestion in the downtown area. The authors concluded that while the realization of a DSRS will require more time due to the need to address specific barriers including the coordination with associated participants and existing policies on other transportation modes related to DSRS, the concept of reservation is more realistic for traffic management for a highway system as it is a closed system.

The success of the reservation system depends mainly on the appropriate determination of reservation fees. Yao et al. (2010) suggest that congestion pricing is an efficient demand management mechanism to decrease total social costs associated with congestion in peak period. They show that congestion is involved with exogenous uncertainties independent of central authority's controls and individual travelers' trips. They further propose financial derivative contracts on congestion in order to reduce total social costs. In this regard, Friesz et al. (2008) develop a derivative contract on commuting time by using an option-pricing approach to mitigate congestion. In contrast to traditional user-optimized flow patterns, the flow patterns used in Friesz et al. (2008) are derived using call options on congestion. They conclude that congestion call options may lower the social costs of congestion.

Unlike Friesz et al. (2008) who compare the value of congestion call options using the difference between the in-office and at-home marginal productivities, the idea of associating the value of the reservation options with the monetary benefits for truck drivers' time-savings is more realistic for freight transportation in terms of the measurement of potential gains and the accessibility to available data. Accordingly, the design of a reservation system with reservation options on truck-only lanes represents a viable solution to improve the efficiency of the highway system in that it guarantees a threshold speed level on the specific lanes (labeled the “option lane” in this study) for freight trucks reserved in advance while other lanes (labeled “regular lane” in this study) operate under mixed traffic flow conditions. This design should be sensitive to uncertainties of travel time on regular lanes in that freight truck drivers may decide to shift into option lanes under the situation that option lanes outperform regular lanes in terms of travel time. In addition, to be consistent with real-world trucking operation, this design should be sensitive to uncertainties in the demand for freight shipping, implying the need for flexibility in the use of the option lanes.

Past studies (Friesz et al., 2008 and Yao et al., 2010) on pricing strategies with options show that the options enable the imposition of a fair rate to the system users who derive benefits from traveling on special purpose facilities since the options are fair-priced as the amount of expected returns when options are exercised. Therefore, the reservation system combined with an option-based pricing scheme can play a significant role in meeting demand and supply for option lanes. Further, it can assist in distributing demand for option lanes for other times evenly through the guarantee of a threshold speed or a certain traffic level of service.

2.2 Preliminaries

2.2.1 The concept of truck only lanes

Truck-only lanes refer to special purpose lanes reserved for the uses of trucks. The objective of this facility is to separate the movement of trucks from other mixed traffic flow physically. This can lead to congestion alleviation, thereby improving productivity, reliability, and safety. Regardless of these merits, truck-only lanes are not common in the U.S. because of their expensive construction costs within limited highway budgets. There exist few applications of truck-only lanes in the U.S. For example, Northbound and Southbound I-5 in Los Angeles County at the State Route 14 split and Southbound I-5 in Kern County at the state Route 99 junction near the Grapevine in

California. It is reported that truck-only lanes are effective under a substantial volume of trucks or in congested areas during peak periods (Fischer et al., 2003).

As the concept of exclusive lanes for freight trucks has been considered in previous studies, various types of truck-only lanes have been proposed. They are summarized briefly according to the cross-sectional configuration of truck lanes (Forkenbrock and Hanley, 2005).

(1) Two additional lanes dedicated for heavy trucks in each direction: Separated by physical barriers from other existing lanes.

(2) One additional lane for heavy trucks in each direction: Possibly located in the median with physical barriers from traffic flows in opposite direction and other existing lanes.

(3) One additional lane in a total of three lanes in each direction: The right lane for trucks, the left for other types of vehicle, and the middle for both groups.

2.2.2 The concept of a highway reservation system

A reservation system for highway functions as an instrument to recognize trip patterns and to control the traffic flow at a desired level by spreading excess demand to other times and routes. Specifically, highway users seeking to travel on a certain route have to make reservations in advance by inputting departure time, travel route, entry ramp, exit ramp and his vehicle ID into the reservation system. The reservation system will decide to accept or reject the request, depending on current and/or future traffic conditions. Rejected reservation request requires the users to choose other times or routes to travel by the acceptance of the request. If the reservation is accepted, the inputted information on the trip will be recorded into a data bank and the traffic volume on highway continues to be in control in a planned period. This process helps highway operators accurately estimate potential demand on highways and alleviate congestion through a timely demand management, thereby improving the performance of the system. Similar to the financial interpretation of reservations proposed by Quan (2002), the action of making reservations on truck-only lanes is interestingly considered as that of buying a financial option contracted between the users and highway operators in a sense that reservations can eliminate impacts of traffic incidents and weather events toward future service quality on highway by shifting from regular lanes to well-controlled truck-only lanes with payment of the premium. In his study, the Black-Scholes framework is applied to develop the reservation-pricing model and a European type of call options on service is priced.

