R&D and Deployment Valuation of Intelligent Transportation Systems: A Case Example of the Intersection Collision Avoidance Systems

by

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Submitted to the Department of Civil and Environmental Engineering
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ABSTRACT

Compared with investments in the conventional infrastructure, those in Intelligent Transportation Technology (ITS) include various uncertainties. Because deployment of ITS requires close public-private partnership, projects concerning R&D and deployment of ITS technology involve project risks and market risks induced by both the public and private sector. This characteristic makes it difficult to evaluate the value of the project through traditional valuation method such as the benefit cost analysis (BCA) or the discounted cash flow (DCF) method. To address the difficulty, this thesis proposes two appropriate valuation methodologies for R&D and deployment of ITS: decision analysis and "hybrid real options" analysis that combines decision analysis and real option analysis.

This thesis applies the proposed methodologies to a case example of the ongoing R&D and deployment project to reduce the automobile crashes at intersection under public-private partnerships. The proposed systems in the project consist of two conflicting concepts; one depends on user acceptance of in-vehicle ITS technology employed, and the other one does not require user acceptance of this ITS technology. To evaluate the value of two concepts, this thesis identifies various uncertainties associated with the project and quantifies them by utilizing various quantitative techniques including the product diffusion model to formulate project risks and market risks.

This thesis finally compares the financial value in two concepts and demonstrates that the concept without in-vehicle ITS technology is a more promising system for crash prevention at an intersection than that with this technology and recognizes the value of real option in case of the unfavorable outcome of the R&D stage. The results imply that developing attractive the new product and obtaining user acceptance of ITS technology are the most crucial factors to influence the project value and future success of the countermeasures.

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Kenichi Hodota
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Table of Contents

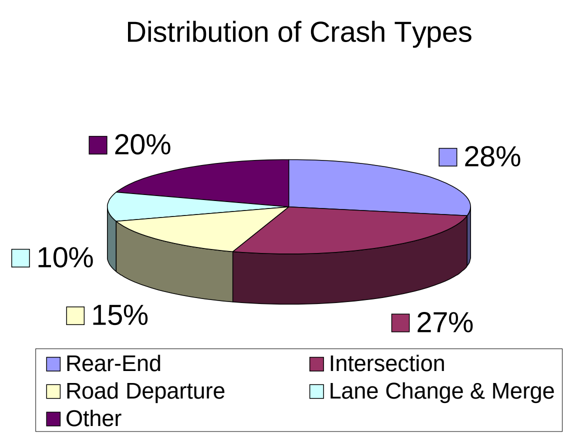
List of Figures

List of Tables

Chapter 1 Introduction

1.1. Outline of Intersection Collisions

Each year, more than 6 million automotive crashes occur on highways in the United States. Given that they kill more than 42,500 people with approximate 2.8 million injured people and cost more than $230 billion, automobile crashes are regarded as one of the most important social problems to be solved [1][2]. Figure 1-1 illustrates the distribution of crash types at highways, indicating that intersection accidents account for 27% of all crashes in 1997 [3].



Source: National Highway Traffic Safety Administration [3]

Figure 1-1: Distribution of Automotive Crash Types

Intersections are areas that expose vehicles approaching these locations to the risk of the potential conflict. Intersection collisions make a clear distinction from other type of crashes in that they are a unique, more complex collision phenomenon. Collision at intersection involves "multiple vehicles" with a complicated mechanism that the varying nature of intersection geometries and the number of vehicles approaching and negotiating through the intersection result in various crash configurations [4].

Recent advances in telecommunication technologies have enabled the collection of large amounts of data. These technologies have been also applied to improve transportation safety and mobility and to enhance productivity. The transportation systems that make most use of these technologies are called Intelligent Transportation Systems (ITS). ITS technologies allow detecting vehicle locations more precisely and transmitting information between vehicles and vehicles or between vehicles and infrastructures. It is considered that ITS technologies would provide an innovative solution to the intricate intersection collision problem.

The government, the public sector and the private sector realize that developing and deploying the measures for these intersection collisions, namely the intersection collision avoidance systems (ICAS), can help save lives by preventing these crashes. With the complex characteristics of crash mechanism, the ICAS must reflect interactions between infrastructure (i.e., roadways) and vehicles. Given that the public sector is responsible for administration and operations for the infrastructure part (i.e. roadways) and that the private sector is in charge of the vehicle side (i.e. manufacturing and selling automobiles), research and development (R&D) and deployment for the countermeasures require close public-private cooperation.

The U.S. Department of Transportation (DOT) has convened the initiative called "Cooperative Intersection Collision Avoidance Systems" (CICAS) as a partnership of the public sector with the private sector for R&D and deployment of the systems that potentially address the intersection crash problems [5]. The potential ICAS will use both vehicle-based and infrastructure-based technologies to help drivers approaching an intersection understand the state of activities occurring in the place [5]. The initiative has currently provided some tentative concepts for the ICAS, which includes two distinct solutions; one is the infrastructure-autonomous ICAS, where the infrastructure provides and displays the warning to the drivers on the intersection. The other is the vehicle-based ICAS, where the in-vehicle component processes the dynamic information around the intersection and provides the warning to the driver through in-vehicle display.

Both sectors agree on that the ICAS will be based on the vehicle-based concept in the future. The private sector recommends constructing the vehicle-based ICAS from the beginning because it wants to put Dedicated Short Range Communication (DSRC), a new telecommunication product, used for the ICAS into the market earlier. DSRC is expected to create new businesses related to transportation services. The public sector believes that the concept suggested by the private sector may produce the slow economic benefit and proposes that the infrastructure-autonomous ICAS should be developed as an intermediate solution. Therefore, the fundamental trade-off exists in the conflict between private sector and public sector. Considering this trade-off, the public sector will make decisions for investments in the appropriate ICAS according to which makes more sense for the public sector and the society.

1.2. Challenges of Designing Intelligent Transportation Systems

It is necessary to consider aspects of ITS investments to carefully analyze this proposition. Systems designers of infrastructure understand that many of their estimates are "always" wrong in that volatility of social affairs, market trends, and public desires considerably affects loads for infrastructure services [6]. Infrastructure investments are still mainly evaluated based on the traditional benefit cost analysis (BCA) or the discounted cash flow (DCF) method [7]. These analyses do not consider uncertainties and flexibilities because they estimate future cash flows based on predetermined single stream of incomes and expenses and overlook the possibilities of managerial flexibilities. The designers do not yet have accessible methods to value the infrastructure investments accounting for the uncertainties and flexibilities.

ITS technology is in the process of development as a solution to improve the transportation environment and have not undergone the same degree of technology evolution as other engineering technologies. There are many ITS solutions that may still not be fully accepted by drivers, and hence ITS possesses the uncertainty regarding the "user acceptance" [7]. Accordingly, the project of developing and deploying the ICAS entails a significant uncertainty of whether ITS technology acquires user acceptance from technology users. These risks associated with the uncertainty are considered market risks. Further, R&D for ITS technology also involves the uncertainty that failure of R&D deteriorates the value of the project. The risks are regarded as project risks.

In conclusion, the model that enables us to address both market risks and project risks is needed to evaluate the project of developing and deploying the ICAS.

1.3. Purpose of This Thesis

This thesis aims to accomplish three goals: (1) propose the appropriate valuation methods for R&D and deployment of Intelligent Transportation Systems (ITS), and (2) apply the proposed methods to a case example that deals with R&D and deployment for the ICAS, and (3) provide suggestions as to which strategy provided by the public sector and the private sector makes the most sense for the public sector and the society.

To meet these goals, first, this thesis analyzes the characteristics including market/project risks associated with R&D and deployment for ITS technology and provides the appropriate methodology to reflect them and to assess the value of the project. Second, the thesis deals with the actual R&D and deployment program whose objective is to reduce intersection accidents by introducing some ITS technologies. Third, the thesis evaluates and compares two distinct concepts of the ICAS: one is to develop the infrastructure-autonomous systems recommended by the public sector, and the other is to do the vehicle-based systems endorsed by the private sector.

1.4. Scope of This Thesis

First, this thesis treats the actual R&D and deployment program for the intersection collision avoidance proposed by the CICAS initiative under cooperation between public sector and private sector as a case example.

Second, the thesis uses decision analysis and "hybrid real options" analysis developed by Neely [8]. Decision analysis is an effective method for valuing projects with uncertain outcomes associated with project risks because it complements vulnerability of the traditional valuation methods, such as the BCA and the DCF method. "Hybrid real options" analysis combines decision analysis and option method that is appropriate for valuing the project vulnerable to market risks. The thesis addresses all relevant risks associated with the project of developing and deploying the ICAS.

Third, the thesis applies the proposed methodologies to the two ICAS concepts and calculates their net present value (NPV). The thesis finally makes suggestions as to which concept makes the most sense by comparing the results.

1.5. Thesis Structure

Chapter 1 provides general information on the intersection collisions and their planned measures and on relevant challenges in evaluating R&D and deployment for ITS. This chapter also identifies the purpose and scope of this thesis.

Chapter 2 starts with describing the fundamental aspects of ITS and the outlines of current R&D and deployment programs regarding the ICAS and proceeds to explain two conflicting ICAS concepts.

Chapter 3 provides the fundamental valuation concepts necessary for appraising the project.

Chapter 4 emphasizes real options as a tool for incorporating the managerial flexibility into the project valuation. This chapter addresses differences between real options and financial options and explains decision analysis and "hybrid real options" analysis as an appropriate method for valuing R&D with a simple case example.

Building upon Chapter 2 through 4, Chapter 5 focuses on the characteristics of investments in ITS by comparing with those in traditional infrastructures and proposes the valuation methods are suitable for evaluating R&D and deployment of ITS.

Chapter 6 first identifies all relevant risks and uncertainties associated with the ICAS R&D and deployment program. This chapter calculates and compares the NPV of the two concepts introduced in Chapter 2 by using the proposed methodologies: decision analysis and "hybrid real options" analysis.

Based on the results of the valuation, Chapter 7 gives conclusions concerning three thesis goals and proposes how the financial results can influence the actual decision-making. Figure 1-2 provides a graphic illustration of the thesis structure.

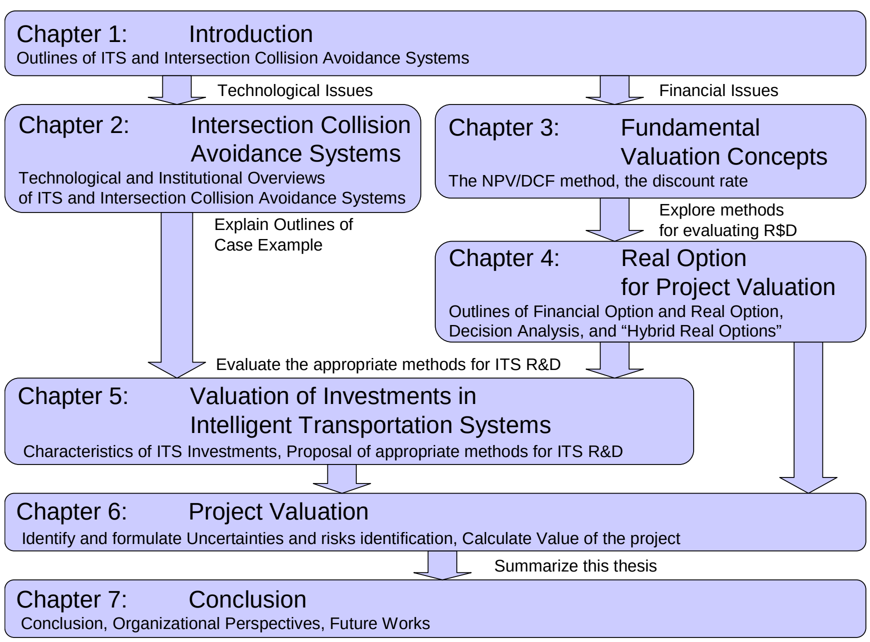


Figure 1-2: Thesis Structure

Chapter 2 Intersection Collision Avoidance Systems

Intersections are areas where vehicles attempting to pass through these locations expose themselves to the risk of potential collisions. Preliminary estimates by the National Highway Traffic Safety Administration (NHTSA) in 2005 indicated that there were about 2.5 million intersection and intersection-related crashes[1] with more than approximately 9,500 fatalities and 1,3 million serious injuries [2][9].

It has been considered that introducing ITS technologies can mitigate the severity of the problem. The intersection collision avoidance systems (ICAS) has developed as a preventive crash measure to help save lives. Since the ICAS provides a service to issue warnings to the driver in case of potential dangers for collision at an intersection, it calls for technically challenging systems with technologies such as sensing vehicles on intersection roadways, determining the intention of the vehicles to slow or turn, and detecting potential violation of traffic control devices. Due to these complexities, the ICAS requires a cooperative vehicle-infrastructure solution and can be viewed as a long-term program with potentially large safety benefits.

This chapter describes characteristics of the ICAS from a viewpoint of ITS and previous and current activities associated with the systems. The chapter first introduces the historical background and technological aspects of ITS.

2.1. Intelligent Transportation Systems

ITS improves transportation safety and mobility and enhances productivity through usage of communications technologies. This section discusses the historical background, technological aspects, functional areas, and institutional issues related to ITS.

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[1] Intersection-related crashes are the harmful events that occur on an approach to or exit from an intersection, and result from an activity, behavior or control related to the movement of traffic units through the intersection [10].

2.1.1. History and Background

In 1986, an informal group of academics, federal and state transportation officials, and the private sector discussed the future of surface transportation system in the United States. The group looked ahead to 1991, when the Interstate highway program in the United States since the mid-1950s would be almost completed; they recognized the necessity of developing a new vision for the transportation systems. At that time, it was recognized that congestion, safety, environmental and productivity issues needed to be addressed by means other than constructing additional conventional highways. Utilizing advanced technologies that included information systems and communications was considered to revolutionize surface transportation, to improve international competitiveness, and to generate new industries and markets.

The concept formulated was simple: “marry the world of high technology and dramatic improvement with the world of conventional surface transportation infrastructure” [11]. This concept came to be called Intelligent Vehicle Highway Systems (IVHS) and eventually Intelligent Transportation Systems. The informal group becomes “Mobility 2000,” which issued a landmark document in 1990 that envisioned ITS [11]. In 1990, in reply to increasing requests for an organization to spearhead innovative transportation systems, the Intelligent Vehicle Highway Society of America (IVHS America) was established as a federal advisory committee for the USDOT.

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) was enacted. Its purpose was transition from an era of highway construction to one of intermodal transportation management. Thereafter, IVHS America announced “A Strategic Plan for Intelligent Vehicle Highway Systems in the United States” and delivered it to the USDOT as a 20-year blueprint for ITS R&D, operational testing and deployment [12]. During the ISTEA period, ITS programs were largely devoted to fundamental research and development in ITS applications and laying the groundwork on which ITS deployment would take place.

In 1998, ITS activities were shifting from R&D to programs that primarily focused on infrastructure deployment. To correspond to the change, the Transportation Equity Act for the 21st Century (TEA-21) became law as a reauthorization for ISTEA in 1998. TEA-21 took over ISTEA's intermodal vision under the situation where the United States was ready for widespread deployment of advanced transportation solution. TEA-21 divided its mission into two primary sections: "ITS deployment" and "ITS Research and Development" [13]. The purpose of "ITS deployment" was to fund incentive grants to states and local governments to deploy integrated intelligent transportation systems, while that of "ITS Research and Development" involved all other aspects of the program not included under deployment. An important project of "ITS Research and Development" was the Intelligent Vehicle Initiative (IVI), one of whose purposes is to offer the ITS solution for preventing intersection collisions.

2.1.2. Fundamental Aspects

<u>Technology Aspects</u>

The importance of disruptive technologies including information systems, communications, sensors, and advanced mathematical methods to realize the ITS concepts has been increasing. There are four innovative technologies called the "ITS-4" technologies, which permitted us to think of transportation systems from a viewpoint of cooperation between infrastructures and vehicles [11]. These give the ability to:

1. Sense the presence and identity of vehicles in real-time on the infrastructure through roadside devices or Global Positioning Systems (GPS)
2. Communicate large amounts of information cheaply and reliably
3. Process this information through advanced information technology
4. Use the information properly and opportunely to achieve better transportation network operations

Since these advances enable collections of large amount of data from vehicles, the ITS technologies become capable of detecting vehicle locations and transmission of information between vehicles and infrastructures to improve transportation safety.

Functional Areas of Intelligent Transportation Systems

"A Strategic Plan for Intelligent Vehicle Highway Systems in the United States" announced by IVHS America in 1992 mentioned the fundamental approaches, R&D, and systems designs for ITS [12]. ITS has integrated innovative technologies into the operations systems including infrastructure and vehicles. To facilitate the integration, it is convenient to classify ITS into the following six functional areas [11]:

1. "Advanced Traffic Management Systems (ATMS)"

ATMS will integrate various managerial functions regarding roadways. It predicts traffic congestion and suggests alternative routing instructions to improve the efficiency of the highway network. Collecting, utilizing, and disseminating real-time data including incident detection is a key specification for technology development.

2. "Advanced Traveler Information Systems (ATIS)"

ATIS provides travelers in vehicles, homes, or workplace with information including location of incidents, road conditions, optimal routings, weather issues, and in-vehicle signings to help them decide what transportation mode should be chosen.

3. "Advanced Vehicle Control System (AVCS)"

AVCS facilitates the control of a driver to make her trip safer and more efficient; the examples of AVCS functions are collision warning systems that would alert the driver to potential imminent collisions, and automatic-braking system that would steer away from crashes. AVCS is an autonomous-vehicle system that enables the driver to enjoy benefits through safety improvement and reduction in accident-induced congestion. Another quite advanced example is Automated Highway Systems (AHS) where motions of all vehicles in specific lanes would be automatically controlled. The latter is regarded as a long-term R&D project.

4. "Commercial Vehicle Operations (CVO)"

CVO allows the private operators of trucks, vans, and taxis to improve productivity of their fleets and efficiency of their operations, and the public sector to better manage the vehicles.

5. "Advanced Public Transportation Systems (APTS)"

Utilizing the technologies discussed above, APTS will improve accessibility of information to public transit users and scheduling of public transportation vehicles and enhance utility of public transport systems.

6. "Advanced Rural Transportation Systems (ARTS)"

Many rural states are now trying to develop ARTS through application of ITS technologies to relatively low-density roadways with the special economic constraints of these areas. The solution is often the major goal of ARTS.

Institutional Issues: Public-Private Partnerships

ITS is facing the considerable institutional challenges. The governmental interactions would have to be strengthened among various levels and the ITS community works expanding public-private partnerships.

The basic characteristic of ITS is deployment of infrastructure largely by the public sector and in-vehicle equipment by the private sector, which require close cooperation between public sector and private sector. In this sense, ITS must overcome many institutional challenges to realize effective public-private partnerships for ITS R&D, operational testing, and deployment.

2.2. R&D and Deployment Programs of Intersection Collision Avoidance Systems

Historically, systems for he intersection collision avoidance were individually developed by a private industry, such as the Mercedes-Benz Stability Enhancement System. They exemplified the potential to detect collision situations and the stability of the vehicle during a collision avoidance maneuver [4]. Making most use of these and other state-of-the-art technologies, the government has sought to improve transportation safety by organizing initiatives that emphasizes for ITS R&D.

This section outlines the institutional issues about three representative initiatives that provide solutions to the ICAS organized by Intelligent Transportation Systems Joint Program Office: the Intelligent Vehicle Initiative (IVI), the Vehicle Infrastructure Integration (VII) initiative, and the Cooperative Intersection Collision Avoidance System (CICAS) Program.

2.2.1. Intelligent Vehicle Initiative (IVI)

Introduction

During the ISTEA period (1991 – 1997), the USDOT sponsored fundamental research in automobile crash avoidance, in-vehicle information systems, and automated highway systems (AHS) to diminish the number of motor vehicle crashes [14]. Previous numerous crashes were analyzed to address collision problem areas and define causal factors. These analyses helped develop performance specifications for the measures and establish an extensive knowledge base related to collision avoidance.

Thanks to the innovative research that covered various ITS technologies, intelligent vehicles with progressive safety and information systems are closer to reality. Since the passage of TEA-21, the successor to ISTEA, the USDOT has integrated these efforts into one program called the Intelligent Vehicle Initiative (IVI) and made this program the backbone for developing intelligent vehicles for practical use.

The initiative first identified safety problem categories about collision avoidance through statistical analyses of previous primary automobile crashes. This approach contributed to the better understanding of the dynamics about specific crash types. Figure 1-1 illustrates the distribution of accident types at highways and indicates that introducing appropriate, effective crash preventive systems/products offers the maximum opportunity for safety improvement [3]. As can been seen from Figure 1-1, the four large subsets of collision types (Rear-End, Intersection, Road Departure, and Lane Change & Merge) account for almost 85 percent of all crashes. The IVI program placed these four crash types as the "IVI primary service category" (Figure 2-1).

The statistical analyses also addressed the "IVI secondary service category" of focused topics, which were relevant to driver performance enhancement. The considerations in determining these topics were technical feasibility and readiness of the potential measures. As a consequence, the IVI program focused on eight safety problem areas that consisted of (1) rear-end collisions, (2) road way departure collisions, (3) lane change and merge collisions, (4) intersection collisions, (5) driver impairment monitoring, (6) vision enhancement, (7) vehicle stability, and (8) safety impacting systems [14].

Goals and Objectives

The Intelligent Transportation Systems Joint Program Office defines the principal goal of "establishing a significant safety transportation environment with greater mobility and efficiency, through widespread deployment of vehicle-based autonomous and infrastructure-cooperative driver assistance features" [14]. The purposes of the IVI program are (1) to "promote development and deployment of safety systems/products by determining the performance requirements," (2) to evaluate the "effectiveness of technologies" that will build on these measures, and (3) to encourage commercial availability [14]. The program consisted of four R&D stages and one deployment stage: "identification and definition of services," "selection of services," "performance of systems design," "operational tests," and "product deployment" [14]. Figure 2-1 illustrates the pipeline R&D and deployment roadmap for the IVI program.

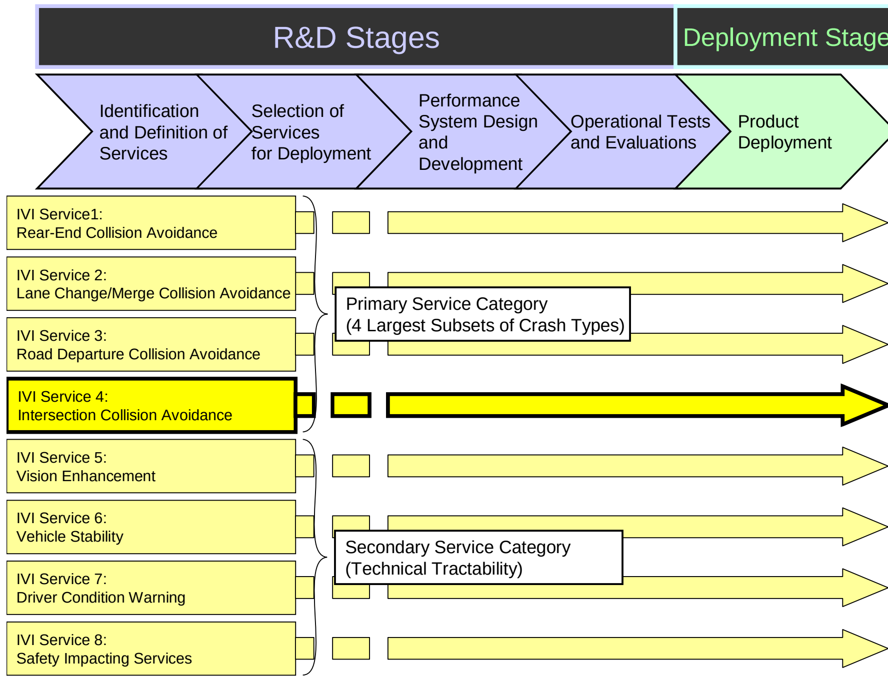


Figure 2-1: Pipeline R&D and Deployment Roadmap for the IVI Program

Potential measures for the eight problem areas range from the vehicle-based systems to the vehicle-infrastructure cooperative communication systems. With completed fundamental research initiated during the ISTEA period, the program concentrated not only on developing performance specifications, operational test procedures, systems architecture, and technical standards but also on pursuing a method to estimate of these measures. With these premises in mind, the USDOT determined its own two important roles: to ensure that safety is not compromised by introducing only in-vehicle systems and to reduce deaths/injuries and economic losses resulting from automobile crashes [14].

Estimating the benefit is one of the crucial objectives of the IVI program. The cost of fatalities, collision severity, and injuries and related lost productivity and property damage is estimated to be more than $230 billion per year [1]. The benefit from introducing the IVI services is a decrease in injuries and fatalities, which would result in a proportional reduction in economic costs. National Highway Traffic Safety Administration (NHTSA) developed the framework to forecast the number of crashes that could be avoided with full deployment of rear end, road departure, and lane change/merge collision avoidance systems [15]. The IVI program applied this method to evaluate the economic of its eight services.

Institutional Issues and Public-Private Partnerships

To attain the goal of commercial availability of safety technology, it is indispensable for the USDOT to work in partnerships with organizations that can contribute to deployment of crash avoidance systems. Public-private partnerships will be a key element of making ITS technologies rapidly available to the user community.

Public-private partnerships in the IVI program are described below. We understand that potential major partners in the program take important responsibilities for development and deployment to provide the IVI solution:

1. "The private sector will primarily develop the IVI systems. The USDOT will work cooperatively with the industries to determine performance specifications for the potential safety systems" [14].

2. "The automobile industry, fleet operators, and local transportation agencies will deploy IVI services/products. The USDOT will support those major participants by providing information on the necessary technical performance, user acceptance, and estimated benefits of the systems" [14].

In these statements, product deployment refers to actions achieved by automobile manufacturers and their suppliers. User acceptance includes availability, affordability, and desirability of the systems concerning the interactions with the drivers. At the final stage of the program, the Field Operational Tests (FOT) was conducted to determine the system performances and potential benefit of the measures. Once the program estimated the benefit, new in-vehicle products for the IVI would be ready for deployment by manufacturers such as OEM (Original Equipment Manufacturers).

Activities of Intersection Collision Avoidance

Veridian Engineering has focused on development of the ICAS as a participant of the IVI program under NHTSA contracts. The company implemented a test bed design for the infrastructure-based, in-vehicle autonomous ICAS[2] [4]. The USDOT and Veridian Engineering conducted the field operational test (FOT) that investigated safety improvement at an intersection without the traffic signals. The systems they developed consisted of devices embedded in the pavement and a computer controller. The devices detected the vehicles waiting to enter the intersection, measured the speed of approaching vehicles, and provided active warning signs to drivers within limited distance at a pilot location. A computer controller located at the intersection gathered the information, estimated arrival times of the various vehicles, and activated roadside warning signs.

This large-scale field operational test demonstrated that the project successfully integrated in-vehicle equipment into commercial vehicles and measured the accuracy of visual, auditory warnings of potential intersection violation to the driver. The company also estimated potential benefits using the methodology developed by NHTSA [15].

The in-vehicle test bed, however, showed a discrepancy between the common crash scenarios and their causal factors and concluded that future work would continue to develop the next-generation vehicle-based solutions and that the USDOT would simultaneously investigate the infrastructure-based sensing systems to recognize dangerous vehicle movements [4][14]. Therefore, further cooperation between the vehicle and the infrastructure would be necessary for the future success in the ICAS.

[2] The initial plan of this test bet design represented a compromise one with a reasonable cost for the reasons that the original radar system was made to use commercially available radar in place of private one and that the plan eliminated some complicated components such as a signal-to vehicle communication system

2.2.2. Vehicle Infrastructure Integration (VII) initiative

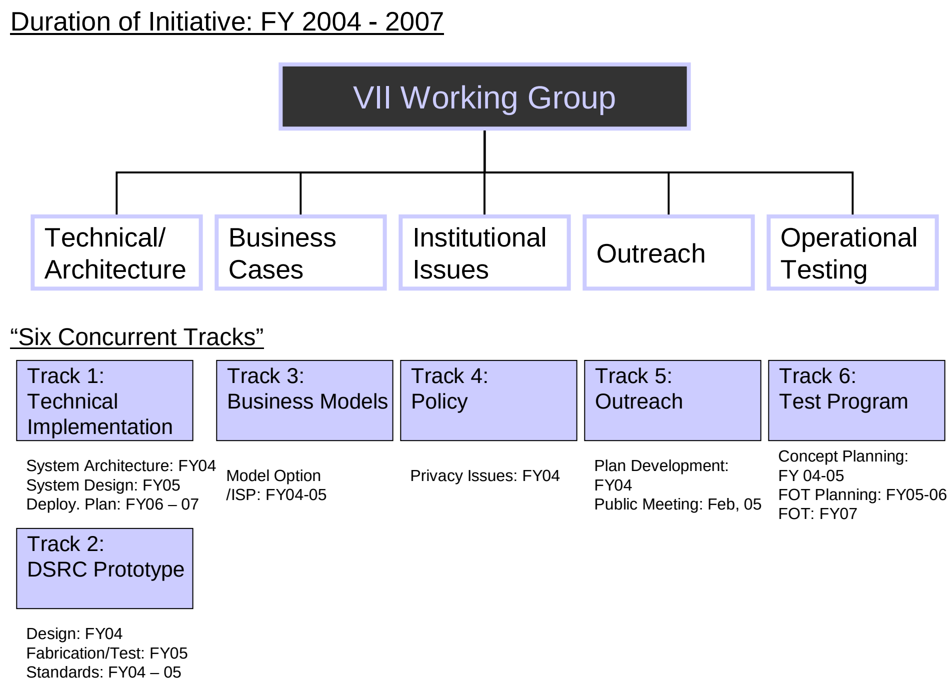
Introduction

Building on the availability of the most up-to-date technologies for vehicle safety previously accomplished in the IVI program, the Vehicle Infrastructure Integration (VII) initiative was established to work toward "deployment of advanced vehicle-vehicle and vehicle-infrastructure communications" [16]. Two impressive events after completion of the IVI program led the USDOT to launch the VII initiative; one is continuous governmental actions for ITS including an announcement of a new strategic ITS plan, and the other is technological advances. A typical example of advances in ITS technology is development of a new telematics product called Dedicated Short Range Communication (DSRC).

