Flexible System Development Strategies for the Chuo Shinkansen Maglev Project: Dealing with Uncertain Demand and R&D Outcomes

by

Masaki Ishii

M.E., Civil Engineering, the University of Tokyo, 2000
B.E., Civil Engineering, the University of Tokyo, 1998

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering Systems
at the
Massachusetts Institute of Technology

June 2007

Signature of Author: ______________________________
Engineering Systems Division
May 17, 2007

Certified by: ______________________________
Joseph M. Sussman
JR East Professor of Civil and Environmental Engineering and Engineering Systems
Thesis Supervisor

Accepted by: ______________________________
Richard de Neufville
Professor of Civil and Environmental Engineering and Engineering Systems
Chair, Engineering Systems Division Education Committee

Flexible System Development Strategies for the Chuo Shinkansen Maglev Project: Dealing with Uncertain Demand and R&D Outcomes

by

Masaki Ishii

Submitted to the Engineering Systems Division
on May 17, 2007 in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Engineering Systems

ABSTRACT

As a large-scale, long-term transportation project, the Chuo Shinkansen Maglev Project in Japan includes various uncertainties. Among them, two major uncertainties are identified in this thesis: the uncertainty of demand and the risk of R&D. Because each Maglev train requires a dedicated Power Conversion System (PCS) but a different one as it moves along the route, it is required to estimate the future demand accurately to determine the number of PCSs to construct. At the same time, the R&D to advance the technologies of PCS has the possibility of improving the project value by enabling staged flexible system development strategies. Since it is difficult to correctly estimate demand and R&D results, a framework that can evaluate projects with explicit considerations of these uncertainties is needed.

In the light of the above background, this thesis develops a quantitative model that is appropriate for evaluating the Chuo Shinkansen Project. More specifically, this thesis applies the hybrid real options model, which is suitable for appraising projects with both market risks and R&D risks, in an innovative manner, addressing four major complexities that arise when applying the model to the project: the difficulty of estimating the demand of a new train system, identification of the possible system designs that vary depending on R&D results, necessity to incorporate capacity constraints into analysis, and the selection of the appropriate discount rate. Analyzing the data and the characteristics of the Chuo Shinkansen Project, this thesis develops an evaluation model that addresses above issues.

Using the quantitative analytic model developed herein and assuming reasonable estimates of R&D costs, probability of success in R&D project, demand growth, volatility of demand, and the discount rate, this thesis estimates the value of the Chuo Shinkansen Project and concludes that it will be advantageous to invest in the R&D of the PCS technology despite its large cost. The thesis also conducts sensitivity analyses to demonstrate how the evaluation model developed in this thesis can be used to analyze the effects, on the project value, of changes in the probability of R&D success (in relation to R&D costs), demand growth and its volatility, and the discount rate, to obtain implications for the development strategies for the Chuo Shinkansen Project.

Thesis Supervisor: Joseph M. Sussman
Title: JR East Professor of Civil and Environmental Engineering and Engineering Systems

Acknowledgments

The writing of this thesis has been the most monumental and exciting adventure in my academic life. I could not have accomplished this journey without the generous and constant support of many people both from within and outside of MIT.

First of all, I would like to express my sincere gratitude to Professor Joseph Sussman. As my academic adviser and thesis supervisor, he has always led me to the right direction of study with crucial insights and heartfelt encouragements. Indeed, I remember that many times he challenged me to go beyond what I thought was possible but he never forgot to encourage me with many helpful suggestions and inspiring words. Owing to his invaluable guidance and encouragements, I have leaned what it takes to create high quality research.

I would also like to thank to the help of the staff and colleagues in Engineering Systems Division. The working atmosphere they created exceeded my expectation and contributed significantly to the quality of my academic work at MIT. Especially, I would like to acknowledge my fortune of being involved in the incredibly inspiring group of friends of Itaru Abe, Susumu Goto, Yoshihiko Sugawara, and Masahiro Sugiyama.

I am also very grateful to many other fellow and former MIT students who have been devoting their time to support me. Salem Esber has been a marvelously considerate mentor; he is still having me in his mind even after he graduated from MIT. Austin Che, my language-exchange partner, has been very generous to share his time with me to discuss various things including my thesis. In spite of the difference of our research fields, his perceptive insight about my study has been very helpful in developing this thesis. Besides the name of friends noted above, there are many others to whom I owe a great deal of thanks for supporting and interacting with me. These friends include Nam Yoon Sung, Kim Ji Hyun, Nobuhiro Iwamura, Shuichiro Daniel Ota, Dai Ohama, and Makoto Eguchi. I would like to thank to all of them.

I am also very grateful to the unfailing support of my parents and sisters in Japan. They might not have expected that I came to the United States for study. However, over the distance between Boston and Japan, I could always feel their cordial support.

Family, I would like to express my deepest gratitude to my dearest wife, Tomoko, and our newborn son, Sohma. Her sacrificing, inexhaustible support and love have never changed even after she became pregnant, and she has never failed to encourage me against the daunting challenge of this thesis work. Furthermore, she gave birth to Sohma, our first son, in the last month of my thesis work, and the joy of his birth gave me the last but ultimate energy to accomplish this thesis. In acknowledgment of their contribution and love, I dedicate this thesis to Tomoko and Sohma.

Masaki Ishii
Cambridge, Massachusetts
May 2007

Table of Contents

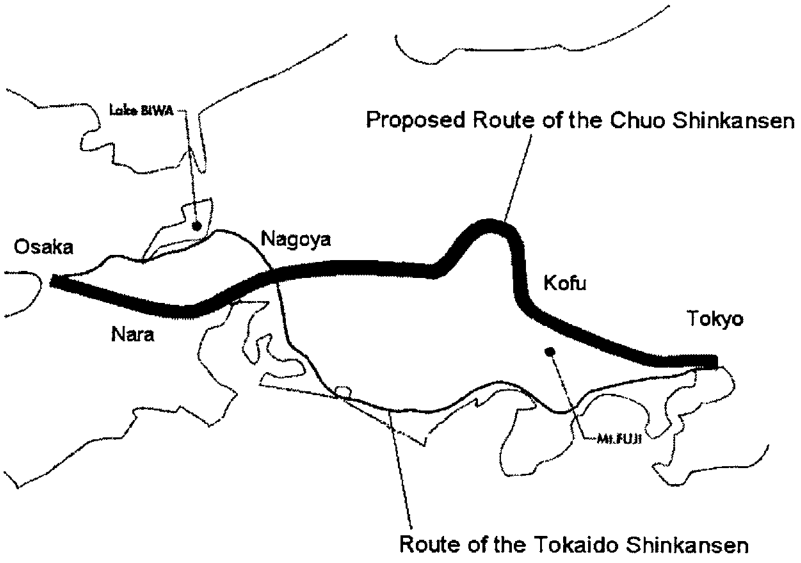
List of Figures

List of Tables

Chapter 1 Introduction

1.1. Introduction to the Chuo Shinkansen Project

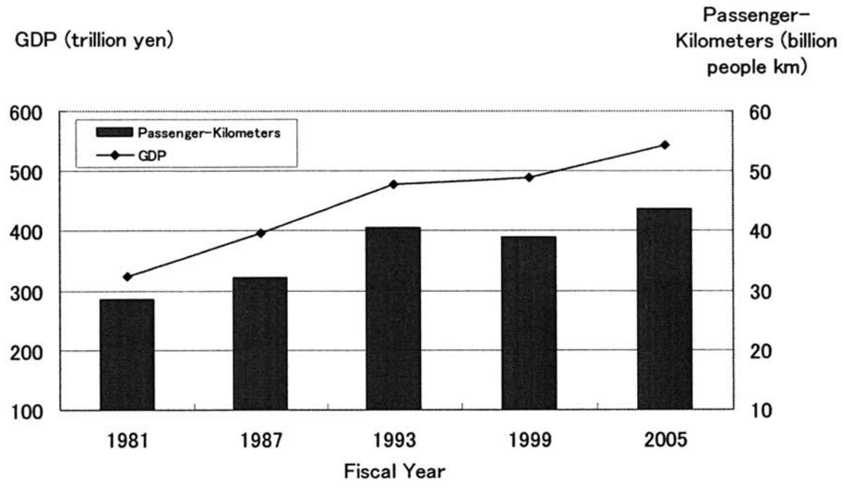
The Chuo Shinkansen Project is intended to construct a high-speed railway between Tokyo and Osaka, the two largest cities in Japan, by way of Kofu, Nagoya, and Nara with a Superconducting Magnetically Levitated Linear Motor Vehicle (Maglev) System [1]. The Chuo Shinkansen Project was originally planned in accordance with the Nationwide Shinkansen Railway Development Law (NRDL) which aims to expedite the development of the network of Shinkansen trains in Japan [1].



Source: Modified, based on *Conference of Scholars along the Chuo Shinkansen* [1]

Figure 1-1: Proposed Route of the Chuo Shinkansen

Japan enacted NRDL in 1970, in the light of the success of the Tokaido Shinkansen, the first Shinkansen running between Tokyo and Osaka. Since its inauguration in 1964, the Tokaido Shinkansen has served 4.4 billion people linking Japan's three largest metropolitan areas, Tokyo, Nagoya, and Osaka [2]. As the principal transportation artery joining these three areas, the Tokaido Shinkansen has seen its passenger-kilometers increase concurrent with Japan's GDP (Gross Domestic Product) growth (Figure 1-2) [2].



Source: Central Japan Railway Company Annual Report 2006 [2]

Figure 1-2: Tokaido Shinkansen Passenger-Kilometers and Japan's GDP

For the coordination of national land development, NRDL defines the Shinkansen routes that are to be constructed, and the budgeting schemes. Currently three routes (six sections) are under construction, and twelve routes are listed in the master plan. The Chuo Shinkansen is one of the routes planned in the master plan [1].

The technology of the Japanese Superconducting Maglev System (JR Maglev) was first investigated by the Japanese National Railways (JNR). In 1972, the Railway Technical Research Institute (RTRI), which was the research and development department of JNR, succeeded in the first levitation run in Kunitachi, Tokyo. Based on this success, a new Maglev test track was constructed in Miyazaki Prefecture in Kyusyu in 1977 to be able to perform more detailed experiments. In 1979, the first test vehicle, ML-500, achieved a world rail speed record of that time of 517km/h [3].

In 1989, two years after the privatization of JNR, a new 18.4km test track was built in Yamanashi Prefecture where the route of the Chuo Shinkansen was already being planned. Since then, research and development activities have been conducted on this test track by the Central Japan Railway Company (JR Central) in cooperation with the RTRI and the then Japan Railway Construction Public Corporation (now Japan Railway Construction, Transport and Technology Agency). On December 2, 2003, a speed of 581km/h was achieved, and a high-speed passing-test at the relative speed of 1,026km/h was carried out successfully on November 16, 2004 [3].

The Chuo Shinkansen Project is expected to be a great innovation in railway transportation because of the advanced system design of the Superconducting Maglev. Unlike the designs of the conventional railway system, it accelerates and decelerates not by adhesion between wheel and rail. Instead, it is a contact-less transport system enabled by the magnetic force that is generated between the onboard superconducting magnets and ground coils. This design makes a stable ultra-high speed operation at the top speed of 500km/h possible [3].

Thanks to this high speed, people in the metropolitan areas of Tokyo, Nagoya, and Osaka will be able to move between these areas in approximately 70 to 80 minutes [4]. With the expansion of one-day trip area, it is expected that the economic activities in these areas will be increased and new life styles will be created.

1.2. The Problem of the Maglev System for the Chuo Shinkansen Project

The essential technologies for the JR Maglev system have been developed, and the capability to achieve the project was approved in March, 2000 by the Maglev Technological Practicality Evaluation Committee under the Japanese Ministry of Land, Infrastructure and Transport (MLIT) [3]. However, details of the Chuo Shinkansen Project, such as the operational frequency, estimated costs of construction and operation, and the estimated revenue, have not yet been developed thoroughly because of many uncertainties in the future, including the demand growth and the possible development of low-cost construction methods.

In addition to these uncertainties, one inflexible system feature of Maglev is making it difficult for the system designers to develop the project plan. Owing to the system design of Maglev, only one train can be controlled by one Power Conversion System (PCS), which is installed in the power substation to convert the frequency of electricity supplied from the utility company into one of the frequencies required for train operation [5]. This relationship translates into the constraint that the number of PCSs installed becomes the maximum number of trains that can be operated simultaneously. For this reason, the Maglev system designers are required to estimate the future demand, though it is difficult to accurately forecast it, to make the important and vital decision about the maximum operational frequency and the number of PCSs to install.

In addition to this difficulty of determining the maximum frequency of operation, the project requires a huge amount of investment at the time of construction, especially if the system designers want to have a large operational capacity. Like other large-scale infrastructure investments, the Chuo Shinkansen Project needs a large initial cost; its construction cost is estimated to fall between 7.7 to 9.2 trillion yen [6]. Although the details of this cost are not currently available to the public, it can be imagined that the cost of PCS accounts for a significant part of the total construction cost since the inverters used for the PCSs in the test line in Yamanashi are the world's largest-class inverters [7]. Therefore, obtaining a large operational capacity, which means installing many PCSs, requires a substantial initial cost, and the project may not be constructed due to financial difficulties.

One way of effectively coping with the issue of the large initial cost and the difficulty of determining the number of PCSs to install is to incorporate "flexibility" into the system design; here, "flexibility" means the system's capability to allow later installation of additional PCSs, which would mean the later expansion of capacity. If a "flexible" system design is developed that permits constructing the Chuo Shinkansen with a small number of

PCSs and increasing the number of PCSs later, project managers will be able to reduce the initial construction cost and defer the cost of the increased capacity until it is needed. In addition, project managers will be able to observe the actual growth of demand to estimate the later demand more accurately, before they decide whether or not to expand the capacity. In this sense, the "flexibility" of the system that enables a staged development strategy such as this is very helpful in dealing with the uncertainty of future demand and making the project feasible.

With regard to the Maglev system of the Chuo Shinkansen Project, further research and development (R&D) activities are required to realize the flexible system design. As described in Section 3.1, it can be demonstrated that the current PCS technology, which is capable of covering 18.4km of track by one PCS, cannot realize the flexibility for the Chuo Shinkansen system. Instead, project managers need to develop the technologies of extending the coverage of PCSs and installing additional PCSs later to realize the flexibility of the system. Therefore, the success of R&D of the PCS technologies is the key for the development of a flexible system design for the Chuo Shinkansen Project.

However, it is still difficult for the project managers to decide whether or not to invest in R&D of the PCS technology, because the success of R&D is also uncertain. While the R&D of the PCS technology may require a large investment, the R&D may not yield satisfactory outcomes. As a result, it is important for the project managers to analyze the uncertainty of R&D success in order to make a decision about the investment in R&D.

To summarize, managers of the Chuo Shinkansen Project are faced with the difficulty of developing the project plan with consideration of many uncertain factors associated with the project. They need to develop the plan analyzing the uncertain demand in the future, though accurate estimation of demand is very difficult. The flexible system design, which may become possible as the result of R&D, can be helpful in coping with the uncertainty of demand. However, they also need to analyze the value of R&D, with consideration of the uncertainty of R&D success, in order to make a decision about the investment in R&D. For these reasons, it is critical for managers of the Chuo Shinkansen Project to develop a method of project evaluation that can handle the uncertainty of R&D, the flexibility of the system, and the uncertainty of future demand.

1.3. Purpose of This Thesis

This thesis aims to develop a quantitative model that can evaluate the Chuo Shinkansen Project with considerations of uncertainties associated with the project as well as the flexible system design. As stated in the previous section, the Chuo Shinkansen Project involves internal and external uncertainties of R&D and the future demand. Although both of these uncertainties are influential in developing the project plan and the flexibility of the system, they are not effectively addressed by the traditional project evaluation methods such as benefit cost analysis (BCA) or the discounted cash flow (DCF) analysis [8]. Therefore, it is critical for the managers of the Chuo Shinkansen Project to develop a project evaluation model that quantitatively incorporates the uncertainties of R&D and future demand, as well as the flexibility of the system into the analysis.

As an evaluation method for projects with R&D, Neely (1998) developed the "hybrid real options" analysis which is a composite evaluation method of decision analysis and real options valuation [9]. The advantage of the "hybrid real options" analysis is that it can evaluate projects with both internal uncertainties, such as the risk of R&D, and external uncertainties, such as the market growth.

However, several complexities arise when applying the "hybrid real options" to the Chuo Shinkansen Project. These complexities include: estimating the demand of the Chuo Shinkansen although it does not exist yet, identifying the potential system designs that are affected by the result of R&D, and handling the constraint of the capacity of the system. Therefore, we need to extend the hybrid real options model in order to cope with these complexities.

In light of this primary purpose, this thesis aims to accomplish the following three goals:

1) To propose an evaluation model by applying the hybrid real options model in an innovative manner; this model can quantitatively evaluate the value of the Chuo Shinkansen Project with considerations of the uncertainties of R&D and demand, as well as the flexible system designs,
2) To apply the proposed method to the evaluation of the Chuo Shinkansen Project, and
3) To provide suggestions as to the best development strategy of the project.

To meet these goals, first, this thesis collects information about the Chuo Shinkansen Project and researches the technological aspects of the JR Maglev system. Second, this work identifies the framework of the analysis of the Chuo Shinkansen Project and defines the scope of analytical model developed in this thesis. Third, the thesis builds foundations of project evaluation methodologies and introduces Neely's hybrid real options analysis. Fourth, the thesis applies the hybrid real options model in an innovative way in order to appropriately evaluate the Chuo Shinkansen Project. Finally, this study analyzes the Chuo Shinkansen Project considering the benefit of the flexible staged development plan, and draws conclusions with regard to the best development strategy for the Chuo Shinkansen Project.

1.4. Thesis Structure

Chapter 1 explains the basic outline of the Chuo Shinkansen Project and associated difficulties in evaluating the project. This chapter also identifies the purpose of this thesis.

Beginning by describing the history and background of the Maglev development in Japan, Chapter 2 explains benefits of the Chuo Shinkansen Project from various points of view. This chapter also provides the basic technological aspects of JR Maglev system.

Chapter 3 explains the challenges in designing the Maglev system for the Chuo Shinkansen

Project by identifying the major uncertainties associated with the project. This chapter also explains the potential benefit of the flexibility of the system design in dealing with these uncertainties, and it identifies the framework of evaluating the Chuo Shinkansen Project with consideration of the uncertainties associated with the project as well as the flexibility of the system design. Finally, this chapter defines the scope of the analytical model that this thesis develops.

Chapter 4 reviews the basic valuation methodologies that are necessary for valuing projects and understanding real options analysis that the following chapter explains.