2.3 Problem statement

The concept of real options has been applied in domains of transportation and logistics. They are assumed to be traded on exchange or over-the-counter. In general, it is reasonable that financial options traded on the exchange are default-free in that a clearinghouse guarantees the fulfillments to mutual obligations to associated participants. However, a previous study in the literature (Cheng, 2010) has a significant gap in operative realm of traffic highway system due to the assumption that an operation agency has perfect knowledge and the ability to operate truck-only lanes on highway seamlessly. In reality, it seems to be less realistic due to intrinsic randomness of the highway system (e.g., traffic volume) and external effects (e.g., accidents and weather events). Therefore, reservation options in a highway reservation system are supposed to account for the likely uncertainty that leads to the failure to guarantee the promised level of service. In this regard, the price of reservation options can be unintentionally over-priced under the assumption of perfect knowledge and management ability of an operation agency. This situation may lead to legal and credibility issues.

In this study, we aim to develop an appropriate pricing mechanism of reservation options considering the operational risks of highway operators (i.e., the default risks of reservation options), whose price is equivalent to the payment of reservation fees, for regulating potential demand and maintaining service quality of truck-only lanes. The reservation options in the pricing mechanism will be priced in a fair sense for the users, while mitigating potential legal and credibility issues. The next chapter models this problem and discusses travel time as an asset that can be used to develop reservations for truck-only lanes using the real options approach.

CHAPTER 3. RESERVATION OPTIONS ON TRUCK-ONLY LANE SUBJECT TO THE RISKS OF HIGHWAY OPERATORS

3.1 Modeling the dynamics of travel time

The accurate prediction of travel time is a key factor in transportation planning, design, operations, and evaluations. In addition, it is a fundamental component to develop advanced transportation systems such as intelligent transportation systems and advanced traveler information systems. In this regard, past studies (e.g., Pu, 2011 and van Lint and van Zuylen, 2005) have found it difficult to estimate travel time and its statistical distributions from data collected by sensors and surveys.

In reality, travel time on road tends to evolve with uncertainty due to complextraffic dynamics and externalities. Thereby, several theoretical and practical efforts have sought to more reliably estimate travel time on highway and to find out an appropriate statistical distribution.

Observed distributions of travel time vary significantly from location to location. This is because the travel time is highly influenced by complicated mechanism of traffic flows that is associated with traffic signal configuration and vehicle mixtures and geographical characteristics of observed locations such as curvatures. For the convenience, we focus mainly on a simple case of a unimodal distribution of travel time. In the literature, there are sufficient supporting studies to demonstrate that the distribution of travel time can be described statistically by a log-normal distribution (e.g., Cambridge Systematics, Inc., and Texas Transportation Institute, the University of Washington, and Dowling Associates, 2003). Additionally, van Lint et al. (2008) and van Lint and van Zuylen (2005) classify four shapes of distributions of travel time on freeway with respect to traffic conditions: free-flow, congestion onset, congestion and congestion dissolve. The authors conclude that traditional log-normal distribution enables to express a probability distribution of travel time more accurately in comparison with other statistical distributions such as Gaussian distribution and gamma distribution, since it covers a wide variation of distribution's shapes to express various traffic conditions by adjusting the values of two parameters. In addition, Rakha et al. (2006) and Pu (2011) indicate that travel time on road is log-normally distributed over days.

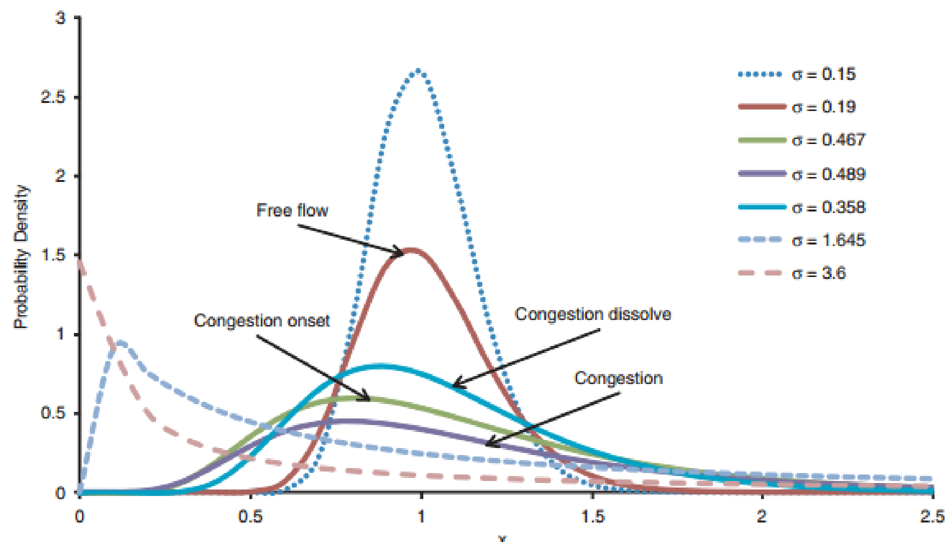

Figure 3.1 Probability density function of standard log-normal distribution

Source: Pu, W.J. (2011) Analytic relationships between travel time reliability measures. p.124

In the context of a highway reservation system, the evolution of travel time is of great importance. The past studies discussed heretofore generate useful insights in that the travel time on a highway can be modeled using a Geometric Brownian Motion (BM), which describes a stochastic process in a continuous-time horizon. Equation 1 shows that the evolution of travel time on highway consists of deterministic increments over time and random disturbing effects on the deterministic path. The term $w(t)$ represents a random effect at time t that disturbs the deterministic evolution of travel time on highway with respect to time.