First, the Intelligent Transportation Society of America (ITS America) and the USDOT announced a new strategic groundwork that required public-private partnerships, *the National ITS Program Plan: A Ten-Year Vision* [17]. The program plan outlined a vision for ITS technology. The vision was "creating, operating, maintaining, and updating the mechanisms that will interact with adjoining external systems by gathering, analyzing, extrapolating, and coordinating data." Although the plan provided processes to achieve the vision, the detailed activities relied on public sector and private industries [18]. In the same way as the IVI program, the plan emphasized cooperation between the public sector and the private sector. To strengthen public-private partnerships in accordance with "*the National ITS Program Plan: A Ten-Year Vision*," ITS America held an exploratory workshop in 2003, where automobile manufacturers and public transportation sector found the VII concept to be feasible [18]. This energy led the USDOT to launch the new VII initiative.

Second, DSRC has been recognized as a tool to support vehicle-vehicle and vehicle-infrastructure communications. Activities for realizing the idea that telematics technology enabled vehicles to communicate with the roadway, however, were not the first appearance at that time. The "*National ITS Program Plan*" proposed by ITS America and the USDOT in 1995 conceptualized the future ICAS consisted of the new telecommunication products, which enabled "the combination of infrastructure-to-vehicle (I2V), vehicle-to-infrastructure (V2I), and vehicle-to-vehicle (V2V) communications" [19]. "*The National ITS Program Plan: A Ten-Year Vision*" took over this plan and delineated the enabling path for crash avoidance by introducing DSRC. Now that many vehicles equip more and more sensors that make efficient, safe operations possible, most agree that constructing vehicle-infrastructure communications through DSRC is technically tractable from an engineering perspective.

These events urged the VII program to convene a public-private "VII Coalition," a cooperative venture of the USDOT, the automotive industry, American Association of State Highway and Transportation Officials (AASHTO), and State DOTs. This coalition is currently resolving technology and policy issues that inhibit deployment of telecommunication systems. Figure 2-2 illustrates the general organizational form and roadmap regarding the "VII Coalition." The subcommittees of the coalition tackle various issues of the VII program, such as "institutional issues" (including security, privacy, data ownership, certification, and registration), "technical/architecture issues" (including standards development and prototyping), "testing" (field operational tests), "business cases" (including development of favorable cases and deployment costs), and "other outreach efforts" [18].



Source: Modified based on The Intelligent Transportation Society of America [18]

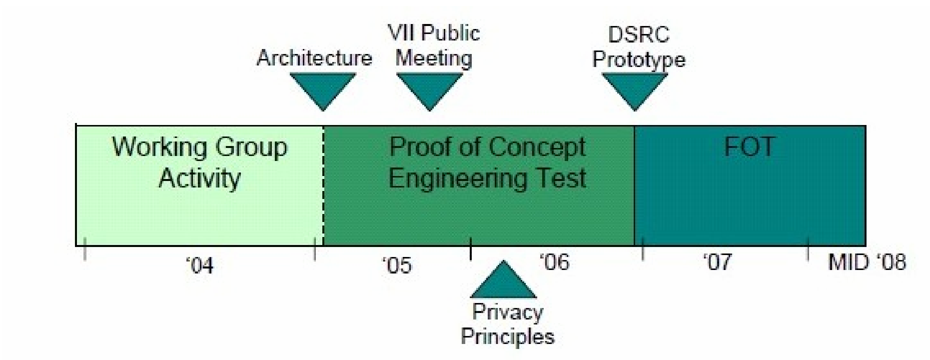
Figure 2-2: General Organizational Form and Roadmap regarding the VII Program

Goals and Concepts

The VII initiative defines its mission "to establish nationwide vehicle-vehicle and vehicle-infrastructure communication capability" and its primary goal to "deploy a communications infrastructure that supports both vehicle-infrastructure and vehicle-vehicle communications and enables a variety of innovative services" [16]. Enabled services include safety improvements (Intersection collision avoidance, Violation warning, Curve warning), mobility applications (Crash data, Weather/road Surface data, Traveler Information, Electronic tolls, Pavement conditions), and commercial benefits (Electronic payment, Auto Manufacturer's customer relations). It should be noted that the goals of the VII initiative differs from those of the IVI program in that the VII initiative emphasizes not only safety benefits but also improvement in mobility and services provided by the private sector.

The fundamental concept is to "develop coordinated deployments of communication technology in all vehicles and on all major roadways" [16]. In other words, the program involves develop, rollout, and deployment of new products that deliver the VII applications. In this respect, we can interpret the VII initiative as a multi-faceted and multi-disciplinary program because it requires public-private partnerships in deploying the I2V, V2I, and V2V communications.

The VII Coalition will determine whether the infrastructure deployment can synchronize with the vehicle integration. The activities include providing necessary information for making decisions about whether or not to move forward with nationwide deployment. With duration of the initiative during the fiscal years 2004 – 2007, the coalition will not make its final decision until the 2008 timeframe [18]. Figure 2-3 illustrates the general timeline of VII initiative.



Source: The Intelligent Transportation Society of America [18]

Figure 2-3: General Timeframe of VII Initiative

2.2.3. Cooperative Intersection Collision Avoidance System (CICAS) Program

Introduction

The Cooperative Intersection Collision Avoidance System (CICAS) Program is an initiative that exclusively emphasizes the design of cooperative communication systems that potentially address the full set of intersection collision problems. Through the CICAS Program, the USDOT works cooperatively with the automobile manufacturers and State DOTs to "construct the combined autonomous-vehicle and autonomous-infrastructure communication systems for the ICAS" [5].

The origin of establishing the organizations to tackle the ICAS dates back to the IVI program period. The IVI program founded a mechanism called the Crash Avoidance Metrics Partnerships (CAMP) [3] for the government and the automotive industry to conduct collaborative research on vehicle-based safety systems.

State DOTs have been involved in fundamental research and demonstrative field tests for the ICAS actively. They collaborated in these activities with universities under "Infrastructure Consortium," a joint research program that focused on the ICAS from a perspective of infrastructures. A representative example of joint research was the California DOT and the University of California at Berkeley; they examined the left turn across problem, one of major causes of the intersection collisions, and conducted the field tests by using commercial vehicles in urban areas [5]. The University of Minnesota and the Virginia Polytechnic Institute also participated in a research program under the Infrastructure Consortium [5].

<u>Institutional Issues and Public-Private Partnerships</u>

The USDOT, State DOTs, and the automotive manufacturers play an important role in the fundamental research necessary for conceptualizing and developing a prototype of the ICAS. The principal role of the government is to encourage potential stakeholders to participate in this activity. The government is also accountable for specifying performance requirements, designing the system development process, appraising effectiveness of the entire systems, and examining the market availability and user

[3] CAMP consists of seven automotive manufacturers: BMW, Daimler-Chrysler, Ford, General Motors, Nissan America, Toyota America, and Volkswagen [20].

acceptance of the ICAS. The public sector, including state and local governments, will be in charge of deploying the infrastructure capabilities. The automobile manufacturers will develop and deploy the ICAS in vehicle product lines.

Goals and Concepts

The CICAS Program sets the following three ultimate goals and five concrete objectives to meet these goals [9]. The goals and objectives of the program are to:

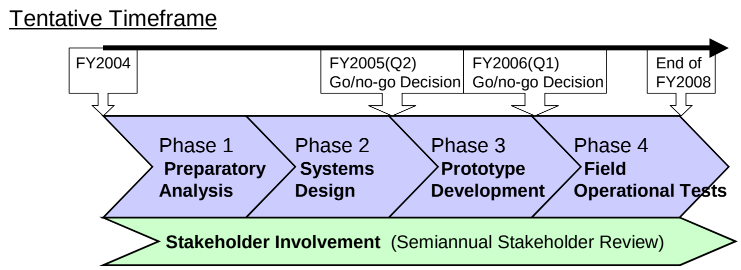
CICAS Program Goals

1. "Develop and demonstrate" the cooperative intersection collision avoidance systems
2. "Evaluate benefits/costs and the value of acceptance of the systems"
3. "Develop and provide instruments to support industry deployments"

CICAS Program Objectives

1. "Establish a groundwork for program development and execution"
2. "Develop prototype system designs in partnerships with industry and public agencies"
3. "Develop and assess prototype systems"
4. "Demonstrate and quantify effectiveness of the systems"
5. "Generate industry support for deployment"

To achieve these goals and objectives, the program has developed the roadmap that consists of four R&D phases shown in Figure 2-4 (preparatory analysis, systems design, prototype development, and field operational test) and one endeavor of stakeholder involvement [20]. The program is to execute the large-scale FOT by 2009 based on the test originally conducted under the IVI program. The CICAS Program will closely coordinate with the VII initiative because it implements the enabling communication capability necessary for the ICAS.



Phase 1 Preparatory Analysis	◆ Establish stakeholder ownership ◆ Formulate Program Definition (systems concepts and their functional requirements) ◆ Define Execution Strategy (program work plan)
Phase 2 Systems Design	◆ Develop system architecture and technology independent performance specifications ◆ Develop needed technologies for prototype assessment ◆ Identify most promising designs for prototyping
Phase 3 Prototype Development	◆ Integrate subsystems and build prototypes ◆ Conduct objective test in a controlled environment ◆ Validate performance of systems
Phase 4 Field Operational Tests (FOT)	◆ Establish FOT design and build FOT preparatory systems (until FY2006) ◆ Conduct tests in real world environment ◆ Develop analysis methods, and build database and tools ◆ Analyze benefits/costs, user acceptance, performance

Source: Modified based on “Cooperative Intersection Collision Avoidance Initiative,” *Proceedings of CICAS Workshop* [9]

Figure 2-4: Roadmap of CICAS Program

2.3. Technology Overview

2.3.1. Dedicated Short-Range Communications (DSRC)

Although DSRC is only one of several wireless telecommunication technologies currently under investigation for an appropriate tool for specific VII applications, it is considered the most promising technology for these applications [18]. The VII initiative has initiated a program to develop DSRC prototypes, validate DSRC standards, and prepare equipment for field operational tests of systems in alignment with the concept.

Advances in “ITS-4” technologies during the past decades have enabled us to collect and process the larger amounts of data from vehicles. For instance, robust sensors and Global Positioning System (GPS) allow detecting locations of vehicles with an ever-increasing degree of accuracy, and communication technology permits transmission of information between vehicles.

With these technological advances, many telematics technologies can provide the cooperative vehicle-infrastructure communication. Of all these technologies, it is highly probable that DSRC will be chosen as a new product to deliver the application because it has the potential to generate multiple applications with regard to transportation services [21]. This section discusses the outline of DSRC technology issues.

DSRC is a new product that utilizes the emerging technology with enormous performance and provides a critical communication link for future ITS. Compared with current cellular and satellite systems, DSRC is a cost-effective communication service.

DSRC technology will provide secure, reliable communication links in vehicle-infrastructure-based safety systems. Using digital radio techniques and operating at the 5.9 GHz band specially allocated by the Federal Communications Commissions (FCC) for ITS safety applications, DSRC supports a whole new range of communication uses with reciprocal high data rate capabilities and larger communication ranges. DSRC is grounded on robust transmissions, such as I2V, V2I, and V2V communications, and used for many public safety and private commercial applications; these applications include in-vehicle signage, collision avoidance, fee collection, and the Internet access. The technology can be leveraged for electric tolling collection (ETC) and mobile 802.11 Wi-Fi deployments, making national interoperable systems possible.

With a view to validating the technology and application in the real-world environment, the DSRC Industry Consortium (DIC) prototype team has been organized through the funding by the USDOT. The prototype team will develop and verify the system architecture, standards, hardware, and testing. Once the fundamental performance is determined, prototype units will be tested in the large pilot trials at the mock-up intersections. The USDOT and the automotive OEMs will make decision on deploying DSRC in the 2008 timeframe [21].

The DSRC systems consist of two types of DSRC transceivers: the roadside unit (RSU) and the on-board unit (OBU). The RSU is embedded along a road or pedestrian passageway with ITS application interface, whereas the OBU is equipped in the vehicles and integrated into Internal Vehicle Network (IVN) and embedded vehicular applications. The RSU provides channel change control and operating instructions to OBUs within its communications zone along with exchanging data, while the OBU receives and contends for time to transmit on radio frequency channels. The DSRC systems activate when an OBU enters the communication zone of an RSU and V2I and I2V communications begin. In case of V2V communication, one of the OBUs starts the data transaction by sending the initial interrogation. In this respect, the OBU also sever as one of primary characteristics of the RSU.

Vehicles will be equipped with GPS and sensors other than the OBU. They can anonymously transmit information on traffic and road conditions from all roadways within the transportation network. They can collect data of their exact position, speed, acceleration, and direction from GPS and of the outside air temperature near the road surface, the road conditions, and presence of antilock braking systems (ABS) from the sensors; these collected data called "probe data" are completely anonymous.

DSRC is also available for transportation safety issues. DSRC-based safety systems would save lives by issuing warnings of approaching hazardous events to drivers and consequently offering more time to take corrective, evasive actions. The driver receives data transmitted from the RSU to the OBU through the driver-vehicle interfaces (DVI) that displays the warning on the screen so that she may not enter the intersection.

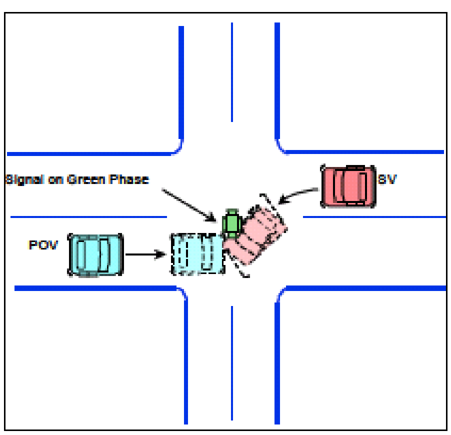
2.3.2. Crash Mechanisms of the Intersection Collision Avoidance Systems

Four Crash Scenarios

Analyzing crash mechanisms and developing corresponding countermeasures are indispensable for making them more effective. To meet this goal, many R&D programs have executed many crash analyses since the ISTEA period, such as pre-crash dynamics and intervention mechanisms, investigation of individual crash cases, and identification of their causal factors. They concluded that changing geometries at intersections and the number of vehicles approaching these locations result in various types of intersection crash configurations. To develop efficient countermeasures, Veridian Engineering categorized intersection collisions into four scenarios [4]. The four scenarios are classified based on signal violations, signal phase conditions on intersected roadways, vehicle states, and maneuver information. The following explains the four scenarios:

1. Intersection Scenario No. 1 – "Left Turn across Path"

In this scenario, "Subject Vehicles (SV)" attempt a left turn across the path of the "Possible Objective Vehicles (POV)." Although the "SV" is required to yield to the "POV," the "SV" does not stop for the traffic control, and hence no violation of the control device occurs (Figure 2-5). Most "SV" approach a traffic signal with a displayed green phase. The "SV" should be either slowing, or at a stop in the traffic lane.

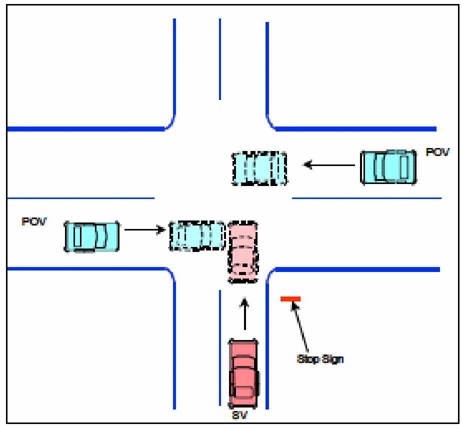


Source: Pierowicz, Jocoy, Lloyd, Bittner, and Pirson [4]

Figure 2-5: Intersection Scenario No. 1 – Left Turn across Path

2. Intersection Scenario No. 2 – "Perpendicular Path (Inadequate Gap)"

The "SV" observes the stop sign and stops prior to entering the intersection, where no traffic control is present on the roadway the "POV" will travel. The "SV" attempts to traverse the intersection or to perform a left turn onto the roadway (Figure 2-6).

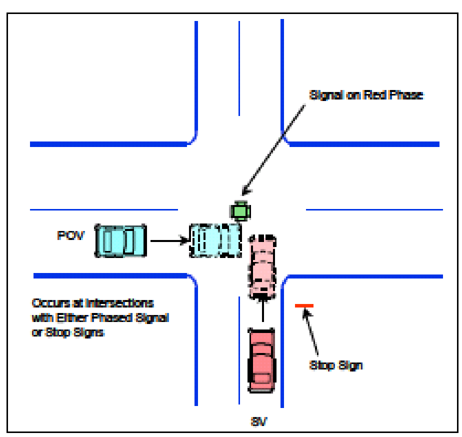


Source: Pierowicz, Jocoy, Lloyd, Bittner, and Pirson [4]

Figure 2-6: Intersection Scenario No. 2 – Perpendicular Path (Inadequate Gap)

3. Intersection Scenario No. 3 – "Perpendicular Path (Violation of Traffic Control)"

Although the "SV" is required to stop, the traffic control violation occurs, with the "SV" proceeding into intersection without stopping. The "POV" are on the right lane of entering the intersection. In most of these crashes, the vehicles try to traverse on straight paths (Figure 2-7).

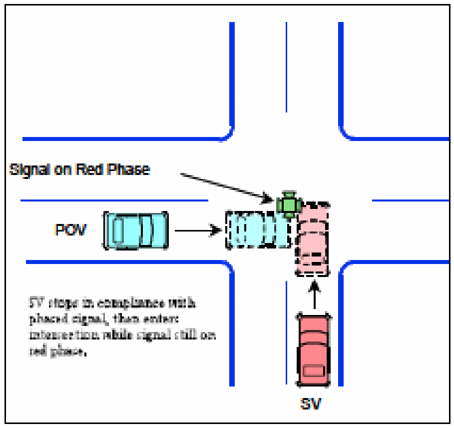


Source: Pierowicz, Jocoy, Lloyd, Bittner, and Pirson [4]

Figure 2-7: Intersection Scenario No. 3 – Perpendicular Path (Violation of Traffic Control)

4. Intersection Scenario No. 4 – Premature Entry

This scenario occurs when the "SV" approaches an intersection with a red-phase signal. The "SV" stops and then prematurely proceeds into the intersection prior to the green phase. This scenario occurs less frequently than the first three scenarios (Figure 2-8).



Source: Pierowicz, Jocoy, Lloyd, Bittner, and Pirson [4]

Figure 2-8: Intersection Scenario No. 4 – Premature Entry

Research and Development Areas

Although the knowledge of the potential ICAS has been accumulated, CAMP, a research consortium of automotive manufacturers, suggests that improving ITS technology in some areas, such as positioning, sensing, computing, and communications should be needed to develop the effective ICAS [20].

Carefully verifying mechanisms of primary causes of the four crash scenarios, CAMP has divided the focused R&D problems into two areas, "signal violation" and "gap acceptance." The "signal violation" area involves the scenarios 3 ("Violation of Traffic Control") and 4 ("Premature Entry"), whereas the "gap acceptance" area deals with the scenarios 1 ("Left Turn across Path") and 2 ("Inadequate Gap"). Table 2-1 represents the breakdown of the intersection crash population.

Table 2-1: Breakdown of Four Crash Scenarios and Relevant Problem Area

	Scenario Description	Problem Area	Population
1	Left Turn Across Path	Gap Acceptance	23.8%
2	Perpendicular Path - Inadequate Gap	Gap Acceptance	30.2%
3	Perpendicular Path - Violation of Traffic Control	Signal Violation	43.9%
4	Premature Intersection Entry	Signal Violation	2.1%
	Total		100.0%

Source: Modified based on Pierowicz, Jocoy, Lloyd, Bittner, and Pirson [4]

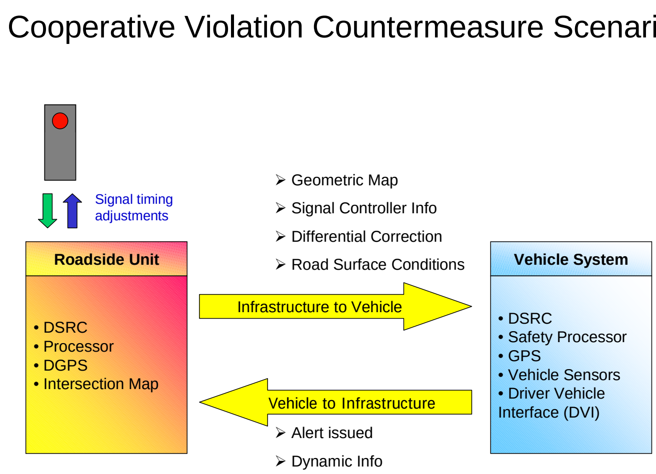
Functions necessary for the potential measures for the ICAS are warning the driver, modifying the signal timing, partial vehicle control, and full vehicle control [20]. The R&D areas that correspond to these functions involve wireless communication (i.e., DSRC), algorithms of traffic control interface, and threat assessment [20]. The "gap acceptance" area is considered more difficult because it requires deep understanding of interaction between driver behaviors and human factors. The CICAS program executes the following actions to design system prototypes and to meet the FOT by 2009 [20]:

1. "Continue research on and develop prototype of countermeasures against control violations and gap acceptance"
2. "Complete a prototype that includes cooperative vehicle-based and infrastructure components and addresses both areas"

2.3.3. Outlines of the Intersection Collision Avoidance Systems

The measures that address the "signal violation" R&D area are called "Cooperative Violation Countermeasure Concepts" [20]. The fundamental capability of this concept is for the vehicle to warn potential stop sign and traffic signal violations to the driver through DVI [18]. The intersection could adjust signal timing in reply to the warning of potential collision sent from the vehicle; this would be an infrastructure-based countermeasure.

Figure 2-9 depicts the outline of "Cooperative Violation Countermeasure Concepts." Receiving information on current phase and time to change phase from the signal, an RSU would transmit not only the signal controller information but also geometrical maps and road surface conditions around the intersection to the OBU. The OBU would decide whether to warn the driver and send alerts and dynamic information around the intersection to the RSU. The RSU replies to the alerts and issues an order to adjust signal timing.

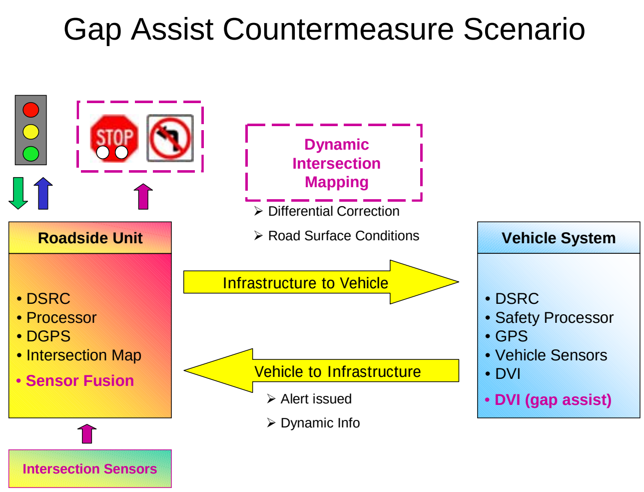


Source: "Cooperative Intersection Collision Avoidance Initiative," *Proceedings of CICAS Workshop* [20]

Figure 2-9: Cooperative Violation Countermeasure Concepts

The measures that address the "gap acceptance" R&D area are called "Gap Assist Countermeasure Concepts" [20]. It would be effective in the situation where there is an inadequate gap between the "subject vehicles" ("SV") and the "possible objective vehicles" ("POV"). This mechanism frequently can be found when the vehicle tries the "left turn against path" or runs into the opposite direction ("LTAP/OD"). This concept is based on the "Cooperative Violation Countermeasure Concepts", but the measures have the additional functions to solve the LTAP/OD problem.

Figure 2-10 illustrates the configuration "Gap Assist Countermeasure Concepts." An RSU transmits the dynamic intersection mapping that displays the state of vehicle approaching the intersection, such as speed, lane location, and distance from the intersection. In the same way as "Cooperative Violation Countermeasure Concepts," an OBU would calculate the algorithms and send alerts and dynamic information on the vehicles to the RSU, which provides a warning signal for the left turn to the signal.



Source: "Cooperative Intersection Collision Avoidance Initiative," *Proceedings of CICAS Workshop* [20]

Figure 2-10: Gap Assist Countermeasure Concepts

2.3.4. Concepts of the Intersection Collision Avoidance Systems

The most important objective of the CICAS Program is that CAMP develops potential concepts of solutions to the ICAS. CAMP has suggested seven ICAS concepts, ranging from the infrastructure-autonomous to the vehicle-based, with combinations of intermediate positions. Table 2-2 summarizes these concepts with their concise descriptions and presence of DSRC in the systems. The concepts can be roughly classified into three distinct models based on which makes decisions of warning against potential crashes: the infrastructure-only model (Concept 1), the vehicle-centric models with DSRC (Concept 3, 5, 6, and 7), and the infrastructure-centric models with DSRC (Concept 2 and 4)[4].

[4] In the CICAS workshop in December 2004, a consensus emerged among the public sector (State DOTs) about developing an infrastructure solution that would merge vehicle-centric concepts in the future. The principle stakeholders agreed that infrastructure only development should be conducted in parallel to its development efforts. Therefore, seven models can be mainly categorized into only two models: the infrastructure-only model and the vehicle-centric models.

Table 2-2: Seven Potential Concepts for Intersection Collision Avoidance Systems

	ICA Models	DSRC	Description
1	Infrastructure Only Systems	RSU Only	Infrastructure autonomous system without DSRC-equipped vehicles
2	Infrastructure Decision Systems	YES (OBU: Low Penetration)	Infrastructure (RSU) decides whether to warn drivers
3	Vehicle Decision Systems	YES (OBU: Low Penetration)	Vehicle decides whether to warn drivers
4	Infrastructure Intensive Decision Systems	YES (OBU: Mediate Penetration)	Advanced version of "Infrastructure Decision Systems" - Infrastructure warns warnings to vehicle based on information sent from all vehicles.
5	Vehicle Decision Systems II	YES (OBU: Mediate Penetration)	Advanced version of "Vehicle Decision Systems" - Vehicle decides whether to warn drivers based on intersection "dynamic mapping" sent from infrastructure
6	Vehicle Decision Systems III	YES (OBU: High Penetration)	Advanced version of "Vehicle Decision Systems II" - Vehicle decides whether to warn drivers based on information sent from vehicles and infrastructure
7	Vehicle Decision Systems IV	YES (OBU: 100% Penetration)	Vehicle autonomous systems - Based entirely on V2V communication

Source: Modified based on "Cooperative Intersection Collision Avoidance Initiative," *Proceedings of CICAS Workshop [20]*

2.4. Problem Set-Up

This section describes two conflicting concepts that the later chapters attempts to analyze and evaluate, which is the cornerstone of thesis: the infrastructure-autonomous systems (Concept 1) supported by the public sector and the vehicle-base systems (Concept 3) recommended by the private sector.

Difference of Opinion and Trade-off

Both sectors agree on that the ICAS will be the vehicle-based model in the future for the wide diffusion of DSRC [20]. Although public-private partnerships are an important factor for future success in the ICAS, however, CAMP, a private sector group, and the public sector have a different opinion on what is the best model and evolutionary path for the ICAS.

CAMP announced the vehicle-centric viewpoint because it consists of vehicle manufactures. It has proposed that the evolutionary path of the ICAS start with the fundamental vehicle-based ICAS (Concept 3) [20]. Concept 3 assumes relatively low level of market penetration of the OBU. Therefore, this concept will consist of a certain level of the in RSU infrastructure and a small portion of OBUs in automobiles, where two-way information can be transmitted between infrastructure and vehicles. The economic benefit will be proportional to the number of the OBU-equipped vehicles, which depends on market penetration of the OBU. In other words, the benefit might be disappointing in an early stage of the product diffusion.

The public sector feels that, in the vehicle-based concept, there will be few reasons to justify an enormous investment in deploying infrastructure devices if there are few DSRC-equipped vehicles. Instead, it proposes an alternative that the ICAS starts with building the infrastructure-autonomous model (Concept 1) and proceeds to the vehicle-based model (Concept 3). Concept 1 does not require any OBU in the ICAS, where collision warnings will be appeared on the driver infrastructure interface (DII), which displays visual information such as flashing lights at the corners of the intersections in place of DVI. All vehicles can enjoy immediate benefits of crash prevention as soon as the public sector deploys the infrastructure-autonomous ICAS.

Therefore, the basic trade-off exists in the conflict between the CAMP and the public sector. Given that the public sector decides to implement the Concept 1, it can improve intersection safety without OBUs. However, if people are willing to purchase the OBU for their automobile, they can provide new services based on Concept 3, but investments in DII by the public sector will be basically wasted.

In conclusion, the infrastructure-autonomous ICAS (Concept 1) produce large amounts of the social benefit immediately but potentially waste investments in components only for this concept, such as DII, whereas implementing the vehicle-based ICAS (Concept 3) directly may result in the slow economic benefit provided that drivers hesitate to purchase the OBU. Comparing these two concepts, this thesis will address the question of which implementation strategy makes more sense for the public sector and the society and propose the flexible deployment strategy. Table 2-3 summarizes these two ICAS concepts.