Chapter 5 explains real options analysis which is suitable for analyzing uncertainties that affect projects and further explains how to evaluate the value of the flexible staged development strategy. In particular, this chapter introduces the hybrid real options analysis developed by Neely (1998), as an appropriate method for valuing projects that have both uncertainties of demand and R&D [9].

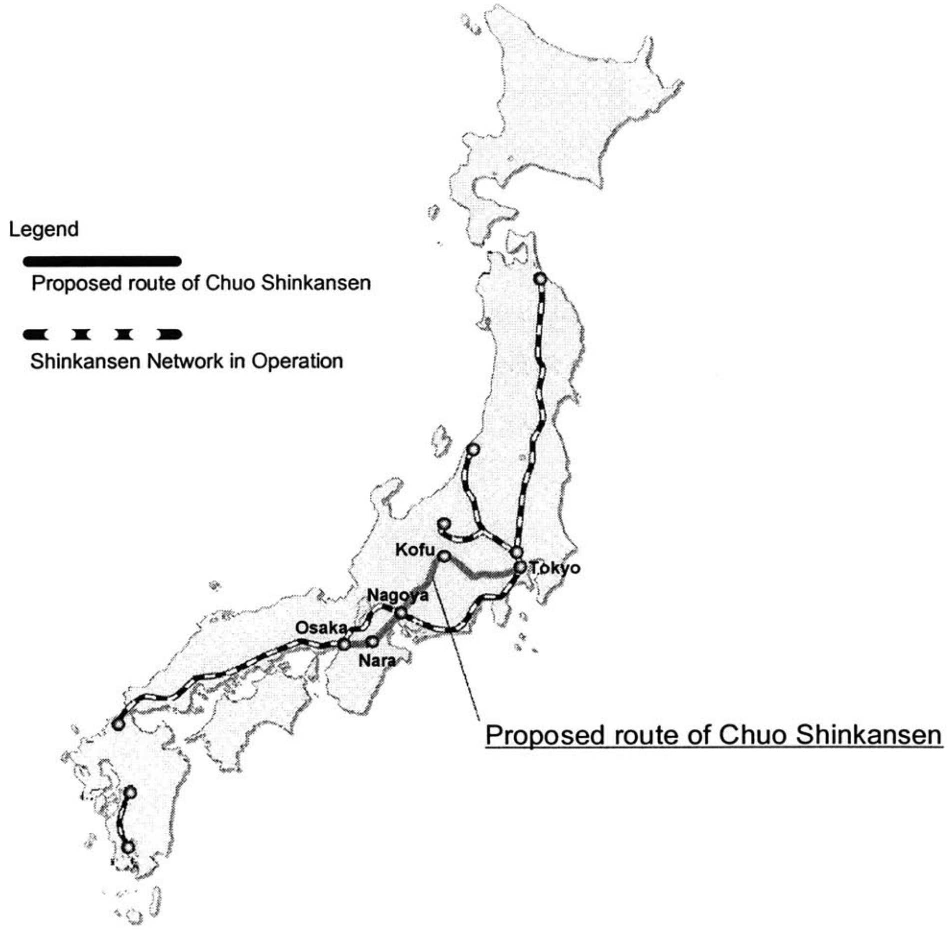
Chapter 6 explains the complexities that arise when applying the hybrid real options analysis to the Chuo Shinkansen Project. By extending Neely's hybrid real options model, this chapter proposes a quantitative model that is appropriate for evaluating the Chuo Shinkansen Project.

Based on the evaluation model proposed in Chapter 6, Chapter 7 analyzes the value of the Chuo Shinkansen Project and the value of the R&D. This chapter also conducts sensitivity analyses of the project value and analyzes the implications that are obtained from the sensitivity analyses.

Finally, Chapter 8 provides conclusions about the extended hybrid real options model and the recommendations that are obtained from the analyses of the Chuo Shinkansen Project with regard to the decision of investment in R&D. This chapter also provides suggestions for the future works.

Chapter 2 The Chuo Shinkansen Project

For the Chuo Shinkansen Project, the plan is to construct a high-speed railway from Tokyo to Osaka by way of Kofu, Nagoya, and Nara (Figure 2-1). The Chuo Shinkansen Project has been developed in accordance with the Nationwide Railway Development Law (NRDL) of Japan which defines the high-speed railway routes that are to be constructed and the budgeting schemes. Currently three routes are being constructed and 12 routes are listed in the master plan. The Chuo Shinkansen is one of the routes listed in the master plan [1].



Source: Modified, based on Tatematsu [6].

Figure 2-1: Route of the Chuo Shinkansen proposed by the Linear Chuo Express Construction Promotion Federation and the Shinkansen Network in Operation

In the plan for the Chuo Shinkansen Project, it is proposed that the Superconducting Magnetically Levitated Linear Motor Vehicle (JR Maglev) System should be adopted for its many advantages including very high speed. With Maglev technology, the three largest metropolitan areas of Japan, Tokyo, Osaka, and Nagoya, will be connected to one another within 70 to 80 minutes [4], and it is expected that economic activities in these areas will be increased and new life styles will be created.

The technology of Superconducting Maglev was first studied by the Railway Technical Research Institute (RTRI) of the Japanese National Railways (JNR) [3]. Since the privatization and division of JNR in 1987, the research and development (R&D) of Maglev has been conducted by the Central Japan Railway Company (JR Central) in cooperation with RTRI and the Japan Railway Construction, Transport and Technology Agency. JR Central is charged with concurrently managing both the Chuo Shinkansen and the Tokaido Shinkansen after the commencement of commercial service of the Chuo Shinkansen [10].

This chapter describes the Chuo Shinkansen Project and the JR Maglev system from the viewpoint of development history, the benefits of the project, and the technological aspects of the system. The chapter begins by introducing the historical background of Superconducting Maglev System.

2.1. History and Background

The Railway Technical Research Institute (RTRI), which was a subordinate organization of JNR prior to 1987, started the research on a linear motor propulsion railway system in 1962 two years before the commencement of operation of the Tokaido Shinkansen. This system was designed as the next-generation ultra-fast link between Tokyo and Osaka with a journey time of about one hour. After the first successful levitation run at RTRI in Kunitachi, Tokyo in 1972, a Maglev test track was constructed in Miyazaki Prefecture in 1977. In 1979, the first test vehicle, ML-500, achieved a world rail speed record at the time of 517km/h [3].

Fundamental tests on the basic performance of the Maglev were carried out on the Miyazaki Maglev Test Track. However, since the Miyazaki test track was only a single track with no tunnels, gradients or curves, a new test line with these features was required. In 1989, two years after JNR was privatized, it was decided to construct the Yamanashi Maglev Test Line (YMTL).

Since the decision to build the YMTL, JR Central has been in charge of the R&D of Maglev as well as the construction of the test line in cooperation with RTRI and the then Japan Railway Construction Public Corporation (now Japan Railway Construction, Transport and Technology Agency) [1][10].

The construction of YMTL began in November 1990. After extensive construction and installation, the 18.4km priority section was completed in March 1997 (the ground plan is 42.8km long). Running tests commenced on the YMTL on April 3, 1997, beginning with low-speed wheel running tests. The first levitation running succeeded on May 30, 1997. It was then confirmed that stable levitation running was possible and that optimal speed for levitation running was identified [3].

Speed increase tests began in June 1997. Maximum speed exceeded 500km/h on November 28, and the maximum designed speed of 550km/h was achieved on December 24, which means that the target speed was achieved around 9 months after the running tests began [3].

Various running tests were conducted to evaluate functions required for the revenue service, including high-speed passing tests, substation cross-over tests, multiple-train control tests, and 5-car trainset running tests. In November 1999, passing tests were conducted at a relative speed of 1,003km/h [3]. A maximum speed of 552km/h was recorded on April 14, 1999 by a manned and loaded vehicle that broke the previous maximum speed records for manned and unmanned operation achieved in December 1997 [3].

In March 2003, the Maglev system received an evaluation by the Ministry of Transport (now the

Ministry of Land, Infrastructure and Transport) Maglev Technological Practicality Evaluation Committee; it stated that "superconducting Maglev technology has reached a stage that makes it a viable ultra-high speed mass transportation system" [3].

Since 2000, with the aim of establishing a basic technology for practical application, technological development and running tests have been promoted with a focus on; 1) verification of reliability and long-term durability of the system, 2) cost reduction, and 3) improvement of the aerodynamics of the cars [3]. The running test on November 7, 2003 traveled 2,876km (89 round trips on the test line), which is equivalent to twice the average distance of 1,400km traveled daily by the Shinkansen vehicle owned by JR Central [3]. On December 2, 2003, a speed of 581km/h was achieved exceeding the previous world record by about 30km/h, and a high-speed passing test at a relative speed of 1,026km/h was carried out successfully on 16 November 2004 [3].

Based on these results of running tests, the Maglev Technological Practicality Evaluation Committee under the Japanese Ministry of Land, Infrastructure and Transport appraised, in March 2005, that all the technologies of the Superconducting Maglev necessary for the future revenue service had been established. For the sake of further verification of long-term reliability, technological development for further cost reduction, and study of the specification of the facility design for revenue service, JR Central announced in its consolidated financial report in April 2006 that it would make a study on a renewal and an extension of the existing test line aiming to improve the system design by changing the specifications of the existing facility into those of the revenue service level [3].

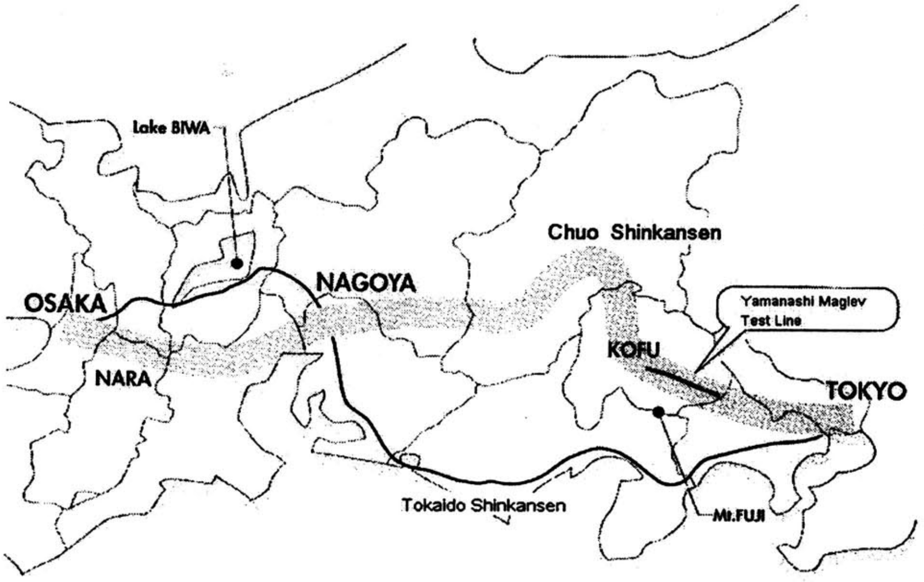
2.2. Benefits of the Chuo Shinkansen Project

As a large-scale transportation project, it is obvious that the Chuo Shinkansen Project will have not only operational benefits (or losses) but also external benefits to the society. These external benefits of the Chuo Shinkansen Project include: 1) increased redundancy of inter-metropolis transportation, 2) increased benefit for local airline passengers, 3) formation of the "Extra Huge" Economic Zone, and 4) technology export. This section explains these benefits one by one.

2.2.1. Increased Redundancy of Inter-Metropolis Transportation

Currently there is already a high speed train called the Tokaido Shinkansen that links the three largest cities in Japan, Tokyo, Nagoya, and Osaka. However, the Chuo Shinkansen is also planned to connect these cities. By building an alternative route to link these cities, the Chuo Shinkansen is expected to complementarily function together with the Tokaido Shinkansen.

Figure 2-2 shows the route of the Tokaido Shinkansen, and the route of the Chuo Shinkansen proposed by Linear Chuo Express Construction Promotion Federation. The Tokaido Shinkansen connects Tokyo, Osaka, and Nagoya by way of Shin-Yokohama, Shizuoka, Hamamatsu, and Kyoto. Though the route is different from the Tokaido Shinkansen, the Chuo Shinkansen is also planned to connect Tokyo, Osaka, and Nagoya, going through Kofu and Nara.



Source: Modified, based on Conference of Scholars along the Chuo Shinkansen [1]

Figure 2-2: Route of the Tokaido Shinkansen and the route of the Chuo Shinkansen proposed by Linear Chuo Express Construction Promotion Federation

The Tokaido Shinkansen was built in 1964, and has been used as the principal transportation for the major cities in Pacific coastal area between Tokyo and Osaka. While the area along the Tokaido Shinkansen – which JR Central covers by the Tokaido Shinkansen and conventional lines – accounts only for 23.7% of the total area of Japan, this area accounts for 58.5% of the country's population and 63.6% of the gross domestic product (GDP) [11]. Considering the importance of the Tokaido Shinkansen as the transportation artery, its operational disruption can have a significant impact on Japanese economy.

In 1995, the Tokaido Shinkansen operation was stopped for three days between Kyoto and Shin-Osaka due to the Great Hanshin Earthquake. The situation was more severe for the Sanyo Shinkansen which is directly linked with the Tokaido Shinkansen, and the operation between Shin-Osaka and Shin-Kobe was stopped for 91 days [12]. The Institution for Transport Policy Studies estimates in its report of 45th colloquium for transport policy that 90 days of operational interruption in the Tokaido Shinkansen would cause a 240 billion yen loss (2.7B yen/day) for passengers excluding the loss for the railway operator [13].

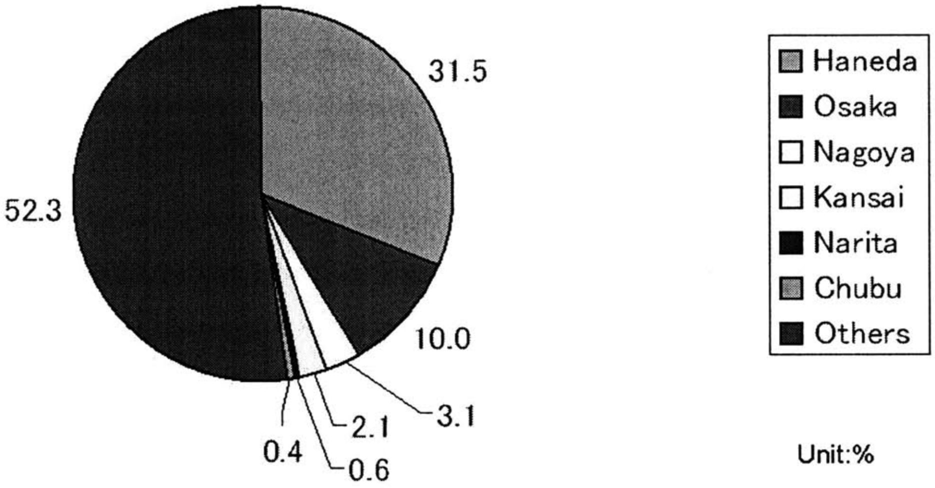
Heavy rain is another major threat to the stable operation of the Tokaido Shinkansen. In 2000, there was a heavy rain in the Tokai area around Nagoya, and the Tokaido Shinkansen operation was stopped for more than 24 hours. About 1.7 billion yen of economic loss was estimated afterwards as a result of only 24 hours of operational interruption [14].

Considering Japan's environment concerning natural disasters, and taking into account the impact of operational disruption of the Tokaido Shinkansen, it is worth considering the construction of another high speed mass transportation linkage among the major metropolitan areas of Tokyo, Nagoya, and Osaka. If the Chuo Shinkansen Project is realized, passengers will have more possibility to attain their travel even when there is an operational disruption in either the Tokaido Shinkansen or the Chuo Shinkansen. From this view point of redundant transportation paths, the Chuo Shinkansen is expected to be beneficial for Japanese economy.

2.2.2. Increased Benefit for Local Airline Passengers

The Chuo Shinkansen Project is also expected to have benefits for nation-wide air transportation management. With the increase in capacity of high speed transportation between Tokyo and Osaka, the Chuo Shinkansen has the possibility of alleviating the congestion of airline routes between the Tokyo International Airport (so called Haneda Airport) and other airports by shifting some demands from airlines to the Chuo Shinkansen.

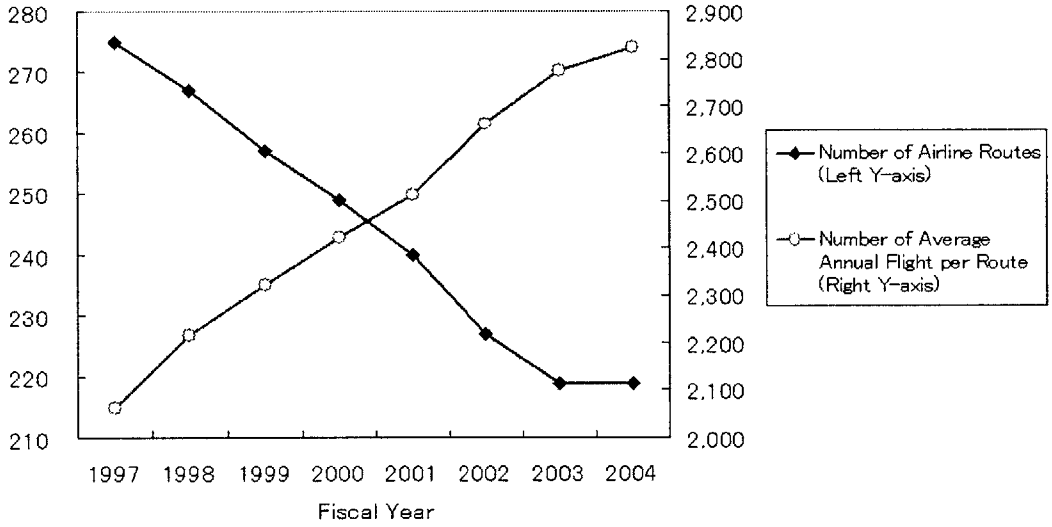
As the center for politics, economy, and culture in Japan, the metropolis of Tokyo has an extremely dense population. Serving as Tokyo's primary airport for domestic airways, Haneda airport has long been severely congested and the flight operation is said to have reached its capacity [15]. Figure 2-3 shows the share of airline passengers by airport.



Source: Modified, based on MLIT [15].

Figure 2-3: Share of Airline Passengers by Airport. Haneda airport is the most popularly used airport in Japan.