A geometric Brownian Motion model of travel time on a highway (Cheng, 2010) has mathematical merits to formulate the pricing scheme of reservation options with a closed-form expression.

$$dX(t) = \alpha X(t)dt + \sigma X(t)dw(t),\ dw(t) \sim N(0, dt) \quad \text{.............................. Eq. 1}$$

where, $X(t)$: Travel time on highway at time t

α : Drift rate (or expected change of the return of travel time)

σ : Volatility (or variance of the return of travel time)

$dw(t)$: The change of the value of random varible during time dt

$N(0, dt)$: Gaussian distribution with zero mean and variance of dt

3.2 Assetization of travel time

The consideration of travel time on highway as a traded asset in this study (i.e. Assetization) is an innovative idea even though there are no markets for trading travel time on highway in the real world. Based on the stochastic variation of travel time on highway, we seek to treat the travel time on highway as a risky asset of reservation options, which can be traded in the market. This is a necessary condition to determine the price of reservation options because of the fundamental principle of real options, in which the value of derivative contracts depends on the value of its underlying asset. It is reasonable that the monetary value of travel time on highway is expressed as the product of travel time and the value of time. As the value of time is assumed a constant in this study, the monetary value of travel time on highway still remains a Geometric Brownian Motion with the same parameters in stochastic differential equation of travel time on the highway, applied in equation 1.

$$d\delta X(t) = \alpha\delta X(t)dt + \sigma\delta X(t)dw(t),\ dw(t) \sim N(0, dt) \quad \text{.......................... Eq. 2}$$

where, δ : value of time

As shown in Equation 2, the price dynamics of travel time on regular lanes consists of a deterministic process and a random process acting as disturbance or noise against the deterministic path over time, with constant coefficients of $\alpha\delta$ and $\sigma\delta$ respectively.

Based on the obtained model of the price dynamics of travel time on regular lanes, we aim to develop a pricing function of reservation options on truck-only lanes. This study focuses only on an European style of reservation options.

3.3 Mechanism of reservation options on truck-only lanes

In the proposed reservation system, freight trucks seeking to use the option lanes have to buy reservation options in advance. Only the freight truck companies/drivers who already purchased reservation options are allowed to have access to the option lanes. That is, the price of reservation options equivalently functions as reservation fees to the users seeking to avoid congestion on regular lanes. Specifically, they can purchase the options prior to the option's expiration day or within a prior time window. Here, the expiration day is defined as the day that the buyers have to decide whether to exercise the options or not. Generally, the expiration day refers to the specific date when the carrier expects a delivery need. It is normally accepted that the farther ahead the expiration day, the higher the price of the reservation options. This higher value of the reservation options is due to the higher uncertainty in the travel time farther into the future. It should be noticed that the reservation options are also designed for handling the uncertainty in freight carrier's schedule by providing the carriers with a right, instead of an obligation, to exercise the options. The reservation options are similar to European call options in finance. Specifically, if it turns out that there is no need to send out trucks on a given day or that freight trucks meet a well-performed traffic condition on regular lanes, the carriers do not necessarily exercise the options by giving up the right to travel at truck-only lanes. This contingent claim gives the option buyers a way to hedge delivery delay on highway, which is a challenging business risk in freight transportation industries.

3.4 Methodological framework

The Black-Scholes model commonly applied in finance assumes that there is a certain market consisting risky and risk-free assets, which are liquidly tradable (e.g., stocks and bonds). The model sets several assumptions on the market and the two assets traded in the market.

1. The rate of the return on a risk-free asset is constant (i.e. risk-free interest rate).
2. The price of a risky asset follows a Geometric Brownian Motion.
3. A risky asset does not involve with any cash flows in the present or future.
4. The market is so liquid that the trading of the risky asset and lending money (or purchasing risk-free bonds) can be implemented at any time as much as traders hope.
5. There exist no arbitrage opportunities.
6. There exist no market frictions (i.e. transaction costs and taxes).

With these assumptions, it is concluded that the price of a derivative contract with a certain type of contract (i.e. European call and put) is a deterministic function dependent of time and initial value of a risky asset. Using the change of hedging position of buying a risky asset and selling a derivative contract, they create a risk-free portfolio during short time period which does not depend on the price of a risky asset. The dynamic rebalance of the hedging position on continuous time leads to Black-Scholes' partial differential equation which depends on time and the initial price of a risky asset.

The Black-Scholes framework has been applied to develop financial derivative contracts on multiple traded assets (such as securities, bonds, commodities, even weather events) in financial markets. In this framework, it is commonly assumed that the price of underlying assets follows a geometric Brownian Motion to capture the stochastic nature of the price itself as it evolves with uncertainty. Based on the behavior of this price's evolution, the past studies in finance have developed various derivative contracts for tradable assets with uncertainty of price. In the Black-Scholes framework, the price of an option can be determined by replicating strategy and self-financing property. In the context of replications, the payoff of the option at the maturity date will be equivalently copied with a financial portfolio with the position consisting both risky assets and risk-free assets under self-financing condition, which implies that the change of the portfolio's value depends only on the change of assets' value in the portfolio. Equivalently, it implies that there is no cash inflow or outflow involved with this portfolio.