Table 2-3: Comparison between Two Conflicting Concepts

ICA Model Concepts	Original Concept of CAMP Model	Warning Decision	Necessary Components		
			Sensors	Interface Devices	Presence of DSRC
Infrastructure Autonomous Systems	Concept 1	Infrastructure	Infrastructure	DII	RSU
Vehicle-Based Systems	Concept 3	Vehicle	Vehicle	DVI	RSU + OBU

2.5. Challenges of the Intersection Collision Avoidance Systems

This section explains two important challenges necessary for analyzing the trade-off: "user acceptance" and "open architecture" [22].

Any product development and system deployment for the ICAS should be executed with the realization that the benefits of a technology are not always determined even after the technology produced and put into the market. It is clear that predetermining the benefits that the technology will bring is difficult. The government, however, endeavors to facilitate successful development of the new technology used for the ICAS. Key issues to achieve this are user acceptance" and "open architecture"

User Acceptance

For the ICAS, it is envisioned that the public sector will invest in the infrastructure capabilities and that the driving users will ultimately pay for the potential countermeasures. This scheme is similar to the diffusion model of mobile communication devices, where companies were willing to invest in both R&D for mobile phones and telecommunication network coverage. The public sector anticipates the potential for a great return on investment when users pay for the services from which they benefit [22].

Let us go back to user acceptance of the ICAS and apply the lesson from the previous case to the ICAS problem. With the expectation of improving their safety and receiving the social benefit by reducing the probability of dangerous collisions, the driving users will purchase the OBU and the public sector will accelerate deployment of the ICAS. As a consequence, effectiveness of the countermeasures is one of the most crucial aspects that will define success of the ICAS. In other words, near-universal market penetration of DSRC (both the OBU and the RSU) is necessary to have a significant impact on transportation fatalities. Anything less might result in a mixture of some vehicles in cooperation with the infrastructure and others that potentially work against, with insufficient benefits from the entire ICAS.

Developing attractive products is the most significant challenge for technology developers because it is highly likely to attain near-universal market penetration in a short time. Successful development of the ICAS, however, will also require continual interactions of private sector with public sector regarding product development, market penetration of the in-vehicle product, and deployment of infrastructure capabilities. This implies that successful product launch does not always mean successful deployment, making it difficult for the project evaluators to forecast the financial benefits.

<u>Open Architecture</u>

The history shows that, with any market evolution, the majority of the market will only adopt new technologies after "innovators" of the technologies have approved them [22]. Developing attractive products, however, is not a sole factor of successful market penetration, because an open architecture is another crucial feature of the transportation systems. The action to build an open architecture promotes diffusion of the underlying technologies and enlarges a platform for developing the ICAS. In this sense, the ITS operational tests is one of the effective actions for an open architecture that greatly influence the successful implementation of the ICAS.

2.6. Conclusion of the Intersection Collision Avoidance Systems

Since fundamental research on the ICAS was almost completed during the ISTEA era, various initiatives are currently trying to develop the prototype ICAS for future practical use. These initiatives develop necessary performance specifications for the ICAS, conduct the large-scale operational tests, and estimate the value of the project. The potential ICAS make the most use of "ITS-4" technologies using several ITS functional areas out of six. The ICAS takes on the ATMS feature in that real-time data will be collected, utilized, and disseminated. It also possesses the ATIS and AVCS characteristics because the OBU provides in-vehicle signing to drivers and because the ICAS helps the driving control make safer and more efficient through collision warning.

Those engaged in the ITS industries and institutions are convinced that coordinated use of ITS functions will produce enormous social benefits. The ICAS systems also require deployment of infrastructure components (i.e., RSU and peripheral components) by public sector and in-vehicle equipment by the private sector. The quintessential factor of successful development and deployment the ICAS is cooperation between public sector and private sector. The government will serve as a "facilitator" for public-private partnerships. Figure 2-11 summarizes the roles of major participants and public-private partnerships for the ICAS.

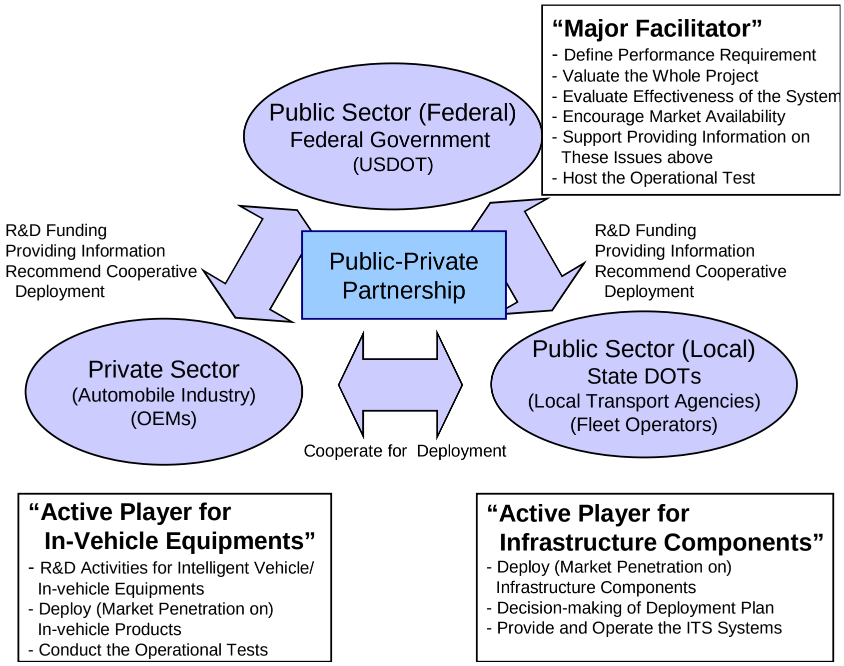


Figure 2-11: Public-Private Partnerships for the Intersection Collision Avoidance Programs

Currently, the Cooperative Intersection Collision Avoidance System (CICAS) Program is developing concepts of the ICAS. The potential countermeasures will utilize DSRC, a new product that enables I2V, V2I, and V2V communications. CAMP, a private sector group, suggested seven DSRC-based ICAS concepts, ranging from the infrastructure-autonomous to vehicle-based. Major participants of the program, CAMP and the public sector, however, express a different view on what is the best model for the ICAS; the CAMP supports the evolutionary path that starts with the vehicle-based concept, whereas the public sector is interested in the infrastructure-autonomous systems. Investigating this conflict, we discover the basic trade-off between two ICAS concepts. To study this conflict, this thesis focuses on addressing which strategy would make more sense for the public sector and the society.

Chapter 3, 4, and 5 explore the appropriate methodologies to evaluate R&D and deployment of two ICAS concepts, and Chapter 6 analyzes the value of these concepts through the proposed methods.

Chapter 3 Fundamental Valuation Concepts

This chapter explains the fundamental financial valuation concepts necessary for evaluating the two ICAS concepts. The chapter provides the definition of net present value (NPV) and three financial theories to determine the discount rate necessary for calculating the NPV: the weighted-average cost of capital (WACC), the capital asset pricing model (CAPM), and the arbitrage pricing theory (APT).

3.1. Net Present Value (NPV) / Discounted Cash Flow (DCF) Method

Net present value (NPV) is a standard financial model that is commonly utilized for evaluating investment opportunities. NPV of a project is the present value of its expected incremental cash inflows and outflows over a specified timeframe.

This methodology requires the future cash flows to be adjusted to account for the time value of money through a discount factor known as the discount rate. To calculate NPV, the expected cash inflows generated by the project, the expected cash outflows necessary for implementing the project, and the discount rate must be determined [24]. NPV is the sum of the discounted benefits and costs (Equation 3-1):

$$NPV = -I_0 + \sum_{t=1}^{N} \frac{E(FCF_t)}{(1+r_i)^t} \qquad \text{Equation 3-1}$$

Where I_0: Investment at time zero

$E(FCF_t)$: Expected value of free cash flow at time t

r_i: The rate of expected return on the investment adjusted for the risk

N: The number of periods into the future when payoffs occur, provided that r_i remains constant in each period

The result of NPV analysis represents the project value and influences the process of a decision-making concerning project planning and portfolio management deeply. Managers intuitively think that an investment in a project with a positive NPV should be made because the project would increase the shareholder value. The sign of NPV is the threshold for making decisions in investments for projects. One can claim that actual managerial decisions for any investments, which should accommodate various expectations and utilities from shareholders, are not so simple. This argument, however, is undermined by the statement that the shareholders are likely to unanimously agree on the investment rule that managers are expected to undertake investments until the marginal return on the last investment is greater than or equal to the opportunity cost of capital determined by the market [24]. Accordingly, it is appropriate that the sign of NPV is a principle benchmark of the decision rule for investments [25].

The discounted cash flow (DCF) method is a standard financial valuation methodology based on the NPV calculation technique. It is recommended for capital budgeting that explores investment opportunities. The DCF analysis as a tool for R&D valuation, however, has a crucial shortcoming that it cannot incorporate any flexibilities and option values into managerial decisions. It is implicitly interpreted that the company that adopts the DCF analysis “passively” possesses its real assets under management [26]. The DCF method assumes that the cash flows are static and predetermined throughout the life span of the project, although in reality the value of the project is always fluctuating depending on updated information and forthcoming decisions [26].

3.2. Weighted-Average Cost of Capital (WACC)

Firms must select and prioritize projects under a perfectly competitive market where their resources are limited. The project value is one of the most important components in decision-making concerning investments. It is strongly affected by the cost of capital. Therefore, they should choose the appropriate cost of capital to estimate the value of the project accurately.

One of the methods to estimate the cost of capital is to adopt the averaged opportunity cost of capital for a public-traded firm. In this technique, the average cost of money is regarded as an aggregate measure for a portfolio of all the firm's current assets [26]. This cost of capital is called WACC (Weighted-average cost of capital) and can be obtained form the weighted average return on debt and equity in the firm (Equation 3-2):

$$WACC = r_d\left(\frac{D}{D+E}\right) + r_e\left(\frac{E}{D+E}\right) \qquad \text{Equation 3-2}$$

Where $WACC$: Weighted-average cost of capital
(Discount rate for an average project)
r_d : Expected rate of return on debt (Cost of debt)
r_e : Expected rate of return on equity (Cost of equity)
D : Debt in dollars
E : Equity in dollars

The weakness of this method is that the WACC formula only works for projects, for which the risk profile closely resembles that of the firm's average. In other words, the WACC method is incorrect for valuing the project that is either riskier or safer than the firm's current assets, such as an R&D project with greater uncertainties [26]. Accordingly, a non-average discount rate should be chosen as the appropriate discount rate for valuing an R&D project. This limitation of WACC leads to the Capital Asset Pricing Model (CAPM), which can adjust the discount rate in accordance with the level of the risk.

3.3. Capital Asset Pricing Model (CAPM)

CAPM is the most well known model for assessing the appropriate discount rate for valuing the project. In CAPM, risks associated with projects are classified into two forms: the systematic (market) risk and the idiosyncratic (unique) risk. The systematic risk can be completely diversifiable, but the idiosyncratic risk cannot. The exogenous market outcomes affect the value of the investment as the systematic risk. The idiosyncratic risks are endogenous and hence can be averaged out by possessing multiple investments.

Based on the premise that the idiosyncratic risk cannot be diversified, CAPM proposes that the risk-adjusted rate of return. This rate implies the opportunity cost that the investors could earn from projects in an equilibrium market can be expressed as a function of the systematic risk component (Equation 3-3):

$$E(r_i) = r_f + \beta_{im}[E(r_m) - r_f] \qquad \text{Equation 3-3}$$

Where $E(r_i)$: Expected return on the capital investment (asset)
r_f : Risk-free rate of interest
$E(r_m)$: Expected return of the market
β_{im} : Sensitivity of the asset returns to market returns

This relationship in Equation 3-3 describes a straight line called the security market line (SML). It indicates that the expected risk-adjusted rate of return for an investment linearly correlates with the market risk components β_{im} , which represents the sensitivity of the asset returns to market returns. The beta can be define as the ratio of the covariance of the returns on the individual capital investment and the market portfolio to the market variance (Equation 3-4).

$$\beta_{im} = \frac{Cov(r_i, r_m)}{Var(r_{m)}} \qquad \text{Equation 3-4}$$

In the securities industry, estimating the market risk component of traded securities is straightforward, since the analysts can obtain the desired estimate of β_{im} from a simple regression model described in Equation 3-4. Practically, securities of similar firms in the same industry are chosen as a basis for comparatively assessing the market risk of a firm whose data for its stock is not available. A typical example is the IPO (Initial Public Offering).

However, it is not possible to directly measure the risk of investments in an R&D project through a regression analysis because they are not traded assets. The cost of capital for projects relies not on the risk profile of the firm but on the project itself. Accordingly, although the firm's projects are highly similar, an individual project should be a different risk-adjusted discount rate to represent its unique level of risk. In this regard, the discount rate for valuing should be based on CAPM, and not just WACC.

3.4. Arbitrage Pricing Theory (APT)

Arbitrage Pricing Theory (APT) is another method to calculate the risk-adjusted discount rate. Similar to CAPM, APT assumes that the risk-adjusted rate of return is influenced by correlation with exogenous factors. APT differs from CAPM in that the expected return on the individual investment is simply obtained from multiple regressed exogenous factors (Equation 3-5):

$$r_i = \alpha + \beta_1 f_1 + \beta_2 f_2 + \ldots + \beta_{n-1} f_{n-1} + \beta_n f_n \qquad \text{Equation 3-5}$$

Where r_i : Expected return on the capital investment (asset)
α : Constant
β_j : Regression coefficients that acts like β_{im} in Equation 3-4 (for j = 1 to n)
f_j : Exogenous regression factors (for j = 1 to n)

This model, however, does not specify the set of exogenous factors to determine the risk-adjusted rate of return [26]. In other words, the expected return of the market may be no more than one of the factors. Common factors include prices of traded assets, GDP growth rates, and interest rate spreads. Campbell, Lo, and MacKinlay provide a detailed discussion and the current state in developing these empirical models related to the APT theory [27].

Building upon the financial concepts discussed in this chapter, the next chapter explorers the valuation methods appropriate for R&D and emphasizes real options and decision analysis.

Chapter 4   Real Options for Project Valuation

This chapter focuses on real options analysis as a tool that considers flexibilities in designing systems and making decisions. The chapter starts with an explanation of financial options and real options with their literature review and differences between financial and real options and proceeds to providing various types of real options. Then, the chapter introduces two important real options methodologies that this thesis applies to value the two conflicting ICAS concepts: decision analysis and "hybrid real options" analysis that combines decision analysis and option analysis.

4.1.   Financial Options

Before discussing real options, this thesis introduces financial options that are the groundwork for developing real options.

4.1.1.   Fundamental Concepts

Many critics, including Hayes and Garvin, have pointed out the drawback of the standard discounted cash flow (DCF) method in that it favors short-term and low-risk investments [28]. Myers summarized the consensus about the DCF method by investigating the application of the DCF method to securities and real corporate projects. While admitting that the DCF method is appropriate for valuing low-risk projects and stocks/bonds, he acknowledged that this technique has a limitation for the project with significant growth or strategic options and that the option-pricing model should be appropriate for valuing such investments [29][30].

Fundamental Concepts

Financial options are classified in two basic types: calls and puts. A call option gives the stockholders the "right to buy underlying assets for a specified price within or at a certain date," whereas a put option gives the stockholders the "right to sell underlying assets for a specified price within or at a certain date" [31]. Table 4-1 summarizes important terms and their definitions for financial options:

Table 4-1: Terms and Definitions for Financial Options

Option Terminologies	Definitions
Underlying Asset	Market-traded stocks, stock indices, foreign currencies, debt instuments, or commodities
European Option	An option contract that may be exercised only during a specified period of time just prior to the expiration date
American Option	An option contract that may be exercised at any time between the date of purchase and the expiration date
Strike Price (Exercise Price)	The stated price per share for which the underlying asset may be purchased (in the case of a call option) or sold (in the case of a put option) by the option holder upon exercise of the option contract
Option Price	The price of an option contract determined in the competitive marketplace, which the buyer of the option pays to the option seller for the rights conveyed by the option contract. If you decide not to use the option to buy the stock, and you are not obliged to, your only cost is the option
Exotic Options	Variant of the traditional vanilla options (a put, a call) that possess different payoff schemes

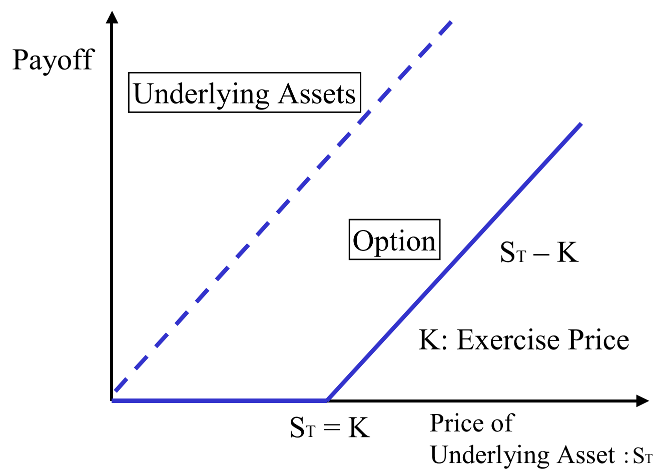
Source: The definition of options is obtained from the Chicago Board Options Exchange web site: (http://www.cobe.com/LearnCenter/Tutorials.aspx#Basics) last accessed on March 17, 2006

A key characteristic of an option is that an option holder has the "right" to exercise the option, but "no obligation" to do so. Rationally, she would exercise only if conditions are favorable [26]. She can avoid downside risks and limit the loss to the price of getting the option, while enjoying the upside risks and the potential gain is unlimited [32]. Once a standard option is purchased, no additional potential for loss exists. Hence, the option has an interesting asymmetric net profit structure called the payoff in most option literature. It should be noted that, unlike the net profit that considers the total incurred expenses of the option holders, the payoff only considers what they may get at expiration.

Figure 4-1 illustrates a payoff diagram for a European call. For any price of underlying assets greater than the strike price, it is favorable to exercise the option. Mathematically, this payoff is the maximum difference between the two prices (Equation 4-1):

$$\text{Payoff (European Call)} = Max[S_T - K, 0] \qquad \text{Equation 4-1}$$

Where S_T : Price of the underlying asset at the expiration date
K : Strike price (Exercise Price)

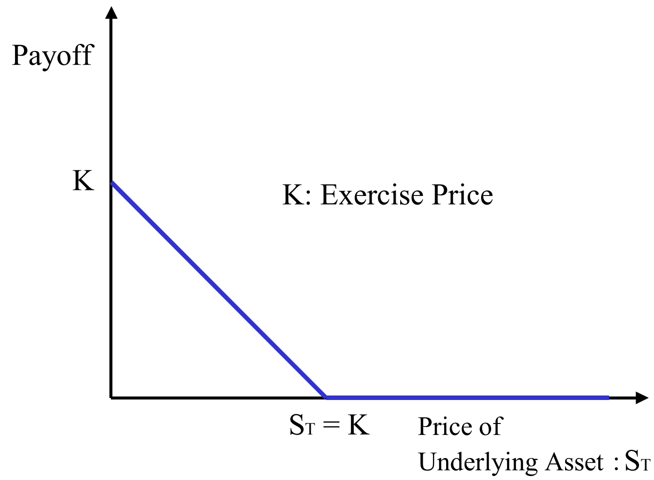


Source: Modified based on Brealey and Myers [26]

Figure 4-1: Payoff Diagram of a European Call Option

Similarly, Figure 4-2 depicts the payoff profile for a European put option. Also note that the American options have the same payoff schemes as the European options do, except that they can be exercised anytime prior to the maturity date. Mathematically, Equation 4-2 gives the payoff for the European put option. As seen from these figures, the option has a non-zero value when it exceeds the exercise price at its expiration.

$$\text{Payoff (European Put)} = Max[K - S_T, 0] \qquad \text{Equation 4-2}$$

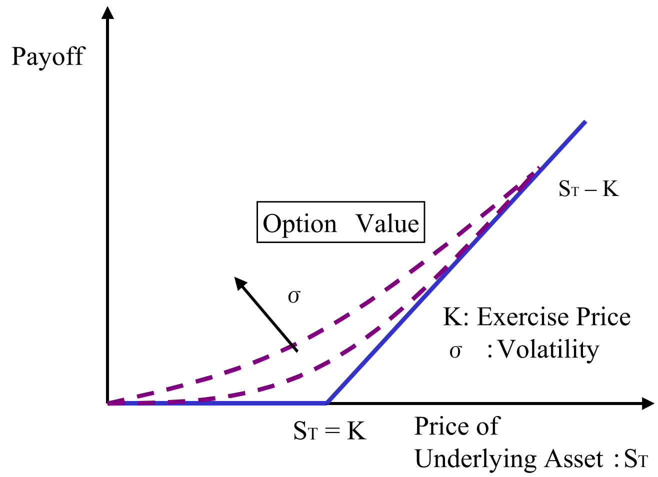


Source: Modified based on Brealey and Myers [26]

Figure 4-2: Payoff Diagram of a European Put Option

Six main drivers affect the value for each financial option: price of the underlying asset (S_T), strike price (K), time to expiration (maturity) (T), volatility of the underlying asset (σ), risk-free rate of interest (r_f), and cash dividends (D).

The value of a call option increases with the current price of the underlying asset and decreases with increase in strike price, and vice versa for the value of a put option. An American option always increases in value as the time to expiration extends, while the time to expiration for a European option cannot have a definite influence on value. Volatility represents the degree of uncertainty and is the most important driver that affects the value of the option. The option value increases as volatility of the underlying asset grows, since higher volatility facilitates an opportunity of large payoffs while the downside payoff remains zero gains. Figure 4-3 illustrates how high volatility increases the payoff of the underlying asset as an example of the European call option. Table 4-2 summarizes how these six drivers affect the option value.



Source: Modified based on Brealey and Myers [26]

Figure 4-3: The Value of a European Call Option Increases with High Volatility (σ)

Table 4-2: Main Influences on Option Value of Financial Options

Drivers/ Option Type	Notation	European Call	European Put	American Call	American Put
Underlying (Stock) Price	S_T	+	-	+	-
Strike (Exercise) Price	K	-	+	-	+
Time to Expiration	T	?	?	+	+
Volatility of Underlying	σ	+	+	+	+
Interest Rates	r_f	+	-	+	-
Cash Dividends	D	-	+	-	+

Source: Hull [31]

4.1.2. Fundamental Assumptions

Financial managers need to understand that there are two crucial assumptions that underlie the pricing of the option value: one is no-arbitrage opportunity and the other is that stock prices randomly fluctuate in a complete, efficient market [33].

<u>Assumption 1: No-Arbitrage Opportunity</u>

Arbitrage, which involves an activity of profiting from differences in two or more markets through simultaneous transactions, allows an arbitrager to make a risk-less profit without any investment. In reality, however, the law of supply and demand immediately negates any arbitrage opportunities in a "well-developed" competitive market. Without arbitrage opportunities, a portfolio of the underlying asset and its option should be traded at the same price and be set up in such a way that the payoffs of the option accurately replicate the payoffs of the underlying asset. There are no risks in establishing such a portfolio. Consequently, it is not necessary to take the investor's idiosyncratic risks into account, and the return on the portfolio equals the risk-free interest rate[5].

Assumption 2: Random Fluctuation of Stock Prices in a Complete Market

In determining the option price theoretically, it is generally assumed that financial commodities are traded in perfect markets, which possess the following characteristics: (1) they operate in "equilibrium," (2) they are "perfectly competitive," (3) they include risk-free asset, (4) each individual has "the same right to access to the capital market," (5) "infinitely divisible securities exist in the market," and (6) there are "no transaction fees and costs" [33].

Samuelson demonstrated that the future price of financial commodities randomly fluctuates although it shows a seasonal pattern [34]. This theory indicates that the probability of changes in the stock price is distributed under a lognormal probability distribution in a short run and that the magnitude of changes is subject to Geometric Brownian Motions based on calculating the value of financial options[6].

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[5] Generally, the risk free rate of interest is approximated as the yield on the short-term U.S. Treasury bills. Reference books about finance theory including Brealey and Myers address detailed arguments on risk and return of the underlying assets [26].

[6] A solution of Geometric Brownian Motions equation subject to the boundary of the European option is equivalent of the Black-Scholes Formula.

4.1.3. Financial Option Valuation Methodologies

This section explores the three major methodologies to calculate the value of financial options: the Black-Scholes Option Pricing Model (OPM), the binomial option-pricing valuation, and Monte-Carlo simulation. Hull elucidated that the value of options can be obtained from arbitrage-enforced pricing [31]. He identified three methods for calculating option values using partial differential equations (PDE), dynamic programming of the binomial tree, and simulation.

Method 1: The Black-Scholes Option Pricing Model (OPM)

The Black-Scholes Option Pricing Model (OPM) is the simplest and most widely used type of the PDE method to calculate the value of financial options. Black and Scholes demonstrated a closed-form model that yields theoretical prices of non-dividend paying European options through the differential equation [35]. Merton extended the model that is applied to European options with cash dividend payment [36]. The closed-form models for the option pricing become difficult to solve, however, as supplemental terms are added to make them more realistic. Regardless of complexity, many innovative arbitrage-enforced option models have been developed. These include stochastic dividend yields [37], compound options [38], and stochastic volatilities [39]. With mathematical insights, the PDE method has been utilized for academic discussion and applied to a variety of problems including technology issues. Pindyck formulated the model that considers technical and input cost in the project with uncertainty [39]. Grenadier and Weiss investigated the options pricing for investment in technology innovations [41].

Black and Scholes first solved the problem of valuing options. This solution known as the Black-Scholes Option Pricing Model [35] is the most familiar model that can calculate the theoretical price of a European call and put option with no cash dividends. The solution of a European call option on a non-dividend-paying stock can be obtained from Equation 4-3:

$$C = S_0 N(d_1) - Ke^{-r_f T} N(d_2) \qquad \text{Equation 4-3}$$

Where C : Theoretical value of a European call option

$$d_1 = \frac{\ln(S_0 / K) + (r_f + \sigma^2 / 2)T}{\sigma\sqrt{T}}$$

$$d_2 = d_1 - \sigma\sqrt{T}$$

$N(x)$: Cumulative probability function for a standardized normal distribution

Similarly, Equation 4-4 formulates the theoretical value for a European put option without cash dividends at time zero:

$$P = Ke^{-r_f T} N(-d_2) - S_0 N(-d_1) \qquad \text{Equation 4-4}$$

Where P : Theoretical value of a European put option

Method 2: Binomial Option-Pricing Valuation

In contrast to the PDE model, the binomial tree is a discrete-time model that takes account of the price volatility through the replicating portfolio that reflects the historical return distribution, the trading strategy used to ensure at a certain date the payoff of an option without trading this option. Cox, Ross, and Rubinstein first introduced the binomial tree method, which approximates the evolution of the value of the underlying assets in a simple but powerful and flexible way, estimating the value of many complicated option features including the early exercise of American options [42]. Luenberger applied this methodology to the valuation of investments in a gold mine [43]. There are two steps to calculate the value of financial option through the binomial option-pricing valuation.

Step 1: Risk-Neutral Approach and Binomial Option-Pricing Valuation

The Binomial Approximation method approximates the payoff of the underlying asset through the binomial lattice that describes how the price of the underlying asset would evolve in a risk-neutral environment [42]. In a risk-neutral situation where the investor requires no compensation for any risks, the value of financial options and the expected return on the assets can be evaluated based on the risk-free rate. In other words, potential cash flows can be adjusted so that the risk-free rate can be applied. This approach known as the risk-neutral approach can solve the problem associated with the discount rate in contingent including complicated derivatives [31].

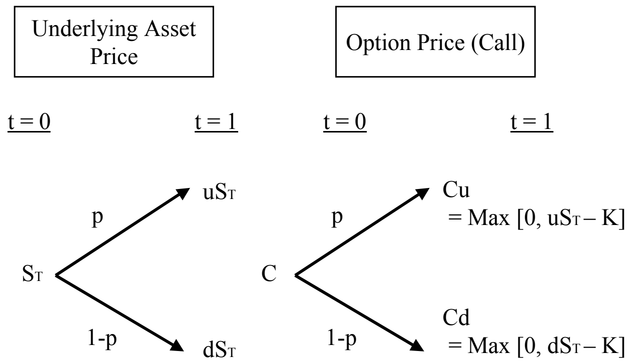
Cox and Rubinstein [44] provided detailed explanations of the binomial lattice model based on the risk-neutral approach. The approach begins with determining the range of the underlying asset in each discrete point. Consider the one-step binomial tree example illustrated in Figure 4-4. During the life of the option, two future outcomes are assumed: the price of the underlying asset either moves up by multiplier u or falls down by multiplier d per step in time. The price of the asset and the payoff of the option will be uS_0 and $Max[uS_T - K,0]$ in a desirable situation, whereas the asset price will be dS_0 and the option pays $Max[dS_T - K,0]$ in the disappointing situation.

The current value of the call option can be obtained from calculating backwards from the binomial tree at t = 1. The probability of shifting the preferable situation can be determined so that the expected sum of each outcome divided by the risk-free rate equals to the initial price of underlying asset. This probability is called the risk-neutral probability. The theoretical price a European call is the expected sum of the payoffs of the preferable and undesirable situation. Equations 4-5 and 4-6 show the risk-neutral probability and the price of the European call through the risk-neutral approach.

$$p = (r - d)/(u - d) \qquad \text{Equation 4-5}$$

$$C = [pC_u + (1 - p)C_d]/r \qquad \text{Equation 4-6}$$

Where C_u : Value of the call option in case of preferable situation
C_d : Value of the call option in case of undesirable situation
$r = 1 + r_f$ (r_f : Risk-free interest rate)
p : Risk-neutral probability



Source: Modified based on Hull [31]

Figure 4-4: Underlying Asset Price and Option Price in a One-step Binomial Tree

Step 2: Binomial Option-Pricing Valuation through Binomial Lattice

Now, we extend the one-period binomial tree model to multiple-stages. Figure 4-5 illustrates evolution of the stock price for three periods. The approach consists of an iterative process that divides the time to maturity of the option into discrete steps. Given that the maturity of the underlying asset would be divided into n equal sections, the period length of each discrete time frame is $\Delta T = T / n$.