As can be seen from Figure 2-3, Haneda airport is the most popularly used airport in Japan. On the other hand, due to the limit of operational capacity at Haneda, airline companies can not simply increase the number of flights between Haneda and other airports. In order to increase the profitability, they have been shifting flights from less profitable routes between Haneda and local cities, to more profitable routes, such as Haneda to Sapporo, Kansai or Fukuoka [16]. This tendency can be also confirmed from Figure 2-4, which shows a decrease in airline route numbers and an increase in average annual flight numbers per route.



Source: Modified, based on MLIT [15]

Figure 2-4: Airline Route Number and the Average Annual Flight Number per Route

As a result of decreasing flight frequency, the benefits to passengers using local routes also have been diminishing. In order to improve the situation, the Japanese government plans to increase the capacity of Haneda airport by constructing another runway. However, the capacity is likely to run short in the future again since the airline demand has been increasing [16], and is estimated to keep on growing [15]. The Chuo Shinkansen, which will take over some of the airline demand between Tokyo and Osaka (Kansai) areas, will alleviate the congestion at Haneda airport, leading to the benefit of airline passengers to/from local cities.

In addition to the alleviation of congestion at Haneda airport, the competition between the

Chuo Shinkansen and airline companies may contribute to the benefit of local passengers even when the congestion problem at Haneda airport is resolved by the construction of another runway. As a result of the competition, airline companies might have the possibility of having a surplus of equipment on the route between Tokyo and Osaka. Faced with the need to shift resources to local routes, airline companies may offer a higher level of service to local passengers, including frequent regional jet service and convenient connections to international flights at Haneda airport in order to attract local passengers.

One should also note that the competition has complex effects on airline companies and JR Central. While the competition will decrease the profitability of airline operators and JR Central, it may also help them transform themselves into lean enterprises. Although both effects seem to contribute to the benefit for passengers, it is important, when evaluating the net economic profit of the Chuo Shinkansen Project, to take into account the benefit for the passengers, which the competition will bring about, as well as the incurred loss for the airline operators and JR Central.

2.2.3. Formation of the "Extra Huge" Economic Zone – Case Examples in Japan and Portugal

As a large-scale transportation investment, the Chuo Shinkansen is likely to have a significant effect on regional economic development. Much research has been done to analyze the effect of a large scale transportation investment on economic development.

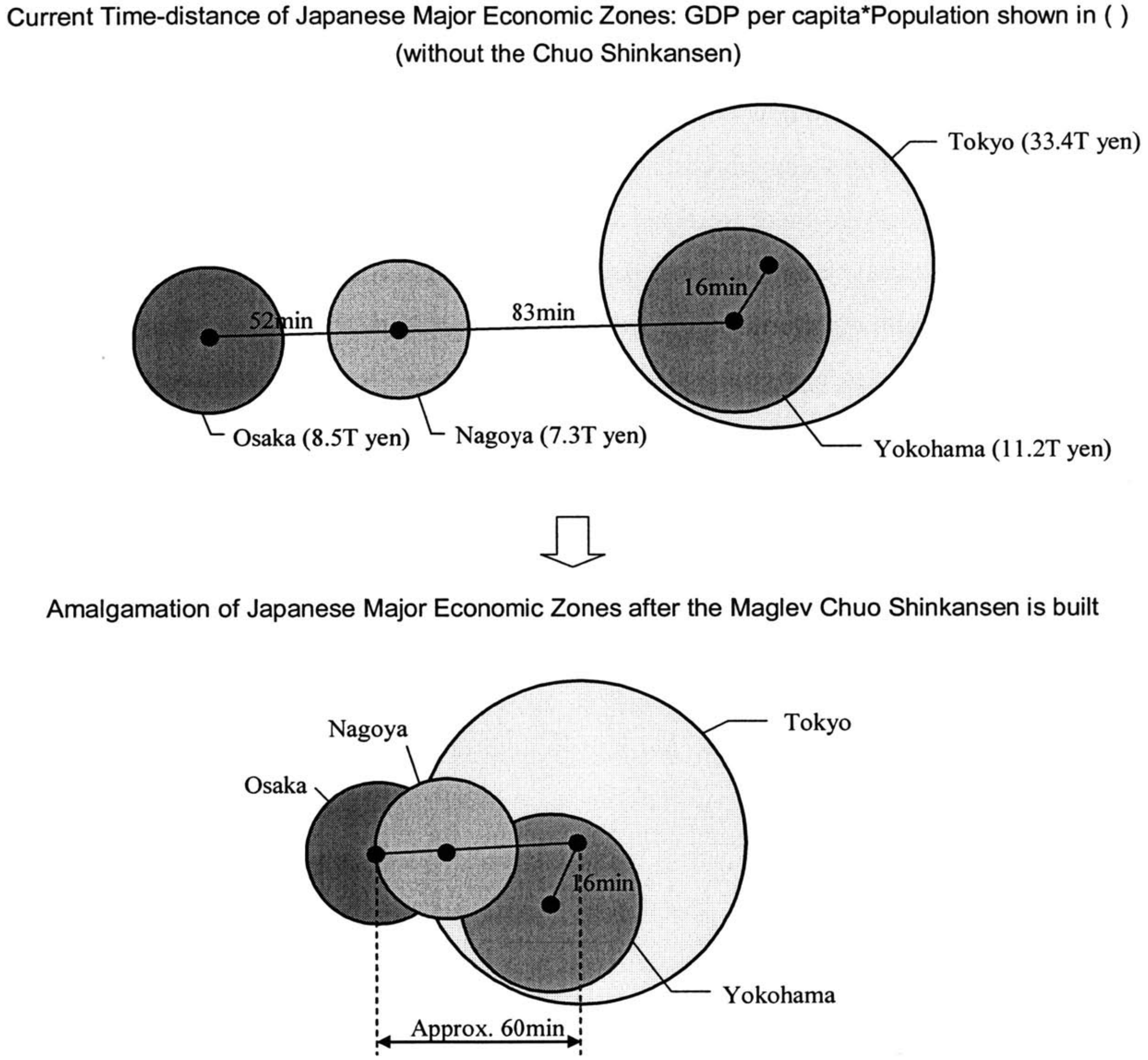
For example, A. Chandra and E. Thompson (2000) examined interstate highway construction to point out the relationship between large infrastructure spending and the level of consequent economic activity [17]. They point out that highways have different impacts across different industries: certain industries grow as a result of reduced transportation costs, whereas others shrink as economic activity is reallocated. They also conclude that highways raise the level of economic activity in the counties that they pass directly through. Euijune Kim (1998) analyzed the effect of hypothetical transportation investments on Korea's GDP [18]. According to Kim's analysis, if the railroad investment had been increased by the amount of 5% of the total transportation investment in 1993, GDP would have risen by 0.392% and the effect would have remain positive (0.012%) seven years later. Considering these analyses, the Chuo Shinkansen seems likely to have a significant effect at least on the regional economic development and it might also improve the nation's GDP.

The Chubu Economic Federation (CEF) of Japan also introduced a unique concept of evaluating the impact of a high-speed railway investment: the formation of "Extra Huge" Economic Zone (EHEZ) [4]. Although EHEZ is basically a qualitative concept, it clearly suggests the potential benefit of a high-speed railway to the society. This section introduces two examples of EHEZ: a case example in Japan which was developed by CEF, and an application of EHEZ to the economy in Portugal, where high-speed railways are being seriously considered.

Formation of the "Extra Huge" Economic Zone in Japan

Owing to the high speed of the Maglev system and to the convenience of railway transportation, the Chuo Shinkansen is expected to drastically reduce the travel time between any metropolitan areas along its route. As a result, it is expected that markets with a total population of about 70 million people will be connected to one another within about one hour, forming a new "Extra Huge" Economic Zone (EHEZ) [4].

Figure 2-5 shows the time-space diagram of major cities in Japan and their economic magnitudes, which CEF defines as GDP multiplied by population [4]. With the Chuo Shinkansen, several major metropolises in Japan will be closely connected to one another. This new EHEZ includes various areas of distinctive attractions: Tokyo as the financial capitol, the Chubu (around Nagoya) area as the manufacturing bases for industries such as automobile makers, the Kinki (around Osaka, Kyoto and Nara) area as the center of tourist attractions, and inland areas for mountain activities. The possibility of the Maglev to connect these areas in a much shorter time than the current high-speed rail service seems likely to enhance the economic activities in these areas significantly [4].



Source: Modified, based on Chubu Economic Federation [4]

Figure 2-5: Time-distance diagram of major cities in Japan, and their economic magnitudes. Economic magnitude is defined as GDP multiplied by population. Time-distance is based on railways [4].

CEF also points out the impact of expansion of the daily activity area. According to CEF's report, the area within one hour from a house is the usual boundary where one goes out for daily activities [4]. This area generally includes places such as hospital, work office, school, and recreational facilities. By taking advantage of the high speed of the Chuo Shinkansen, the area within one hour of travel time will expand and it is expected that people who live along the Chuo Shinkansen will easily enjoy more activities. CEF introduces a concrete example of the new life style that will become possible with the Chuo Shinkansen:

"When I was watching TV news this morning, it reported about the ski run of Minami-alps city in Yamanashi. The weather forecast says it will be fine there today. It will be a little more than one hour to go there from here, Tokyo by the Chuo Shinkansen. Even if I enjoy skiing until dark, I will be able to come back home by eight o'clock in the evening, and that will not interfere with my work tomorrow" [4].

After the Chuo Shinkansen is built, life styles such as this will be possible. Workers will be able to enjoy a wide variety of activities without sacrificing their jobs. The Chuo Shinkansen is expected to create benefits by broadly expanding people's field of activities by offering high speed transportation service.

Formation of the "Extra Huge" Economic Zone in Portugal

The formation of EHEZ seems advantageous not only for Japan but also for other countries. This section explains the benefit of a high-speed railway project, applying this concept in Portugal since currently there are plans to build two new high-speed rail lines in Portugal: Lisbon-Madrid and Lisbon-Porto [19]. This section explains the benefit of Lisbon-Porto high-speed railway project employing the EHEZ concept.

Lisbon is the capital city of Portugal and the urban agglomeration of Lisbon accommodates about 2 million people [20]. Porto, which is located in the northern part in Portugal, has the second largest population in this country. It holds about 1.3 million residents. The geographical locations of these cities are shown in Figure 2-6 with their population.

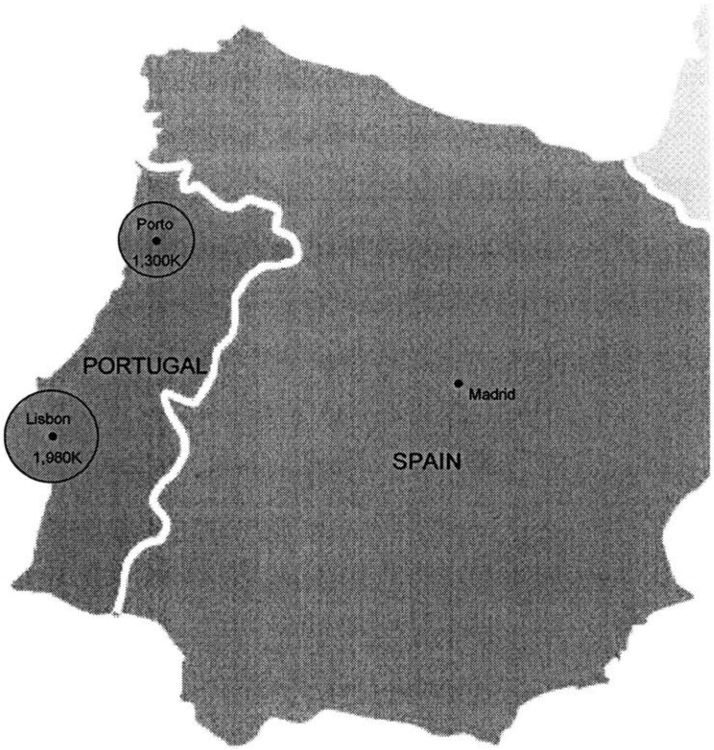


Figure 2-6: Geographical Location and Population of Lisbon and Porto. The population of the metropolitan area of Lisbon, the capital city of Portugal, is about 2.0 million people. Porto, the second largest urban agglomeration in Portugal, accommodates about 1.3 million people and is located about 340km north from Lisbon [20].

The economic magnitudes of these cities can be calculated using GDP and the population size, as defined in the report of CEF. According to the United Nations Statistics Division, the GDP per capita of Portugal was US$ 17,346 in 2000 [21]. By multiplying the GDP per capita with the city population, the economic magnitudes of Lisbon and Porto are calculated as US$ 34.4 billion and US$ 22.6 billion, respectively.

In order to analyze the current relative economic sizes of Lisbon and Porto against other cities, the economic magnitudes of these cities are compared with those of urban agglomerations with 750,000 inhabitants or more in the European Union (EU). Table 2-1 shows the result of the ranking. As can be seen from this table, Lisbon and Porto are the 25th and 46th largest cities in the EU, respectively.

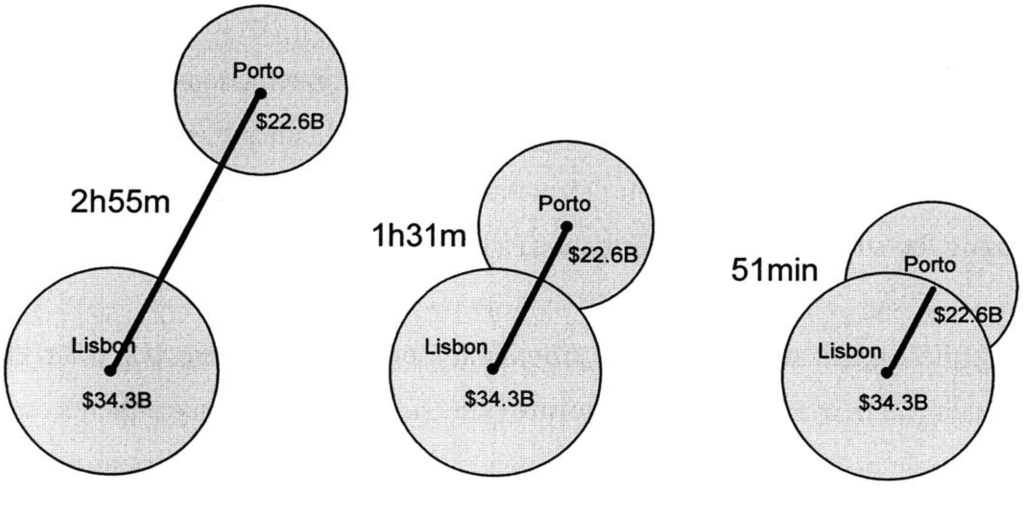
Table 2-1: Economic Magnitude of Urban Agglomeration in EU; Lisbon and Porto are the 25th and 46th largest cities from the viewpoint of Economic Magnitude.

Ranking	City (Urban Agglomeration) with 750,000 inhabitants or more	Country	GDP per capita (2000)	Population (2000)	Economic Scale (=GDP of City)
			(US$)	(Thousand people)	Billion $
1	Paris	France	$25,318	9,693	245.4
2	London	United Kingdom	$24,675	7,628	188.2
3	Rhein-Ruhr North	Germany	$26,075	6,542	170.6
4	Milan	Italy	$24,936	4,183	104.3
5	Madrid	Spain	$19,969	5,036	100.6
6	Rhein-Main	Germany	$26,075	3,688	96.2
7	Barcelona	Spain	$19,969	4,378	87.4
8	Berlin	Germany	$26,075	3,325	86.7
9	Rhein-Ruhr Middle	Germany	$26,075	3,238	84.4
10	Rhein-Ruhr South	Germany	$26,075	3,055	79.7
11	Naples	Italy	$24,936	2,995	74.7
12	Stuttgart	Germany	$26,075	2,677	69.8
13	Hamburg	Germany	$26,075	2,668	69.6
14	Rome	Italy	$24,936	2,743	68.4
15	Vienna	Austria	$27,995	2,158	60.4
16	Munich	Germany	$26,075	2,295	59.8
17	Birmingham	United Kingdom	$24,675	2,243	55.3
18	Manchester	United Kingdom	$24,675	2,223	54.9
19	Athens	Greece	$16,714	3,179	53.1
20	Rhein-Neckar	Germany	$26,075	1,609	42.0
21	Stockholm	Sweden	$24,526	1,641	40.2
22	Leeds	United Kingdom	$24,675	1,417	35.0
23	Lyon	France	$25,318	1,362	34.5
24	Marseille-Aix-en-Provence	France	$25,318	1,357	34.4
25	**Lisbon**	**Portugal**	**$17,346**	**1,977**	**34.3**
26	Bielefeld	Germany	$26,075	1,298	33.8
27	Hannover	Germany	$26,075	1,287	33.6
28	Copenhagen	Denmark	$29,337	1,079	31.7
29	Nuremberg	Germany	$26,075	1,193	31.1
30	Turin	Italy	$24,936	1,247	31.1
31	Amsterdam	Netherlands	$27,229	1,127	30.7
32	Katowice	Poland	$9,935	3,069	30.5
33	Rotterdam	Netherlands	$27,229	1,094	29.8
34	Dublin	Ireland	$30,028	989	29.7
35	Aachen	Germany	$26,075	1,064	27.7
36	Helsinki	Finland	$25,141	1,019	25.6
37	Karlsruhe	Germany	$26,075	980	25.6
38	Lille	France	$25,318	1,007	25.5
39	Brussels	Belgium	$26,491	962	25.5
40	Tyneside	United Kingdom	$24,675	993	24.5
41	Saarland	Germany	$26,075	893	23.3
42	Bremen	Germany	$26,075	882	23.0
43	Liverpool	United Kingdom	$24,675	924	22.8
44	Budapest	Hungary	$12,705	1,787	22.7
45	Nice-Cannes	France	$25,318	894	22.6
46	**Porto**	**Portugal**	**$17,346**	**1,303**	**22.6**
47	Warsaw	Poland	$9,935	2,194	21.8
48	Genoa	Italy	$24,936	847	21.1
49	Toulouse	France	$25,318	779	19.7
50	Goteborg	Sweden	$24,526	792	19.4
51	Bordeaux	France	$25,318	763	19.3
52	Prague	Czech Republic	$13,967	1,181	16.5
53	Thessaloniki	Greece	$16,714	797	13.3
54	Lodz	Poland	$9,935	974	9.7
55	Gdansk	Poland	$9,935	854	8.5
56	Crakow	Poland	$9,935	818	8.1
57	Riga	Latvia	$7,617	761	5.8

Source: Modified, based on United Nations [20][21]

The construction of a new high-speed railway between Lisbon and Porto will expedite the formation of a new EHEZ. Currently, even the most rapid train service takes about three hours to connect Lisbon to Porto, which is about 340km north from Lisbon [22]. Because of multiple stops and this long travel time, it would not be an exaggeration to say that the economic zones of these two cities are basically separated. However, if the new high-speed rail line between Lisbon and Porto is constructed, the new train service will enable people to move between the two cities more easily, leading to the formation of a larger economic zone.