This framework can be applied to resolve issues related to uncertainty in the domains of transportation and logistics. For example, Friesz et al. (2008) and Tsai et al. (2011) examine the feasibility of derivatives contracts on commuting time and capacity in truckload freight to alleviate social costs from congestion and to reduce transportation costs, respectively. Cheng (2010) presents a highway reservation pricing system for truck-only lanes using the Black-Scholes framework. He develops the pricing mechanism by charging reservation fees to freight companies or road users seeking to use truck-only lanes, where the users reserve truck-only lanes with payment of reservation fees equivalent to the price of reservation options developed. It is economically fair because the reservation options are priced based on monetizing expected returns (i.e., savings of travel time from traveling on option lanes).

In the real world, it is common that options are highly honored with no default risks on the contract because it articulates rights and obligations of the stakeholders (i.e. the option buyer and seller, respectively), and entails legal responsibilities on fulfilling the obligations. In addition, ordinary options which are traded on the exchanges seem valid due to the existence of a clearinghouse acting as an intermediary entity between the buyer and the seller in order to prevent obligations from defaulting. Nevertheless, options traded over-the-counter may face a situation that the option's seller declares default related to its obligations to generate promised transactions. Similarly, reservation options are subject to default risks of highway operators (the option seller in reservation options) due to unexpected events (such as accidents and weather effects), which in turn significantly affect the ability to manage traffic flows on the highway. Under these situations, the highway operators may not be able to guarantee the promised level of service (such as travel speed or traffic condition) on the option lanes even under advanced demand control and management strategies on the option lanes.

Accordingly, the uncertainty of travel time on truck-only lanes can entail the possibility of default by the highway operators such that the advantage of introducing reservation options (such as economically fair fees) is deeply undermined. In other words, the non-consideration of default risks embedded in reservation options in relation to highway operations can cause the option to be over-priced for the users. In addition, the default, although not determined by the operators, may impose legal responsibilities in terms of damages paid to freight companies or road users based on the failure to provide the promised savings in travel time on the option lanes when the freight companies or road users decide to exercise the reservation options on the maturity date. From the literature, this type of options is referred to a "vulnerable option" in finance, which refers to options under default risks. This concept of reservation option plays a significant role in achieving a fair price of reservation options by reflecting operational limitations in highway management.

3.5 Formulation of pricing vulnerable reservation option on truck-only lanes

With the Black-Scholes framework mentioned above, a pricing-function for European reservation option on truck-only lanes is developed based on assumptions on the market:

1. The travel time on highway is tradable as a risky asset with a monetary value and its price evolves continuously without sudden jumps.
2. Only the European style of call option is considered.
3. The market does not incur any frictions (such as transaction costs and taxes).
4. There exist no arbitrage opportunities.
5. The risk-free interest rate is constant during option period.
6. The highway operators have perfect knowledge and strategies to manage the system timely and seamlessly under any situations (i.e. no default risks).

For simplicity, this study focuses on the formulation of a pricing function of reservation options without default risks of the highway operator (Cheng, 2010) and further considers the case under the existence of default risks of the highway operator.

Based on the mathematical representation of the price dynamics of travel time on regular lanes (labeled the underlying asset below) as the following geometric BM:

$$dS(t) = \alpha S(t)dt + \sigma S(t)dw(t)\ ,\ dw(t) \sim N(0, dt) \quad \text{Eq. 3}$$

where $S(t)$: The price of travel time on regular lanes at time t

α : Drift rate (or expected change of the return of travel time)

σ : Volatility (or variance of the return of travel time)

δ : Value of time

$dw(t)$: the change of the value of random varible during time dt

$N(0, dt)$: Gaussian distribution with zero mean and variance of dt

We model the reservation option's price as an explicit function which is dependent on time t and the price of the underlying asset $S(t)$, labeled pricing function *F*. The payoff of the reservation options at the maturity time T is defined as $\max[S(T) - K_{\text{LOS A}}, 0]$. This contract function illustrates that if the option buyer exercises the reservation options at the maturity date T and in turn has access to option lanes under traffic condition of LOS A, the payoff of the options is equivalent to savings of travel time experienced during travel on the option lanes; that is, the difference between the expected travel time on regular lanes and the expected travel time on option lanes. Alternatively, the option buyer has no need to exercise reservation options if the traffic conditions on regular lanes are better than those of the option lanes. Then, the payoff of reservation options at the maturity T becomes trivial. To price the reservation options, we construct a risk-free portfolio whose value at the maturity T exactly equals that of reservation options without uncertainty, so-called replicating strategy. Assume that the portfolio takes a certain position with selling one share of reservation options and buying a certain portion of risky asset, and travel time on regular lanes is measured as $\frac{\partial}{\partial S(t)} F(t, S(t))$. The monetary value of this portfolio $V(t)$ at time t is determined as follows:

$$V(t, S(t)) = F(t, S(t)) - \frac{\partial}{\partial S(t)} F(t, S(t)) \cdot S(t)$$

At an infinitesimal interval of time dt, the change of the value of this portfolio is dependent on the change in the prices of reservation options and the underlying asset, instead of the change of the portion of the underlying asset under a self-financing condition. Therefore:

$$dV(t, S(t)) = dF(t, S(t)) - \frac{\partial}{\partial S(t)} F(t, S(t)) \cdot dS(t)$$