Equation 4-7 gives the factors u, d that describe the price dynamics on the asset[7]:

$$u = e^{\sigma\sqrt{\Delta T}}$$

$$d = e^{-\sigma\sqrt{\Delta T}} = 1/u \qquad \text{Equation 4-7}$$

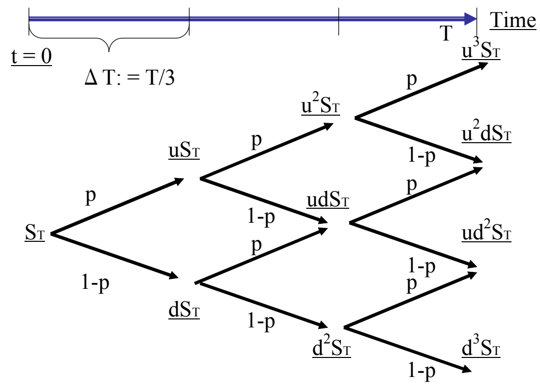
Where σ : Volatility of natural logarithm of the underlying cash flow returns in percent

ΔT : Unit Period Length of the Binomial Lattice

[7] In case of the infinitesimal ΔT, the general binomial option-pricing formula approximates to the continuous Black-Scholes formula.

If the price of the underlying assets annually increases with the rate of ν, the risk-neutral probability will be modified shown in Equation 4-8:

$$p = \frac{1}{2}(1 + \frac{\nu}{\sigma}\sqrt{\Delta T}) \qquad \text{Equation 4-8}$$



Source: Modified based on Hull [31]

Figure 4-5: Three-step Binomial Lattice

In this binomial lattice model with multiple periods, the estimated option value can be calculated by moving backwards from the last period to the present. Equation 4-9 formulates the value of a European call with three-period binomial tree through the recursive procedures until time zero. Likewise, Equation 4-10 provides the general binomial option-pricing formula with n stages. In an American option, the optimal action for the option holder is determined at each discrete period.

$$C = \frac{\begin{array}{c} p^3 \max[(u^3 S_T) - K, 0] + 3p^2(1-p)\max[(u^2 d S_T) - K, 0] \\ + 3p(1-p)^2 \max[(ud^2 S_T) - K, 0] + (1-p)^3 \max[(d^3 S_T) - K, 0] \end{array}}{(1+r_f)^3}$$

Equation 4-9

$$C = \frac{\sum_{j=0}^{n} \binom{n}{j} p^j (1-p)^{n-j} \max[u^j d^{n-j} S_T - K, 0]}{(1+r_f)^n} \qquad \text{Equation 4-10}$$

Method 3: Monte-Carlo Simulation

Development of computer technology has enabled the construction of large computer simulations such as Monte Carlo simulation to estimate the value of options that the simple PDE and the binomial tree method cannot solve. Merck has adopted the simulation model for decision-making to evaluate the option values to prioritize the focused pharmaceutical R&D programs since the 1980s [45]. Tufano and Moel demonstrated implementation of Crystal Ball © to value options on mining property bidding process [46]. Schwartz simulated values inherent in pharmaceutical patents and R&D programs [47].

Monte-Carlo simulation is an analytical method that produces the stochastic distribution of possible outcome of outputs (Y) that correspond to probability-distributed sampled inputs (X). Spreadsheet software such as Excel and Crystal Ball © performs Monte-Carlo Simulations. The simulated result helps managers figure out characteristics of outputs.

4.2. Real Options

Unlike financial options that function as contracts, the options for systems or projects are "real" because they deal with "real projects" [32]. They are associated with flexibilities in the systems design or the evolution of projects. Systems and projects often contain option-like flexibilities that represent opportunities to enhance the value of the project through design or through management actions, allowing decision-makers not only to enjoy upside opportunities but also to avoid downside losses. These flexibilities are called "real" options.

Managers have applied real options analysis to business strategies including corporate finance, project valuation, contract valuation, security analysis, portfolio management, and risk management. This analysis is finding widespread application not only in industries including pharmaceutical, infrastructure, manufacturing, real estate, R&D-oriented firms, and venture capital but also in policy fields including environmental pollution, and governmental regulatory issues.

4.2.1. Real options versus Financial Options

Buying financial options is not the “obligation” but the “right” to purchase or sell the underlying asset at a predetermined cost [31]. In this sense, real options are similar to financial options that do not represent “obligations” but “rights.” Real options, however, differ from financial options in two points: the definition of the “underlying” and the time span [48].

First, the “underlying” of financial options is the underlying asset, while the “underlying” of real options is the agent that influences the value of the project [48]. Financial options need a uniquely defined underlying asset to assess their value. For example, the underlying asset of the stock option is the stock price. In real options, however, a generalized concept of the underlying has to be first addressed. The “underlying” of the real options can sometimes be financial assets, but can also be other agents such as market size [48]. If the distribution of uncertainty in the “underlying” follows a lognormal distribution, the Black-Scholes formula or the binomial option-pricing valuation method can applicable for calculating the value of real option; otherwise, the value of real option can be estimated through “options thinking” discussed in Chapter 4.3.

Second, real options differ from normal financial options in that they treat long-term projects. The project length of real options is usually longer than that of financial options. The maturity of financial options is usually below two years, whereas real options projects can last for decades. This feature requires special efforts to model future value of asset and hence the value of real options often cannot be simply projected from historical data [49].

4.2.2. Types of Real Options

Real options can be found everywhere in projects and systems design. This section explains various types of real options by using three examples listed in Table 4-3. In the first two examples, the options that the manager possesses are to shut down (Type 1) and to abandon (Type 2). In these cases, the options occur naturally. In the last example, the manager finds an opportunity to increase the profit by expanding the capacity. This case requires the extra cost to exercise the option.

Table 4-3: Three Examples of Real Options

Type	Details
1	A copper mine explores whether to open the mine after the exploration period. The primary uncertainty concerns the future price and amount of the ore, which will impact uncertainty in the future revenue and the value of the project to open the mine. If the copper price decreases to the extent that the future revenue cannot offset the exploration costs, they can exercise the option to close the mine (Tufano, Moel, 1997).
2	R&D firms possess the flexibility to kill projects if they realize that the unattractive R&D outcomes result in the negative NPV of the project.
3	Manufacturers can build product platforms that can support many different products. Those companies possess flexible facilities that enable to switch rapidly from one type of models to another. The manufacturing design requires careful treatment but gives management the opportunity to follow markets and orders as they develop (Neely, de Neufville, 2001).

Source: Modified based on Tufano and Model [46], Neely and de Neufville [51]

Learning the type of real options is fundamental to value the project through real options analysis. Table 4-4 summarizes the various types of real options. Properly applying these concepts allows project evaluators to actively manage risks and uncertainties [50].

Table 4-4: Various Types of Real Options

Projects	Descriptions	Examples
Deferral Options	The firm is capable of deferring its investment to gather information or to wait for the best entry time into the market.	All natural resource extraction industries; Real estatte development; Paper product
Abandonment Options	Under the undesirable market conditions, the firm can abandon current operations permanently and realize the resale value of capital equipment and other assets in secondhand markets.	New product penetrations in uncertain markets; Capital intensive industries such as airlines and railroads; Financial services
Sequential Options (Staged Investments)	The firm can partition its investment as a series of outlays, create the option to abandon the enterprise in midstream if new information is unfavorable. Each stage can be viewed as an option on the value of subsequent stages.	All R&D intensive industries, especially pharmaceuticals; Capital-intensive projects in the long span (such as large-scale construction, energy-generating plants, or start-up
Scaling Options	The firm can expand, contract, or temporarily close.	Natural resource industries such as mine operations; Fashion apparel; Consumer goods; Commercial real estate
Growth Options (Barrier Options)	An early investment is a prerequisite in a chain or interrelated projects. The early entry and associated knowledge gain allow the firm to capture future opportunities.	All infrastrucure-based or strategic industries, especially high-tech, R&D industiries.
Compound Options (Multiple Interaction Options)	The firm holds multiple options in its projects. The collection of options, both upward-potential enhancing calls and downward-protection put options in combination. Their combined option value may differ from the sum of separate option values because of interaction. They may also interact with financial flexibility	Real-life projects in most industries.

Source: Trigeorgis [52]

4.2.3. Real Options "on" Projects and "in" Projects

Real options exist in capital investment projects including R&D. The firms can improve the value of the project by managing the uncertainty associated with the environment surrounding on the project or by proactively utilizing the flexibility inherent in the project itself. In other words, real options can be classified into two types in terms of where the primary flexibility exists around the project and systems design: real options "on" projects and "in" projects.

Real Options "On" Projects

Of three examples of real options shown in Table 4-3, the uncertainty of the first example differs from that of the last two examples; it arises from the "exogenous" market factors (i.e., copper price) that the firm cannot control and lies "on" the projects. The flexibility associated with the uncertainty is called real options "on" the project [32]. This option is like financial options and can be valued through the option pricing theory such as the Black-Scholes Formula and the binomial option-pricing valuation.

Real Options "In" Projects

On the other hand, the last two examples create the options through the design of technical systems. This type of real options is called real options "in" projects. Unlike real options "on" projects, real options "in" projects exist in the systems design and require further technical understanding to obtain the option and special efforts to model feasible flexibilities within the system. A typical example of technical capability is repositioning of communication satellites [53].

4.2.4. Literature Review of Real Options

Built upon various characteristics of real options discussed above, this section provides with a literature review about how real options have been developed.

Dixit and Pindyck focused on the investment behaviors of firms and stressed their implications for industry dynamics and government policy [24]. They insisted on the importance of irreversibility of most investment decisions and the ongoing uncertainty under decision-making and recognized the option value of "waiting" to obtain better information.

Trigeorgis proposed a fundamental framework for assessing various types of options (Table 4-4) [54]. He explored the interactions of these options individually and in combination, proving that the combined value is not additive for interdependent options[55]. He also reviewed other real options models including growth options and staged approach [52].

Although the concept of real options has successfully introduced to many areas, it has been slow to extend to the engineering. de Neufville, Scholes, and Wang focused on the introduction of real options to engineering systems design and conceptualized that projects with flexibilities and consequent real options are categorized into two distinct ways: "on projects" and "in projects" [6].

Real options concern market uncertainty surrounding the project. Historically, various case studies of real options "on projects" has been developed, many of which concentrate on investments in natural resources on account of accessibility of market pricing data of the underlying asset associated with the project. Brennan and Schwartz referred to the effectiveness of long-term supply contracts through timing options in copper mining industry [56]. Siegel, Smith, and Paddock applied the options framework to assess offshore oil properties [57]. Kemma examined multiple types of options including timing, growth, and abandonment in oil and gas industries [58].

4.3. Decision Analysis for R&D Project Valuation

This section explores how the concept of options could be used for an R&D project. Before providing the methodology to value the price of flexibility, this thesis should identify two important risks that an R&D project potentially carries: project risks and market risks. After that, the section introduces decision analysis as a methodology to model the flexibility and to calculate its value by using a case example of the R&D project of new product development.

4.3.1. Risk Identification: Project Risks and Market Risks

Identifying all relevant investment risks associated with an R&D project is indispensable for designing the flexible systems. The investment risks are categorized into two different types: one concerns uncertainties associated with the project itself (project risks), whereas the other deals with uncertainties in the value of the product when it is put into the market (market risks) [32].

This classification is grounded on the CAPM theory that there are “endogenous” project-specific risks (project risks) that investors can remove through diversification of their portfolio and “exogenous” market-oriented risks (market risks) that they cannot eliminate. From a financial perspective, “endogenous” uncertainties can be diversifiable without correlating external market events and require no risk premium, while “exogenous” uncertainties affect the overall rise and drop of the underlying assets traded on the market exchanges [26]. From a standpoint of real options, project risks have nothing to do with the “exogenous” market outcomes and market risks may cause great variability in the future value resulting from market acceptance of new application technologies employed.

Project risks can be effectively dealt with by decision analysis, whereas market risks can be evaluated through options analysis. The decision tree analysis applies the risk-free discount rate to calculating the project value since the firms can diversify their investments so that unexpected losses in one project can be compensated by other plans. Representative examples of project risks are the probability of success (POS), the possibility of cost overruns, and the impact on the available market [32].

Market risks, on the other hand, cannot be hedged through portfolio diversification. As a typical example, petroleum production firms and the oil-drilling companies cannot protect themselves against a worldwide crash in the oil market. They are vulnerable to the market risk that the falling price of crude oil lowers their revenues. In this case, only options analysis can appropriately reflect these market risks.

4.3.2. "Options Thinking"

Although there may be cases where using the Black-Scholes formula or the option pricing theory is the best approach to value the project, Faulker pointed out the "counter-intuitiveness" of these methods as a tool for managerial decisions [50]. From the point of view of the project planners, he emphasized the implication of the options approach to formulate business and R&D strategy in a "visible and understandable" way [50]. He also stressed that the "mindset" of the option pricing theory, namely "options thinking," should be applied to the decision-making for R&D investments.

"Option thinking" allows us to recognize the option values of the project in a simple way [50]. This concept addresses how the additional value will be embedded in an uncertain environment and explains how firms can strategize the flexible designs of their project. The next sections explain how "option thinking" is applied to the valuation of flexibility in an R&D project by using decision analysis.

4.3.3. Decision Analysis

Although not strictly providing accurate values of options, decision analysis allows us to develop insights on real options and to approximate the value of flexibility. Faulkner addressed how decision analysis is applicable for "options thinking" valuation [50]. Decision analysis can be used to appraise projects in engineering systems design. Ramirez evaluated the infrastructure development projects for water supply systems through a comparative analysis between the DCF method, decision analysis method, and the arbitrage-enforced pricing. She examined the theoretical pros and cons and concluded that real options analysis requires information that are usually not available for infrastructure assets regardless of its superiority in the pricing of flexibility [59].

Decision analysis is a conceptual device for enumerating each of the possible decisions; each of the possible outcomes may occur according to each of the events or states that may occur [60]. With a structured view of projects, decision analysis is an effective methodology for valuing potential projects whose outcomes are uncertain. Unlike a predetermined plan that commits to a pre-defined set of activities, this method recognizes that uncertainty resolution reveals what is most appropriate in subsequent stages and emphasizes the creation of valuable options and especially endogenous uncertainties in projects [60].

The decision tree represents the pattern of actions that one can take concerning a particular problem. The alternation of two elements comprises the decision tree; one is "decision nodes" that indicate the moments when possible decisions are considered, and the other is "chance nodes" that are periods coming after a decision in which outcomes are determined by prevailing events or states of nature [60]. It is easy to add more decision points and to increase the number of discrete outcomes considered. Figure 4-6 illustrates a decision tree that includes two decisions for an R&D project.

The analysis consists of calculating the expected value associated with each possible decision at the available decision nodes. Decision-makers can understand which decision is the best at each decision node.

Case Example: Decision Analysis and "Option Thinking" Application for R&D Project

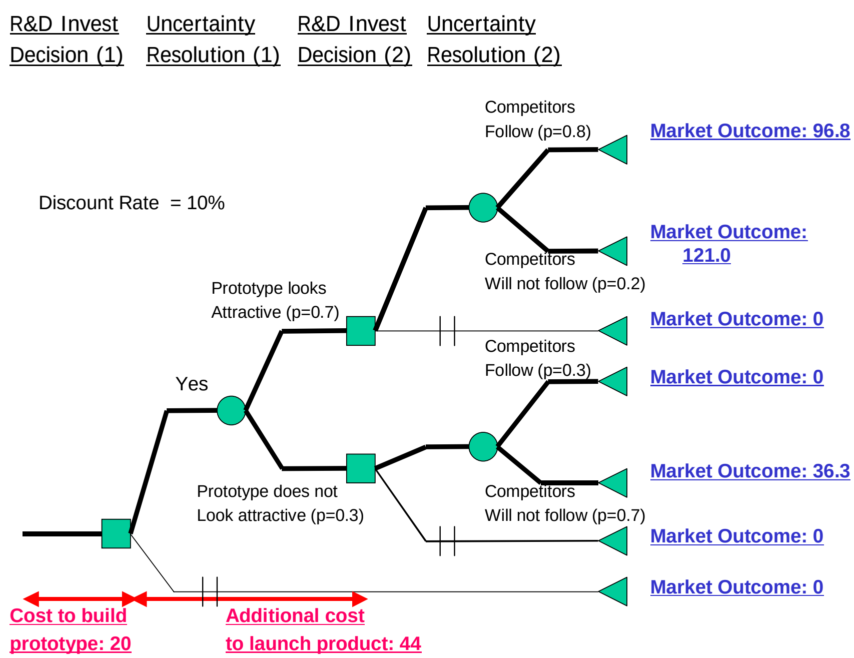
Decision analysis provides an "understandable" explanation for decision-makers [50]. Imagine that an R&D project attempts to develop a new product and put it into an emerging market. The first decision will be made after the prototype of the new product has been built, and the second occurs between initiation of product development and implementation of product launch. Squares represent "decision nodes," circles are "chance nodes," and triangles are "end-points." Figure 4-6 illustrates two principal uncertainties in the R&D model: the probability of success (POS) in the R&D project and the likelihood of the competitor's entry into the market. The project includes three discrete probabilities to model the project-oriented flexibilities; the first probability represents the probability that the new product looks attractive. The other two probabilities are the chances of the competitor's access to the market, which are conditional upon the result of the first stage.

In general, the conditional probability of an "attractive" outcome is expected to be higher than that of an "unattractive" outcome because introduction of the attractive product intensifies competition between firms [61].

If we decide to undertake this project, an initial investment of $20 million is required. One year later, the uncertainty associated with product development will be resolved; the better outcome is an "attractive" result with a chance of 70%, but there is still a 30% chance of the "unattractive" outcome. The R&D phase is followed by a one-year commercialization stage that requires an additional investment of $44 millions. In the "attractive" scenario, the chance of the competitors' entry into the market is 0.8, while this probability decreases to 0.3 in an "unattractive" scenario. In this example, Figure 4-6 represents the returns over the life of the product brought back to the date of introduction as NPV. The range of possible revenues varies from $ 0 to $ 121.0 million.

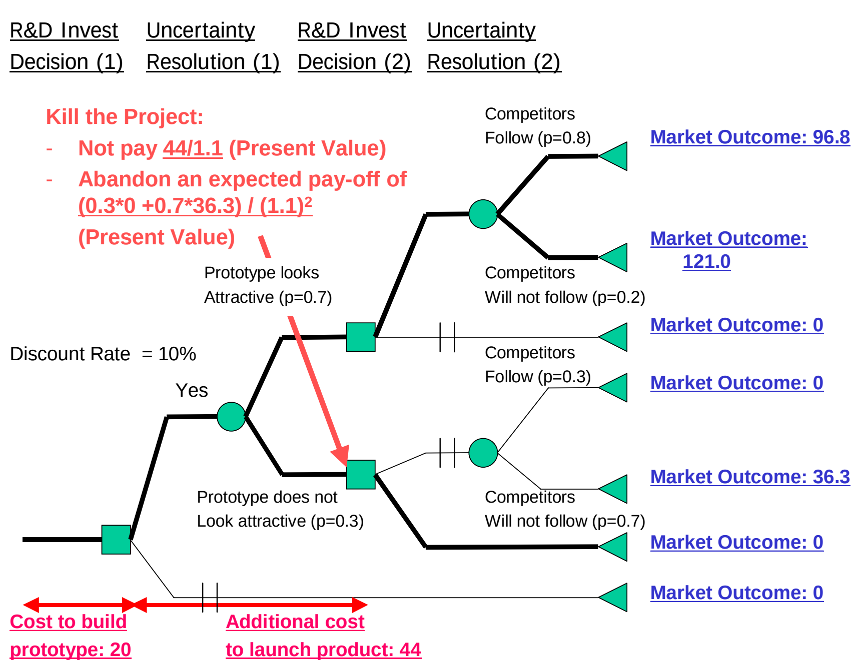
In the DCF method, although recognizing uncertainties associated with the project, the firm continues to put the product into market once making investments in R&D. The R&D project yields positive NPV of $5.1 million (Table 4-5), but the firm may hesitate to undertake the R&D project due to the low return on investment (ROI) (5.1/ 64 = 8.0%).

The "option thinking" analyst can explicitly identify the future managerial flexibility [50]. She does not need to make decisions of whether to launch the new product until recognizing the outcome of the R&D phase. In this case, immediately after realizing that the prototype looks "unattractive" and that the new product is not a profitable business, she can discontinue the project prior to the second stage of market penetration (Figure 4-7). In the "unattractive" scenario, although abandoning the expected payoffs, the firm avoid paying the additional investment of $44 million by skillfully killing the R&D project. This proactive action is an abandonment option. With this exercise of the option to abandon the R&D project, the firm can obtain an expected payoff of $10.8 million, which is $5.7 million higher than the original expected payoff (Table 4-5). The value of the abandonment option in this R&D project is $5.7 million.



Source: Modified based on Faulker [50] and Terwiesch [61]

Figure 4-6: Decision Tree for Sample R&D Project



Source: Modified based on Faulker [50] and Terwiesch [61]

Figure 4-7: Example of Exercise of the Abandonment Option in R&D Project

Table 4-5: Value of the R&D Project (DCF Method versus "Option Thinking" Valuation)

Valuation Method	Year 0	Year 1	Year 2	NPV
DCF Method	- 20.0	$-\frac{44.0}{1.1}$	$\frac{(0.7)*[(0.8)*96.8+(0.2)*121.0]+(0.3)*[(0.3)*0+(0.7)*36.3]}{1.1^2}$	$ 5.1M
"Option Thinking" Valuation	- 20.0	$(0.7)*-\frac{44.0}{1.1}$	$\frac{(0.7)*[(0.8)*96.8+(0.2)*121.0]}{1.1^2}$	$ 10.8M

4.3.4. Sensitivity Analysis for Decision Analysis

Decision analysis quantifies project risks by using the discrete probability so that it can calculate the value of the flexibility. The probability, however, sometimes comes from intuition, and hence may only be a rough estimation. Project analysts need to understand how far the change in the probability impacts on the NPV of the R&D project through sensitivity analysis against the discrete probability.

Estimating Discrete Probabilistic Outcomes

Quantifying uncertainties includes estimation of the discrete probabilistic outcomes and makes it difficult to value all projects including R&D. This aspect is sometimes criticized as a shortcoming of decision analysis. Despite this vulnerability, estimating the discrete probabilistic outcomes is indispensable for decision analysis. There are two ways to forecast the probabilities.

One approach is by interviewing with experts and taking average of probabilities they provide. Clemen, Robert, and Reilly introduced fundamental assessment techniques and provided references to additional resources [62]. Merkhofer presented a formalized procedure for measuring cumulative distributions [63]. Although this process has the advantage of capturing a specific decision-maker's beliefs about the likelihood of certain outcomes, it can be undermined by the facts that they do not reflect actualities and that subjective probabilities are hard to gauge with much precision.

The other method to estimate the discrete probabilistic outcomes is to use the historical probability from the similar R&D projects. Pharmaceutical industries where databases of many trials for new drug development estimate the probability of success in R&D and calculate the value of R&D projects [45].

Sensitivity Analysis

Forecasted discrete probabilities are considered subjective. The NPV of the project defined by decision analysis is vulnerable to these probabilities, since changes of the probability may result in a drastic change in the value of the project. One way to alleviate this weakness is to use sensitivity analysis.

In the R&D project case example illustrated in Figure 4-6, a change in the probability of success in the R&D stage shifts NPV as shown in Figure 4-8. This sensitivity analysis demonstrates that a threshold probability of the R&D project is 0.454. This figure provides an opportunity for intuitively making the decision of whether to kick off the project. If the probability of success is above this figure, it makes sense to initiate the project with positive NPV.

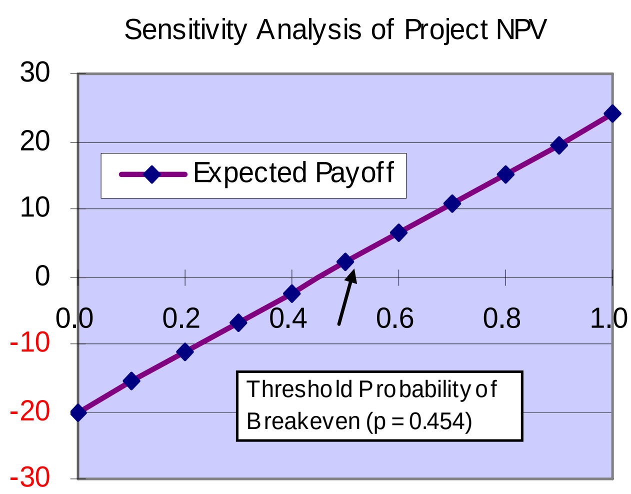


Figure 4-8: Sensitivity Analysis for Sample R&D Project (Probability of Success)

4.4. Hybrid Real Options Analysis

This section explains "hybrid real options" analysis developed by Neely [8]. It also discusses the "options lattice valuation" technique, which is necessary for calculating the value of the options resulting from market "exogenous" risks in "hybrid real options" analysis, provided that the project is expected to possess the significant chance to improve the NPV by exercising the option.

4.4.1. Characteristics

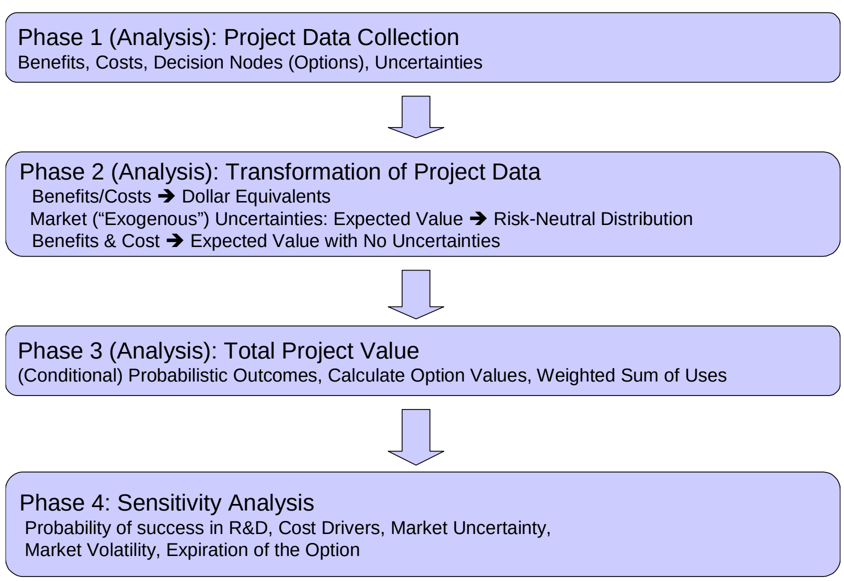
Decision analysis alone has the drawback that it is difficult to find the risk-adjusted discount rates and does not address the discount rate problem that plagues NPV [8]. To overcome this weakness, Smith and Rau proposed that a "full decision analysis," a methodology that added a utility function to the traditional decision analysis to model time and risk preferences, could produce similar outcomes to those of the real options methods [64]. They also extended the option pricing methods to markets with incomplete information. In his doctor dissertation, Neely developed "hybrid real options" analysis that combines the best features of decision analysis and real options analysis for a project with risky product development [8]. Amram and Kulatilaka applied this hybrid approach to investment strategy in pharmaceutical R&D programs [65].

"Hybrid real options" analysis combines the options methods appropriate for the market risks and decision analysis suitable for project risks and has a significant advantage in that it properly serves as a practical means to accurately value projects [51]. In this method, technical uncertainties inherent in the project are treated as "endogenous" risk and market uncertainties are dealt as "exogenous" risk. This approach is also suitable for valuing R&D because it allows results to treat both market risks and project risks without changing the discount rate [51].

In response to the previous efforts to value the project with various types of uncertainties, Borison observed strengths and weaknesses of the major proposed valuation methodologies, such real options and decision analysis and criticized the financial option-oriented methodologies, such as the replicating portfolio and the arbitrage-enforced pricing method, because these methods made so many restrictive assumptions that they could not treat a specific type of uncertainties [66]. He concluded that a hybrid approach modeled these two risks separately and would be appropriate to treat surrounding uncertainties comprehensively. In this sense, "hybrid real options" analysis skillfully incorporates these aspects into one framework so that there is no further commitment to change the discount rate even though the risk profiles of the project varies [51].

4.4.2. Hybrid Real Options Analysis

The overall valuation methodology basically consists of four phases: "project data collection," "transformation of the project data," "total project value," and the "sensitivity" analysis of the results [8][51]. Figure 4-9 illustrates a flow chart of "hybrid real options" methodology.



Source: Modified based on Neely [8]

Figure 4-9: Flow Chart of "Hybrid Real Options" Analysis

Phase 1: Analysis – "Project Data Collection"

Managers first gather the necessary data for valuing the project. In this process, the evaluator has to quantify the expected stream of benefits and costs during the project period and to specify uncertainties associated with the decision opportunities.

Phase 2: Analysis – "Transformation of Project Data"

They also need to develop data on the benefits and costs associated with the new project or product and to transform them into "monetary equivalents" [8]. Although those drivers are usually provided in financial terms such as the manufacturer's retail price, some are not directly financial ones.