To illustrate, Figure 2-7 shows the change of the time distance between Lisbon and Porto. Figure 2-7(a) indicates the current travel time; Figure 2-7(b) shows the time-distance diagram assuming a TGV line with current technology (222km/h of average speed); and Figure 2-7(c) illustrates the time distance which would be realized if a Maglev line was constructed.



(a) Current Time-distance (b) with TGV (c) with Maglev

Figure 2-7: Time-distance diagram of Lisbon and Porto, with the Economic Magnitudes. Time-distances are based on the scheduled speeds of railways; current scheduled speed, which is 115 km/h [22], would be 222 km/h with TGV [23], and 400 km/h with Maglev [4]. No stops are assumed in the calculations of travel time with TGV or Maglev.

As is clear from Figure 2-7, high-speed railway projects have the potential to expedite the formation of a larger economic zone. Even with the current TGV technology, the travel time between these two cities will become about half of the current one. With the Maglev system, the effect is clearer; the economic zones of Lisbon and Porto will be connected within one hour, the time-distance of daily activities, and a new economic zone with the 17th largest scale of economy in Europe (US$ 56.9 billion) might emerge.

As the result of the formation of EHEZ, we can expect that Portugal will have an increased economic attractiveness. The following three reasons will underpin this claim;

First, CEF points out that the enhanced opportunity of information collection is the key to the attractiveness of an economic zone, especially for knowledge-intensive industries [4]. According to a white paper on the national lifestyle in Japan, Tokyo, which is one of the major financial districts in the world, has attracted large business enterprises, especially financial institutions, primarily because of the increased opportunity for collecting information about markets, industries, and customers [24]. By forming an EHEZ, Lisbon and Porto economies will be able to provide more broad interactions of people, businesses, and industries than they do now, making it possible to gather business information more efficiently. From this reason, the formation of the new EHEZ has the possibility of increasing the attractiveness of Portugal as a business district.

Second, the organization called *the Conference of Scholars along the Chuo Shinkansen* insists that the new EHEZ is likely to provide cheaper land for investments, compared to the magnitude of economic activity of this area [1]. In general, land prices tend to increase with the magnitude of economic activity. However, taking advantage of the high-speed transportation, the new EHEZ will be capable of simultaneously increasing the economic magnitude and offering vast land for industrial use in rural areas. From this point of view, an EHEZ with a very high speed transportation system will attract companies seeking industrial sites.

Finally, Prud'homme (1997) analyzed the relationship between the productivity of cities and their sizes to point out that the larger a city, the higher its productivity [25]. He states that the urban growth, particularly the growth of large cities, is a powerful engine of economic growth, because the marginal productivity of large cities is larger than that of the rest of the country. He also proposes a reasonable hypothesis for this relationship; larger cities are more productive because they have larger labor markets. He explains that the justification for this hypothesis is twofold. First, the larger the labor market, the higher the probability for an enterprise to find exactly the workers it wants, and the higher for a worker the probability of finding exactly the job he or she wants. Then, a larger labor markets also justifies and facilitates specialization of workers and jobs, a well known way of increasing productivity. Since the new EHEZ will be able to offer a larger labor market compared to the current labor markets of Lisbon or Porto, new EHEZ is likely to have a better productivity.

Based on the reasons stated above, it could be said that the formation of a new EHEZ in Portugal has the possibility of increasing the attractiveness of Portuguese economy for investors. Though it is unlikely that the Japanese Maglev system will be adopted in Portugal because the country has been granted significant financial support from the EU [19] and the European rail technology will be considered for the high-speed rail projects in Portugal for the compatibility with existing rail networks, the advancement of the European rail technology also has the possibility of forming an EHEZ in Portugal. For example, TGV has made the speed record of 515.3km/h on May 18, 1990, and a new speed trial is said to be held in 2007 [26]. By utilizing and advancing the European high speed rail technology, it will be possible to develop an EHEZ in Portugal and to increase the level of economic activities in this area.

2.2.4. Technology Export

The previous section explained the benefits of the Chuo Shinkansen as a function of high-speed transportation. In addition to these benefits, R&D of the Chuo Shinkansen also contributes to the development of other industries that utilize the superconducting technology.

According to the report of New Energy and Industrial Technology Development Organization (NEDO), an independent administrative agency in Japan, the superconducting technology is one of the most important research themes for Japanese industry [27]. NEDO's report illustrates eight categories of superconductive technology to be developed. These categories include: 1) application in energy and electricity, 2) application in industry and transportation, 3) application in medical and diagnostic devices, 4) application in information technology, 5) fundamental technology of superconducting wire rod production, 6) fundamental technology of bulk superconducting material production, 7) fundamental technology of integrated circuit device processing, and 8) fundamental technology of cooling systems. Since the Chuo Shinkansen Project is the direct application of superconductive technology to the field of transportation (i.e., the second category in NEOD's list), the project is of great importance for the nation in developing the superconducting technology.

Besides this direct application of superconducting technology to transportation, JR Central is contributing to other application fields of the superconducting technology through the R&D activities of the Maglev technology. For example, JR Central has been entrusted with a national project of developing a 50 kWh-class Flywheel Energy Storage System (FESS) from NEDO. Using a new type of axial superconducting magnetic bearing technology, which is based on powerful magnetic force generated by a superconducting coil [28], the superconducting FESS is expected to be used for various purposes in industrial fields such as electric-load leveling, stabilization for distributed electricity, and stable operation of regenerative brake for railway systems [29].

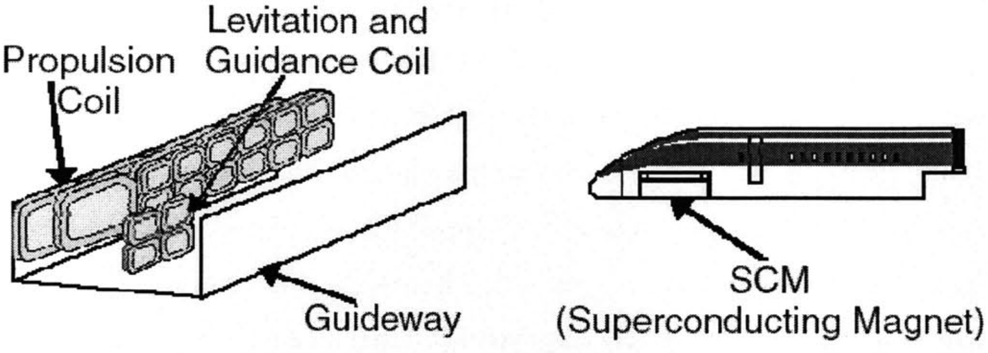
As stated above, the superconducting technology has an extensive number of potential applications in various fields of industry. Since R&D activities of the JR Maglev system contributes to the development of the superconducting technology, progresses of the Chuo Shinkansen Project can have great benefits to the Japanese technological industries.

2.3. Technological Overview of Superconducting Maglev System for the Chuo Shinkansen Project

The JR Maglev system for the Chuo Shinkansen is an internationally acclaimed, cutting edge technology unique to Japan. Unlike the conventional railway system, it adopts a contact-less transport system using the magnetic force between the onboard superconducting magnets and ground coils. This section provides the basic technological overview of the JR Maglev system.

2.3.1. The Principle of the Superconducting Maglev System

In the JR Maglev system, all vehicles are installed with superconducting magnets (SCM) on both sides. On the guideway, there are two types of ground coils installed: Propulsion coil and Levitation coil. The vehicle is propelled, levitated, and guided by the electromagnetic force acting between the on-board magnets and the ground coils [5]. Figure 2-8 illustrates the structure of the guideway and the SCM on the vehicle.

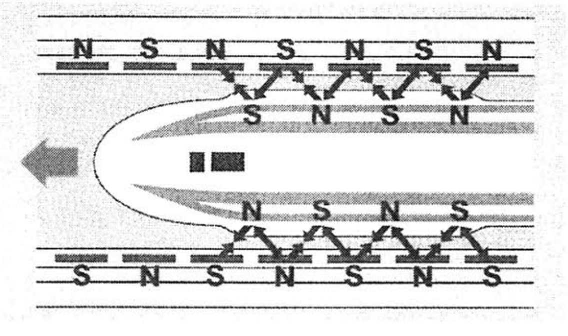


Source: K. Sawada [5]

Figure 2-8: Ground coil, Guideway, and the Superconducting Magnet (SCM) of the JR Maglev. The Maglev vehicle is propelled, levitated, and guided by the electromagnetic force acting between the on-board magnets and the ground coils.

Propulsion System

Propulsion is done by the electromagnetic force between the propulsion coils on the guideway and the Superconducting Magnets (SCM) on the vehicle. By passing an electric current through propulsion coils on the guideway, a magnetic field (north and south poles) is produced, and the vehicle is propelled forward by the attracting force of opposite poles and the repulsive force of the same poles acting between the ground coils and the SCM on the vehicle [3]. Figure 2-9 provides the scheme of the propulsion system.

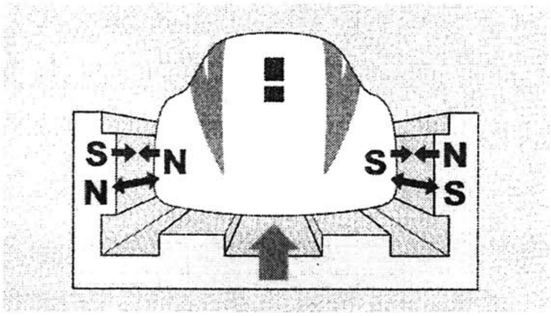


Source: Central Japan Railway Company [3]

Figure 2-9: Principle of Propulsion of Maglev. The Maglev vehicle is propelled forward by the electromagnetic force between the ground coils and the SCM on the vehicle.

Levitation / Guide System

Unlike the propulsion system, the levitation or guide system requires no power from outside. When SCM passes over the "8" figured levitation coil at high speed, a current is induced in it and passes through the levitation and guidance coils on either side generating an electromagnetic force that both pushes up (repulsive force) and pulls up (suction power) the car [3]. By connecting the appropriate levitation coils of both sidewalls, it is also possible to make these coils a guide system. When the vehicle runs nearer to one sidewall, a circulating current between these two coils is induced and this current produces a guiding force [5]. Figure 2-10 illustrates the principle of the levitation/guide system.

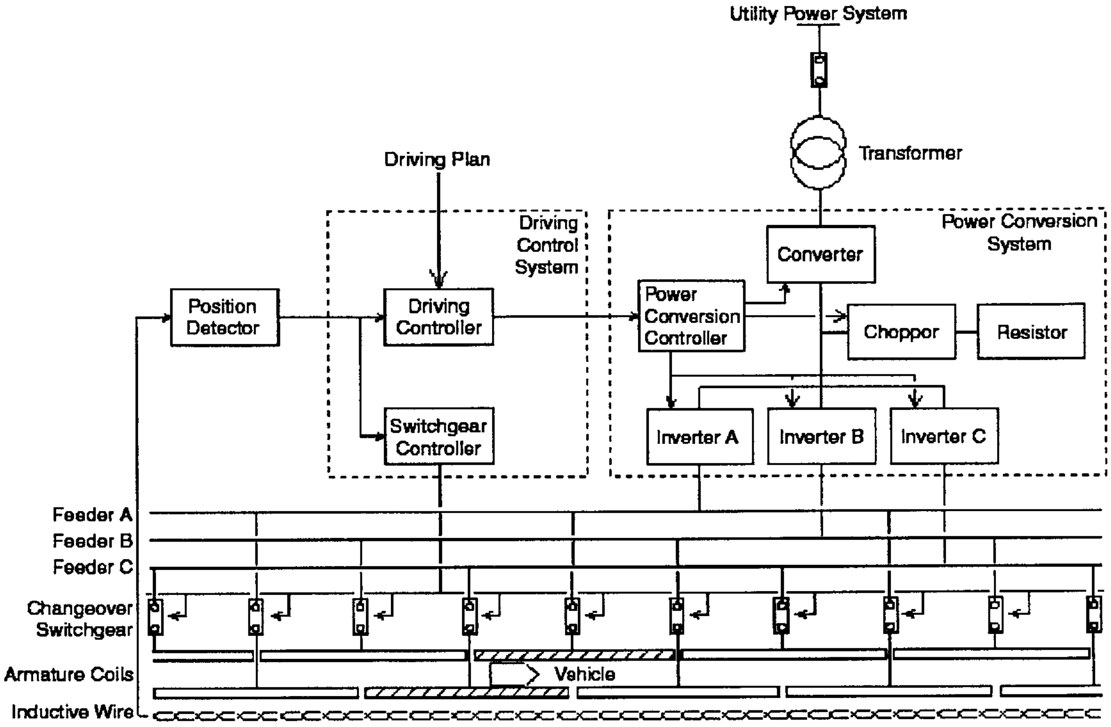


Source: Central Japan Railway Company [3]

Figure 2-10: Principle of Levitation of Maglev. The electric current, which is induced when SCM passes over the levitation and guidance coil, levitates the vehicle. When the Maglev vehicle runs nearer to one sidewall, a circulating current is induced between the connected two coils on the sidewalls, and this current produces a guiding force.

2.3.2. Electric Power Conversion and the Drive Control System

A Maglev train of the Yamanashi Maglev Test Line is controlled by two systems: the Power Control System (PCS) and the Drive Control System (DCS). Figure 2-11 shows the outline of PCS and DCS.

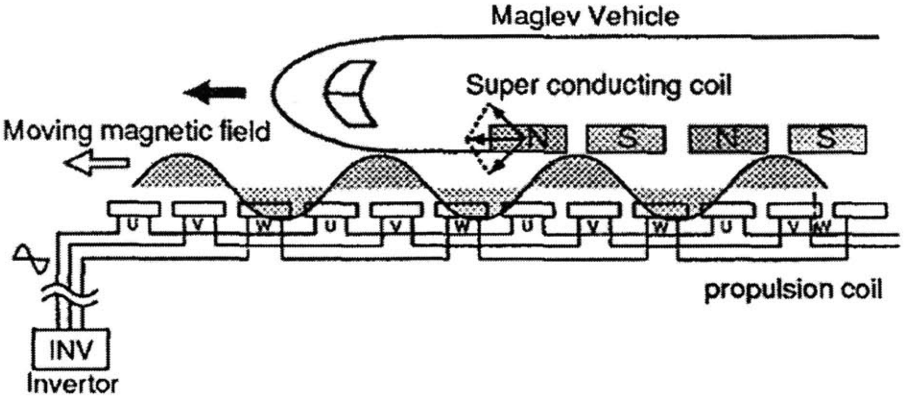


Source: M. Ono, S. Koga and H. Ohtsuki [7]

Figure 2-11: Power Conversion System and the Drive Control System for the Yamanashi Maglev Test Line

DCS generates the running pattern. The vehicle speed is calculated from the vehicle position information detected by the cross-inductive wire system. DCS sends the phase and amplitude references of current to PCS so as to enable it to control the vehicle based on the running pattern [7].

PCS has a converter, chopper, three-phase inverter, and a control device. Every third propulsion coil on the sidewall of the guideway is electrically connected and made into a three-phase armature of a motor. Fed by the three-phase alternative current, these coils produce a moving magnetic field. By synchronizing the field's moving speed and the SCM's moving speed, the train is propelled smoothly [7]. Because the field's moving speed is proportional to the current's frequency, inverters in PCS must control the current's frequency according to the train speed [5]. This system is called as the Linear Synchronous Motor (LSM). Figure 2-12 graphically illustrates the mechanism of LSM.



Source: K. Sawada [5]

Figure 2-12: Scheme of the Linear Synchronous Motor (LSM). Every third coil is connected and made into a three-phase armature of a motor. Fed by the three-phase alternative current, these coils produce moving magnetic fields, which then propel the Maglev vehicle.

As is clear from the above description, the operation of a Maglev train requires a dedicated PCS. Unlike the conventional train system in which a power substation can send electricity to multiple trains, the Maglev system is not capable of operating trains beyond the number of PCSs. Therefore, in the Maglev system, the number of PCSs defines the maximum number of trains that can be operated simultaneously. This distinctive system feature of Maglev is making the system design inflexible. This difficulty leads to the problem discussed in the following chapter.

Chapter 3 Problem Set-up: Challenges in Designing the Maglev System for the Chuo Shinkansen Project

This chapter explains the challenges in designing the Superconducting Magnetically Levitated Linear Motor Vehicle (JR Maglev) System for the Chuo Shinkansen Project. It also provides the framework for the evaluation of the project. The previous chapter explained the technological features of the JR Maglev system. The most distinctive technological aspect is that, in the JR Maglev system, every Maglev train requires a roadside dedicated Power Conversion System (PCS). This system feature is fundamentally different from the power supply system in conventional train systems and is making it difficult for the project planners to design competitive systems and choose the appropriate one. This chapter explains the difficulties in designing the Maglev system by identifying the major uncertainties associated with the plan-making of the project. It also provides the project evaluation framework with which later chapters analyze the Chuo Shinkansen Project considering the identified uncertainties.

3.1. Identification of Uncertainties

3.1.1. Exogenous Uncertainty

As stated above, in the JR Maglev system, each Maglev train requires a dedicated PCS but a different one as it moves along the route. This means that the system designers of the Chuo Shinkansen Project must accurately estimate demand. In addition, they must decide how many trains are to be operated simultaneously at peak hours in order to determine the number of PCSs to construct if the operational speed is given.

If the future demand could be forecast correctly, the best policy would be to construct the precise number of PCSs to meet this demand. However, forecasting the future demand is always difficult. Flyvbjerg et al (2005) conducted a study of the accuracy of transportation-demand forecasting, and their result showed the tendency to overestimate in railway projects [30]. According to their study, 84% of the rail projects have actual traffic over 20% below forecasted traffic. This data clearly shows the difficulty of accurately forecasting the future demand of transportation projects. In other words, it is important to take the uncertainty of demand forecasting into account when evaluating a rail project; thus, this thesis considers the uncertainty of demand as one of the major risks associated with the project.

3.1.2. Endogenous Uncertainty

In addition to taking the uncertainty of demand into consideration, it is helpful to incorporate flexibility into the system design in order to make the project development plan more feasible. By developing the technology that permits later installation of PCSs after the initial construction, the designers can make it possible to construct the line with a small number of PCSs for the early period of operation and to add more PCSs only if the demand grows enough. This "flexible" system development strategy not only alleviates the difficulty of deciding the number of PCSs to construct, but also makes the project more attractive to investors by reducing the large initial costs. However, in order to make the flexibility of the system possible, Central Japan Railway Company (JR Central) needs to conduct further research and development (R&D) of the Maglev technology. This section provides information about the potential cost-reducing benefit of R&D for flexible system design, and it also identifies the technological uncertainty associated with the R&D.