From the Ito formula, the change of the value of reservation option during time dt is formulated as follows:

$$\frac{\partial}{\partial t} F(t, S(t))dt + \alpha \frac{\partial}{\partial S(t)} F(t, S(t))dS(t) + \frac{1}{2}\sigma^2 S(t)^2 \frac{\partial^2}{\partial S(t)^2} F(t, S(t))dt - rF(t, S(t)) = 0$$

Under the condition of no arbitrage opportunities, the return of this portfolio at time dt is the return of risk-free interest rate r at banks during time dt. Namely:

$$dV(t, S(t)) = rV(t, S(t))dt = dF(t, S(t)) - \frac{\partial}{\partial S(t)} F(t, S(t)) \cdot dS(t)$$

The elimination of $dw(t)$ which represents uncertainty in the equation indicates that the portfolio is risk-free at time dt. Finally, we obtain a partial differential equation labeled the Black-Scholes Formula as follows:

$$rF(t, S(t)) = \frac{\partial}{\partial t} F(t, S(t)) + \frac{1}{2}\sigma^2 S(t)^2 \frac{\partial^2}{\partial S(t)^2} F(t, S(t)) + rS(t) \frac{\partial}{\partial S(t)} F(t, S(t))$$

While a partial differential equation has infinitely many solutions mathematically, the unique solution of this equation above is well-known under the terminal condition of $\max[S(T)-K_{\mathrm{LOS\,A}},0]$ (Black and Scholes, 1973) and is expressed as follows:

$$C(t,S(t)) = F(t,S(t)) = S(t)N(d_1) - K_{\mathrm{LOS\,A}}e^{-r(T-t)}N(d_2) \quad \text{......................... Eq. 4}$$

where $N(\cdot)$: cumulative probability density function of Standard Gaussian distribution, $N(x)=\int_{-\infty}^{x}\frac{1}{\sqrt{2\pi}}e^{-\frac{z^2}{2}}dz$

$$d_1 = \frac{\ln\left(\frac{S(t)}{K_{\mathrm{LOS\,A}}}\right)+\left(r+\frac{1}{2}\sigma^2\right)\cdot(T-t)}{\sigma\sqrt{T-t}}$$

$$d_2 = \frac{\ln\left(\frac{S(t)}{K_{\mathrm{LOS\,A}}}\right)+\left(r-\frac{1}{2}\sigma^2\right)\cdot(T-t)}{\sigma\sqrt{T-t}}$$

$S(t)$: the price of travel time on regular lanes at time t

$K_{\mathrm{LOS\,A}}$: the price of travel time on regular lanes corresponding to LOS A

σ : volatility (or variance of the return of travel time on regular lanes)

T : maturity of reservation options

r : risk-free interest rate

Both terms of $N(d_1)$ and $N(d_2)$ have mathematically important implications. The term $N(d_1)$ indicates the sensitivity of the price of reservation options with respect to the price of travel time on regular lanes as $\frac{\partial}{\partial t}F(t,S(t))$; and the term $N(d_2)$ indicates that the possibility that the travel time on regular lanes exceeds the guaranteed value under traffic condition of LOS A on regular lanes, which will be realized on option lanes.

The Black-Scholes formula of pricing European reservation options on truck-only lanes can be interpreted in a conventional way in economics; the action of buying a single share of reservation option is interpreted as that of investing a self-financing portfolio which consists of buying a risky asset of travel time on regular lanes with amount of $N(d_1)$ and borrowing loans with value of $K_{\mathrm{LOS\,A}}$ (i.e. promised level of travel time on option lanes) at a risk-free rate for financing to purchase the risky asset. This is because the payoff of the reservation option is replicable with this portfolio's position under the assumption that the market is complete and arbitrage-free.

The option buyers with a risk-neutral perspective are willing to invest this reservation option using the expenditure with the same amount as expected return (i.e. expected savings of travel time on option lanes) of this portfolio. It is intuitive that the expected return of this option at time t of $C(t, S(t))$ is the difference between the expected revenue worth of purchased travel time at time t of $S(t)N(d_1)$ and the present value of the expected costs of $K_{\mathrm{LOS\,A}}e^{-r(T-t)}N(d_2)$ (i.e. repayment of loans) conditional on a given event that travel time on regular lane at the maturity T exceeds the promised travel time, which is labeled "strike travel time" in this study. This relationship holds only under two conditions: (1) there exist no default situations when the buyer and the seller of the reservation options absolutely honor the fulfillment of mutual obligations that the options impose, and (2) when the reservation options incur no additional costs involved with market frictions (such as transaction costs and taxes) under the Black-Scholes framework.

Now, let A be an event that travel time of $S(T)$ on regular lanes at maturity T exceeds strike travel time of $K_{\mathrm{LOS\,A}}$ on option lanes. Under no default risks of highway operators, the pricing-formula of reservation options is modified as follows. Here, the term of $Ke^{-r(T-t)}E(I_A|A)$ denotes the expected repayment conditional on event A which is equivalent to the expected costs of $K_{\mathrm{LOS\,A}}e^{-r(T-t)}N(d_2)$ in Equation 4.