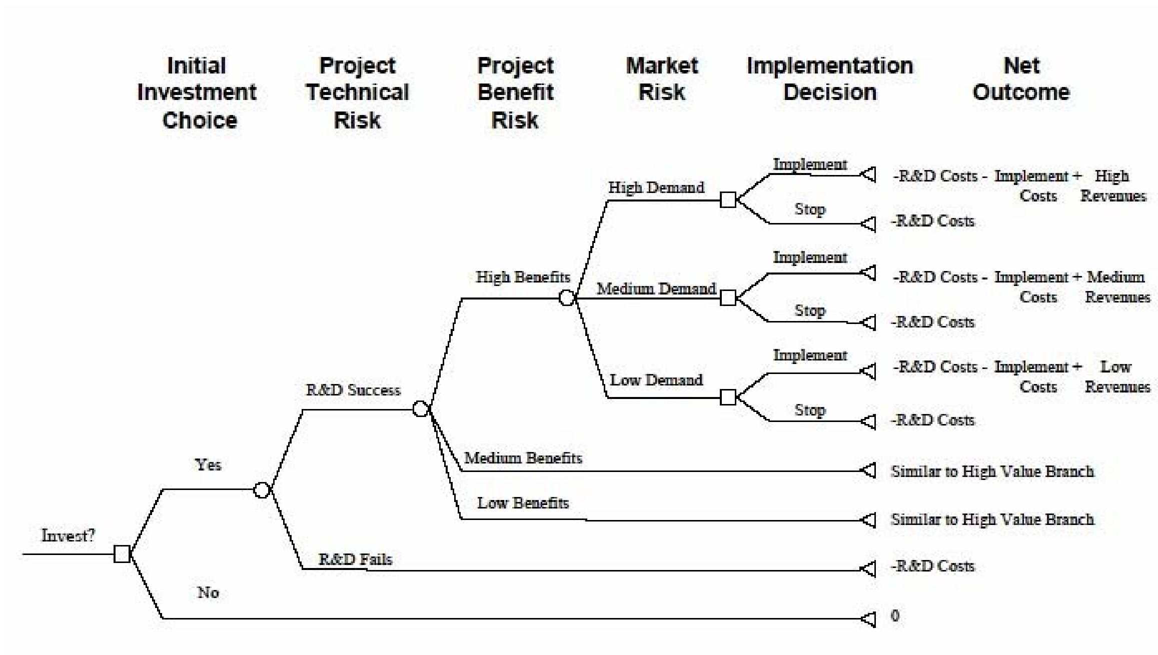
The next step is to quantify market risks and project risks. Quantifying market risks is more difficult than project risks [51]. The treatment of "exogenous" market risks varies with the valuation framework employed [8]. In "hybrid real options" analysis, formulating those risks consists of a two-step procedure: identifying the "priced factor" that affects the stream of cash flow and the project revenues and transforming this factor into the risk-neutral distribution. In other words, market risks would be evaluated based on the binomial lattice. The next section provides the detailed explanation of the way of making the binomial lattice for "hybrid real options" analysis. The result of the value in the binomial lattice will be adjusted for the market risk and discounted at the risk-free rate. Estimating project risks in "hybrid real options" analysis is similar to decision analysis. A typical example is the probability of success in R&D.

Phase 3: Total Project Value

They end up with the analysis by establishing the decision tree. These quantified risks in Phase 2 are put into one decision tree shown in Figure 4-10. The hybrid method combines decision analysis and options analysis to lead an overall accurate assessment of the value of flexibility in a proposed investment in a new project or product development [51]. Figure 4-10 illustrates "hybrid real options" analysis that identifies three uncertainties: technical, benefits, and market.

Phase 4: "Sensitivity Analysis"

Any valuation processes should incorporate a sensitivity analysis because the outcomes of real projects are based on many assumptions [51]. The scope of the sensitivity analysis for "hybrid real options" analysis ranges from the assumption on project risks to on market risks. The typical parameters that should be analyzed include the volatility of the market uncertainty factors, the probability of success of R&D, and the price of the new product.



Source: Neely and de Neufville [51]

Figure 4-10: "Hybrid Real Options" Valuation

4.4.3. Options Lattice Valuation

The options lattice valuation applies the binomial lattice. If the primary uncertainty arises from "exogenous" market risks, real options can be evaluated using option-pricing theory. This method is a one of the option-based valuation techniques suitable for the case where flexibility exists. In "hybrid real options" analysis, market risks can be evaluated through this method. The principle of this method is a multi-stage decision analysis based on the binomial option-pricing theory. The way of modeling the evolution of price in the binomial lattice is similar to financial options discussed in Chapter 4.1.

This method also allows managers to recognize a chance of exercising the option in the binomial lattice. For example, managers can abandon the project when the unfavorable outcome resulting from market risks occurs. Using the first case example that refers to a copper mine in Table 4-3, this section explains the options lattice valuation method and shows how to calculate the value of real options.

Case Example: Process of Lattice Valuation of Option in Copper Mine

Consider a copper mine producing 5,000 tons per year with the ore price of $5,000 per ton. The annual operation cost of the mine is the sum of $1 million and $2,200 times the amount of the copper in tons. The price of copper increases by 5% ± 10% (volatility) per year. Assume that the discount rate is 12%.

Step 1: Evolution of Price through Binomial Lattice

The project analysts first calibrate the parameters to set up the probability binomial lattice and the outcome lattice shown in Table 4-6 by using Equations 4-7 and 4-8:

$$u = e^{\nu\sqrt{\Delta T}} \quad = 1.10$$
$$d = e^{-\nu\sqrt{\Delta T}} = 1/u \quad = 0.91$$
$$p = \frac{1}{2}(1 + \frac{\nu}{\sigma}\sqrt{\Delta T}) \quad = 0.75$$

Table 4-6: Probability Lattice and Outcome Lattice of Case Example

Probability Lattice						
1.00	0.75	0.56	0.42	0.32	0.24	0.18
	0.25	0.38	0.42	0.42	0.40	0.36
		0.06	0.14	0.21	0.26	0.30
			0.02	0.05	0.09	0.13
				0.00	0.01	0.03
					0.00	0.00
						0.00
Outcome Lattice ($)						
2,000,000	2,210,342	2,442,806	2,699,718	2,983,649	3,297,443	3,644,238
	1,809,675	2,000,000	2,210,342	2,442,806	2,699,718	2,983,649
		1,637,462	1,809,675	2,000,000	2,210,342	2,442,806
			1,481,636	1,637,462	1,809,675	2,000,000
				1,340,640	1,481,636	1,637,462
					1,213,061	1,340,640
						1,097,623

Source: Modified based on de Neufville [49]

The next step is to obtain the revenue lattice of the copper mine. The revenue of the copper mine will be obtained through the following equation (Table 4-7, Equation 4-11):

$$[\text{Net Revenue}] = (\text{Production Amount}) * [(\text{Price}) - 2{,}200] - (\text{Fixed Cost})$$
$$= 5000\,(\text{price}-2200) - 1{,}000{,}000 \qquad \text{Equation 4-11}$$

Table 4-7: Revenue Lattice of Case Example

Revenue Lattice ($)						
-2,000,000	-948,291	214,028	1,498,588	2,918,247	4,487,213	6,221,188
	-2,951,626	-2,000,000	-948,291	214,028	1,498,588	2,918,247
		-3,812,692	-2,951,626	-2,000,000	-948,291	214,028
			-4,591,818	-3,812,692	-2,951,626	-2,000,000
				-5,296,800	-4,591,818	-3,812,692
					-5,934,693	-5,296,800
						-6,511,884

Source: de Neufville [49]

<u>Step 2: Decision to Exercise the Options at a Particular State</u>

In call-like real options, if the strike price is greater than the value of the "underlying," then exercise the option; otherwise, do not exercise the option. In this case, the option value is zero. Likewise, in put-like real options, if the strike price is smaller than the value of the "underlying," then exercise the option.

Managers can close the copper mine when they realize that it is not a profitable business. Therefore, this case is like a put option and "on" the system project. The criterion for exercising the option is whether the revenue in each state exceeds the fixed cost (i.e., $ 1 million). If a particular state satisfies this condition, the best choice for the firm is to exercise the option and to close the mine, which avoids larger losses resulting from falling prices and revenues.

Calculation of the option begins with the last period. In this case example, the values of the lower right lattice will change to the state illustrated in Table 4-8, because the firm decides to close the mine in this state. Simultaneously, the present value of closing the mine should be discounted over one year:

Table 4-8: Change of Values through Exercise of Options

From		→	To	
-5,934,693	-5,296,800		-5,934,693	-1,000,000
	-6,511,884			-1,000,000

Source: de Neufville [49]

$$\text{(Present Value)} = \frac{p*(-1{,}000{,}000)+(1-p)*(-1{,}000{,}000)}{1.12} = -892{,}857$$

In valuing the upper right lattice, they realize that keeping the mine open is the better choice and that they do not have to exercise the option to close the mine. In this case, the present value will be calculated in the following way:

$$\text{(Present Value)} = \frac{p*(6{,}221{,}188)+(1-p)*(2{,}918{,}247)}{1.12} = 4{,}817{,}369$$

The process ends up with adding the value of each state in the last year to the corresponding present value in the next year (Table 4-9).

Table 4-9: Present Value of the Project in the 5th Period

State at 5th	Present Value ($) from 6th	Sum
4,487,213	4,817,369	9,304,582
1,498,588	2,001,957	3,500,545
-948,291	-303,106	-1,251,397
-2,951,626	-892,857	-3,844,483
-4,591,818	-892,857	-5,484,675
-5,934,693	-892,857	-6,827,550

Source: Modified based on de Neufville [49]

Step 3: Calculating Recursively from the Last to the First

The next step is to calculate the value of all states from the right to the left. Throughout this process, they should choose the better choice, keeping mine open or exercising option. Working backward recursively from the last period, they can obtain the value of the project with the option (Table 4-10).

Table 4-10: Expected Payoff Lattice with Exercise of Options

Expected Payoff (with Real Option) ($)					
763,158	2,421,144	5,995,975	8,657,050	9,930,365	9,304,582
	-3,844,483	-2,892,857	-68,027	2,278,813	3,500,545
		-4,705,549	-3,844,483	-2,892,857	-1,251,397
			-5,484,675	-4,705,549	-3,844,483
				-6,189,657	-5,484,675
					-6,827,550

Source: Modified based on de Neufville [49]

Step 4: Calculating the Option Value

Providing that the firm does not exercise any options at each state in the binomial lattice, the upper left value of the binomial lattice in Table 4-11 represents the value of the project with no flexibilities ("Base Case"). In conclusion, the value of the real options in the copper case is 763,158 – (–398,112) = $ 1,161,270.

Table 4-11: Expected Payoff Lattice in Base Case

Expected Payoff (Base Case) ($)					
-398,112	2,155,929	5,941,522	8,657,050	9,930,365	9,304,582
	-8,251,327	-3,917,661	-311,976	2,278,813	3,500,545
		-11,989,676	-7,655,193	-3,985,748	-1,251,397
			-13,667,311	-9,114,736	-5,141,959
				-13,313,998	-8,327,281
					-10,935,203

Source: Modified based on de Neufville [49]

4.4.4. Conclusion of Valuation Methods for R&D

As a summary of the option-based valuation methods for R&D, this section provides a literature review about decision analysis and "hybrid real options" analysis and explains how these methods are appropriate for valuing an R&D project.

Few papers have explored implementing the concept of real options to investments in R&D prior to the 1990s. For instance, Grossman and Shapiro [67] addressed the financial characteristics of R&D programs and attempts to develop optimal timing models for investments. Mitchell and Hamilton [68] compared the R&D projects to a financial call option and proposed that real options model should be suitable for valuing an R&D project with high uncertainty. In this approach, benefits are the stock price of the underlying assets, implementation costs represent a strike price, and the implementation date indicates the expiration date of options.

Nichols addressed the implementation of financial options for R&D projects at Merck that utilizes real options analysis for prioritizing its pharmaceutical R&D [45]. Faulker applied decision analysis at Kodak to make the decision to continue the R&D program for developing the new film product [50]. In these studies, organizational characteristics influence which valuation framework to implement. Although these companies recognize that the options valuation is suitable for the flexible R&D strategy on the grounds that the traditional DCF method overlooks valuable features, Merck preferred real options models, while Kodak utilized decision analysis. Table 4-12 summarizes four major types of valuation approaches that this thesis focuses and their application examples [48].

Table 4-12: Summary of Various Valuation Approaches

		Real Options Valuation			
Projects	Decision Tree Analysis	Partial Differential Equation (PDE)	Binomial Tree (Binomial Lattice)	Simulation	Hybrid Real Options Model
Automobile R&D Portfolio (Neely and de Neufville, 2001)					X
Bogota Water Suuply Expansion (Ramirez, 2002)	X		X	X	
Merck (Nichols, 1994)			X		X
Kodak (Faulker, 1996)	X				

Source: Wang [48]

In conclusion, real options analysis is appropriate when “exogenous” market risks dominate uncertainties associated with investments, while decision analysis works well when “endogenous” project risks dominate [8]. Because the “hybrid real options” analysis has the advantages of both decision analysis and real option analysis, it can be appropriate for valuing the projects including an R&D project that are vulnerable to both project risks and market risks.

Based on the various valuation techniques, the next chapter analyzes the characteristics of investments in ITS R&D and deployment program and identifies why decision analysis and “hybrid real options” analysis are appropriate for evaluating the project of R&D and deployment of the ICAS.

Chapter 5 Valuation of Investments in Intelligent Transportation Systems

Designers of infrastructure systems understand that many of their estimates are "always" wrong as the volatility of social affairs, market trends, and public desires considerably affects demand for infrastructure services [6]. Given that the majority of the market will only adopt new technologies after "innovators" have tried and approved the technology [69], the uncertainty associated with investments in ITS is greater than that of conventional infrastructures because deploying ITS entails user acceptance of ITS technologies. Further, viewed as an alternative solution to traditional infrastructures to improve transportation safety and mobility and to enhance productivity, ITS provides a significant opportunity to design the flexible systems and make operations strategy for the ITS project planners.

Building on the previous two chapters that identified various valuation techniques including real options, this chapter discusses how these frameworks should be applied to evaluate the investments in ITS. To meet this objective, the chapter (1) focuses on the characteristics of ITS investments in comparison with those of the conventional infrastructures, (2) points out the uncertainties and flexibilities inherent in ITS investments, and (3) identifies why decision analysis and "hybrid real options" analysis are appropriate for evaluating the R&D and deployment of the ICAS.

5.1. Literature Review

Since ITS has been widely recognized as an effective solution for improving transportation networks, many papers explored the appropriate valuation methodology for ITS investments. Haynes, Arieira, Burhans, and Pandit identified the difference between financing in ITS and that in traditional infrastructures [70]. Bristow, Pearman and Shires suggested that, like the method to estimate the value of investments in conventional transport infrastructures, the method to value investments in ITS needed to be developed

[71]. However, after reviewing the current ITS valuation techniques, they concluded that valuation methods suitable for appraising ITS investments were not established. Comparing traditional road infrastructure investments and ITS investments, Leviäkangas proposed that there be many aspects for valuation techniques for ITS besides the traditional benefit cost analysis (BCA) [72]. Leviäkangas and Lähesmaa continued this research and proposed some recommendations for the use of the valuation techniques appropriate for evaluating the profitability of ITS investments including real options [7]. McConnell analyzed various characteristics of ITS services and applied the concepts of real options to ITS [73].

5.2. Characteristics of ITS Investments

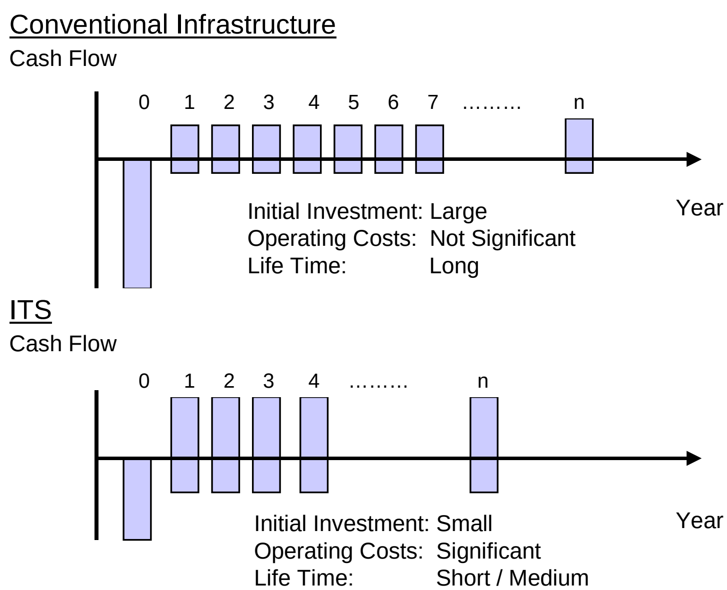
Haynes, Arieira, Burhans, and Pandit suggested that financing in ITS differs from that in conventional infrastructure for the following three reasons [70]:

1. Financing in ITS intends to improve the present traffic situation with greater participation of the private sector, whereas that in traditional infrastructure aims to provide the fundamental amenities to meet requests for social welfare under the "government-driven" provision.
2. ITS is oriented toward performance improvements through implementing innovative technologies, while the traditional infrastructure is grounded on the "already-known" technologies.
3. Introducing ITS contributes to improving the social environment including air pollution and public safety, which are "externalized" in the traditional transportation infrastructures.

These statements provide three important issues to assess the value of ITS investments: the risk-return profile, flexibility, and benefits/costs identification.

5.2.1. Risk-Return Profile

The profile of cash flows in investing ITS is radically different from that of traditional infrastructures (Figure 5-1). This figure demonstrates that conventional infrastructures characterizes heavy initial investments and consequent back-end loading of benefits with insignificant operating costs and requires a long time (e.g., 30 –50 years) to recover the costs, while ITS includes relatively small investments with significant annual operating costs. This disparity indicates that risk profiles for traditional infrastructure investments are different from those for ITS investments, requiring careful treatment for choosing the discount rate. The project planners must choose the appropriate discount rate according to the length of the project.



Source: Modified based on Leviäkangas and Lähesmaa [7] and Sussman [11]

Figure 5-1: Comparison between Investments in Conventional Infrastructures and ITS

Arrow and Lind focused on the risk and uncertainty in public investment decisions and concluded that risk adjustment of the discounting rate is necessary as long as the behavior of private organizations affect the uncertain benefits and costs associated with a particular project [74]. Little and Mirrlees demonstrated how the CAPM theory could be applied to the public-driven investments and derived an alterative project risk measure based on gross domestic product (GDP) instead of the market risk components β_{im} that indicates the sensitivity of the asset returns to overall market returns in CAPM (Equation 3-3 and Equation 3-4) [75]. Equation 5-1 describes the modified CAPM theory to appraise the public-oriented projects.

$$E(R_p) = R_s + \beta_s[E(R_{GDP}) - R_s]$$

$$= R_s + \frac{Cov(R_p, R_{GDP})}{Var(R_{GDP})}[E(R_{GDP}) - R_s] \qquad \text{Equation 5-1}$$

Where $E(R_p)$: Expected social return on the project
R_s : Minimum allowed social return on the projects
$E(R_{GDP})$: Expected growth of gross domestic product (GDP)
β_s : Social market risk components compared to GDP

This model, however, suggests some further discussion. Unlike the CAPM theory where the reference minimum rate can be chosen as the risk-free rate that is accessible from the U.S. Treasury or similar financial assets, the public investment decision has a burdensome problem. The minimum allowed social return (R_s), which is equivalent of the risk-free rate in the private-oriented investments, is ambiguous although the social return on a project is conceptually clear [7]. One solution to eliminate this vulnerability is to use the decided discount rate, which is 6% (annual basis) for the public-oriented projects in the United States [49]. Although this assumption can theoretically lead even to a negative discount rate in case of large β_s and lower R_{GDP} than R_s, this treatment stands provided that annual GDP growth might be less than 6% [75].

5.2.2. Flexibility of ITS Investments

Investments in ITS are characterized by the uncertainty involved in implementing new technologies, which traditional valuation methods cannot treat. This section first reviews the characteristics of these valuation methods for evaluating investments in conventional infrastructure.

In the United States, investments in roadways have been mainly evaluated using the benefit cost analysis (BCA), a widely used valuation method for estimating the value of the project in the transportation sector. Leviäkangas and Lähesmaa concluded that, despite an appropriate analysis for investments in the physical infrastructures, the BCA and the DCF method do not capture all the benefits and costs associated with the ITS project because they have some important defects as a valuation technique to capture the essentials of ITS investments and that "the option valuation techniques can recognize some of the ITS investment benefits" [7].

There are two reasons why these methods are not suitable for valuing financing in ITS. First, they treat the cash flows in such a deterministic manner that they overlook the flexible values the ITS investment will produce. Second, they cannot identify the risk-return profile. This defect cannot treat the modern investment theory that the higher the risks of the project, the higher the discount rate.

Consequently, the uncertainty associated with investments in ITS to pursue flexible systems design should be addressed. Table 5-1 identifies the behavioral pattern of investments in ITS and traditional infrastructure. We understand that the uncertainty of ITS investments can be categorized in project risks and the market risks, which is exactly same as many R&D programs.

Project risks concern the outcome of an R&D project for ITS technology. As discussed in Chapter 4, decision analysis captures this feature well and provides an opportunity to incorporate the flexibility in decision-making of ITS R&D.

The primary market risk of ITS technology is user acceptance discussed in Chapter 2. With better access to more advanced technology and applications, drivers get accustomed to various services provided by new communications technology in the automobile society [7]. On the other hand, ITS technologies as a method to solve the transportation environment are in the process of development. Given that many ITS technologies may not be fully accepted by the majority of driving users, deploying these ITS technologies carries the risk of user-acceptance. Real options analysis enables us to identify market risks associated with the market penetration of ITS technology.

Table 5-1: Comparative Behavioral Investment Pattern between Conventional Infrastructure and ITS

Risk Profile	Associated Impact	Conventioanl Infrastructure	ITS
Project Risk	R&D Outcome Technology Performance	Low (Risk-Averse)	High (Risk-Taker)
Market Risk	User Acceptance Market Penetration	Product-out, Demand-Driven Low (Risk-Averse)	Market-in High (Risk-Taker)
	Flexibility	Low	High

Source: Modified based on Leviäkangas and Lähesmaa [7]

"ITS as Real Options"

Project risks and market risks associated with investments in ITS provide a chance to design the flexible systems. This section provides a case example of real options of ITS and explores how real options can be applied to various ITS services.

Suppose a road authority is considering whether to expand the traditional infrastructure or to deploy ITS components such ATIS and ATMS (Chapter 2) with a view to alleviating the current severe traffic congestion. In this case, the planners possess the "option to wait" because they can defer infrastructure investments in the ITS capabilities until gathering additional information on the future transportation systems. Carefully reviewing the flexible characteristics of ITS investments as an alternative tool for traditional transportation infrastructure investments, McConnell is applying the concepts of real options tabulated in Table 4-4 concept to the ITS investments (Table 5-2) [73].

Table 5-2: Examples of Real Options in ITS

Option Types	ITS Example
Wait	The use of ITS capabilities to defer infrastructure investments until additional information is gathered on future transportation system conditions.
Abandon	End of service for most types of ITS capabilities is possible and is easier to accomplish than with fixed infrastructure. For example, ending service to customers is simple, compared with removing infrastructure.
Expand / Contract	Variable Message Signs can be used to expand the types of information available to travelers or Electronic Toll Collection technologies can have their use expanded upon, first as dedicated ETC and then to help monitor congestion.
Growth	ITS infrastructure, such as embedded roadside sensors, can be invested in during routine construction, before there is an identified need for full ITS capabilities. This can result in new capabilities being added at a later date.
Switch	ITS capabilities, such as cameras, can be switched between functions. In a normal state, they can be used to observe traffic flows and identify traffic accidents, though their functionality could be switched to incorporate the cameras into a security system in the event of terrorist threats.
Compound	ITS capabilities that enhance user operations can be deployed sequentially – GPS onto trucks first, then tracking equipment, then two way communications, then real time scheduling capabilities, etc.

Source: McConnell [73]

5.2.3. Benefits and Costs Identification

Estimating benefits and costs related to the ICAS program is not simple. The benefits and costs of developing and deploying the ICAS cannot be directly estimated through a simple calculation, such as the product of the number of sales of DSRC and its retail selling price (RSP). The benefit of the ICAS comes from the economic benefit by preventing crashes at the intersection. Since reducing collisions at the intersection has wide-ranging effects, such as saving healthcare costs, it is necessary to analyze the economic benefit corresponding to automobile crashes at the intersection. The cost of the ICAS includes R&D expenses for developing DSRC, deployment of the infrastructure capabilities, and the operation cost of the ICAS.

5.3. Appropriate Valuation Methods for R&D and Deployment of ITS

This thesis demonstrates that investments in R&D and deployment for ITS involve market risks and project risks. Market risks mainly come from user acceptance of ITS technology. Project risks primarily result from the probability of success in R&D or the accuracy of ITS technology. Given that the project of developing and deploying the ICAS includes R&D and deployment of ITS telecommunication technologies, decision analysis and "hybrid real options" analysis are the best methodologies to evaluate the value of the project. These methods allow the ITS project planners to make the flexible R&D strategy and systems design.

5.4. Conclusion

In conclusion, this chapter identifies the characteristics of ITS investments in comparison with traditional infrastructures and demonstrates that investments in ITS involve market risks and project risks and that the project of developing and deploying the ICAS also involves these risks. Decision analysis and the "hybrid real options" analysis can be regarded as the most appropriate method to assess the ICAS project because they can incorporate all relevant risks associated with the project into the valuation.

The next chapter applies these proposed methodologies to the ICAS case example and calculates and compares the NPV of the two conflicting concepts of the ICAS program.

Chapter 6 Project Valuation

The previous chapters have demonstrated the appropriateness of decision analysis and "hybrid real options" analysis as a tool for evaluating R&D and deployment for ITS. This chapter applies these techniques to the cases; in particular, it estimates the project value of two counterpart ICAS concepts: the "infrastructure-autonomous" ICAS (Concept 1) and "vehicle-based" ICAS (Concept 3). As discussed before, decision analysis does not deal appropriately with market "exogenous risks," whereas "hybrid real options" analysis can do both market "exogenous" risks and project "endogenous" risks. Given that the process of decision analysis is included under that of "hybrid real options" analysis, this chapter explains the valuation of two concepts in accordance with "hybrid real options" analysis illustrated in Figure 4-9.

6.1. Project Data Collection

First, project analysts should collect the necessary data for valuation by specifying uncertainties associated with the project and quantifying the stream of benefits and costs throughout the project.

6.1.1. Identifying Uncertainties

Table 6-1 identifies potential risks inherent in the R&D and deployment project for the ICAS. Two principal uncertainties, the technical effectiveness for the ICAS and the probability of success in the R&D stage, comprise project risks. The degree of market penetration of the OBU and RSU and the demand growth fluctuation associated with market expansion are primary market risks. This section attempts to quantify these uncertainties.

Table 6-1: Project Risks and Market Risks of the Intersection Collision Avoidance Systems

Risk Profile	Uncertainties	Quantification Methods	Data Source
Project Risks	* Technical Effectiveness ("Systems Effectiveness")	* Evaluation Model developed by private industry	* Previous test data
	* Success/failure of R&D for new products	* Determine discrete probability * Decision Tree	* Expert Opinion
Market Risks	* Market Penetration of DSRC (OBU/RSU)	* Product diffusion model ("Bass Model," S-shape function)	* Historical diffusion data of similar products
	* Demand Growth Fluctuation	* Binomial Option-Pricing Valuation Method * Regression model	* # of automobile sales per year * GDP Growth

Project Risk 1: Technical Effectiveness – "System Effectiveness"

To assess effectiveness for the ICAS, the USDOT has established a framework that compares the number of crashes that occur in the current traffic environment and utilizes relevant performance data to evaluate the number of collisions prevented through introduction of the systems [4]. This framework can be quantifiable by identifying "System Effectiveness," which is given by the prevented relevant crashes divided by the total number of intersection automobile collisions. This parameter depends on reliability of communication technology in DSRC components such as the ability to detect objects and frequency bands. Although the "Systems Effectiveness" for the ICAS is scheduled to be determined based on the coming field operational tests (FOT) under the CICAS Program, it is possible to estimate this parameter from the previous large-scale FOT conducted by the USDOT and Veridian Engineering [4].

To estimate "systems effectiveness," it is necessary to analyze the causal factors of four crash scenarios tabulated in Table 2-1, because the ICAS brings about a different level of effectiveness for each crash scenario. Unfortunately, however, we cannot directly determine the "Systems Effectiveness" by analyzing individual scenarios, because DSRC consists of three major components with a different level of accuracy of measurement: "Threat Detection System" (Sensor/ Radar), "Global Positioning System (GPS)," and

"Signal Controller Interface" (Figure 6-1). Instead, we can estimate the "system effectiveness" from the accuracy of these three components examined in the previous FOT.