Potential Cost-Reducing Effect of R&D

The Chuo Shinkansen Project is expected to require a large initial construction cost. According to Tatematsu (2004), the Ministry of Land, Infrastructure and Transport (MLIT) in Japan announced that the estimated construction cost of the Chuo Shinkansen Project would be about 7.7 trillion yen to 9.2 trillion yen [6][1]. In this announcement, MLIT did not

---

[1] About 66 to 79 billion US dollars at the rate of US$1 = 117 Yen.

clarify the cost of PCSs nor how many PCSs were assumed. However, because the inverters used in the PCS in the Yamanashi Maglev Test Line (YMTL) are the world's largest-class inverters [7], the cost of PCSs may account for a significant amount of the total construction cost. Therefore, reducing the number of PCSs to install at the time of construction has the possibility of increasing the profitability of the Chuo Shinkansen Project.

Although the detailed cost information on the Chuo Shinkansen Project is not publicly available, for the sake of analyzing the effect of system design flexibility, at least three data elements must be determined: the cost of a PCS, the number of PCSs to install, and the total cost of the rest of the components. In order to calculate these data, this thesis assumes that the following assumptions are used in MLIT's calculation of the construction cost of the Chuo Shinkansen Project.

First, this thesis assumes that 20km of coverage of a PCS is used in the estimation of MLIT (Assumption 1). This is because 20km is the approximate length of the test track of the YMTL (18.4km). As a result, total 50 PCSs (25 PCSs for each direction[2]) are to be needed for the entire route.

Second, the thesis assumes that the cost of a PCS used in the MLIT's calculation of construction cost is the 18.5 billion yen (Assumption 2). There is little available information about the cost of a large-scale electricity converter system. Thus this thesis uses this value which is the cost of a large-capacity electricity converter in Shin-Shinano Substation of Tokyo Electric Power Company [31].

Finally, by assuming that the total construction cost is 8,450 billion yen which is the median value of the range of the estimated construction cost suggested by MLIT [6] (Assumption 3), the cost information needed for the analysis of the project are obtained as shown in Table 3-1.

---

[2] 500km (length of the entire route) / 20km (assumed coverage of a PCS) = 25 PCSs (necessary number of PCSs per track.

Table 3-1: Assumed Construction Cost of the Chuo Shinkansen Project

Item	Value	Unit	Comment
Number of PCSs	50 (25 per track)		Assumption *1
Cost of one PCS	18.5	¥ Billion	Assumption *2
Total PCS Cost	925	¥ Billion	11% of the Total Construction Cost
Total Construction Cost	8,450	¥ Billion	Assumption *3
Total Cost less PCS Cost	7,525	¥ Billion	

*1: Assume 20km of control coverage technology of a PCS, which is approximately the same as the current technology in the Yamanashi Maglev Test Line (18.4km). 25 PCSs (500km/20km=25) are needed per track (i.e., each direction).

*2: Assume the same cost as the electricity conversion system in Shin-Shinano [31]. Last accessed on March 6, 2007.

*3: Assume median value of the range of estimates proposed by MLIT [6].

From the information in Table 3-1, PCSs are calculated to account for about 11% of the total construction cost: a large expense considering the amount of the total construction cost. In this calculation, 25 PCSs per track are considered. However, this number of PCSs is much larger than the number of PCSs necessary to realize the operational frequency proposed in the government's plan (10 trains/hour[3]) [6]; therefore, if the R&D succeeds in developing a new PCS which covers a longer length of track yet does not cost more than the current one, it will be possible to reduce the construction cost by decreasing the number of PCSs to construct.

To illustrate, Equations 3-1 and 3-2 give the necessary number of PCSs, N_{PCS}, to realize an operational frequency, f.

---

[3] This frequency corresponds to the capacity of 10,000 passengers per hour [32][32].

$$N_{PCS} = \frac{L_T}{L_c}$$ **Equation 3-1**

$$L_c = \frac{V}{f}$$ **Equation 3-2**

Where N_{PCS}: Number of PCSs to construct per track

L_T: Total length of track for each direction
(=500km for the Chuo Shinkansen)

L_c: Coverage of a PCS (minimum interval between any two trains)
(km/train)

V: Average speed of a train (= 400km/h for the Chuo Shinkansen[4])

f: Operational frequency (trains/hour)

Using these equations with the currently established coverage length of a PCS (20km), the realizable operational frequency is calculated to be 20 trains per hour, which is double the frequency in the government's plan. Instead, if the coverage of a single PCS is extended from 20km to 40km, for example, we will need to construct only 26 PCSs (13 PCSs per track) to offer the operational frequency in the government's plan. This extension of the coverage of PCSs will lead to the reduction 24 PCSs, which will then mean the reduction of the initial construction cost by 5%. Of course, if the demand grows significantly later, we will need to install additional PCSs; otherwise, we will just be able to save the initial construction cost by this fraction. Considering the large construction cost, R&D of the technology that can reduce the initial cost by extending the coverage of a PCS, and decreasing the number of initially installed PCSs has the possibility of significantly improving the feasibility of the project.

---

[4] According to Chubu Economic Federation (2003), the travel time between Tokyo and Osaka (500km) is projected to be 70 to 80 minutes [4]. This thesis assumes 75 minutes of travel time and 400 km/h of average speed (500km / 75min * 60min/hour = 400 km/hour).

Critical Technical Uncertainty

For the sake of improving project feasibility, it is important to develop a flexible project strategy: constructing fewer numbers of PCS at the time of construction and installing additional PCSs later only if the demand grows enough. However, in order to take advantage of the flexible development plan, JR Central has to address at least three technological issues: 1) the safety requirement, 2) the development of the technology to extend the coverage of a single PCS, and 3) the development of technology to install PCSs later at a low cost.

The first issue, the safety requirement, is the most important problem for a transportation system. However, in the Chuo Shinkansen Project, this requirement will not become the binding constraint in developing the flexible system design.

In order to run multiple trains safely, it is absolutely vital to secure the minimum interval requirement between any two trains. In the JR Maglev system, a Maglev train at the top speed requires about 5 to 6 km to stop [10], thus, the minimum interval must be at least 6km. This distance requirement means that the number of PCSs must not exceed 83 per track (500/6=83.3). As explained earlier, even 25 PCSs per track will enable twice as many trains to depart compared to the government's plan; therefore, it is unlikely that the safety requirement constrains the development of the flexible system design. To conclude, we only need to make sure that no more than 83 PCSs per track are planned.

The second issue, the development of the technology to extend the coverage of a PCS, is critical for the flexibility of the system. Thus far, JR Central has been conducting test runs at YMTL, a test line which is 18.4km long, and the technology to control the Maglev train over this distance has been established. However, even assuming 20km of coverage instead of 18.4km, at least 25 PCSs would be needed for each direction for the Chuo Shinkansen Project. This number of PCS would mean that up to 20 trains per hour could depart, which would be double the peak-hour departure frequency proposed in the government's plan [6].

Without the extended coverage of a PCS, Maglev system designers will need to construct the Chuo Shinkansen with a large capacity (compared to the capacity proposed in the government's plan) with higher than the needed costs, regardless of the size of the demand they want to meet.

Currently, JR Central is planning to extend the YMTL to 42.8km for further experimentation [2]. If the technology to develop a new PCS that covers 40km of track (without inducing a large extra cost compared to the current PCS cost) is developed, it will be possible to construct the Chuo Shinkansen with only 13 PCSs per track to realize the plan proposed by the government and to reduce the initial construction cost. Therefore, the technology to extend the coverage of a PCS is the essential step for the flexibility of the system design.

The third technology, to be able to install PCSs later at a low cost, is also important. If the cost to install a PCS later is very large compared to the initial construction cost, the expansion of capacity will not be advantageous and the flexibility will be virtually meaningless. Among the costs of installing a PCS later, the cost of a PCS itself will be basically the same as that of the initial construction. Unfortunately, no information about the cost of the rest of the work – modifying the existing wiring – is available as of now. However, this technology of adding PCSs later at a low cost becomes meaningful only after it becomes possible to construct the Chuo Shinkansen with small numbers of PCS (compared to the government proposed plan). Therefore, the priority should be placed on the technology of extending the coverage of a PCS and reducing the number of PCSs to construct initially (i.e., the second issue), rather than lowering the cost of later installation of PCSs (i.e., the third problem).

Based on the above discussion, this thesis addresses the second issue – extending the coverage of a PCS – as the main technical uncertainty associated with the project. Since R&D is not a Yes-No problem, this study considers several outcomes of R&D: a total success, a partial success, and a total failure. For the total success case, this thesis assumes

40km of coverage, as the approximated value of the projected track length of YMTL (42.8km) which JR Central is planning to extend. For the total failure case, it assumes 20km of coverage, the same technology level as the current YMTL. As the median value, the thesis assumes 30km for the partial success case. Considering these three outcomes of R&D to extend the PCS coverage, this work aims to incorporate the technical uncertainty into the total appraisal of the project.

To conclude, this thesis deals with both the uncertainty of demand and the technical uncertainty of R&D. Considering both the volatility of demand growth and three different outcomes of R&D activity, the thesis attempts to build a framework for evaluating the Chuo Shinkansen Project that explicitly includes these uncertainties.

3.2. Framework of the Analysis

In order to appropriately evaluate the Chuo Shinkansen Project, which has both the uncertainty of demand and the uncertainty of R&D, a framework that can explicitly treat both of these uncertainties is needed. The "hybrid real options" analysis, which Neely (1998) developed, is a composite analysis method of the decision analysis and the options analysis and is suitable for appraising projects with these uncertainties [9]. The decision analysis is an effective method for valuing projects with uncertain outcomes associated with project risks (endogenous risks) such as R&D, because it complements the inadequacy of traditional valuation methods such as the benefit-cost analysis (BCA) and the discounted cash flow (DCF) method [9]. The options method is appropriate for valuing projects with either managerial or system flexibility against market risks (exogenous risks). Taking advantage of the hybrid real options analysis, this thesis constructs a valuation model suitable for the Chuo Shinkansen Project, considering both the uncertainty of demand and the uncertainty of R&D which results in different system designs.

Figure 3-1 illustrates the general framework of the analysis for the Chuo Shinkansen Project. Based on the results of demand estimation and the R&D outcomes, the requirements for the system capacity can be determined. By comparing the requirements with the possible R&D outcomes, the system designers can identify the potential design specifications and several scenarios for modification of the system design. Considering the volatility of demand growth and the options for modifying the system design, the hybrid real options analysis calculates the total value of the project.

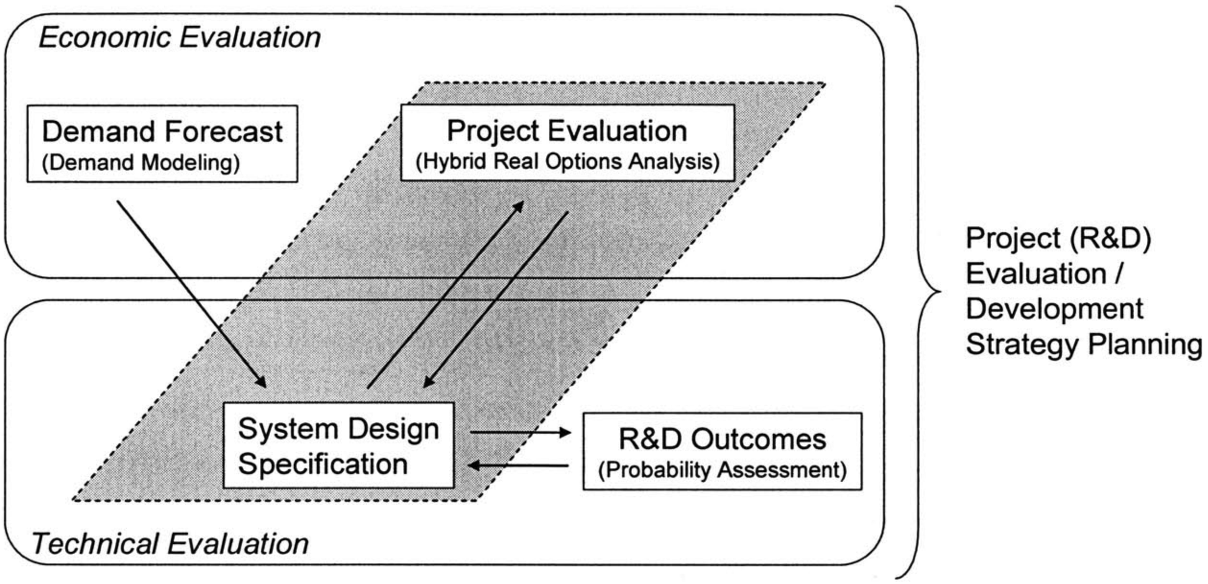


Figure 3-1: General Framework of Analysis for the Chuo Shinkansen Project. This thesis focuses on the development of hybrid real option valuation model appropriate for the Chuo Shinkansen Project (i.e., the grey-colored part in the diagram), which considers both the demand uncertainty and different levels of R&D outcomes.

Among the components in this analysis framework, this thesis places the main priority on the development stage of the model of the hybrid real options analysis for the Chuo Shinkansen Project. Both the demand forecast and the R&D probability assessment are important. However, the Ministry of Land, Infrastructure and Transport (MLIT) of Japan has already developed the forecast of demand for the Chuo Shinkansen though the data is only partially available to the public currently [4]. The assessment of the success of R&D still remains to be developed; however, it is beyond the scope of this thesis and it could require another thesis-equivalent work. Therefore, this thesis simply assumes several sets of probabilities for the three levels of R&D outcomes stated above and analyzes the sensitivity of the project value against these probabilities. As a result, this thesis focuses on the application of the hybrid real options analysis to the Chuo Shinkansen Project, assuming volatility of demand growth as well as three different outcomes of the R&D with their probabilities.

Based on this analytical framework, the following two chapters explain the fundamental valuation concepts for project evaluation and options analysis methods including the hybrid real options analysis.

Chapter 4 Basic Concepts for Project Valuation

The value of a project is defined as the net present value of net cash flows in the life of the project. It serves as a basis for capital budgeting, which is concerned with the allocation of resources among investment projects on a long-term basis [33]. Although firms utilize different evaluation criteria such as discounted cash flow (DCF), internal rate of return (IRR), cost-benefit ratio, decision analysis, and real option analysis methods in capital budgeting depending on their preferences, the essence of these methods is the same: the net present value (NPV) analysis [34]. This chapter explains basic concepts in NPV analysis including the time value of money, the discount rate, the calculation methods of NPV, and the decision analysis.

4.1. Time Value of Money

In many projects, especially with large systems, the cost of initial investment is reimbursed over a long time; the investments today generate benefits for many years in the future. Therefore, when analyzing whether a project is worthwhile an investment, it is imperative to compare the costs and the benefits that occur at different times.

The essential problem in evaluating projects over time comes from the fact that money has a time value [35]. In general, a dollar now is worth more than a dollar in the future because the dollar can be invested to earn interest immediately [34]. Therefore, to compare a cash flow in the future with a cash flow today, we need to convert the future cash flow into Present Value (PV) by discounting it by the discount rate:

$$\text{PV (Present Value)} = \frac{CashFlow}{(1+r)^t} \qquad \textbf{Equation 4-1}$$

Where r: the discount rate

t: the number of periods into the future when the future cash flow occurs.

From a practical point of view, the values generated by this formula are quite sensitive to the two parameters, the duration of "life" of the project, N, and most particularly, the discount rate. Furthermore, these factors, especially the discount rate, cannot be known precisely [35]. Therefore, it is important to select an appropriate method of calculating the discount rate based on the characteristics of risks the project faces. The following section introduces several commonly used methods of estimating the discount rate.

4.2. The Discount Rate

"Finance theory does provides guidance on how to select an appropriate discount rate for a project [9]". It suggests utilizing several techniques of calculating the discount rate based on the risk profile of the project. These methods include, Weighted Average Cost of Capital (WACC), Capital Asset Pricing Model (CAPM), and Arbitrage Pricing Theory (APT). This section explains these estimating methods of the discount rate.

4.2.1. Weighted Average Cost of Capital

The Weighted Average Cost of Capital (WACC) is one of the commonly used methods of calculating the discount rate. When a firm invests in a project, it generally needs to raise fund from various sources. WACC indicates the expected rate of return on the capital which a firm raises for its project from these sources. Therefore, if a project indicates a positive project value with WACC being the discount rate, the project is considered to yield a positive profit.

WACC is calculated as the product of the fraction of total capital from each source and the cost of capital from that source, summed over all sources. Equation 3-3 shows the simplified formula of WACC only looking at debt and equity sources [36].

$$WACC = \left(\frac{D}{D+E} \cdot r_d + \frac{E}{D+E} \cdot r_e \right)$$ **Equation 4-2**

Where $WACC$: Weighted Average Cost of Capital,

r_d: Expected rate of return on debt (Cost of debt)

re: Expected rate of return on equity (Cost of equity)

D: Amount of debt

E: Amount of equity

The first thing to notice about WACC is that all variables in it refer to the firm as a whole. As a result, the formula gives the right discount rate only for projects that are just like the firm undertaking them. The formula works for the "average" projects [36]. Therefore, if the risk profile of a project is not similar to the firm's average risk characteristics, it is inappropriate to use WACC to estimate the discount rate for the project. This limitation of WACC leads to the Capital Asset Pricing Model (CAPM) which adjusts the discount rate according to the level of the risk.

4.2.2. Capital Asset Pricing Model

For more than 30 years, financial theorists have generally favored the notion that using the Capital Asset Pricing Model (CAPM) is the preferred method to estimate the cost of equity capital [37]. In spite of much criticism that CAPM adopts several strong assumptions such as the existence of a perfect market where stock prices are not affected by their trade and all the information is perfectly shared among investors [38], it still is the most widely used model for estimating the cost of equity capital, especially for larger companies [37].