$$C(t,S(t)) = F(t,S(t)) = S(t)N(d_1) - K_{\text{LOS A}}e^{-r(T-t)}N(d_2)$$

$$= S(t)N(d_1) - K_{\text{LOS A}}e^{-r(T-t)} \cdot \Pr(S(T) \geq K_{\text{LOS A}})$$

$$= S(t)N(d_1) - Ke^{-r(T-t)}E(I_A | A)$$

where, $I_A = \begin{cases} 1 & \text{if event A happens} \\ 0 & \text{otherwise} \end{cases}$

$$d_1 = \frac{\ln\left(\dfrac{S(t)}{K_{\text{LOS A}}}\right) + \left(r + \dfrac{1}{2}\sigma^2\right) \cdot (T-t)}{\sigma\sqrt{T-t}}$$

$$d_2 = \frac{\ln\left(\dfrac{S(t)}{K_{\text{LOS A}}}\right) + \left(r - \dfrac{1}{2}\sigma^2\right) \cdot (T-t)}{\sigma\sqrt{T-t}}$$

In the above pricing-formulas, since the term $N(d_2)$ represents the possibility that event A happens at the maturity *T*, the price of reservation options $C(t,S(t))$ can be interpreted as the expected profits from this portfolio of buying travel time on regular lanes with amount of $N(d_1)$ and of repaying debts conditioned on event A.

However, the realm on the operation of traffic highway system tends to impose additional costs as a compensation for situations defaulting to guarantee the promised savings of travel time through truck-only lanes since highway operators do not have perfect knowledge on future traffic conditions and strategies to all possible situations on highway. Therefore, the reservation options have to be fair-priced through the process of deducting potential monetary losses to the original price under no defaults. The amount of money to be deducted is determined as the product of penalty rate (ρ) and the original price of reservation options ($C(t,S(t))$) and the possibilty ($N(d_2^{TOL})$) that the option lanes deteriorates under the traffic condition corresponding to LOS *i* written on the contract. We add the term ρ which can function as a penalty. It may vary within a predetermined interval, depending on the amount of damages related to promised savings of travel time on option lanes. The term of $\rho \cdot N(d_2{}^{TOL})$ in Equation 5 denotes the deduction rate to original price of reservation options when the default risks are considered. Consequently, the modified pricing function on the reservation options is expressed as follows:

$$C^{\text{default}}(t, S(t)) = \mathrm{S(t)N}(d_1) - Ke^{-r(T-t)}N(d_2) - \rho \cdot C(t, S(t))N(d_2{}^{TOL}) \ \ldots\ldots\ldots \text{ Eq. 5}$$

$$= \left\{1 - \rho \cdot N(d_2{}^{TOL})\right\} \cdot \left\{S(t)N(d_1) - Ke^{-r(T-t)}N(d_2)\right\}$$

where, $d_2{}^{TOL} = \dfrac{\ln\left(\dfrac{t_0{}^i}{K^i}\right) + \left(r - \dfrac{1}{2}\sigma^2\right) \cdot (T-t)}{\sigma\sqrt{T-t}}$

t_0^i : free flow travel time corresponding to LOS *i*

K_{i} : strike travel time corresponding to LOS *i*

ρ : penalty rate

As mentioned above, the term $N(d_2{}^{TOL})$ indicates a deduction rate which is equal to the probability that truck-only lanes fail to maintain the promised level of service if the penalty rate is equal to one. This study adopts the volatility of travel time on regular lanes into that of travel time on option lanes due to no available observed data on travel time on truck-only lanes and the transferability of volatility in the sense that they share geographical and environmental conditions together.

CHAPTER 4. CASE STUDY: THE TAIWAN HIGHWAY NETWORK

This chapter presents numerical experiments on a highway network in Taiwan, which is operated with Electronic Toll Collection System (ETC). Traffic data collected from January 1st to December 31st in 2007 includes entry times, exist times and types of vehicles, and traffic flow volumes between adjacent toll stations. Figure 4.1 illustrates the geographical configuration of a total of 9 road segments divided with adjacent two electronic toll stations built over Taiwan highway systems.

Figure 4.1 Taiwan highway road map and locations of toll stations

Source: Cheng (2010): Highway reservation pricing for freight industry: A real options approach, p. 28.

In addition, Table 4.1 summarizes basic geographical information and statistics on travel time on each road segment, respectively.

Table 4.1 Geographic information and statistics on segments between toll stations

Segment	Origin - Destination	Distance (km)	Free flow travel time (min)	Estimated distribution of travel time	Variance of travel time
L1-L2	Gangshan – Sinshih	33.2	19:28	Lognormal	2.11660
L2-L3	Sinshih – Sinying	32.9	19:42	Lognormal	2.15174
L3-L4	Sinying- Dounan	34.0	19:47	Lognormal	1.96723
L4-L5	Dounan – Yuanlin	28.5	16:32	Lognormal	1.99749
L5-L6	Yuanlin – Houli	55.6	33:00	Lognormal	2.76586
L6-L7	Houli – Zaociao	44.9	27:28	Lognormal	2.07605
L7-L8	Zaociao – Yangmei	46.3	28:16	Lognormal	2.55734
L8-L9	Yangmei – Taishan	36.1	22:20	Lognormal	2.87402
L9-L10	Taishan – Sijhih	24.9	15:37	Lognormal	2.14918

Source 1 : Taiwan Area National Freeway Bureau, MOTC

Source 2: Cheng (2010): Highway reservation pricing for freight industry: A real options approach, p. 30.

This study sets up traffic flow condition corresponding to LOS C as a criterion on whether to exercise reservation options or not, to enable consistency with the previous study (Cheng, 2010). Besides, this study applies identical conditions associated with pricing reservation options without defaults (such as the same Returns of Investment and monetary value of time). The results illustrate how much the price of reservation options can be over-priced compared to that without defaults.