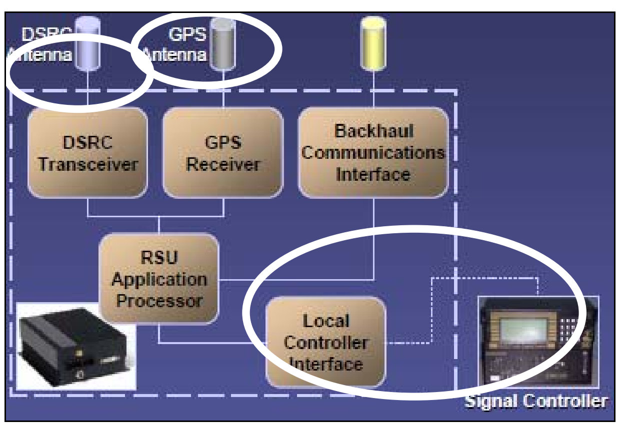
For example, in Scenario 3 (Perpendicular Path – Violation of Traffic Control) that accounts 43.9 % of all intersection collisions, 23.3% of causes derive from the function of the Signal Controller Interface and 20.6% do from the GPS. Table 6-2 describes the relationship between crash scenarios and three DSRC components. The previous FOT concluded that the accuracy of three devices is 80.0%, 90.0%, and 75.0%, respectively [4]. In other words, provided that the CICAS initiative successfully develops the product, we assume that 80% of crashes in Scenario 1 (Left Turn Across Path) will be prevented through DSRC.

Calculating a weighted sum of individual scenario is appropriate for estimating the total "Systems Effectiveness" [4]. Equation 6-1 represents how to do this for the ICAS.

$$\text{"System Effectiveness"} = \sum_{i}^{4} (p_i * Effectiveness_{Scenario\_i}) \qquad \text{Equation 6-1}$$

Where p_i : the intersection crash population in Scenario i ($i = 1 - 4$)

Effectiveness $_{\text{Scenario } i}$: the ICAS "system effectiveness" in Scenario i



Source: "VII System Architecture," *Proceedings (Presentation) of VII Public Meeting* [76]

Figure 6-1: Three Major DSRC Components

Table 6-2: Relation between Crash Scenarios and Corresponding DSRC Components

	Scenario Description	Population	DSRC Components	
1	Left Turn Across Path	23.8%	Threat Detection System (Sensor) 23.8%	
2	Perpendicular Path - Inadequate Gap	30.2%	Threat Detection System (Sensor) 30.2%	
3	Perpendicular Path - Violation of Traffic Control	43.9%	Signal Controler Interface 23.3%	GIS/GPS 20.6%
4	Premature Intersection Entry	2.1%	Signal Controler Interface 2.1%	
	Total	100.0%		

Source: Modified based on Pierowicz, Jocoy, Lloyd, Bittner, and Pirson [4]

R&D Difficulty

Without fully successful R&D, there will be deterioration of the "systems effectiveness." Out of two R&D areas associated with crash prevention at intersections, "gap acceptance" is more difficult than "signal violation" (Chapter 2). With this information, we can postulate that the R&D program may yield three possible outcomes:

1. "Success," the R&D program will address both R&D areas
2. "Medium Success," the R&D program will only solve "signal violation" area
3. "Failure" that implies the CICAS initiative will forgo deployment and product launch of DSRC.

Based on Equation 6-1 and Table 6-2, the "System Effectiveness" can be estimated in Table 6-3. This value, however, is not a perfect figure, because effectiveness of the ICAS on the actual intersections will differ from that in the laboratory. Therefore, these figures should be evaluated through sensitivity analysis discussed in Chapter 6.4.

"Success" Scenario

23.8%*80% + 30.2%*80% + (23.3%*75% + 20.6%*90%) + 2.1%*75% = 80.8%

"Medium Success" Scenario

(23.3%*75% + 20.6%*90%) + 2.1%*75% = 37.6%

Table 6-3: "System Effectiveness" of Individual Crash Scenario

	Scenario Description/ Population	Which part of DSRC Components does work ?		"System Effectiveness"	R&D Result		
					"Success"	"Medium Success"	"Failure"
1	Left Turn Across Path 23.8%	Threat Detection System (Sensor) 23.8%		23.8% * 80% = 19.04%	X		
2	Perpendicular Path - Inadequate Gap 30.2%	Threat Detection System (Sensor) 30.2%		30.2% * 80% = 24.16%	X		
3	Perpendicular Path - Violation of Traffic Control 43.9%	Signal Controler Interface 23.3%	GIS/GPS 20.6%	23.3%*75%+20.6*90%= 36.02%	X	X	
4	Premature Intersection Entry 2.1%	Signal Controler Interface 2.1%		2.1%*75%= 1.58%	X	X	

Project Risk 2: Probability of Success (POS)

Although CAMP expects that they have little chance of addressing the "gap acceptance" R&D area until 2009, telecommunication technologies employed for DSRC development rely on the existing technology. In other words, it is highly likely that R&D achieves either "Success" or "Medium Success." With this information, the probability of success (POS) in each R&D scenario can be estimated in Table 6-4.

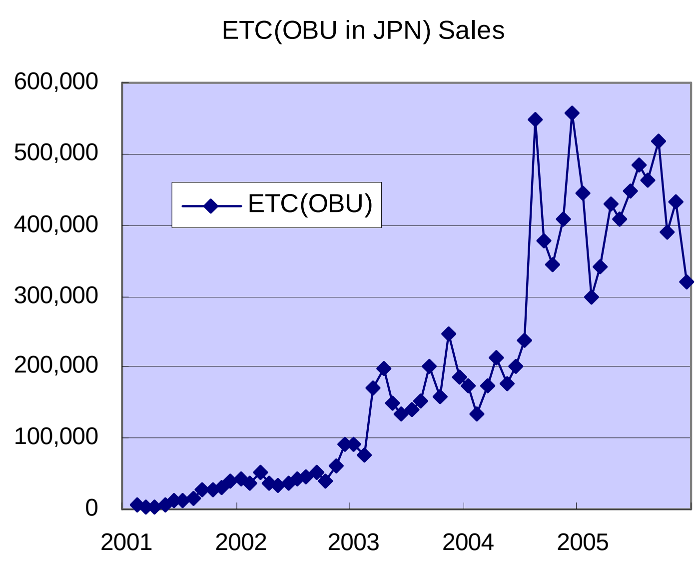
Table 6-4: Probability of Success and "Systems Effectiveness" for Each R&D Scenario

R&D Scenario	Prob. of Success (POS)	"Systems Effectiveness"
Success	30.0%	80.8%
Medium Success	60.0%	37.6%
Failure	10.0%	0.0%

Market Risk 1: Market Penetration of DSRC

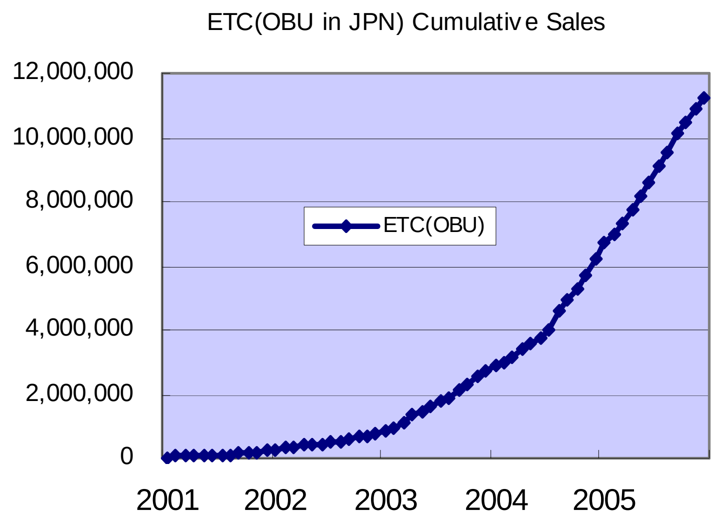
There are two types of product/service diffusions in deploying the ICAS systems: the market penetration of the OBU as in-vehicle equipment and the diffusion of the RSU embedded in the intersection. Although predicting the demand for DSRC is difficult because of no historical data for the new generic classes of products, we assume that the diffusion pattern of similar products can be applied to forecast the growth model of deployment.

The diffusion pattern of the OBU utilized for electronic toll collection (ETC), an in-vehicle telecommunication product, better reflects the diffusion pattern of the OBU in that the tollgate converses with passing vehicles through the radio-frequency band. Figures 6-2 and 6-3 describe the sale growth pattern and the cumulative sales of on-board ETC units in Japan. Likewise, the infrastructure components of ITS services deployed under supervision of the USDOT can reflect the diffusion pattern of the RSU.



Source: Modified based on Road Bureau, Ministry of Land Use and Infrastructure [77]. Last accessed on April 13, 2006

Figure 6-2: Sales Growth Pattern of the OBU for ETC in Japan (2001 – 2006)



Source: Modified based on Road Bureau, Ministry of Land Use and Infrastructure [77]. Last accessed on April 13, 2006

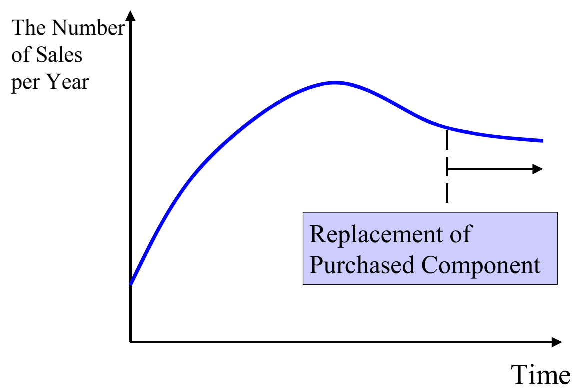
Figure 6-3: Cumulative Sales of the OBU for ETC in Japan (2001 – 2006)

Product Diffusion Model – The "Bass Model"

The demand for DSRC is difficult to forecast since there are no historical data for the new generic classes of products. However, a growth model that concentrates on the timing of the initial purchase of new products was developed to help estimate the degree of diffusion. Fourt and Woodlock [78], Haines [79], and others proposed growth models of the expected sales growth of new products.

Bass paid attention to the "timing of initial purchase" and proposed a growth model called "Bass Model" [80] for new products by applying the theory of adoption and diffusion of new technologies or new products in a social system [81]. Bass tested this model empirically against data for consumer durables and demonstrated that the "Bass Model" well predicts the sales peak and the timing of the peak.

The proposed model assumes that sales grow to a peak and then level off at some lower level than peak. Mathematically, it formulates that the sales increases exponentially and then decrease toward an asymptotic steady state, represented by the replacement of purchased component (Figure 6-4).   In case of the OBU, it will be installed in a new automobile and its sales will also level off in accordance with the replacement of the car.



Source: Modified based on Bass [80]

Figure 6-4: Growth of a New Product with Some Asymptote

The literature has taught us that customers are classified into five categories, each of which tends to adopt innovative technology at a different rate, defined as "the diffusion process" [82].   This framework helps expect the diffusion pattern of products put into the market. The five categories are shown as below:

1. "Innovators" – are willing to experience new technology
2. "Early Adopters" – will adopt since they have special problems to solve
3. "Early Majority" – will adopt once an innovation is considered mainstream
4. "Late Majority" – will adopt late due to their preference of risk aversion
5. "Laggards" – may never adopt the innovation

There are two fundamental notions in this theory; one is, "apart from innovators, adopters are influenced in the timing of adoption by the pressures of the social system, the pressure increasing for late adopters with the number of previous adopters," and the other is that potential purchasers are categorized based on the "diffusion process" [80].

To formulate the theory mathematically, Bass aggregated the four groups other than "innovators" and defined them as "imitators" and translated these concepts into the "Bass Model," which describes that "the probability of purchases of new product at time t is a linear function of the number of previous buyers, given that no purchase has been made" (Equation 6-2) [80]. In this equation, the product $(q/m)Y(t)$ represents the pressures operating on "imitators" as the number of previous purchasers is increasing.

$$P(t) = p + (q/m)Y(t) \qquad \text{Equation 6-2}$$

Where P(t): Probability of an initial purchase of the new product at time t

Y(t): The number of previous purchasers and Y(0) = 0

m: Total number of purchases during the period for the density function was made until time t

p: Constant coefficient of "innovators" that represents the probability of an initial purchase at t = 0

q: Constant coefficient of "imitators"

Equation 6-3 defines f(t) as the probability of purchases at time t and F(t) as the diffusion rate of the new product.

$$\frac{f(t)}{1-F(t)} = p + (q/m)Y(t) = p + qF(t) \qquad \text{Equation 6-3}$$

Where $F(t) = \int_0^t f(s)ds, F(0) = 0$

Given that S(t) is the number of sales at time t, Equation 6-3 translates into the formulas shown in Equation 6-4.

$$S(t) = pm + (q-p)Y(t) - (q/m)[Y(t)]^2$$

$$= \frac{m(p+q)^2}{p} \frac{\exp\{-(p+q)t\}}{[(q/p)*\exp\{-(p+q)t\}+1]^2}$$

$$f(t) = \frac{(p+q)^2}{p} \frac{\exp\{-(p+q)t\}}{[(q/p)*\exp\{-(p+q)t\}+1]^2} \qquad \text{Equation 6-4}$$

The next step is to estimate the parameters p and q. This is done the regression analysis using the historical data of diffusion rate for similar products. Bass did by using Equation 6-5. Compared with Equation 6-4, a, b, and c correspond to pm, $q-p$, and $(-q/m)$.

$$S_t = a + bY_{t-1} + cY_{t-1}^2 \qquad \text{Equation 6-5}$$

Table 6-5 and Figure 6-5 provide the result of the regression analysis about the quarterly sale diffusion of the OBU of ETC in Japan. This model suggests that the peak of sales of the OBU occur 5.38 (= 21.54/4) years after the product launch and that the coefficients of "innovators" and "imitators" are 0.0036 and 0.17725, respectively. Based on Equation 6-4 and the results shown in Figure 6-5, Equation 6-6 estimates the number of sales the OBU.

$$\begin{aligned} S(t) &= pm' + (q-p)Y(t) - (q/m')[Y(t)]^2 \\ &= \frac{m'(p+q)^2}{p} \frac{\exp\{-(p+q)t\}}{[(q/p)*\exp\{-(p+q)t\}+1]^2} \\ &= 9.09m' \frac{\exp\{-0.181t\}}{[49.20*\exp(-0.181t)+1]^2} \qquad \text{Equation 6-6} \end{aligned}$$

Where m': The number of the vehicles of the targeted market segment

t: Time from the year of product launch of the OBU

Table 6-5: Regression Result of the OBU for ETC in Japan (2001 – 2006)

Regression Results				
Period Covered	a (10^3)	b	c (10^-7)	R-Square
2001 - 2006	42.916	0.286	-0.1488	0.930
Product Data				
Cumulative Sale m (10^3)	Innovators p	Imitators q	q/p	Predicted Sales Peak Time T* (Quarterly Basis)
11,912	0.0036	0.17725	49.20	21.54

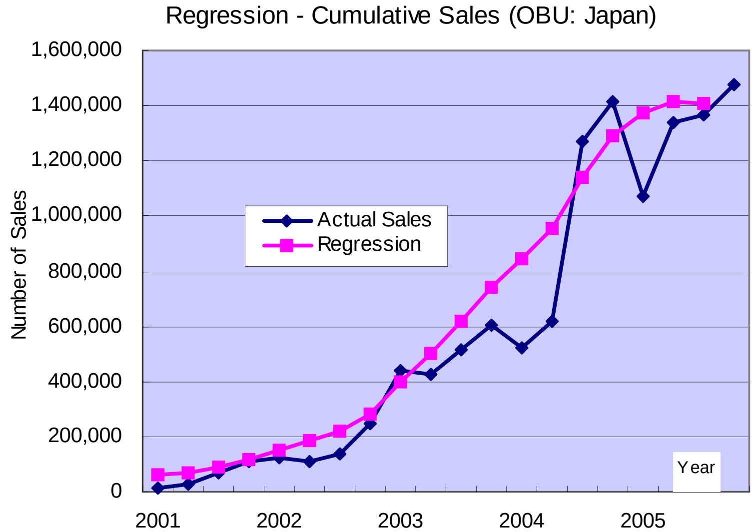
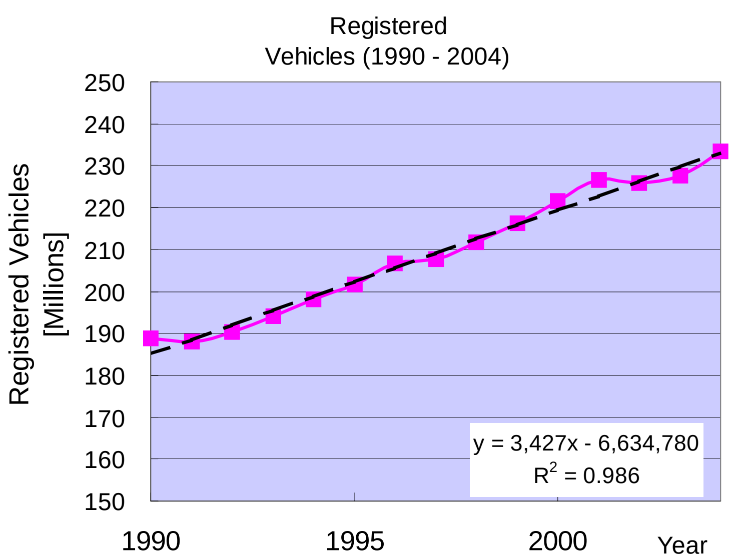


Figure 6-5: Regression Result (the OBU for ETC in Japan: Quarterly Basis)

The number of registered vehicles changes every year (Figure 6-6). Based on the regression result, Equation 6-7 estimates the future number of registered vehicles in the United States in each year.



Source: U.S. Department of Transportation, Federal Highway Administration [83]
Last accessed on April 23, 2006

Figure 6-6: The Number of Registered Vehicles in the United States (1990 – 2004)

$R_T = 3{,}427 * T - 6{,}634{,}780$ Equation 6-7

Where R_T: The total number of registered vehicles in Year T

Market Penetration for the OBU

Next, we must identify the number of potential purchasers of the OBU. We can assume that the diffusion pattern of the OBU is subject to the “Bass Model” and that the OBU will be installed in the new automobiles. In other words, provided that the OBU achieves 100% market penetration, all new automobiles produced a year will equip the OBU. The OBU, however, is not likely to be perfectly accepted by all drivers. In such a situation, drafting the appropriate marketing strategy is necessary to maximize the total social benefits resulting from the ICAS systems. With a good marketing strategy for product development, firms can focus on the targeted market segment to attain good sales of the product.

This strategy is available for in-vehicle equipment. A typical example is “LoJack,” a successful product developed by LoJack Corporation. “LoJack” is a hidden radio-transmitter device used for retrieving stolen vehicles and helps prevent automobile thefts in cities and districts [84]. Some drivers, however, do not feel the necessity of purchasing the product. Their behavior is supported by the fact that “LoJack” achieves higher sales in cities with the higher crime rate [85]. In other words, the focused market segment supports the higher sales and user acceptance.

The VII program, however, regards DSRC as a promising product that will provide a variety of innovative services such as mobility applications and commercial benefits as well as the safety improvements with which we are concerned in this thesis. It believes that DSRC has great potential to achieve near-universal market penetration and wide user acceptance. In this regard, it is possible that the future driving environment will bring about standardization of DSRC for all vehicles.

Based on these two possibilities for the diffusion of DSRC, we prepare two possible patterns for product diffusion: the "Fast Diffusion" and "Slow Diffusion." The "Fast Diffusion" scenario assumes that the OBU will attain 100% ultimate market penetration, while the "Slow Diffusion" scenario presumes that the saturation rate of the OBU is only 40%. Given the announcement provided by the CICAS program and the VII initiative, we can assume that the diffusion of the OBU will start from 2010, one year after from the final decision of product launch by the CICAS Program. Figure 6-7 represents the possible diffusion pattern of the OBU for new cars by using Equations 6-6 and 6-7.

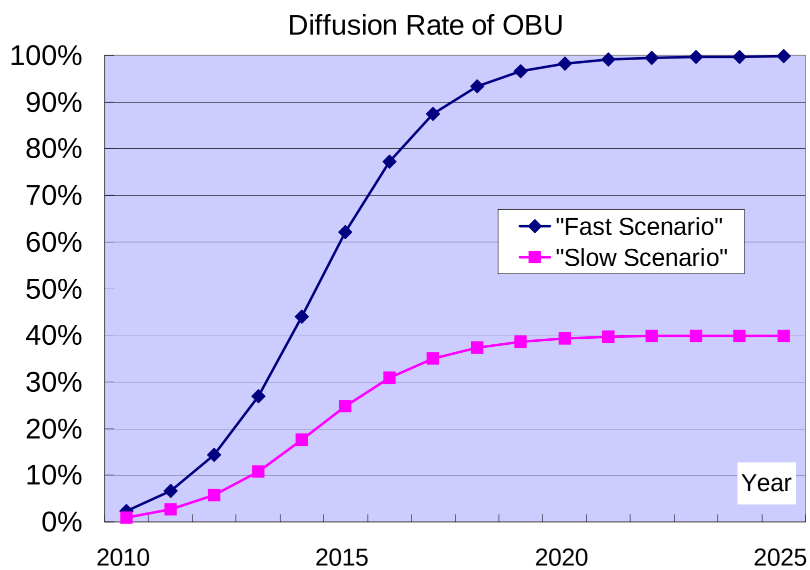


Figure 6-7: Diffusion Scenarios of the OBU in the New Automobile Market

Even though the OBU achieves 100% market penetration for new automobiles, many of the cars with original sales will be retired. Registered vehicles consist of the existing vehicles on the roadways and new automobiles. Given that the OBU will be installed in new automobiles, its diffusion rate in the entire automobile environment will be below that in the new automobile market. Equation 6-8 provides the relation between the number of registered vehicles in the previous year and that of newly appeared automobiles on the basis that vehicles retire form the fleet linear over an assumed life of 13 years. Note that the number of newly registered vehicles reflects the market segment of the OBU.

$$R_T = \frac{12}{13} R_{T-1} + N_T \qquad \text{Equation 6-8}$$

Where N_T: The number of newly registered vehicles in Year T

With the assumption for the future number of registered vehicle in Equation 6-7, N_T can be described with a simple linear function (Equation 6-9).

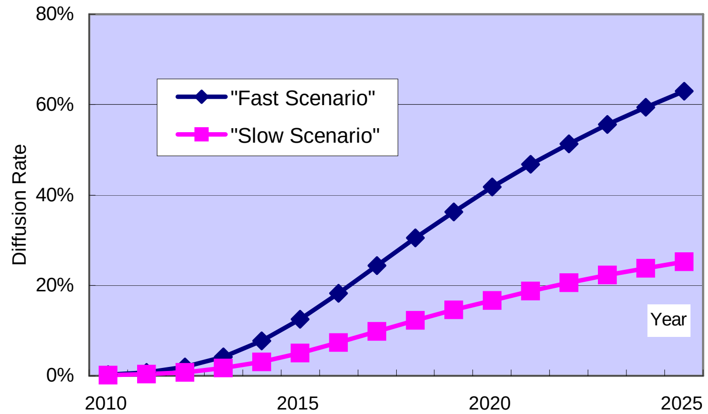
$$N_T = R_T - \frac{12}{13} R_{T-1} = (3{,}427T - 6{,}634{,}780) - \frac{12}{13}\{(3{,}427(T-1) - 6{,}634{,}780\}$$

$$= 263.6T - 507{,}204 \qquad \text{Equation 6-9}$$

The number of vehicles with the OBU is the sum of the existing registered vehicles with the OBU installed in the previous years and a portion of the new automobiles with the OBU equipped in accordance with the "Bass model." Mathematically, Equation 6-10 provides the total number of the vehicles with the OBU. Figure 6-8 illustrates the diffusion rate of the OBU in the entire automobile environment.

$$D_T = \sum_{i=T-13}^{T} \left(\frac{12}{13}\right)^{t-i} f(i) N_i \quad (\text{For, } i = \text{T-13 to T}) \qquad \text{Equation 6-10}$$

Where D_T: The number of the vehicles with the OBU in the entire automobile Environment



			"Fast Scenario"				"Slow Scenario"			
Year T	Total Vehicles R(T) (Thousands)	New Vehicles N(T) (Thousands)	Bass Model f(T)	New OBU	Cumulative OBU D(T)	Diffusion Rate	Bass Model f(T)	New OBU	Cumulative OBU D(T)	Diffusion Rate
2010	253,740	22,682	2%	510	510	0.2%	1%	204	204	0.1%
2011	257,168	22,946	7%	1,510	1,981	0.8%	3%	604	793	0.3%
2012	260,595	23,209	14%	3,343	5,172	2.0%	6%	1,337	2,069	0.8%
2013	264,022	23,473	27%	6,338	11,112	4.2%	11%	2,535	4,445	1.7%
2014	267,449	23,737	44%	10,440	20,697	7.7%	18%	4,176	8,279	3.1%
2015	270,876	24,000	62%	14,909	34,014	12.6%	25%	5,963	13,605	5.0%
2016	274,303	24,264	77%	18,741	50,139	18.3%	31%	7,497	20,055	7.3%
2017	277,730	24,527	87%	21,451	67,733	24.4%	35%	8,581	27,093	9.8%
2018	281,157	24,791	93%	23,161	85,683	30.5%	37%	9,264	34,273	12.2%
2019	284,585	25,055	97%	24,206	103,298	36.3%	39%	9,682	41,319	14.5%
2020	288,012	25,318	98%	24,871	120,223	41.7%	39%	9,949	48,089	16.7%
2021	291,439	25,582	99%	25,337	136,312	46.8%	40%	10,135	54,525	18.7%
2022	294,866	25,846	99%	25,700	151,527	51.4%	40%	10,280	60,611	20.6%
2023	298,293	26,109	100%	26,013	165,884	55.6%	40%	10,405	66,354	22.2%
2024	301,720	26,373	100%	26,300	179,424	59.5%	40%	10,520	71,770	23.8%
2025	305,147	26,636	100%	26,576	192,198	63.0%	40%	10,630	76,879	25.2%

Figure 6-8: Diffusion Pattern of the OBU

Next, correlation between the outcome of the R&D stage and the market penetration of the OBU should be defined as a discrete probability. Assuming that it is highly probable that success in developing the OBU at the R&D stage will result in fast market penetration, Table 6-6 provides the correlation matrix.

Table 6-6: Correlation Matrix between the R&D Stage and the Market Penetration of the OBU

R&D/ Penetration	"Fast" Penetration	"Slow"Penetration
"Success" Scenario	80%	20%
"Medium Success" Scenario	20%	80%

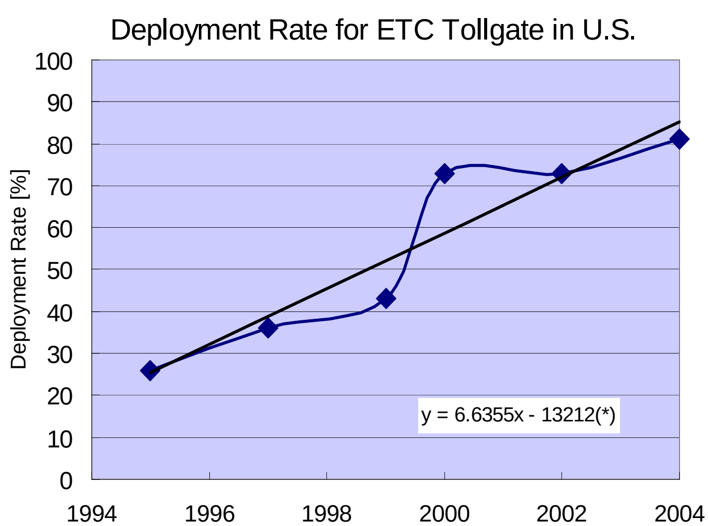
Diffusion Pattern of the RSU

The "Bass Model" cannot be applied to the growth model of deployment executed by the public sector because the behavior of the public sector toward deployment is different from the "diffusion pattern" applied to the private sector. However, we can apply historical deployment data of ITS deployment to estimate the deployment pattern of the RSU. Figure 6-9 illustrates the historical deployment rate of ITS services by the government (ETC Tollgate) in the United States. Equation 6-11 shows the regression result, which will be directly applied to the forecasted model for deployment of the RSU.

$$y = 6.6355x - 13{,}212 \quad (R^2 = 0.88) \qquad \text{Equation 6-11}$$

Where x: Year
y: Deployment rate in percentage

This result indicates that the public sector will deploy the RSU in annual increment of 6.64%. We also assume that the public sector reaches the 100% diffusion rate of the RSU. The diffusion rate of the RSU should be analyzed based on the sensitivity analysis discussed in Chapter 6.4.



Source: ITS Joint Program Office [86]. Last accessed on April 23, 2006
Note: Regressed by Author

Figure 6-9: Deployment Pattern of ITS Services in the United States

Market Risk 2: Demand Growth Fluctuation

This section provides the method of formulating the market uncertainties into the "hybrid real options" analysis.

For the DCF method and decisions analysis, Equation 6-7 represents the model for estimating the number of registered vehicles at the time T. For the "hybrid real option" analysis, Neely formulated the market uncertainty by introducing a regression model that correlated production with the stock price of an automobile manufacturer to estimate the value of R&D portfolios in an automobile manufacturer [8].

In case of R&D and deployment of the ICAS, the sales growth and market penetration of the OBU are vulnerable to the "exogenous" market uncertainty. The primary market risk associated with the market penetration of the OBU is fluctuation in the number of registered vehicles equipping the OBU and users' willingness to buy the OBU. Chapter 5 addresses the modified CAPM theory [75] for the public-driven investment, which suggests that the social market risk compared to GDP should be chosen in place of the asset beta (Equation 5-1). Consequently, the market uncertainty for the "hybrid real options" analysis can be described as the regression model that correlates the number of registered vehicles and GDP. Equation 6-12 formulates the relationship between the number of vehicles and GDP.