In CAPM, risks associated with projects are classified into two categories: the systematic (market) risk and the idiosyncratic (unique) risk [8]. Idiosyncratic risk stems from the fact that many of the perils that surround an individual company (project) are specific to that company (project). Therefore, idiosyncratic risks can be eliminated by broadly diversifying investments. In contrast, the systematic risk, which stems from the fact that there are other economy-wide perils that threaten all businesses, cannot be diversified. As a result, CAPM proposes that the level of return an equilibrium market requires from an investment is a function of its systematic risk component [8]. Equation 3-4 mathematically summarizes the findings of the CAPM.

$$E(r_i) = r_f + \beta_{im}\left[E(r_m) - r_f\right]$$ **Equation 4-3**

Where $E(r_i)$: Expected rate of return of the capital investment (asset)

r_f: Risk-free rate of return[5]

$E(r_m)$: Expected rate of return of the market

β_{im} : Sensitivity of the asset returns to the market returns

As is clear from its form, Equation 3-4 implies a straight line called the security market line. This relationship means that the expected rate of return for an investment is linearly correlated with β_{im} (beta) which is the sensitivity of the asset return to the market return [8]. Equation 3-5 defines β_{im} :

$$\beta_{im} = \frac{Cov(r_i, r_m)}{Var(r_m)}$$ **Equation 4-4**

Where $Cov(r_i, r_m)$: Covariance between the expected rate of return of the investment (r_i) and the expected rate of return of the market (r_m)

$Var(r_m)$: Variance of the expected rate of return of the market.

---

[5] Usually, bonds are considered risk free. Therefore, the interest rate on a bond is often used as the risk-free rate of return.

A capital investment has, by definition, a β equal to 1.0 if its return moves up and down in accordance with the market portfolio (a broad set of investments). Instead, if a project has a return that moves with greater magnitude in the same direction as the market (i.e. $\beta > 1.0$), this project is considered riskier and investors require a larger return on it than the market portfolio.

In the security industry, β is a widely published and periodically updated statistic. It is measured by regressing changes in the price of the stock against changes in the market index. The slope of that regression line is labeled as β and is a widely used measure of a stock's riskiness. Many investment advisory services compute and publish estimates of β [39]. Using the data of β and the data of expected rate of return on market and on bonds, CAPM provides a practical method of calculating the discount rate.

4.2.3. Arbitrage Pricing Theory

The Arbitrage Pricing Theory (APT) is another way of calculating the expected rate of return of an asset. Contrary to CAPM, the derivation of APT does not require the existence of an efficiently diversified market portfolio; APT attempts to minimize idiosyncratic (unique) risk by involving simultaneous buying and selling of different assets that have highly correlated returns [40]. As a result, it makes use of more than one index to explain returns: the following equation expresses the form of the APT.

$$E(r_i) = r_f + \beta_{i,1}\lambda_1 + \beta_{i,2}\lambda_2 + \cdots + \beta_{i,n}\lambda_n \qquad \textbf{Equation 4-5}$$

Where r_f : Risk-free rate

$\beta_{i,j}$: Security i's "beta" for risk factor j ($j = 1, 2, \ldots$, n)

λ_j : Premium for risk factor j.

Equation 3-6 indicates that if $\lambda_1 = \lfloor E(r_m) - r_f \rfloor$ and all the other $\lambda_j = 0$, then APT reduces to CAPM. In this way, CAPM can be said to be a special case of APT. APT applies to any subset of assets and does not require the existence of an efficiently diversified market portfolio. Therefore, APT is considered more robust than CAPM.

However, Broyles (2003) notes that after more than two decades, the use of CAPM appears to be more frequent than APT for estimating expected rates of return for individual assets such as individual company shares or capital projects [40]. Development of a more generally accepted methodology for using APT for estimating expected return rates seems to have not yet arrived either. In the meantime, CAPM appears to continue to provide a simple and useful way to estimate expected returns [40].

The next section explains the Net Present Value / Discounted Cash Flow method, based on the concepts of the time value of money and the discount rate.

4.3. Net Present Value / Discounted Cash Flow Method

The Net Present Value (NPV) method, which is also known as the Discounted Cash Flow (DCF) method, is one of the most commonly used financial methods for evaluating investments. The NPV of a project is the present value of its expected future incremental cash inflows and outflows. Therefore, to calculate NPVs, the expected cash inflows generated by the project, the expected cash outflows required to implement the project, and the discount rate must be determined [41]. NPV is then calculated as the sum of the discounted inflows and outflows (Equation 4-6).

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{E(FCF_t)}{(1+r_i)^t}$$ **Equation 4-6**

Where I_0: Investment at time zero

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

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

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

With a rather straightforward calculation, NPV intuitively tells us whether or not the project is worth more than it costs: if a project has a positive NPV, the project is worth implementing. Furthermore, NPV gives us an estimate of how much value the project would add for shareholders. Perhaps owing to the intuitiveness and the ease of calculation, NPV has become the most frequently used technique for capital budgeting[6].

However, NPV also has a critical limitation: it cannot appraise the possible modification of projects in the future. In real world businesses, it often happens that the forecasted future scenario differs from the reality, and the management modifies the project. Nevertheless, NPV cannot consider this situation because it calculates the project value based on a single

---

[6] According to the survey of J. R. Graham and C. R. Harvey (2001), the NPV and the IRR which shares the same concept with the NPV were the most frequently used capital budgeting technique [42].

predetermined scenario of future cash flows. This limitation of NPV has led to the development of decision analysis explained in the next section.

4.4. Decision Analysis

Decision analysis is a powerful tool for depicting and facilitating the evaluation of projects, especially those that involve sequential decisions and variable outcomes over time. Decision analysis has great usefulness in practice because it makes it possible to look at a large complicated problem in terms of a series of smaller simpler problems, and it enables objective analysis and decision-making that include explicit consideration of the risk and effect of the future project modification [39]. The analysis utilizes a tree-like structure to model decision alternatives and select the best choice based on the expected value of each alternative. Figure 4-1 provides an example of a one-stage decision tree model.

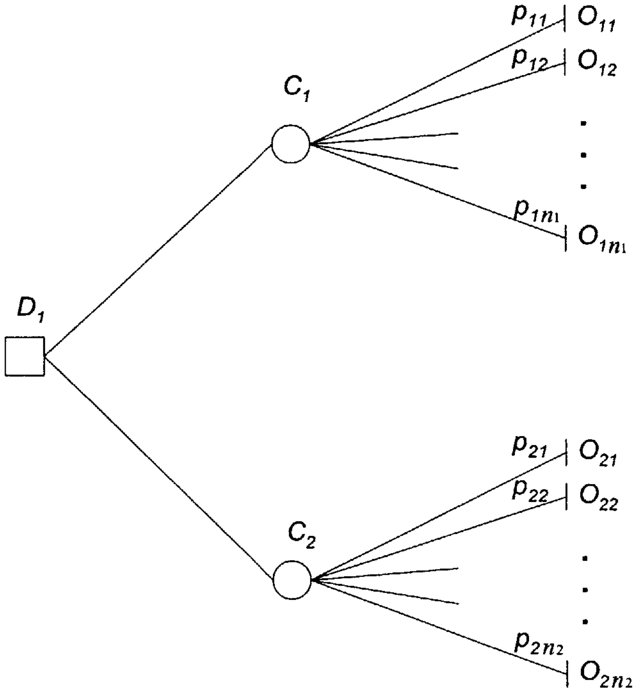


Figure 4-1: One stage decision tree

In the model represented by Figure 4-1, there is one decision stage, D_1, where two alternatives are available: C_1 and C_2. These alternatives, C_1 and C_2, have multiple possible outcomes, O_{11} through O_{1n_1}, and O_{21} through O_{2n_2}, respectively, with associated probabilities, p_{11} through p_{1n_1}, and p_{21} through p_{2n_2}.

The expected value of each alternative is calculated using the next equation [35]:

$$E(C_j) = \sum_{i=1}^{n_j} p_{ji} \cdot O_{ji}$$ **Equation 4-7**

Where $E(C_j)$: Expected value of alternative C_j (j=1 or 2)

p_{ji}: Probability of outcome O_{ji}

O_{ji}: ith outcome of alternative C_j

n_i: Number of outcomes associated with alternative C_j

By comparing $E(C_1)$ with $E(C_2)$, the decision-maker can choose the alternative that will yield the better result. This analysis can be easily extended to projects with more stages or more decision alternatives. Project managers can find the best scenario by: calculating expected values of each alternative at each stage and selecting the best choice at the stage, and repeating the same calculation from the last stage to the first stage [35].

Decision analysis differs from the traditional economic evaluations, such as NPV; while traditional economic evaluations calculate the project value based only on the most likely scenario of the project, the decision analysis takes the project-associated uncertainties and the evolution of the project into account. By incorporating multiple outcomes and their probabilities into the analysis, decision analysis enables analysts to evaluate the project considering the uncertainties associated with the project. From this viewpoint, decision analysis is a basis of real options analysis that evaluates both flexibilities and uncertainties of projects.

4.5. Conclusion about Basic Concepts for Project Valuation

This section explains fundamental concepts necessary for evaluating projects: time value of money, the discount rate, the net present value method, and decision analysis.

It first introduces the notion of time value of money. This concept is important for the analysis of the net present values of projects because, in most projects, the cost of initial investment is reimbursed over a long period of time. By discounting the future cash flow by an appropriate discount rate, project managers can compare cash flows that occur at different times.

This thesis also explains three methods to obtain the discount rate which is necessary in the calculation of the net present values of projects: the weighted average cost of capital, the capital asset pricing model, and the arbitrage pricing theory. In particular, the thesis emphasizes CAPM because it appears to continue to provide a simple and useful way to estimate expected rate of return on a project [40].

Based on the concepts of the time value of money and the discount rate, the thesis introduces two methods of calculating the value of projects: NPV and decision analysis. Although NPV is one of the most commonly used financial methods for evaluating investments, it suffers from the limitation that it calculates the project value based only on a single pre-determined scenario of cash flow. In contrast, decision analysis is capable of considering several scenarios by incorporating multiple outcomes and their probabilities into the analysis. In this sense, decision analysis can be said to be the base for real options analysis.

Building upon the theoretical foundation of project evaluation described in this chapter, the next chapter explains theories of real options analysis and the hybrid real options analysis developed by Neely (1998) [9].

Chapter 5 Real Options Analysis

Real options analysis is an evaluation method for projects with decision opportunities. It applies financial options theory to the real-world projects, such as infrastructure developments, real asset investments, manufacturing projects, and research and development (R&D) activities. In these projects, decision makers generally hold options that include the option to defer, the option to alter the operation scale, and the option to abandon. This chapter begins by introducing the basic concepts of options theory, and explains the hybrid real options analysis developed by Neely (1998) [9], as an appropriate real options model for the Chuo Shinkansen Project.

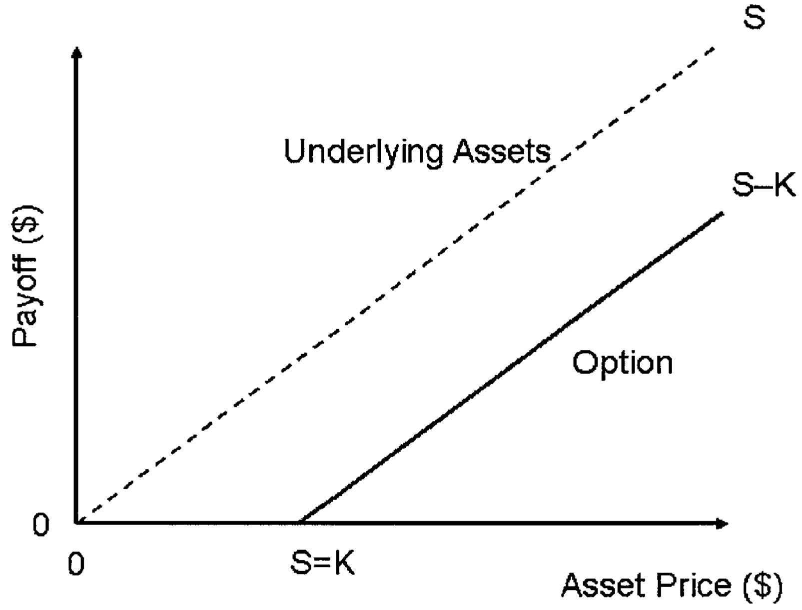
5.1. Financial Options Methods

Financial options theory provides the theoretical basis of the real options analysis. In finance, an option contract is an agreement in which the owner has the right, but not the obligation, to buy or sell an "underlying asset," such as a stock, at a pre-determined price on or before the expiration date [34].

Options are basically classified into four categories based on the types of the right and the expiration; a call option refers to the right to buy a stock at the strike price, the pre-determined price, and a put option indicates the right to sell a stock at the strike price [43]. Options are called American if the owners are allowed to exercise them on or before the expiration date, and options known as European options can be exercised only on the expiration date [43].

The essential point is that the option is not the obligation but the right to buy or sell the underlying asset. Therefore, the owner would exercise the option only when it is favorable to do so [36]. For instance, the option holder would exercise a call option only if the price of the underlying asset, S, is higher than the strike price, K, and would earn a profit of S-K;

otherwise, he or she would buy the asset not through the option, but from the market. Figure 5-1 depicts the general payoff scheme of a European call option, and Equation 5-1 gives the mathematical formulation of this payoff scheme [8].



Source: Modified, based on Brealey and Myers [36]

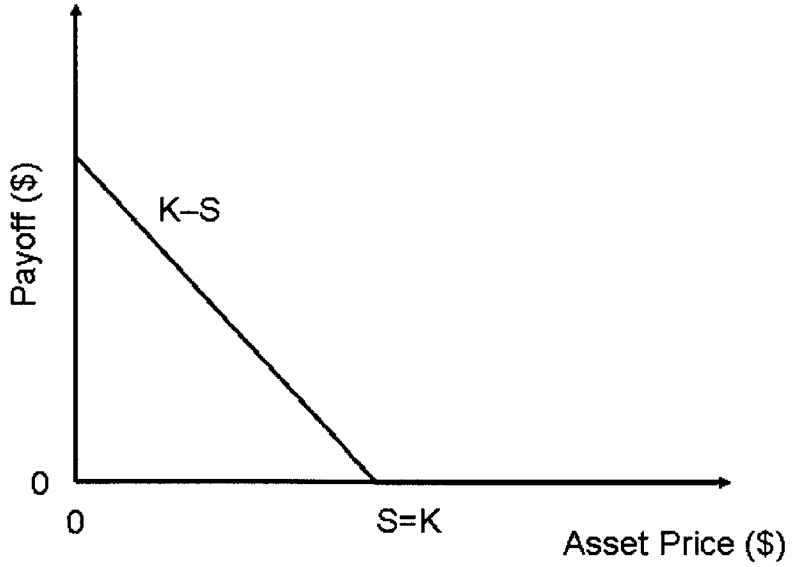
Figure 5-1: Payoff Diagram for a European Call Option with Strike Price (K) for Asset Price (S)

Payoff (European call) = $Max(S-K, 0)$ **Equation 5-1**

Where S: Price of the underlying asset at the expiration date

K: Strike price

A European put option has a different payoff scheme from a call option. Since it is the right to "sell" the underlying asset at a certain price, it is advantageous to exercise the option only when the market price of the asset, S, is lower than the strike price, K. In this case, the option holder can make the profit of K-S. This payoff scheme of a European put option is illustrated in Figure 5-2, and the mathematical formulation is shown in Equation 5-2 [8].



Source: Modified, based on Brealey and Myers [36]

Figure 5-2: Payoff Diagram for a European Put Option with Strike Price (K) for Asset Price (S)

Payoff (European put) = $Max(K\text{-}S, 0)$ **Equation 5-2**

Where S: Price of the underlying asset at the expiration date

K: Strike price

American type options have the same payoff schemes as European options do. The difference is, however, that American options can be exercised at any time on or before the expiration date.

Building upon these basic options concepts, the following sections explain two well known models to evaluate the value of an option: the Black-Scholes model and the Binomial Lattice model.

5.1.1. Black-Scholes Option Pricing Model

The Black-Scholes option pricing model (OPM) is the most well known solution to the option pricing problem as it applies to those European call and put options that do not pay dividends [9]. It derives the theoretical value of the option using five factors: the price of the underlying asset (S), the strike price (K), the time until expiration (T), the risk-free rate of interest (r_f), and the volatility (i.e., standard deviation) of returns on the stock (σ) [9]. Equation 5-3 provides the theoretical value of a European call option [8]:

$$C = S \cdot N(d_1) - K \cdot e^{-r_f T} \cdot N(d_2)$$ **Equation 5-3**

Where C: Theoretical value of a European call option with no dividends

$$d_1 = \frac{\ln(S/K) + \left(r_f + \sigma^2/2\right) \cdot T}{\sigma\sqrt{T}}$$

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

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

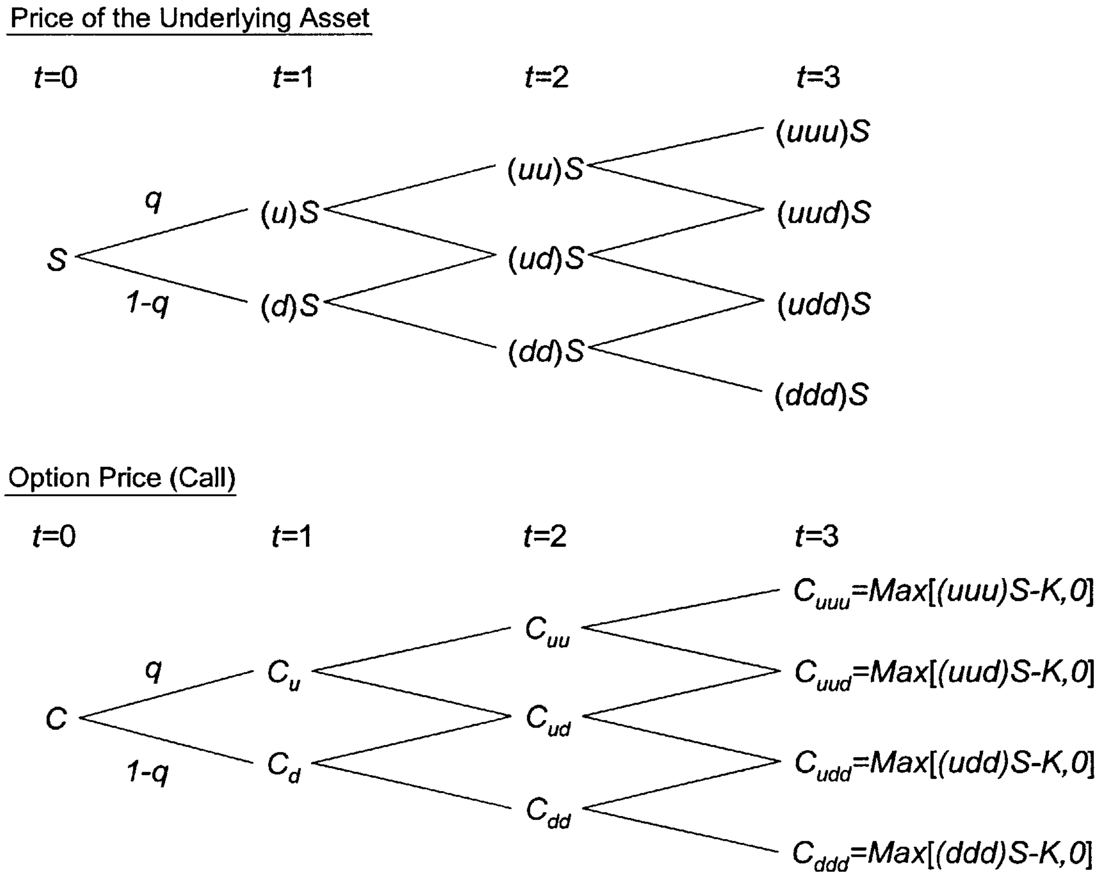
Similarly, the theoretical value of European put options with no dividends can be calculated by the Black-Scholes OPM. Equation 5-4 provides the mathematical formulation of this value [8]:

$$P = K \cdot e^{-r_f T} \cdot N(-d_2) - S \cdot N(-d_1)$$ **Equation 5-4**

Where P: Theoretical value of a European put option with no dividends

5.1.2. Binomial Lattice Model

Another widely used method for pricing options is the Binomial Lattice Model developed by Cox, Ross and Rubistein (1979) [44], a more simplified discrete-time approach to valuation of options compared to the Black-Scholes OPM [45]. It is called the binomial model because it assumes that, during the next period of time, the price of the underlying asset will go to one of only two possible values. Figure 5-3 illustrates a three-stage binomial example.