4.1 Experiment setup

The case study is implemented based on the following. The monetary value of travel time is NT $2.47584 per minute (Cheng, 2010). Table 4.2 presents detailed values of spot price of travel time on regular lanes and those of strike travel time corresponding to LOS A across all road segments under the penalty rate of 1, respectively. Since this study focuses mainly on the determination of the fair price of reservation options with default risks, the detailed data related to the simulation of traffic flows (such as the volume of traffic and the number of option lanes and regular lanes) are not necessarily required in the experiment.

Table 4.2 The setup of spot travel time and strike travel time on all road segments

Segment	Spot price on travel time on regular lanes, NT $	Price on strike travel time on truck-only lanes, NT $
L1-L2	65.50	48.20
L2-L3	74.40	48.77
L3-L4	72.30	48.98
L4-L5	45.30	40.93
L5-L6	84.56	81.70
L6-L7	75.68	68.00
L7-L8	77.91	69.98
L8-L9	63.12	55.29
L9-L10	70.39	38.66

4.2. Experiment results

The results suggest that the default risk of highway operators is an important factor to influnce the price of reservation options on truck-only lanes, depending on the level of service on option lanes guaranteed. For example, there are cases that the reservation option on several segments is highly subject to the chance of defaulting LOS A (e.g., the traffic condition on option lanes guaranteed by highway operators in the contract). The evolutionary patterns of the price of vulnerable reservation options over the option period can be classified into three types: neutral to default-risk, sensitive to default-risk, and highly sensitive to default-risk. The figures below illustrate that, in comparison with that without default risks, the price of vulnerable reservation options declines over the option peroid, depending on the acceptance of the default situation that truck-only lanes fail to maintain the promised level of service A but still maintain a level of service at least LOS B. Also, it helps identify certain segments that need to be focused on by allocating additional resources so that systematic operational strategies for those segments could be prepared.

Group I (Neutral to default-risks): this type of price's evolution over the option period is not correlated with any default risks correponding to the violation of promised level of service. Several road segments (such as L1-L2, L2-L3, L3-L4, L5-L6 and L6-L7) belong to this group.

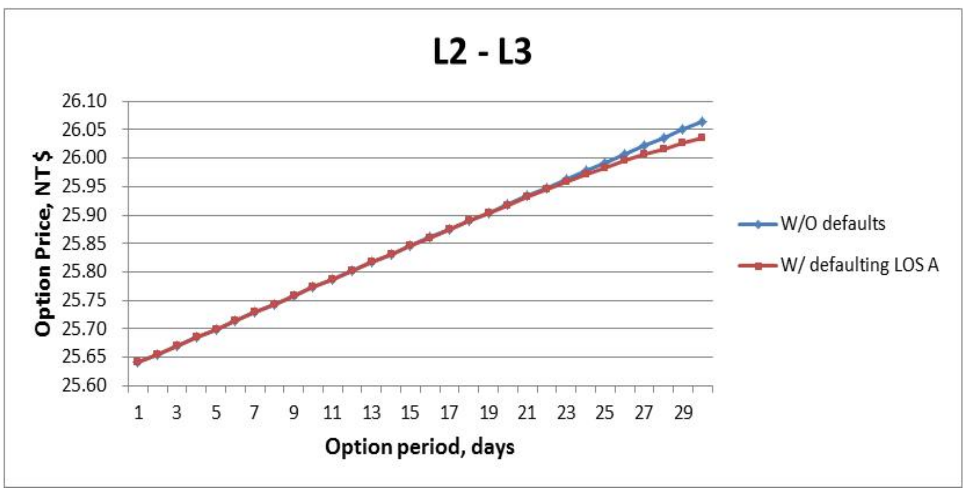

Figure 4.2 An example of the price of the group neutral to default-risks

Group II (Sensitive to default-risks): This group indicates that some segments (such as L4-L5 and L7-L8) are sensitive to the default risk of violating LOS A, which means that after 15 days, the truck-only lanes are likely to fail to maintain the traffic condition of LOS A, but not in another level of service substantially below LOS A.