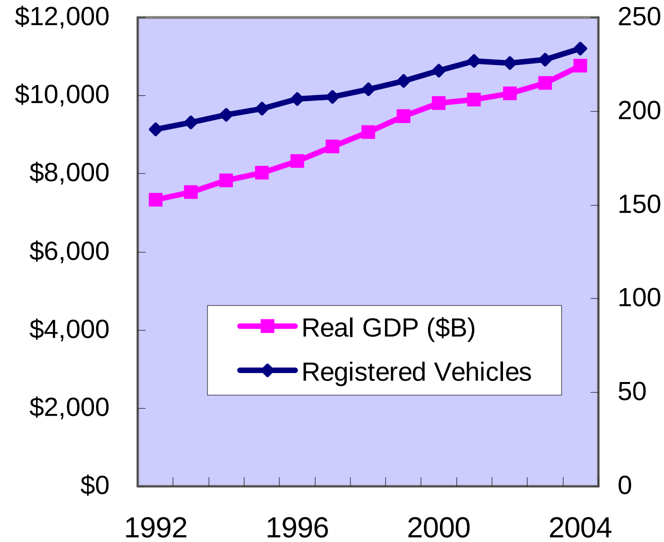
$$R[T] = A' + B' * GDP[T] \qquad \text{Equation 6-12}$$

Where $GDP[T]$: Real GDP at Year T

A', B' : Regression Parameters

Figure 6-10 presents data on the registered vehicles and the real GDP based on 2000.

Year	Registered Vehicles (Millions)	Real GDP ($B in 2000)
	X	Y
1992	190.36	$7,337
1993	194.06	$7,533
1994	198.05	$7,836
1995	201.53	$8,032
1996	206.57	$8,329
1997	207.75	$8,704
1998	211.62	$9,067
1999	216.31	$9,470
2000	221.48	$9,817
2001	226.65	$9,891
2002	225.77	$10,049
2003	227.48	$10,321
2004	233.27	$10,756



Source: Federal Highway Administration [83]. Last accessed on April 23, 2006
Johnston and Williamson [87]. Last accessed on May 6, 2006

Figure 6-10: The Number of Registered Vehicles and GDP in U.S. (1992 – 2004)

Figure 6-11 provides the regression result between two resources based on Equation 6-12.

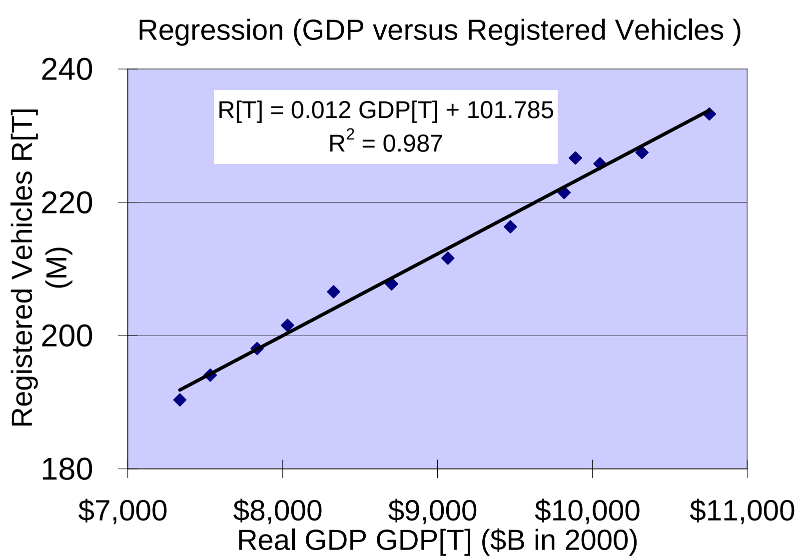


Figure 6-11: Regression between GDP and Number of Registered Vehicles

Equations 6-13 and 6-14 provide the method for calculating the growth rate and volatility of GDP. Based on this method, the range of growth rate of GDP is 1.38% ± 0.487%.

GDP Growth Rate for "Hybrid Real Options" Methodology ($\overline{GDP}$)

$$= \frac{\sum_{T}^{N-1} \frac{Log(GDP[T+1])}{Log(GDP[T])}}{N-1}, \text{ (T = 1992 to 2004, N = 13)} \qquad \text{Equation 6-13}$$

GDP Volatility for "Hybrid Real Options" Methodology

$$= \sqrt{\sum_{T}^{N} \{\overline{GDP} - \frac{Log(GDP[T+1])}{Log(GDP[T])}\}^2 / (N-1)} \qquad \text{Equation 6-14}$$

6.1.2. Estimating the Economic Benefit

The next step is to determine the economic benefit of preventing an automobile crash. According to NHTSA, the total economic cost for automobile vehicles crashes in the United States in year 2000 was $ 230.6 billion, which represents the present value of lifetime costs for 41,821 fatalities, 5.3 million non-fatal injuries, and over 27.5 million damaged vehicles[8] [1]. We cannot directly estimate the benefits and costs from the ICAS in financial terms because the primary benefit result from reducing collisions at intersections, which can have wide-ranging effects such as diminishing healthcare costs.

Table 6-7 tabulates the total economic cost that consists of two major cost drivers: "injury components (medical, emergency services, market productivity, household productivity, insurance administration, and legal costs)" and "non-injury components (property damage and travel delay)."

Table 6-7 divides the total economic cost into three accident types: "property damage," "injury," and "fatality." It indicates that the economic cost of the accidents per fatality is $40,868 million, which is equivalent to $977,208 (= $40,868 million / 41,821) per victim. Likewise, the economic cost per damaged vehicle is $189,700 million ($6,885 per vehicle).

[8] This figure includes the "property damage only" vehicles in which nobody was injured, which are not reported to the NHTSA's "Traffic Safety Facts" [2]

Table 6-7: Total Economic Costs of Automotive Crashes, 2000

	Property Damage	Injury	Subtotal	Fatality	Total	Note
# Vehicles	23,631,696	3,919,807	27,551,503			
# Victims				41,821		
Injury Components						
Medical	0	31,698	31,698	924	32,622	$M
Emergency Services	733	685	1,418	35	1,453	$M
Market Productivity	0	36,002	36,002	24,989	60,991	$M
Household Productivity	1,111	11,030	12,141	8,010	20,151	$M
Insurance Administraion	2,741	10,874	13,615	1,552	15,167	$M
Workplace Cost	1,208	2,900	4,108	364	4,472	$M
Legal Costs	0	6,846	6,846	4,272	11,118	$M
Subtotal	**5,793**	**100,124**	**105,917**	**40,056**	145,973	**$M**
Non-injury Components						
Travel Delay	18,976	6,201	25,177	383	25,560	$M
Property Damage	35,069	23,537	58,606	430	59,036	$M
Subtotal	**54,046**	**29,737**	**83,783**	**812**	**84,595**	**$M**
Total	**59,938**	**129,762**	**189,700**	**40,868**	**230,568**	**$M**
Economic Cost per vehicle			**6,885**			**$/Vehicle**
Economic Cost per fatality				**977,208**		**$/Fatality**

Source: Modified based on Blincoe [1]

Note: "Property Damage Only" accidents are crashes involved vehicles in which nobody was injured. All injury vehicles, including those involved in injury crashes, are included under "Property Damage Only" vehicles.

6.1.3. R&D, Deployment, and Operating Costs

We must identify three types of costs to evaluate the projects: R&D expenses, deployment costs, and operating costs. First, we postulate that the R&D expense from 2007 to 2009 is $ 20.0 million.

Next, we must determine the cost for deployment and operation of the ICAS. Table 6-8 shows the framework for calculating investments in deployment of the systems. The cost of deploying the ICAS includes the retail selling price (RSP) of the capabilities of infrastructure and relevant engineering cost. For components necessary for the ICAS with no price data, the price of manufacturing prototype for the previous operational tests is applied [20]. Table 6-9 tabulates costs per intersection necessary for implementing and operating the ICAS: "Infrastructure-autonomous system" (Concept 1) and the "Vehicle-based systems" (Concept 3). This table does not address the price data concerning in-vehicle components, since the private industry will promote market penetration for these products to encourage driving users to purchase them. It is important to note that the "Infrastructure-autonomous system" (Concept 1) costs much more to construct than the "Vehicle-based systems" (Concept 3).

Table 6-8: Framework of Calculating Costs

Factors	
Deployment Costs	The number of intersections deployed * Total cost of deploying RSUs at Intersections
Operating Costs	Operating Costs

Table 6-9: Implementation and Operating Costs for Two ICAS Concepts

Components for Intersection	Infrastructure-autonomous System (Concept 1)	Vehicle-based System (Concept 3)	Note
Roadside Unit (RSU)	2,200	2,200	**1
Driver Infrastructure Interface (DVI)	8,000	N/A	**1
Traffic Controller Cabinet	5,000	1,000	**2
VORAD radar systems	16,500	N/A	**3
Pedestrian Sensors	500	500	
Construction	10,000	2,000	**2
Deployment Cost ($ per intersection)	**42,200**	**5,700**	
Operating Cost ($ per Intersection)	**5,000**	**1,000**	

Note: (**1) Source: "Cooperative Intersection Collision Avoidance Initiative," *Proceedings of CICAS Workshop* [20]
(**2) Price varies with which location makes decisions for warning, intersection or vehicles
(**3) Source: Blincoe, etc. [1]

6.2. Transformation of Project Data

This section transforms the data of benefits, costs, and identified uncertainties into "monetary equivalents" [8]. Table 6-10 illustrates the framework of estimating the total benefits through introduction of the ICAS with the associated relevant uncertainties and their appropriate formulation methods. It estimates the total project benefits by subdividing them into individual elements. Equations 6-15 and 6-16 indicate how to calculate the economic benefits and number of collisions prevented through introducing the ICAS.

Table 6-10: Framework of Estimating Benefits of the Intersection Collision Avoidance Systems

Factors				Uncertainty	Formulation
Economic Benefits	The Number of Collisions Prevented by Introducting ICAS *	The number of Intersection Collisions *			
		The Probability that the ICAS functions "Efficiency Factor" *	Linear Function of Deployment Rate of RSUs		"Pareto Distribution"
					Linear Regression (RSUs)
		System Performance "Systems Effectiveness" *		Technology Uncertainty (Systems Accuracy)	Weighted Sum of Crash Scenarios
		Accumulated Sales of OBU *	Diffusion Rate of OBU *	Market Peneration	"Bass Model"
			The Number of Registered Vehicles *		
			Market Growth Factor	Market Uncertainty (Automobile Market Expansion)	Regression & Risk-Neutral Probability
	Economic Benefits of Accidents per Automobile	Economic Cost to Society			

*: Multiplication

<u>Economic Benefits</u>

= (The Number of Collisions Prevented through Introduction of ICAS) *

(Economic Benefits of Accidents per Automobile) Equation 6-15

<u>The Number of Collisions Prevented through Introduction of ICAS</u>

= (The number of Intersection Collision)

* (The probability that the ICAS systems function: “Efficiency Factor”)

* (System Performance: “Systems Effectiveness”)

* (Accumulated Sales of the OBU) Equation 6-16

Efficiency of the Intersection Collision Avoidance Systems – "Pareto Distribution"

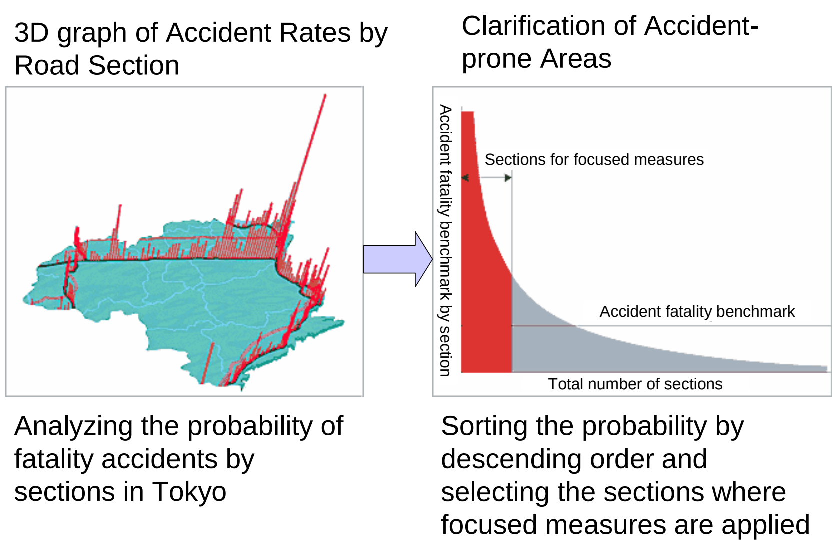
Most of the factors in these equations can be directly obtained by gathering relevant data. It is necessary, however, to formulate the probability that the ICAS function, namely "Efficiency Factor," to measure how partial deployment of the ICAS will contribute to decrease in the number of deaths at the intersection (Equation 6-16). In a practical way, it can be assumed that "Efficiency Factor" is subject to the Pareto distribution.

Grounded on a power law probability distribution found in a large number of real-world situations, the Pareto distribution, named after the Italian economist Vilfredo Pareto, is applicable for to many situations in which an equilibrium is found in the distribution of the "small" to the "large". Pareto originally used this distribution to describe the allocation of wealth among individuals. The idea is sometimes expressed more simply as the "Pareto principle" or the "80-20 rule," which describes that 20% of the population possesses 80% of the wealth. In the mathematical way, the "probability" or fraction of the population $f(x)$ that owns a small amount of wealth per person (x) is rather high, and then decreases steadily as wealth increases. This distribution is not limited to describing wealth or income distribution but applied to multiple academic fields including natural science and social science. The examples of the areas where the Pareto distribution is applicable are:

- The value of oil reserves in oil fields (a few large fields, many small fields)
- The length distribution in jobs assigned supercomputers (a few large ones, many small ones)
- The standardized price returns on individual stocks
- Size of sand particles

The Pareto-distribution can be also applied to the transportation safety field. A typical example of demonstrating the "Pareto Principle," is accidents on highways occurring at specific locations; Ministry of Land Infrastructure and Transport of Japan (MLIT) demonstrated that 53% of accidents occur at only 6% of sections on highways in Japan [88]. MLIT is currently carrying out intensive traffic accident measures with Public Safety

Commissions for about 4,000 locations where the probability of occurring fatalities and casualty accidents at a designated section is high ("Accident Black Spots")[9] to promote safety measures on highways efficiently and effectively. Analyzing the probability of fatality accidents by sections and sorting this number by descending order and selecting the sections where the focused measures are applied, MLIT showed that the probability of fatalities and casualty accidents is approximately Pareto-distributed (Figure 6-12).



Source: Modified based on Road Bureau, Ministry of Land Infrastructure and Transport [89]

Figure 6-12: Analysis of Fatality and Casualty Accidents in Japan

<u>Formulation of "Efficiency Factor" through Pareto Distribution</u>

We can assume that the probability of occurrence of accidents at an intersection is subject to the "Pareto principle" or "80-20 rule." In other words, 80% of intersection-related collisions happen at 20% of the most problematic intersections. The assumption helps estimate how the deployment of the RSU prevents relevant accidents. The next step is to formulate the relationship between the deployment of the RSU and the "Efficiency Factor."

[9] MLIT selected "Accident Black Spots" under the condition that the ratio of fatalities and casualty accidents of these places is five times more than that of average artery roadways.

Given that a "random" variable has a Pareto distribution, Equation 6-17 gives the probability that X is greater than some number x. If this distribution is used to model the distribution of wealth, then the parameter *k* is called the Pareto index.

$$P(X > x) = 1 - (\frac{x}{x_m})^{-k} \qquad \text{Equation 6-17}$$

for all $x \geq x_m$,

Where x_m: Minimum possible value of *X* (Necessary positive)
k: Positive parameter.

The continuous Pareto probability density function (PDF) and the cumulative density function (CDF) are given by Equations 6-18 and 6-19:

$$\text{PDF:} \quad f(x : k, x_m) = k\frac{x_m^k}{x^{k+1}}, \text{ for } \quad x \geq x_m \qquad \text{Equation 6-18}$$

$$\text{CDF:} \quad F(x; k, x_m) = 1 - (\frac{x}{x_m})^{-k}, \text{ for } \quad x \geq x_m \qquad \text{Equation 6-19}$$

The USDOT has historically deployed ITS components other than the ICAS to reduce the number of automobile crashes. An example of deployed ITS component currently is "Signalized Intersections with Dilemma Zone Protection." [10] The U.S. government chooses about 152,600 locations where fatal accidents frequently occur as a spot for this countermeasure. Provided that the public sector begins deploying the countermeasure from the most problematic intersection, the Pareto distribution implies that completion of deploying 152,600 intersections will prevent 80% of intersection accidents. Based on the assumption, "Efficiency Factor" can be determined through Equation 6-20. Figure 6-13 illustrates the "Efficiency Factor" of the ICAS.

$$\text{Efficiency Factor} \ = 1 - (\frac{1}{R})^{0.35} \qquad \text{Equation 6-20}$$

Where R: Deployment Rate of the RSU in percentage

[10] This device located at a signalized intersection serves the singular purpose of informing the controller that a vehicle is present on a particular approach to an intersection at any point in time.

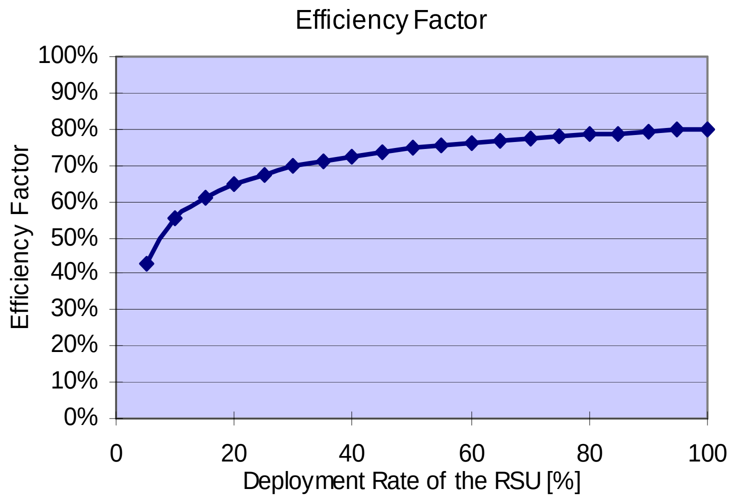


Figure 6-13: Efficient Factor

Transformation into Risk-Neutral Distribution

For only the “hybrid real options” analysis, market uncertainties should be transformed into risk-neutral quantities to obtain the binomial lattice by using Equations 4-7 and 4-8. Before setting up the binomial lattice, the discount rate, the period length of the binomial lattice, and the length of the project must be provided:

- Discount Rate = 6% (equal to the annual risk-free rate)
- Period Length of the Binomial Lattice (T) = 1 Year
- Length of the Project = 20 Years (2007 – 2026)

Equations 6-14 and 6-15 provide parameters necessary for obtaining the binomial lattice:

- GDP Growth rate (ν) = 1.38%, GDP Volatility (σ) = 0.487%

$$u = e^{\sigma\sqrt{\Delta T}} \quad = \quad e^{0.00487} \quad = 1.005$$

$$d = e^{-\sigma\sqrt{\Delta T}} = 1/u \quad = 0.995$$

$$p = \frac{1}{2}(1 + \frac{\nu}{\sigma}\sqrt{\Delta T}) \quad = \quad \frac{1}{2}(1 + \frac{0.00487}{0.0138}\sqrt{1}) \quad = 0.676$$

6.3. Total Project Value

With the assumptions discussed above, the analysts can build up the spreadsheet to calculate the value of the "infrastructure-autonomous" systems (Concept 1) and "vehicle-based" systems (Concept 3). Recall the following characteristics of the two conflicting concepts:

"Infrastructure-Autonomous" ICAS (Concept 1)

- Does not need any market penetration of the OBU
- Requires instead large initial investments in infrastructure components
- 100% of vehicles will obtain the social benefit from this concept

"Vehicle-Based" ICAS (Concept 3)

- Its value is vulnerable to the degree of market penetration of the OBU
- Does not require great initial investments in infrastructure
- Only vehicles equipped with the OBU can enjoy the benefits from this concept

6.3.1. Decision Analysis

Given that the R&D program continues and invests $20 million per year until the development of the product for the ICAS, the pay-off in the "failure" R&D scenario equals to the perpetuity value of annual $20 million at the discount rate of 6% (Equation 6-21):

$$\text{Payoff in the "Failure"} = -\frac{0.02}{0.06} = -0.33 \text{ (\$ Billion)} \qquad \text{Equation 6-21}$$

Tables 6-11 and 6-12 demonstrate the spreadsheet for calculating NPV of Concepts 1 and 3 through decision analysis. Table 6-13 summarizes the results of project value of the two concepts defined by decision analysis.

The results demonstrate that NPV of the "infrastructure-autonomous" ICAS (Concept 1) is greater than that of "vehicle-based" ICAS (Concept 3) even in the "Fast" market penetration scenario and that Concept 1 is a more promising system for preventing crashes and saving lives although Concept 1 requires large initial investments in constructing the ICAS. The reasons are that it takes long time for the vehicles with the OBU to be widely deployed in all roadways in Concept 3 and that the diffusion of the OBU in Concept 3 cannot keep up with the social benefit that Concept 1 produces. The results show that NPV of Concept 3 will decrease as user acceptance of the OBU decreases. In other words, user acceptance of the OBU is the most significant factor for future success in Concept 3. This is due to the important feature of the innovative technology and product that the majority of the market will only adopt new technologies after "innovators" approved them [69].

Table 6-11: Spreadsheet for Valuation of Concept 1 (Decision Analysis)

			Data Source
System Effectiveness:	**80.80%**		U.S. DOT Business Plan
OBU Market Penetration Rate	**100.00%**		Assumption
RSU Market Penetration Rate	**100.00%**		Assumption
Fatality	**9,500**		NHTSA Traffic Facts (2004)
Accident	**1,300,000**		NHTSA Traffic Facts (2004)
Social Benefit (Fatality):	$977,208	per Crash	NHTSA Report (Blincoe, 2002)
Social Benefit (Crash):	$6,885	per Crash	NHTSA Report (Blincoe, 2002)
Deployment Cost:	$42,200		CICAS Workshop Report
Operating Cost:	$5,000		Assumption
Targeted Intersections:	152,600		ITS Joint Program Office
R&D Expenses:	$20,000,000	(Year 07-09)	ITS Joint Program Office

								Rf:	6.0%
T	Year	Registered Vehicle (Thousands)		Penetration Rate (RSU)	Efficiency Factor	**Benefits ($M)**	**Costs ($M)**	**PV ($M)**	Discount Factor
1	2007	243,209		0.0%	0.0%	**0.00**	**20.00**	**-20.00**	0.94
2	2008	246,636		0.0%	0.0%	**0.00**	**20.00**	**-20.00**	0.89
3	2009	250,063		0.0%	0.0%	**0.00**	**20.00**	**-20.00**	0.84
4	2010	253,490		6.4%	47.9%	**454.42**	**463.86**	**-9.44**	0.79
5	2011	256,917		12.9%	59.1%	**1,121.84**	**512.99**	**608.85**	0.75
6	2012	260,344		19.3%	64.5%	**1,836.71**	**562.13**	**1,274.58**	0.70
7	2013	263,771		25.8%	67.9%	**2,577.91**	**611.27**	**1,966.64**	0.67
8	2014	267,198		32.2%	70.3%	**3,336.70**	**660.40**	**2,676.30**	0.63
9	2015	270,625		38.6%	72.2%	**4,108.44**	**709.54**	**3,398.90**	0.59
10	2016	274,052		45.1%	73.6%	**4,890.27**	**758.68**	**4,131.59**	0.56
11	2017	277,479		51.5%	74.8%	**5,680.28**	**807.82**	**4,872.46**	0.53
12	2018	280,906		58.0%	75.9%	**6,477.10**	**856.95**	**5,620.15**	0.50
13	2019	284,333		64.4%	76.7%	**7,279.73**	**906.09**	**6,373.64**	0.47
14	2020	287,760		70.8%	77.5%	**8,087.40**	**955.23**	**7,132.18**	0.44
15	2021	291,187		77.3%	78.2%	**8,899.50**	**1,004.36**	**7,895.14**	0.42
16	2022	294,614		83.7%	78.8%	**9,715.53**	**1,053.50**	**8,662.03**	0.39
17	2023	298,041		90.2%	79.3%	**10,535.10**	**1,102.64**	**9,432.46**	0.37
18	2024	301,468		96.6%	79.8%	**11,357.86**	**1,151.78**	**10,206.08**	0.35
19	2025	304,895		100.0%	80.0%	**11,793.42**	**981.95**	**10,811.47**	0.33
20	2026	308,322		100.0%	80.0%	**11,793.42**	**763.00**	**11,030.42**	0.31
							NPV @6.0%	**40,896.40**	

Table 6-12: Spreadsheet for Valuation of Concept 3 (Decision Analysis)

			Data Source
System Effectiveness:	80.80%		U.S. DOT Business Plan
OBU Market Penetration Rate	100.00%		Assumption
RSU Market Penetration Rate	100.00%		Assumption
Fatality	9,500		NHTSA Traffic Facts (2004)
Accident	1,300,000		NHTSA Traffic Facts (2004)
Social Benefit (Fatality):	$977,208	per Crash	NHTSA Report (Blincoe, 2002)
Social Benefit (Crash):	$6,885	per Crash	NHTSA Report (Blincoe, 2002)
Deployment Cost:	$5,700		CICAS Workshop Report
Operating Cost:	$1,000		Assumption
Targeted Intersections:	152,600		ITS Joint Program Office
R&D Expenses:	$20,000,000	(Year 07-09)	ITS Joint Program Office

Rf: 6.0%

T	Year	Registered Vehicle (Thousands)	**Diffusion Rate (OBU)**	Penetration Rate (RSU)	Efficiency Factor	**Benefits ($M)**	**Costs ($M)**	**PV ($M)**	Discount Factor
1	2007	243,209	**0.0%**	0.0%	0.0%	**0.00**	**20.00**	**-20.00**	0.94
2	2008	246,636	**0.0%**	0.0%	0.0%	**0.00**	**20.00**	**-20.00**	0.89
3	2009	250,063	**0.0%**	0.0%	0.0%	**0.00**	**20.00**	**-20.00**	0.84
4	2010	253,490	**0.2%**	6.4%	47.9%	**0.91**	**65.84**	**-64.93**	0.79
5	2011	256,917	**0.8%**	12.9%	59.1%	**8.64**	**75.67**	**-67.03**	0.75
6	2012	260,344	**2.0%**	19.3%	64.5%	**36.45**	**85.50**	**-49.05**	0.70
7	2013	263,771	**4.2%**	25.8%	67.9%	**108.49**	**95.33**	**13.17**	0.67
8	2014	267,198	**7.7%**	32.2%	70.3%	**258.22**	**105.15**	**153.07**	0.63
9	2015	270,625	**12.6%**	38.6%	72.2%	**515.89**	**114.98**	**400.91**	0.59
10	2016	274,052	**18.3%**	45.1%	73.6%	**893.87**	**124.81**	**769.06**	0.56
11	2017	277,479	**24.4%**	51.5%	74.8%	**1,385.31**	**134.64**	**1,250.67**	0.53
12	2018	280,906	**30.5%**	58.0%	75.9%	**1,973.91**	**144.46**	**1,829.45**	0.50
13	2019	284,333	**36.3%**	64.4%	76.7%	**2,642.38**	**154.29**	**2,488.09**	0.47
14	2020	287,760	**41.7%**	70.8%	77.5%	**3,375.88**	**164.12**	**3,211.77**	0.44
15	2021	291,187	**46.8%**	77.3%	78.2%	**4,162.49**	**173.95**	**3,988.54**	0.42
16	2022	294,614	**51.4%**	83.7%	78.8%	**4,992.66**	**183.77**	**4,808.89**	0.39
17	2023	298,041	**55.6%**	90.2%	79.3%	**5,858.69**	**193.60**	**5,665.09**	0.37
18	2024	301,468	**59.5%**	96.6%	79.8%	**6,754.19**	**203.43**	**6,550.76**	0.35
19	2025	304,895	**63.0%**	100.0%	80.0%	**7,428.13**	**182.17**	**7,245.95**	0.33
20	2026	308,322	**66.2%**	100.0%	80.0%	**7,807.25**	**152.60**	**7,654.65**	0.31

NPV @6.0% **17,474.83**

Table 6-13: Results of Decision Analysis Valuation

Concept	R&D Outcome	Market Penetration (OBU)	NPV ($B)
1 (Infrastructure-Autonomous)	Success		40.90
1 (Infrastructure-Autonomous)	Medium Success		15.41
3 (Vehicle-Based)	Success	Fast	17.47
3 (Vehicle-Based)	Success	Slow	6.29
3 (Vehicle-Based)	Medium Success	Fast	7.50
3 (Vehicle-Based)	Medium Success	Slow	2.30

6.3.2. Hybrid Real Options Analysis

Likewise, NPV of infrastructure-autonomous ICAS (Concept 1) and vehicle-based ICAS (Concept 3) are calculated based on "hybrid real options" analysis through the options lattice valuation technique. Table 6-14 displays the revenue lattice of "hybrid real options" method as an intermediate state. Table 6-15 represents the results of "hybrid real options" valuation considering market uncertainty. Compared with decision analysis (Table 6-13), Table 6-15 shows that "hybrid real options" analysis provides larger NPV in all scenarios because the expected value of the "underlying" with the market uncertainty (i.e., the number of registered vehicle in the ICAS case) evaluated through the replicating binomial lattice is greater than the number of registered vehicle without the market uncertainty evaluated based on decision analysis. This result reflects the fundamental aspects of the real options that the highly uncertain project will produce higher expected value.

Comparing the uncertainty value that means the difference of NPV between decision analysis and "hybrid real options" analysis in Concept 1 and 3, Table 6-16 proves that Concept 3 possesses larger options values. This result demonstrates that Concept 3 is more vulnerable to the market uncertainty resulting from the fluctuation of the number of vehicles with the OBU because the social benefit of Concept 3 develops slowly.