Source: Modified, based on F. K. Reilly and K. C. Brown [46]

Figure 5-3: Binomial Tree Representations of Changes in Underlying Asset (*S*) and Associated Changes in Call Option Value

As Figure 5-3 indicates, in the Binomial Lattice Model, the price of an underlying asset at a certain time can move in one of only two directions: an upward movement with multiplier u at the probability of q, and a downward movement with multiplier d at the probability of $1-q$. The values of u and d can be calculated by Equation 5-5 [44]. Using these values, with the initial value of the asset (S), the number of time period (n), and the strike price (K), the expiration date payoffs to the option (i.e., C_{uuu}, C_{uud}, C_{udd}, and C_{ddd}) can be determined.

$$u = e^{\sigma\sqrt{T/n}}$$

$$d = e^{-\sigma\sqrt{T/n}} = 1/u$$

Equation 5-5

Where σ : Volatility (standard deviation) of natural logarithm of the underlying free cash flow return in percent

T: Time to the expiration date of the option

n: Number of time period until the expiration of the option

The value of the call option at any point of time can be calculated by working backward from the subsequent time period. Equation 5-6 calculates the value of the call option at jth state [44]:

$$C_j = \frac{p \cdot C_{ju} + (1-p) \cdot C_{jd}}{r}$$

Equation 5-6

Where $p = \dfrac{r-d}{u-d}$

C_j: Value of the call option in the jth state

C_{ju}: Value of the call option in the $(j+1)$th state which corresponds to the upward movement from the jth state

C_{jd}: Value of the call option in the $(j+1)$th state which corresponds to the downward movement from the jth state

r: one plus the risk-free rate, r_f, provided that r_f remains constant in each period

Note that C_j does not depend on q or $1-q$, the actual probabilities of the up and down movements. Instead, if p in Equation 5-6 is interpreted as the probability of an up movement in the price of the underlying asset, which would then mean that $(1-p)$ is the probability of a down move, then the formula for C_j has an intuitively appealing interpretation. That is, the option's value at any point in time can be viewed as its expected value discounted backward from the subperiod to the current time. In fact, p is the value q would have in equilibrium (i.e., after demand and supply of the option is balanced [38]) if investors were risk-neutral [44]. This probability, p, is called "risk-neutral probability", and this option pricing calculation based on risk-neutral probability is called "risk-neutral approach" (See Cox, Ross and Rubistein (1979) for more detailed explanation of this approach [44]).

When the price of the underlying assets increases annually with the rate of ν, the probability of up-movement, p, can be modified, by adopting a sufficiently large n, as expressed in Equation 5-7 [47][48]:

$$p = \frac{1}{2}\left(1 + \frac{\nu}{\sigma}\sqrt{T/n}\right)$$ **Equation 5-7**

Where ν : Annual growth rate of the underlying asset

A repetition of the calculation of Equation 5-6 from the last period to the first period will determine the initial value of the call option. Equation 5-8 provides the general formula for n periods:

$$C = \frac{\sum_{j=0}^{n} \frac{n!}{j!(n-j)!} p^{j}(1-p)^{n-j} Max\left[u^{j} d^{n-j} S - K, 0\right]}{\left(1 + r_f\right)^{n}}$$ **Equation 5-8**

5.1.3. Underlying Assumptions of the Black-Scholes OPM and the Binomial Lattice Model

The Black-Scholes Model, a theoretical method for option pricing, and the Binomial Lattice Model, a simplified discrete-time valuation method, are cornerstones in the development of options theory and project valuation methodologies [34]; they have revolutionized the way academics and practitioners think about investment projects by explicitly incorporating management flexibility into the analysis [49].

However, these two models require several important assumptions. Since these assumptions are based on the valuation of financial options, they may be inappropriate for dealing with real assets. Therefore, it is essential to understand these assumptions in order to properly apply the models to real-world projects. This section explains these assumptions, quoting from the comprehensive list compiled by Tsui (2006) [34].

Assumption I: "Options and stocks are traded in a perfect market. A perfect market possesses the following characteristics: (1) it operates in equilibrium, (2) it is perfectly competitive, (3) risk-free assets exist in the market, (4) individuals have equal access to the capital market, (5) there are infinitely divisible securities, (6) short-selling is allowed, and (7) there are no transaction costs or taxes [34]."

Assumption II: "Option price and stock price depend on the same underlying uncertainties [34]."

Assumption III: "There is a continuum of stock prices. This assumption may seem unrealistic since the trading is not continuous. Nevertheless, Black-Scholes model performs quite well in the real world where stocks trade only intermittently with price jumps [34]."

Assumption IV: "Stock prices fluctuate randomly in a complete, efficient market [34]." It is proven that even though there may be a known seasonal pattern in the current price of a stock, the future price will fluctuate randomly in a short period of time [50]. Therefore, "stock price jumps are characterized by a normal or lognormal probability distribution; this fact means that the logarithm of 1 plus the rate of return follows a normal or bell-shaped curve [34]." This behavior of stock prices is known as the Geometric Brownian Motion (GBM) [43].

Assumption V: "There are no arbitrage opportunities. Arbitrage is the act of profiting from differences in price on two or more markets. As an asset is bought in one market and sold immediately at a higher price in another market, the investor makes a risk-free profit without investing anything. In a competitive, well-developed market, if arbitrage opportunities exist, the law of supply and demand will soon force the two asset prices to be the same. Therefore, no arbitrage exists in such a market [34]."

Assumption VI: "A risk-free rate is used to discount future cash flows [34]." In a perfect market where no arbitrage opportunity exists, "a portfolio consisting of the underlying stock and the stock option can be set up in such a way that there is no uncertainty about the value of the portfolio [51]." The reason why such a risk-less portfolio can be created is that the stock price and the option price are both affected by the same courses of uncertainty: stock price changes [43]. When an appropriate portfolio is established, the gain or loss from the stock option in a short period of time is always offset by the loss or gain of the stock so that the value of the portfolio is known with certainty at the end of a short period of time. Because the portfolio has no risk, the return earned on it must equal the risk-free interest rate [51].

In addition to the above assumptions, the Binomial Lattice Model adopts the following assumptions for the asset price evolution:

Assumption VII: "The price evolution is stationary over time [34]."

Assumption VIII: "Each state leads to two other states over one time period (or a time

step). The intermediate branches all recombine [34].”

Assumption IX: “The paths to a state are independent of each other [34].”

While some assumptions seem applicable to real projects, others do not. For example, Assumption VIII, which is seemingly unrealistic for real assets because only two directions of price evolution exist, is capable of expressing many scenarios of asset price development by adopting a short time increment. On the other hand, Assumption V, no arbitrage opportunities, may not hold for real assets; it is not always possible to make a risk-less portfolio consisting of a real asset and an option since real assets are not always traded in markets. In such a case, special treatments are required for the proper evaluation of projects. For example, Wang (2005) claims that the Binomial Lattice Model can be applied to real projects by using the actual probabilities and discounting at a properly risk-adjusted discount rate [51]. McDonald and Siegel (1984) suggest a dividend-like adjustment in option valuation [52]. The hybrid real options analysis, which Neely (1998) developed, proposes separating the market risk in a project from the project-specific risk. By doing so, the method makes it possible to transform the market risk component into a distribution with the risk-neutral probability, as well as to apply the risk-free rate to discounting the project payoffs [9]. To summarize, it is important for project appraisers to compare these assumptions with the characteristics of the project and to choose an appropriate method for the option valuation.

5.2. Hybrid Real Options Analysis

The hybrid real options analysis is a composite evaluation method combining the decision analysis and the real options valuation developed by Neely (1998) [9]. By taking advantages of these two analytical methods, it effectively evaluates projects with both exogenous uncertainties and endogenous uncertainties. Since this thesis aims to evaluate the Chuo Shinkansen Project, which involves the exogenous uncertainty of demand growth as well as the endogenous risk of R&D outcomes, the hybrid real options analysis can be considered the appropriate method for appraising the value of the project.

The rest of this section explains the methodology of the hybrid real options analysis. After providing the explanation of the characteristics of the method, it illustrates the flow chart of the analysis.

5.2.1. Characteristics of the Hybrid Real Options Analysis

Most real-world projects carry two types of risks: project-specific risks and market risks [53]. For example, in a project to construct an oil platform, events such as a higher construction cost than the projected expense or a smaller amount of available oil deposit are classified as project risks [53]. In contrast, the other kind of risk concerns the uncertainties in the value of the product when it is brought to market. For example, a worldwide drop of oil price is considered a market risk. Each of these two kinds of risks has quite different implications for the discount rate that should be used in the valuation of the project [53].

By definition, project risks are unique to the project. Therefore, if investors and project managers can broadly diversify investments, unexpected losses in one project will be compensated on average by unexpected gains in others [53]. In such a case, they can avoid project risks and these risks can be properly evaluated by the decision analysis method using the risk-free discount rate.

Market risks, which stem from the economy-wide perils or the industry-wide risks that threaten all businesses in the industry, cannot be diversified. Therefore, as extra compensation, market risks require a higher discount rate than the risk-free rate [53]. The level of these market risks, moreover, changes when a project is actively managed [53]. Choices about exercising options, such as the option to defer the project and the option to expand the capacity, change the risks and the associated level of discount rate. In this regard, options analysis is appropriate for evaluating projects with market risks.

The hybrid real options analysis is an efficient evaluation methodology for projects with both project risks and market risks. Splitting the analysis into financial and technological parts is the key feature of this analysis [53]. By separately applying options analysis to the appraisal of market risks and the decision analysis to the evaluation of project risks, the hybrid real options analysis effectively deals with real-world projects (Figure 5-4).

Source: Neely and de Neufville [53]

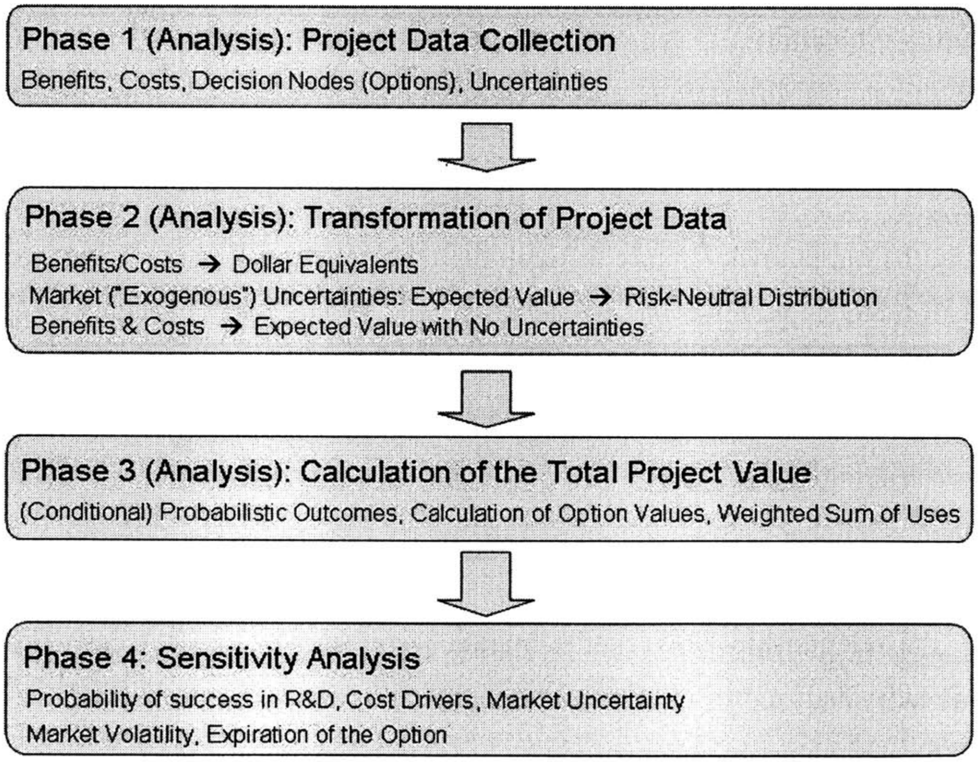
Figure 5-4: Separation of the Analysis into Decision Analysis and Options Analysis

The advantage of the hybrid real options analysis is that it uses a consistent discount rate for the valuation, the risk-free rate. This use of risk-free rate becomes possible when the project risks can be avoided by diversifying investments and the market risks can be transformed by the options analysis so that no further compensation for risk is required in the discount rate [53]. While the diversification of investments is a managerial choice, the transformation of market risks is an analytical technique. Therefore, the hybrid real options analysis adopts a special process of transforming market risks into the risk-neutral distribution in order to make the use of the risk-free discount rate possible.

The process which the hybrid real options analysis uses in transforming project outcomes is known as "risk-neutral valuation." Hull (1989) provides a detailed explanation of this approach [43]. The risk-neutral valuation relates the project outcomes with market-traded priced factors such as stocks. Therefore, identifying the appropriate assets is essential for carrying out the transformation of the market risks [9].

5.2.2. Flow of the Hybrid Real Options Analysis

Hodota (2006) succinctly summarized the general analytical flow of the hybrid real options method [8]. He explains that the hybrid real options analysis basically consists of four phases: 1) project data collection, 2) transformation of the project data, 3) total project value calculation, and 4) sensitivity analysis. Figure 5-5 illustrates the flow chart of the hybrid real options analysis.



Source: Modified, based on Hodota [8]

Figure 5-5: Flow Chart of the Hybrid Real Options Analysis

Phase 1: Project Data Collection

The first step in the hybrid real options method is to gather the necessary data for analyzing the project. In this process, project evaluators have to estimate the timing and the magnitude of cash flows that the project generates. They also need to identify the decision opportunities and uncertainties associated with the project [8].

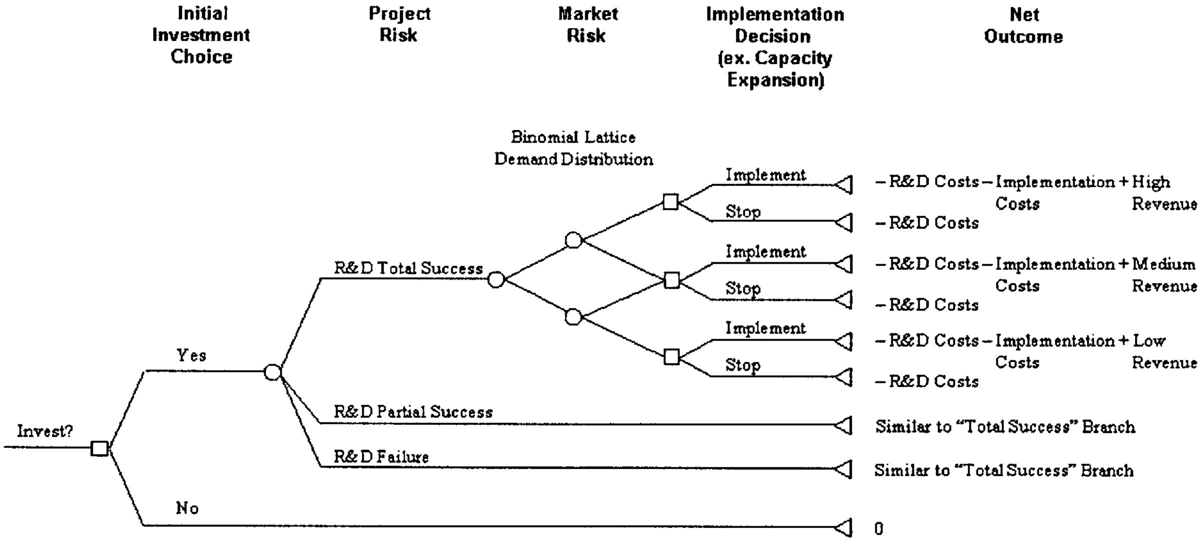
Phase 2: Transformation of Project Data

The second phase deals with the quantification of the two types of risk: the project risk and the market risk [8]. The former has no relation to external market events. Therefore, the same procedure as the decision tree analysis can be used to quantify the project risk [9].
In order to analyze the project risk using the decision tree analysis, two sets of information are required: discrete outcomes and associated probabilities. Several practical ways to estimate the outcomes and probabilities have been proposed. These include subjectively estimating the probability of each outcome, or assuming a form of distribution, estimating the means and standard deviation, and developing discrete estimates using the distribution [9].

Quantifying the market risk is more difficult than the project risk [53]. This process can be explained in three steps. First, *the project cash flow driving factor*, which is a factor that primarily affects the project revenues, must be identified. Second, this cash flow driving factor must be related to one or more exogenous market factors [9]. There would be several methods of relating the cash flow driving factor to the market factor. A simple way of relating them is a linear regression model. Finally, the risk-neutral distribution of the market factor can be calculated by applying an options method such as the Binomial Lattice Model [9]. Since the relationship between the market factor and the project cash flow driving factor is already analyzed in the second step, the risk-neutral distribution of the cash flow driver will be automatically obtained.

Phase 3: Calculation of the Total Project Value

From the results of Phase 2, a decision tree can be constructed. Figure 5-6 shows an example. The discrete outcomes and the associated probabilities compose the "Project Risk" branches. The "Market Risk" branches are structured from the risk-neutral distribution of the project cash flow driver. In the same way as in the decision analysis, project managers can choose, at each decision stage, the decision alternative that maximizes the expected value of the later cash flows. Summing up all the expected values of each stage discounted by the risk-free discount rate yields the total present value of the project.