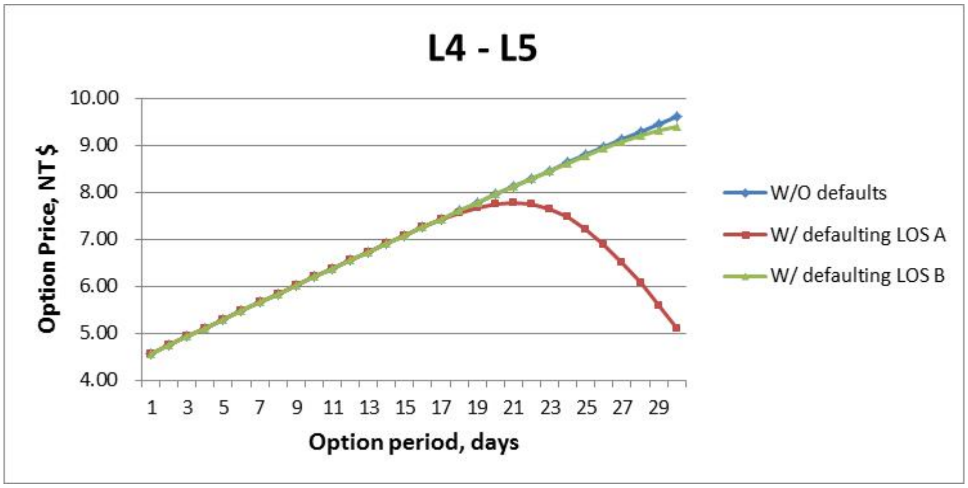

Figure 4.3 An example of the price of the group sensitive to default-risks

Group III (highly sensitive to default-risks): the evolution of the price over option period indicates that two segments of L8-L9 and L9-L10 are highly correlated with defaut risk that truck-only lane will fail to maintain the traffic condtion of LOS A. That is, the reservation options on truck-only lanes are highly likely to fail to guarantee the promised traffic condition of LOS A.

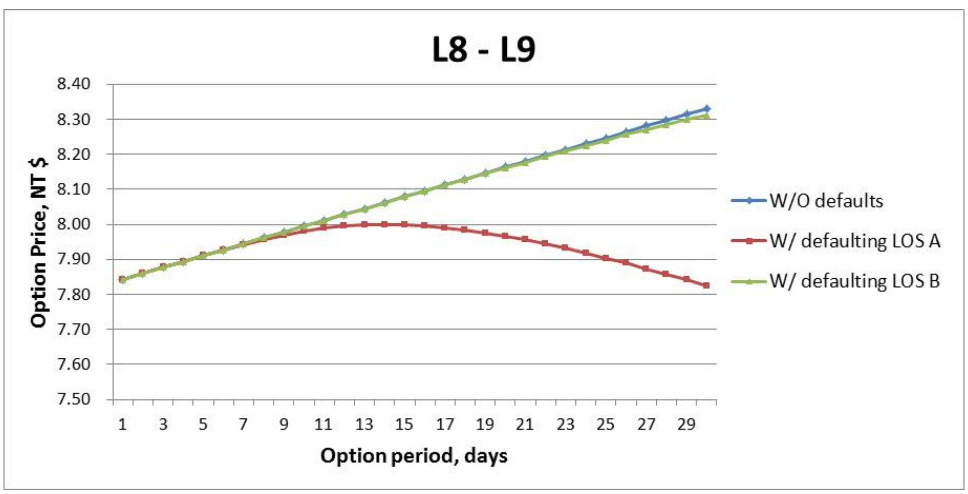

Figure 4.4 An example of the price of the group highly sensitive to default-risks

It is observed that the price of reservation options is highly correlated with the volatility of travel time on truck-only lanes. It is reasonable that the longer the option peroid, the higher the uncertainty of travel time on truck-only lanes, the greater the possibility of default on promised traffic flow, and the cheaper the price of reservation options over time.

CHAPTER 5. CONCLUSIONS

This chapter summarizes the research insights and key contributions, and proposes directions for future research.

5.1 Summary

This study highlights that a pricing strategy of real options for a reservation system on truck-only lanes has the potential to address issues related to congestion, safety, loss of productivity and funding sources for highway operators. The proposed real options-based pricing strategy can be further applied to other projects in highway infrastructure systems. The proposed pricing strategy enables a mutually beneficial situation to all the associated stakeholders involved in a highway system. In addition, it is an economically feasible solution to determine fair rates or fees in the context of using highway facilities in a sense that the rates are determined as the amount equivalent to the expected returns obtained from those facilities.

The case study illustrates that the real-world data collected by ETC in Taiwan validates that the travel time on highway is log-normally distributed and is consistent with the results shown in the literature. Furthermore, the log-normal distribution of travel time on highway enables travel time to be described as a geometric Brownian Motion and has a mathematical merit to induce a closed-form formulation of a pricing function when designing its derivatives contracts. In addition, this study identifies the fundamental difference between derivative contracts traded in financial markets and those traded in the highway system in that there are unhedgeable risks related to highway system operations, which must be considered in designing derivative contracts for the operational planning of a highway system.

This study seeks to compare the prices of reservation options on truck-only lanes with and without default risks. Depending on the relaxation of how much the promised traffic condition of truck-only lanes can be aggravated according to the acceptable level of service, the obtained patterns of the reservation price over the option period provide useful insights to highway operators about how vulnerable the reservation option is from the perspective of risks of highway operation, and help the reservation system to reflect them.

The numerical experiments have been implemented with real data on travel times collected in the Taiwan highway network through the ETC system. The numerical results identify that the default-risk is a significant variable to impact the price of vulnerable reservation options on truck-only lanes due to the fact that the current operation on highways cannot be completely free of failures arising from unexpected events and external effects.

5.2 Future research directions

This study can be applied for the design of highway reservation systems requiring the pricing of the fair value of the options under realistic assumptions on highway operations. Especially for vulnerable reservation options on truck-only lanes, it is essential to reflect daily patterns of travel time since the evolution of travel time highly depends on the time of day. This implies that there are cyclic patterns on travel time on highway since the stochastic process of travel time on regular lanes seems to be homogeneous over time. Besides, this point will assist highway operators to determine a fair price of reservation options on truck-only lanes, reflecting the day-to-day pattern of traffic flows on highway, and increase the credibility of the reservation system for the users of a reservation system and truck-only lanes.

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