Table 6-14: Example of the Revenue Lattice for Concept 3 ("Hybrid Real Options")

Revenue Lattice																				
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
0	-19	-18	-17	-52	-51	-35	9	99	247	449	692	959	1237	1513	1782	2036	2274	2493	2614	2618
1		-18	-17	-52	-51	-35	9	98	244	444	685	950	1225	1499	1764	2017	2252	2469	2589	2593
2			-17	-51	-50	-35	9	97	242	440	678	941	1213	1484	1747	1997	2230	2445	2564	2568
3				-51	-50	-34	9	97	240	436	672	932	1201	1470	1730	1978	2209	2421	2539	2543
4					-49	-34	9	96	237	432	665	923	1189	1456	1714	1959	2187	2398	2514	2518
5						-34	9	95	235	427	659	914	1178	1441	1697	1940	2166	2375	2490	2494
6							9	94	233	423	652	905	1167	1428	1681	1921	2145	2352	2466	2470
7								93	230	419	646	896	1155	1414	1664	1902	2124	2329	2442	2446
8									228	415	640	887	1144	1400	1648	1884	2104	2306	2418	2422
9										411	634	879	1133	1386	1632	1866	2083	2284	2395	2398
10											628	870	1122	1373	1616	1847	2063	2262	2372	2375
11												862	1111	1360	1601	1830	2043	2240	2349	2352
12													1100	1346	1585	1812	2023	2218	2326	2329
13														1333	1570	1794	2004	2197	2303	2307
14															1555	1777	1984	2175	2281	2284
15																1760	1965	2154	2259	2262
16																	1946	2133	2237	2240
17																		2113	2215	2219
18																			2194	2197
19																				2176

Table 6-15: Results of "Hybrid Real Options" Valuation

Concept	R&D Outcome	Market Penetration (OBU)	NPV ($B)	Uncertainty Value ($B)	Increase
1 (Infrastructure-Autonomous)	Success		41.84	0.94	2.30%
1 (Infrastructure-Autonomous)	Medium Success		15.78	0.37	2.40%
3 (Vehicle-Based)	Success	Fast	17.94	0.47	2.67%
3 (Vehicle-Based)	Success	Slow	6.46	0.17	2.77%
3 (Vehicle-Based)	Medium Success	Fast	7.71	0.21	2.74%
3 (Vehicle-Based)	Medium Success	Slow	2.37	0.07	3.01%

6.3.3. Real Options in the Intersection Collision Avoidance Systems

Although the base case where the probability of success (POS) in the R&D is 30% in "Success," 60 % in the "Medium Success," and 10% in the "Failure" assumes that the project gets never cancelled, the project managers can abandon the project when they realize that R&D ends up with "Failure" and avoid the losses resulting from the undesirable R&D outcomes. In the ICAS case, the first decision of whether to abandon the project is 2009 when the large field operational test will be conducted. The difference in the value between the case with and without the option to abandon is the option value in the ICAS project. Equation 6-22 represents the present value in the "failure" R&D scenario given that the managers kill the project in 2009.

Payoff in the "Failure" with the option

$$= -\frac{0.02}{1.06} + \frac{0.02}{1.06^2} + \frac{0.02}{1.06^3} = -0.05 \text{ (\$ Billion)} \qquad \text{Equation 6-22}$$

Figures 6-14 through 6-17 illustrate the decision tree of the "infrastructure-autonomous" ICAS (Concept 1) and "vehicle-based" ICAS (Concept 3) in the base case. Figure 6-18 illustrates the value at risk (VaR) curve that describes the cumulative function of the expected NPV. Table 6-16 summarizes the expected NPV of two concepts with and without the option to abandon.

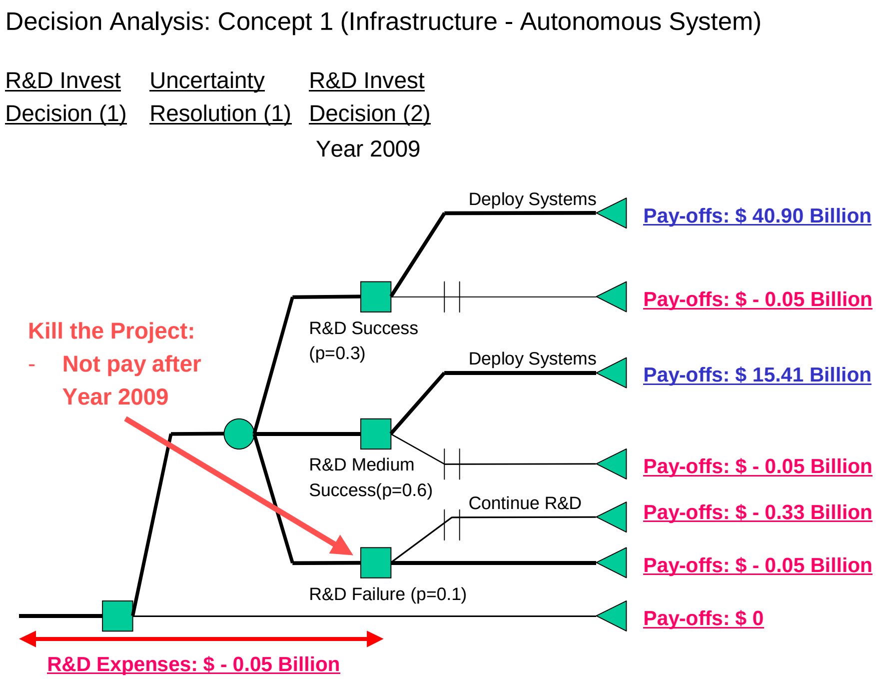


Figure 6-14: Decision Tree – Decision Analysis (Infrastructure-Autonomous ICAS: Concept 1)

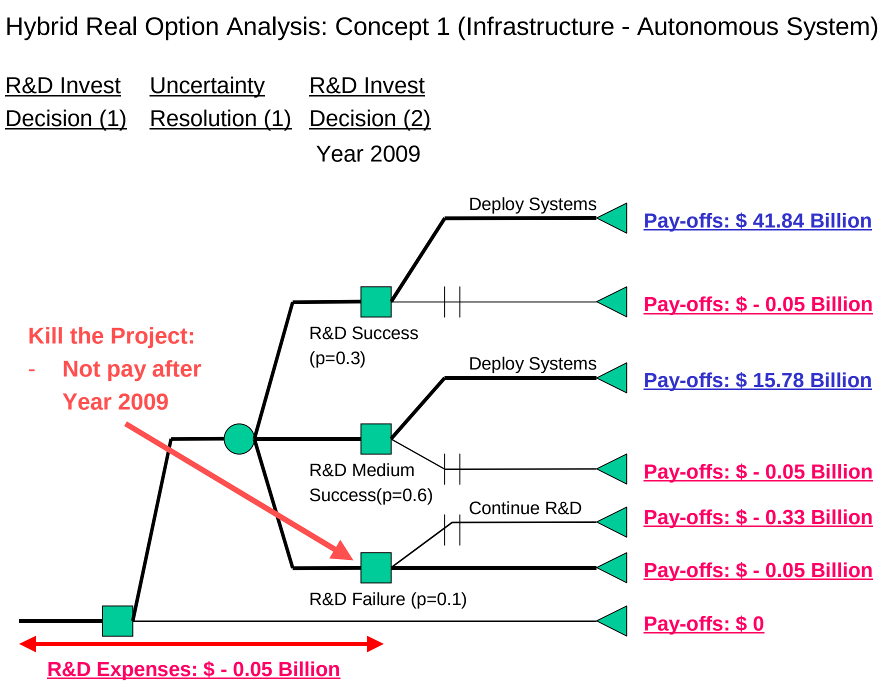


Figure 6-15: Decision Tree – Hybrid Real Options (Infrastructure-Autonomous ICAS: Concept 1)

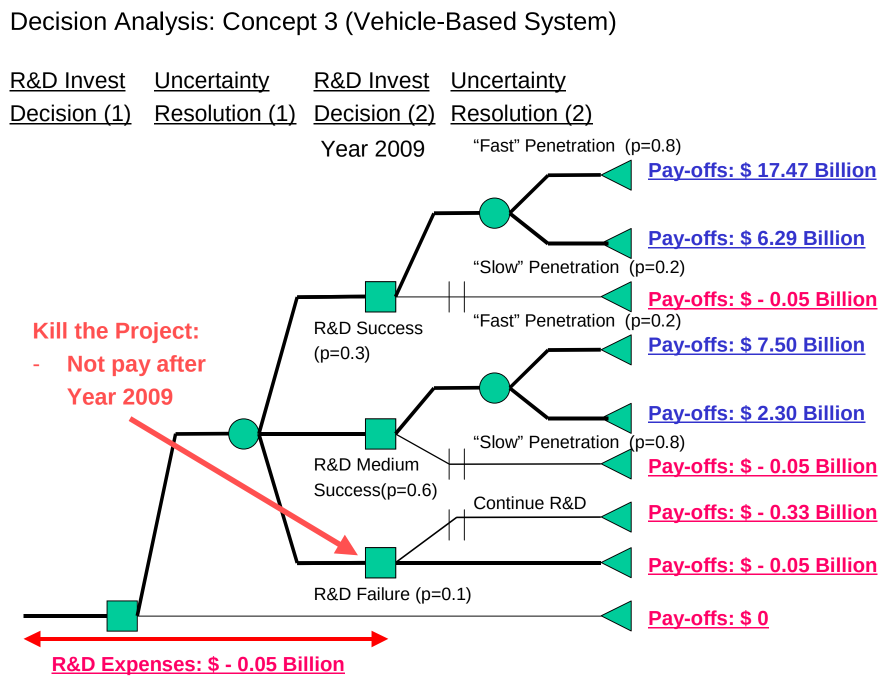


Figure 6-16: Decision Tree – Decision Analysis (Vehicle-Based ICAS: Concept 3)

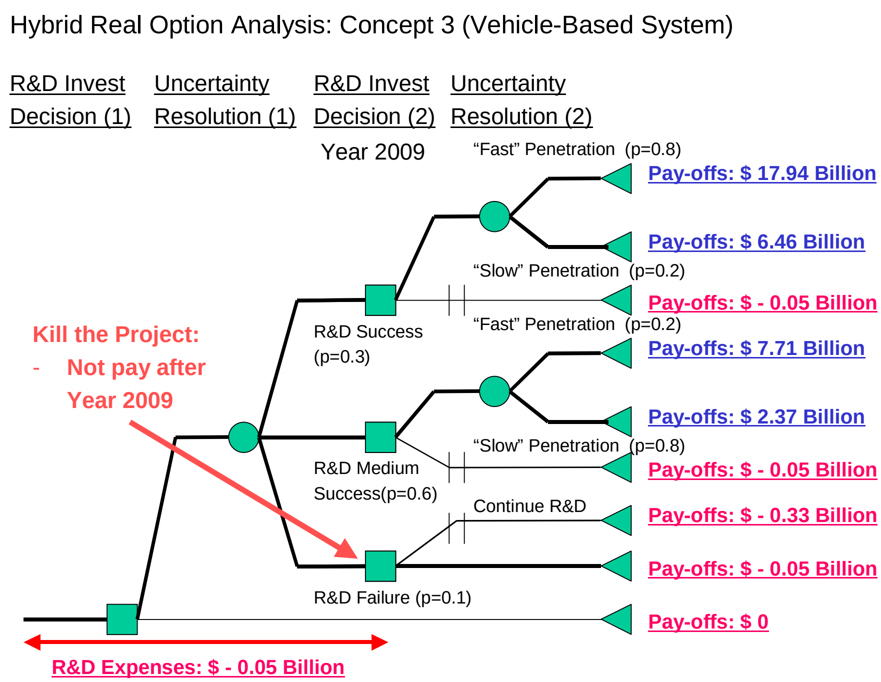


Figure 6-17: Decision Tree – Hybrid Real Options (Vehicle-Based ICAS: Concept 3)

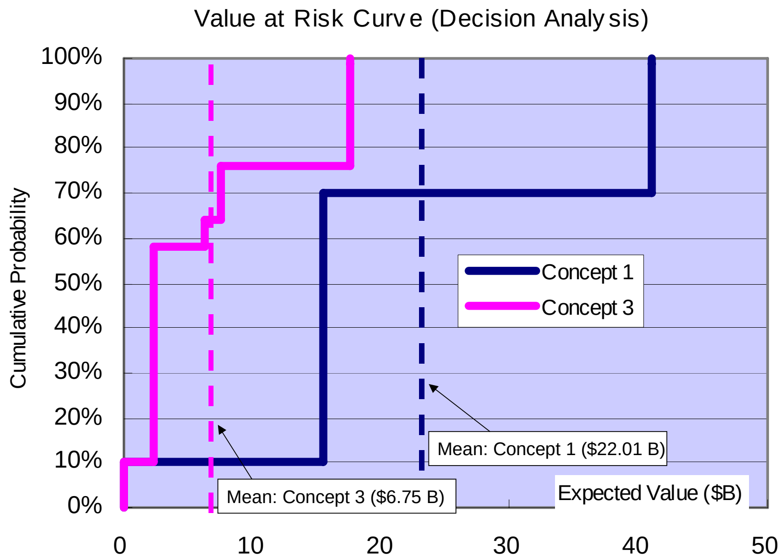


Figure 6-18: Value at Risk Curve with and without Option to Abandon

Table 6-16: The Value of Real Option to Abandon

Concept	Decision Analysis ($B)	Hybrid Real Options Analysis ($B)	Option Value ($B)
1 (Infrastructure-Autonomous)	21.986	22.014	0.028
3 (Vehicle-Based)	6.722	6.750	0.028

6.4. Sensitivity Analysis

Proposed models in this thesis make several assumptions to estimate the expected value of the projects. This section provides sensitivity analysis in terms of the three assumptions: the probability of success of the R&D, the market of penetration of the OBU and the RSU.

(1) Probability of Success in the R&D Stage

The analysts are interested in how change in POS influences the expected value of two concepts. Provided that the ratio of the probability that "Success" and "Medium Success" occurs is 1:2, Figure 6-19 describes the sensitivity analysis of the expected NPV in a different POS of the R&D. These results demonstrate that the infrastructure-based design

(Concept 1) is a more promising system regardless of requiring enormous initial investments in constructing the systems because this concept is not exposed to the risk of the user acceptance of the OBU.

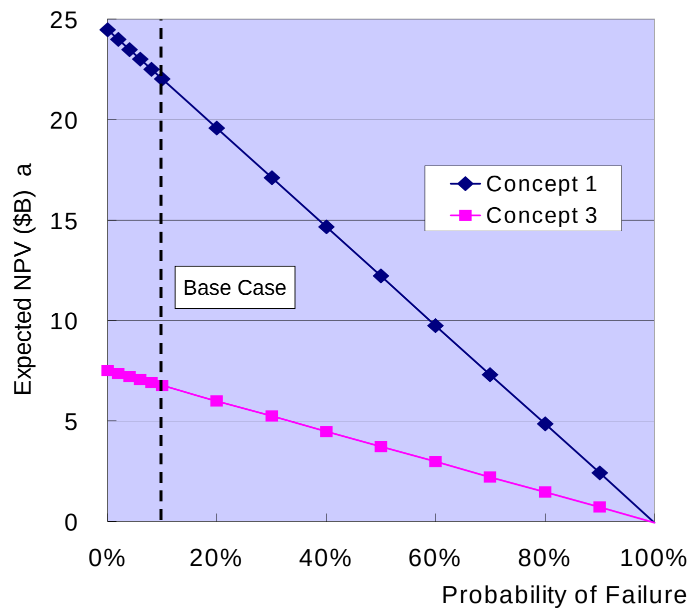


Figure 6-19: Sensitivity Analysis (Probability of Success in R&D)

(2) Market Penetration of the OBU

The managers that support the vehicle-based concept are most anxious about the user acceptance of the OBU. Assuming that the ultimate market penetration rate in the "Slow" scenario is 40% of that in "Fast" scenario, Figure 6-20 illustrates the sensitivity analysis of the OBU with the value of the option to abandon. It demonstrates that the expected NPV of Concept 1 that does not require the OBU is insensitive to the ultimate market penetration rate of the OBU. The key to success of the vehicle-based ICAS depends on user acceptance of the OBU.

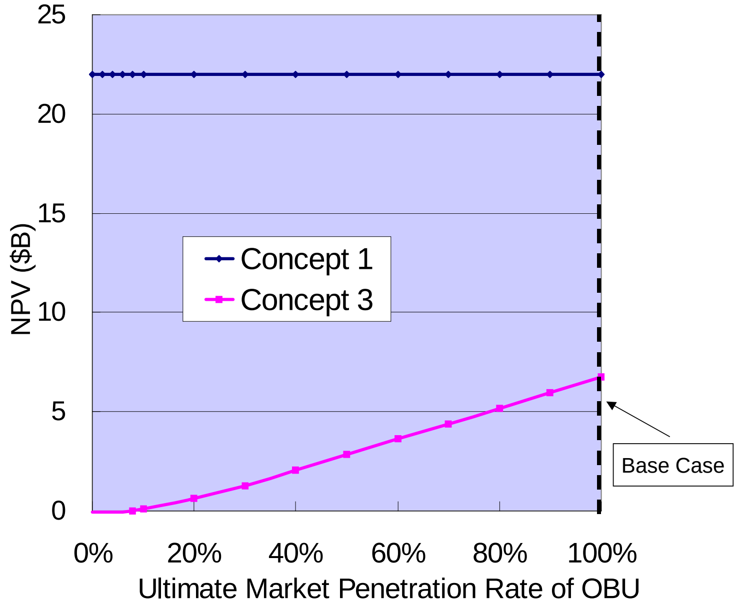


Figure 6-20: Sensitivity Analysis (Market Penetration Rate of the OBU)

(3) Market Penetration of the RSU

As the public sector may feel that the ICAS are necessary not to be fully deployed at their targeted intersections and that the partial deployment of the ICAS saves the operating cost, the RSU does not acquire the full acceptance from the public sector. Figure 6-21, however, implies that the larger ultimate market penetration rate of the RSU provides the larger social benefit. Therefore, user acceptance of the RSU from the public sector is also a significant factor for the success of the ICAS.

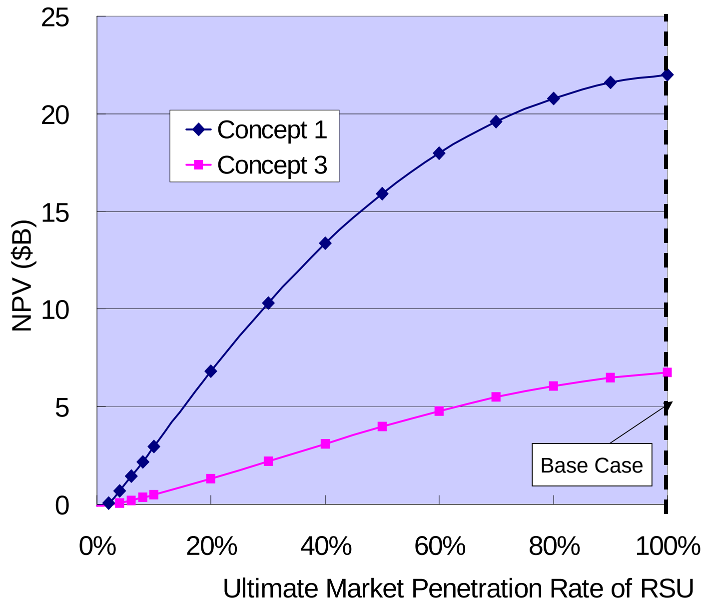


Figure 6-21: Sensitivity Analysis (Market Penetration Rate of the RSU)

6.5. Conclusion of Analysis

This chapter emphasizes the analysis of the project by utilizing the two appropriate methodologies for evaluating R&D and deployment project for ITS technology. The chapter addresses and formulates all relevant project risks and market risks associated with R&D and deployment of the ICAS.

Calculating NPV of two conflicting ICAS concepts and comparing them, this chapter demonstrates that NPV of the infrastructure-autonomous ICAS (Concept 1) is larger than that of the vehicle-based ICAS (Concept 3), even though the OBU obtains the full user acceptance from the drivers and the RSU does from the public sector, because the slow diffusion of the OBU in Concept 3 cannot keep up with the social benefit that the infrastructure-autonomous systems yield. This chapter proves that NPV of the vehicle-based ICAS decreases as the ultimate market penetration rate of the OBU decreases, suggesting that developing attractive the new product and obtaining user acceptance are the most crucial elements for future success of the ICAS.

The chapter also calculates NPV based on the "hybrid real options" analysis. Compared with decision analysis, "hybrid real options" analysis provides larger NPV in all scenarios, indicating that the higher uncertainties can produce the expected value. The results show that the upward shift of NPV resulting from the market uncertainty in the Concept 3 is larger than that in Concept 1. In other words, Concept 3 is more exposed to the market uncertainty of the fluctuation in the number of vehicles.

This chapter realizes that this R&D and deployment project has chances to exercise the option to abandon the project when the R&D program ends up with the failure and calculates the value of real options. If the project stops the future R&D until the success of product and systems development at the decision point of year 2009, the project obtains the option value that equals to the future value of killing the project. The proposed methodologies demonstrate that the realistic value of the system is different from the value defined based on the standard DCF/NPV method.

Based on the results, Chapter 7 gives conclusions concerning three thesis goals addressed in Chapter 1, policy implications, and future works.

Chapter 7 Conclusion

7.1. Conclusion of Project Valuation

This section discusses three fundamental purposes of this thesis and explains accomplished works for each purpose.

Purpose 1: To propose the appropriate valuation methods for R&D and deployment of Intelligent Transportation Systems

Purpose 2: To apply the proposed methods to a case example that deals with R&D and deployment for the ICAS

Investments in ITS technology carry various uncertainties. This thesis identifies the risks associated with R&D and deployment project of ITS technology. With public-private partnerships, the project of ITS R&D and deployment is exposed to the risks induced by both the public and private sector. This thesis addresses these risks by dealing with a case example of the ongoing intersection collision avoidance program conducted cooperative by the public and private sectors. With complicated crash mechanisms, the intersection collision is considered a difficult R&D area and involves various types of uncertainties associated with R&D and deployment. This thesis analyzes the characteristics of investments in ITS in comparison with those of conventional infrastructure, identifies the behavioral pattern of ITS investments and demonstrates that they possess both project risks and market risks. Project risks originate in the outcomes of R&D in ITS technologies and market risks originates in the user acceptance of ITS technologies employed.

This thesis introduces the essential financial valuation concepts. Building upon these concepts, this thesis explains real options in detail as a methodology that can take relevant uncertainties and risks into account and demonstrates and that decision analysis and "hybrid real options" methodology are the most appropriate method for evaluating the R&D and deployment programs because they identify both project risks and market risks in a single method and allows the project planners to make the flexible design.

This thesis concentrates on evaluating two competing concepts for crash prevention at intersections: one involves the public-oriented, infrastructure-autonomous systems and the other is the private-driven, vehicle-based ones. In evaluating these two concepts, this thesis provides the framework of calculating benefits and costs associated with the R&D and deployment project for traffic safety. This thesis utilizes various quantitative frameworks to model the associated project risks and market risks, such as the probability of outcomes in R&D, the product diffusion model ("Bass model"), the correlation between the number of vehicles and GDP, and the Pareto Distribution.

Purpose 3: To provide suggestions as to which strategy provided by the public sector and the private sector makes sense for the public sector and the transportation society

Comparing two concepts proposed by public sector and private sector, this thesis demonstrates that, even through the new product (DSRC) obtains full user acceptance from driving users, NPV of the systems suggested by the public sector (Concept 1) is larger than those proposed by the public sector (Concept 3). The primary reason is that the diffusion of in-vehicle ITS technology takes so long a time that it cannot match the social benefit the Concept 1 will produce.

The thesis compares the result of the NPV through two proposed methodologies, showing that the "hybrid real options" method provides higher NPV than the decision analysis does. This implies that the market uncertainty resulting from the automotive market increases the expected NPV of the project and that Concept 3 is vulnerable to the market uncertainty, because the slowly evolving benefits of Concept 3 increase the value of uncertainty.

In conclusion, this thesis shows the following conclusions:

1. Decision analysis and "hybrid real options" analysis are the most appropriate methods for valuing the R&D and deployment project for ITS with various types of uncertainties.

This is because they can take the value of the real option into account and allow the design of a flexible strategy.

2. The infrastructure-autonomous ICAS proposed by the public sector is a more promising system than the vehicle-based ICAS by the private sector because the former is not sensitive to the market penetration of in-vehicle ITS technology.

For future success of the vehicle-based ICAS, developing attractive the new product and obtaining user acceptance are the most crucial elements.

7.2. Policy Implications

This conclusion, however, cannot be the only consideration in selecting the public-oriented, infrastructure-autonomous ICAS. We should note that there are two additional considerations to make the strategy for improving the traffic safety: the NPV consideration and organizational perspective.

NPV Consideration

First, the identified benefits are not "real" cash equivalent. In other words, no institution or people can obtain the money through safety improvement. The results demonstrate that the infrastructure-autonomous plan produces larger social benefits but simultaneously incurs considerable investments to construct the systems and that the vehicle-based concepts also yield positive NPV, which sufficiently satisfies the condition for implementing the plan.

<u>Organizational Perspective</u>

The results are based on the financial analysis. However, the actual decision for implementing the project involves various organizational aspects. There are the five organizational perspectives for implementing the technology policy: (1) political, (2) cultural, (3) engineering, (4) strategic, and (5) economic point of view [90][91].

Politically, some cities may have serious problems with traffic injuries and deaths. In this case, the project for traffic safety might be prioritized with the violation of the NPV decision rule. Culturally, the NPV decision rule will be also weakened in the case where some nations have the cultural backgrounds of valuing the life above everything else. From a strategic and engineering standpoint, some institutions hesitate to introduce the innovative technology for fear that the technology cannot acquire the user acceptance and that the systems do not completely function. Economically, some local government has the restricted budgets for traffic safety. In this case, the vehicle-based systems may be the most appropriate measure for crash prevention.

In conclusion, the planners should consider all perspectives to implement the technology policy and strategy for traffic safety. However, the proposed methodology in this thesis provides more accurate valuation of the project related to R&D and deployment for ITS and enables the planners to make the dynamic, flexible plan for traffic safety through introduction of ITS technology.

7.3. Future Works

The proposed methods are applied to evaluate the value of the R&D and deployment program for ITS where the value of the project greatly depends on project risks such as outcomes of the R&D and on market risks such as the user acceptance of the new product. This thesis suggests two future directions: the more accurate analysis of the ICAS project and wide application to multiple R&D programs.

First, the data on prices and deployment costs used in this thesis are rough estimates partly because the new products for the ICAS have not developed. With more accurate data on the deployment costs, the result can provide the best flexible strategy of implementing the ICAS.

Second, the proposed valuation methodology can be widely applied to many R&D and deployment program, not limited to ITS. For instance, the IVI initiative, whose goal is to establish a significant safety transportation environment with greater mobility and efficiency, involves R&D for product development to prevent various types of collisions. Another example is the VII initiative that can provide multiple services including safety improvements, mobility applications, and commercial benefits. This program also involves R&D and deployment of new product development (i.e., DSRC), with its value greatly depending on the outcome of the R&D and user acceptance of the drivers. The proposed real options-based analysis can help the project managers realize the "realistic" value of the project.

END

Abbreviation and Terminologies

ABS:	Antilock Breaking Systems
APT:	Arbitrage Pricing Theory
APTS:	Advanced Public Transportation Systems
ARTS:	Advanced Rural Transportation Systems
ATIS:	Advanced Traveler Information Systems
ATMS:	Advanced Traffic Management Systems
AVCS:	Advanced Vehicle Control Systems
BCA:	Benefit Cost Analysis
CAMP:	Crash Avoidance Metrics Partnerships
CAPM:	Capital Asset Pricing Model
CDF:	Cumulative Density Function
CICAS:	Cooperative Intersection Collision Avoidance Systems
CVO:	Commercial Vehicle Operations
DCF:	Discounted Cash Flow
DIC:	DSRC (Dedicated Short Range Communication) Industry Consortium
DSRC:	Dedicated Short Range Communication
ETC:	Electric Toll Collection
FCC:	Federal Communications Commission
FCF:	Free Cash Flow
FOT:	Field Operational Test
GDP:	Gross Domestic Product
GIS:	Geographic Information System
GPS:	Global Positioning Systems
I2V:	Infrastructure-to-Vehicle
ICAS:	Intersection Collision Avoidance Systems
IPO:	Initial Public Offering
ISTEA:	Intermodal Surface Transportation Efficiency Act
ITS:	Intelligent Transportation Systems
ITS America:	Intelligent Transportation Society of America
IVHS:	Intelligent Vehicle Highway Systems
IVI:	Intelligent Vehicle Initiative
IVN:	Internal Vehicle Network
LTAP:	Left Turn Against Path
MLIT:	Ministry of Land Infrastructure and Transportation
NHTSA:	National Highway Traffic Safety Administration
NPV:	Net Present Value
OBU:	On-board Unit
OD:	Opposite Direction
OEM:	Original Equipment Manufacturers
OPM:	Option Pricing Model
PDE:	Partial Differential Equation
PDF:	Probability Density Function

POS:	Probability of Success
POV:	Possible Object Vehicle
R&D:	Research and Development
RSP:	Retail Selling Price
RSU:	Roadside Unit
SML:	Security Market Line
SV:	Subject Vehicle
TEA-21:	Transportation Equity Act for the 21st Century
USDOT:	United States of America Department of Transportation
VaR:	Value at Risk
V2I:	Vehicle-to-Infrastructure
V2V:	Vehicle-to-Vehicle
VII:	Vehicle Infrastructure Integration
WACC:	Weighted-Average Cost of Capital

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