Source: Modified, based on Neely and de Neufville [53]

Figure 5-6: Decision Tree for the Hybrid Real Options Analysis

Phase 4: Sensitivity Analysis

Finally, since any analysis of real projects involves assumptions, the sensitivity of the obtained results should be analyzed [53]. By conducting the sensitivity analysis, project managers can test the implications of the results of the project evaluation. The scope of the sensitivity analysis for the hybrid real options analysis ranges from the assumption on project risks to that on market risks [8]. The parameters that should be analyzed include but are not limited to the volatility and the growth rate of the market risk factor and the probability of success of R&D.

5.3. Conclusions about Real Options Analysis

This chapter explains theories of financial options analysis including the Black-Scholes Option Pricing Model and the Binomial Lattice Model. It also introduces the hybrid real options analysis developed by Neely (1998) as the suitable model for appraising the Chuo Shinkansen Project [9].
Financial options models are the bases for real options analysis. In most real-world projects, project managers have decision opportunities such as the option to defer the implementation of the project and the option to expand the project scale. Therefore, analyzing the value of these options is important for accurate evaluation of the project. In this sense, the Black-Scholes OPM and the Binomial Lattice Model provide powerful tools for evaluating real-world projects with decision opportunities.

The hybrid real options analysis is a composite method of real options analysis and decision analysis. Real options is suitable for projects with risks that are derived from the market and decision analysis is appropriate for analyzing projects with risks that are unique to those projects [9]. By taking advantages of these two analysis methods, the hybrid real options analysis properly evaluates the value of a project which has both market risks and project-specific risks.

Building upon the general analytical scheme of the hybrid real options analysis, the next chapter develops this model further in order to deal with several difficulties that arise when applying the model to the Chuo Shinkansen Project.

Chapter 6 Development of the Hybrid Real Options Model for the Chuo Shinkansen Project

This chapter develops the hybrid real options analysis further in order to appropriately evaluate the Chuo Shinkansen Project. Although the previous chapter provides the general analytical scheme of the hybrid real options model, further extension of the model is needed to deal with the unavoidable complexities that arise when applying it to the Chuo Shinkansen Project. These complexities include the followings: 1) estimating the stream of cash flows of the Chuo Shinkansen even though it does not exist yet, 2) identifying the potential system designs which depend on both the results of the research and development (R&D) activity and the operational requirements, 3) developing the Binomial Lattice Model that takes into account the operational capacity constraint and the option to expand capacity, and 4) selecting an appropriate discount rate. This chapter begins by explaining the cost model which is necessary for estimating the cash flow stream of the project.

6.1. Estimating the Cash Flows of the Chuo Shinkansen Project

When applying the hybrid real options analysis to a project, the cash flow stream of the project must be estimated. In order to estimate the cash flows of the Chuo Shinkansen Project, it is crucial to calculate the commercial revenues as well as the operational costs. This section develops and explains the calculating models of these data for the Chuo Shinkansen Project.

6.1.1. Operational Cost Model

With regard to the operational cost of the Chuo Shinkansen, this thesis assumes, for the sake of simplifying the problem, that the cost will depend primarily on the number of trains operated and that the cost of the Chuo Shinkansen per train per trip between Tokyo and Osaka will be the same as that of the Tokaido Shinkansen. By applying this assumption, project managers can calculate the operational cost, based on the configurations of the system they adopt including the operational frequency and the daily operational hours. Equation 6-1 provides the estimated annual operational cost of the Chuo Shinkansen.

$$C_{ope.}(f) = C_{train} \cdot f \cdot H_{daily\_ope.} \cdot 365 \qquad \textbf{Equation 6-1}$$

Where $C_{ope.}(f)$: Annual operational cost of the Chuo Shinkansen (billion yen/year)
C_{train}: Operational cost of the Tokaido Shinkansen per train per trip between Tokyo and Osaka (billion yen/train)
f: Operational frequency (trains/hour)
$H_{daily\_ope.}$: Daily operational hours (hours/day)

6.1.2. Operational Revenue Model

Evaluators of the Chuo Shinkansen Project also need to estimate the commercial revenues. It seems reasonable to assume that the demand for the Chuo Shinkansen will be the principal driving factor of the service revenue. Therefore, the first task in analyzing the service revenue will be to estimate the demand for the Chuo Shinkansen Project.

However, estimating the demand for the Chuo Shinkansen is not easy because the Shinkansen does not exist yet. Project managers cannot directly forecast the demand in the future based on the tendency of the demands in the past. Instead, they have to estimate the demand using other available information.

To forecast the demand of the Chuo Shinkansen, this thesis utilizes two different sets of data. First, the thesis analyzes the expected relationship between the demands of the Chuo Shinkansen and of the Tokaido Shinkansen. Second, it develops a model that calculates the distribution of demand for the Tokaido Shinkansen from the GDP and demand data in the past. By combining these results, the thesis calculates the distribution of demand for the Chuo Shinkansen based on the forecast of the demand for the Tokaido Shinkansen.

Relationship Between the Demands for the Chuo Shinkansen and the Tokaido Shinkansen

One of the potential sources of information for estimating the demand for the Chuo Shinkansen is the forecast of demand which the Ministry of Land, Infrastructure and Transport (MLIT) of Japan developed. Unfortunately not all the data has been made public but the available data contains the following estimates: 1) the demands for the Chuo Shinkansen and the Tokaido Shinkansen in 2020, on the condition that the Chuo Shinkansen is in operation, and 2) the demand for the Tokaido Shinkansen in 2020, assuming that the Chuo Shinkansen is not built. Although these data cannot be directly used as the estimated demands for the two Shinkansens because they are point-estimates and no growth rate is indicated, the relationship between the demands for the two Shinkansens can be calculated based on them. Once the above relationship is determined, it will be possible to calculate the distribution of demand for the Chuo Shinkansen because there are other available data for estimating the demand of the Tokaido Shinkansen and its growth rate.

Table 6-1 summarizes the forecasts of demands for the Chuo Shinkansen and the Tokaido Shinkansen developed by MLIT. As shown in this table, the ratio of the demand for the Chuo Shinkansen to that of the Tokaido Shinkansen is calculated to be approximately 0.72. This thesis assumes that this relation will hold at all times. Accordingly, Equation 6-2 is obtained.

$$k_d = \frac{D_{Chuo}}{D_{Tokaido}} = 0.72$$

Equation 6-2

Where k_d: Demand ratio coefficient between the Chuo Shinkansen and the Tokaido Shinkansen

D_{Chuo}: Demand for the Chuo Shinkansen

$D_{Tokaido}$: Demand for the Tokaido Shinkansen provided that the Chuo Shinkansen is not constructed

Using this relationship and the result of the demand forecasting model of the Tokaido Shinkansen which the next section explains, the thesis develops the distribution of the demand for the Chuo Shinkansen.

Table 6-1: Estimated Annual Demands for the Chuo Shinkansen and the Tokaido Shinkansen Developed by MLIT.
Based on this data, the ratio of the demands for the Chuo Shinkansen and the Tokaido Shinkansen can be calculated.

Assumed GDP Growth Rate	2000 Actural Record	2020 Without Chuo Shinkansen	2020 With Chuo Shinkansen		Ratio of Demands for Chuo Shinkansen and Tokaido Shinkansen (Z=Y/X)
	Tokaido Shinkansen	Tokaido Shinkansen (X)	Tokaido Shinkansen	MagLev (Y)	
Unit	Billion People Km	Billion People Km	Billion People Km	Billion People Km	-
2%	39.7	43.3	23.2	31.4	0.725
1%	39.7	41.0	22.0	29.7	0.724
0%	39.7	39.0	20.9	28.3	0.724
Average	39.7	41.1	22.0	29.8	0.72

Source: Modified, based on the East Japan Linear Motor Train Promotion Conference [54].

Demand Forecasting Model for the Tokaido Shinkansen

The next step in estimating the demand distribution of the Chuo Shinkansen is to analyze the demand for the Tokaido Shinkansen. This analysis can be done in many ways depending on what empirical data is used. However, the hybrid real options analysis requires the demand to be related to one or more market factors so that the demand is calculated as the risk-neutral distribution (see Section 5.2).

As an example of the market factor that is closely related to the project cash flows driving factor, Neely (1998) proposes using the stock price of the company which implements the project [9]. For a public-driven investment, Hodota (2006) proposes using the gross domestic product (GDP) [8].

Among these two market factors, stock prices seem to be more appropriate than GDP as the cash flow driving factor of projects because GDP is not a traded asset. Therefore, if GDP is adopted as the market factor, some assumptions of real options analysis may not hold and the risk-free rate will not necessarily become the appropriate rate to discount the cash flows (see section 5.1.3). Nevertheless, there are difficulties in relating the stock price and the demand data of the Tokaido Shinkansen. For example, while the stock price fluctuates momentarily, the demand data can only be obtained as a total demand during a certain period of time. Therefore, it is difficult to identify the price of the stock that corresponds to the agglomerated data of demand. In addition, the *Conference of Scholars along the Chuo Shinkansen* (2001) points out that the demand for the Tokaido Shinkansen has been strongly related to the entire economy of Japan [1]. In this sense, the Tokaido Shinkansen is highly related to the entire economy of Japan; thus the risk of the entire market should be also reflected in the process of estimating the demand for it. Therefore, this thesis adopts GDP as the market factor that influences the demand for the Tokaido Shinkansen.

Although there are several methods that are available for relating the project driving factor (i.e., the demand for the Tokaido Shinkansen in this case) to the market factor (GDP), this thesis uses a simple linear regression model for the demonstrating purpose. Equation 6-3 provides the formula of the linear regression model:

$$D_{Tokaido}(t) = A + B \cdot GDP(t) \qquad \textbf{Equation 6-3}$$

Where $D_{Tokaido}(t)$: Demand for the Tokaido Shinkansen at time= t
$GDP(t)$: Real GDP at time= t
A, B: Regression parameters

The values of the parameters, A and B, can be calculated based on the demand data and the GDP data in the past. Table 6-2 shows the real GDP in Japan and the average daily number of passengers of the Tokaido Shinkansen from 1980 through 2000. Using the data in this table, the regression model shown in Figure 6-1 is obtained.

Table 6-2: Real GDP and the Tokaido Shinkansen Daily Number of Passengers

Fiscal Year	Real GDP (based on 1995 value)	Average Daily Demand for the Tokaido Shinkansen
Unit	Billion yen	Thousand people
1980	315,175	250
1981	324,078	250
1982	332,655	250
1983	338,397	255
1984	351,662	255
1985	367,658	270
1986	378,071	275
1987	396,958	280
1988	423,384	305
1989	441,613	320
1990	467,913	355
1991	478,035	365
1992	483,182	365
1993	478,347	360
1994	489,302	350
1995	500,979	365
1996	519,289	365
1997	522,378	370
1998	517,302	360
1999	521,762	350
2000	537,870	355

Source: Cabinet Office, Government of Japan [55] and Conference of Scholars along the Chuo Shinkansen [1].

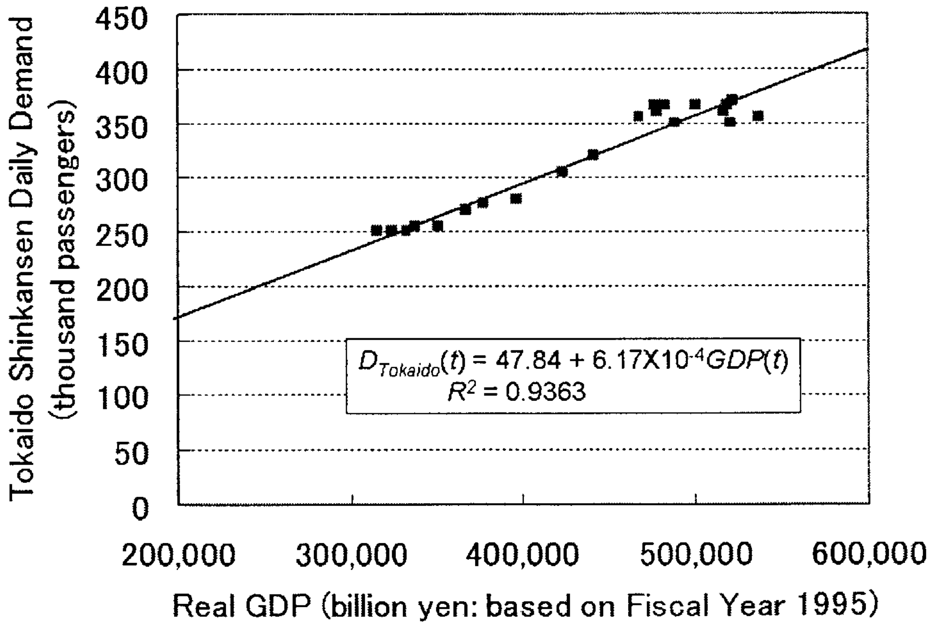


Figure 6-1: Result of Regression between Tokaido Shinkansen Daily Demand and Real GDP. Data sets of daily demand and GDP from 1980 through 2000 are used for this regression.

Demand and the Operational Revenue Calculating Model for the Chuo Shinkansen

The results of above two models lead to a formula that calculates the demand estimate of the Chuo Shinkansen from the GDP data. Equation 6-4 provides this formula.

$$D_{Chuo}(t) = k_d \{A + B \cdot GDP(t)\}$$ **Equation 6-4**

$$= 0.72\{47.84 + 6.17 \times 10^{-4} \cdot GDP(t)\}$$

Where $D_{Chuo}(t)$: Daily demand for the Chuo Shinkansen at time = t (thousand passengers)

$GDP(t)$: Gross Domestic Product at time = t (billion yen)

Finally, project managers need to calculate the estimated annual revenue of the Chuo Shinkansen. Since the demand shown in Equation 6-4 is based on the daily number of passengers, managers first need to transform this number into the annual demand (Equation 6-5). By multiplying the annual demand with the fare per unit demand, they can calculate the estimated annual revenue of the Chuo Shinkansen Project (Equation 6-6).

$$D_{annual\_Chuo}(t) = D_{Chuo}(t) \cdot k_t \cdot 365 \times 10^{-6}$$ **Equation 6-5**

$$R_{ope.}(t) = k_f \cdot \left(D_{Chuo}(t) \cdot k_t \cdot 365 \times 10^{-6}\right)$$

$$= k_f \cdot 0.72 \cdot \{47.84 + 6.17 \times 10^{-4} \cdot GDP(t)\} \cdot k_t \cdot 365 \times 10^{-6}$$ **Equation 6-6**

Where $R_{ope.}(t)$: Annual operational revenue of the Chuo Shinkansen at year t (billion yen/year)

k_f: Fare per unit demand for the Chuo Shinkansen (yen/passenger/km)

k_t: Average travel distance per passenger (= approximately 300 km[7])

Note that in the real world, demand will be a function of fare. However, to simplify the

---

[7] Obtained from the data of the Tokaido Shinkansen in 2000 [1][54][54].

analysis, this thesis assumes that demand is not affected by fare. Furthermore, this thesis uses fixed values for the fare per unit demand, k_f, and the average travel distance per passenger, k_t. As a result, the annual operational revenue, which is expressed by Equation 6-6, can be considered a function of only GDP.

Chapter 7 describes the calculation of the volatility and the growth rate of GDP and analyzes the operational revenue of the Chuo Shinkansen using Equation 6-6.

6.2. Identifying the Potential System Designs

When applying the real options analysis to a project, it is essential to identify the decision opportunities in order to evaluate the value of the project, taking the decision opportunities into account. In the case of the Chuo Shinkansen Project, one of the major decisions that managers need to make is concerned with how many Power Conversion Systems (PCSs) to build at the time of construction and how many PCSs at what time to add to the system.

The numbers of PCSs required in the system at the time of construction and at the time of capacity expansion depend on both R&D outcomes and operational requirements. Therefore, project managers need to analyze the relationship among these factors, to identify the possible development scenarios of PCSs.

The timing of adding PCSs is also an important decision because the timing affects the value of the project. However, unlike the numbers of PCSs required in the system, project managers can decide this timing arbitrarily. Furthermore, it is possible for them to find the optimal timing that maximizes the value of the project after they develop the project evaluation model; by repeatedly changing the timing to add PCSs and calculating the value of the project, they can compare the project values and find the best timing for adding PCSs. Therefore, this thesis analyzes the optimal timing for adding PCSs after the evaluation model is developed and calculates the value of the project using this optimal timing.

Based on the above discussion, the rest of this section develops a model that specifies the necessary numbers of PCSs based on the R&D outcomes and the operational requirements.

6.2.1. System Design Specifying Model for the Chuo Shinkansen Project

Specifying the System Design based on the R&D Outcomes

The degree of success of R&D is the key for the flexible system design for the Chuo Shinkansen. As explained in Chapter 3, if R&D succeeds in extending the coverage of a PCS, it becomes possible to expand the system later only when the demand grows sufficiently; otherwise, the Chuo Shinkansen must be constructed with a large capacity regardless of the size of demand it will serve. Therefore, project managers need to specify the possible system designs based on the assumptions about R&D outcomes that they make.

As described in Section 3.1.2, this thesis assumes three discrete levels of coverage of a PCS as the possible results of R&D. These three levels of coverage are: L_0=20km as the case of total failure, L_1=30km as the partial success case, and L_2=40km for the case of total success.

These assumptions are derived based on the actual length of the Yamanashi Maglev Test Line (YMTL) and the proposed plan of extending the test line. The length of YMTL is 18.4km, and the technology to cover this length is already established. Therefore, for the case of total failure of R&D, this thesis assumes 20km of coverage as the approximate value of 18.4km. On the other hand, Central Japan Railway Company (JR Central) is planning to extend YMTL to 42.8km for further experimentation [2]; thus, this thesis assumes 40km for the total success case as the approximate value of 42.8km. Finally, the thesis assumes 30km, which is the median value of the total success and total failure cases, as the outcome of partially successful R&D.

In any of these three cases, the actual coverage of a PCS in the system of the Chuo Shinkansen must not exceed the coverage obtained from R&D; therefore, Equation 6-7 must be satisfied.

$$L_c \leq L_k$$ **Equation 6-7**

Where L_c: Actual coverage of a PCS (km)

L_k: Maximum length over which a PCS can control a Maglev train which is obtained as the result of R&D ($k = 0, 1, 2$) (km)

Combining Equation 6-7 and Equation 3-1, the necessary number of PCSs to build, N_{PCS}, can be expressed as the function of L_k and L_T (the total length of track between the Tokyo and Osaka) as shown in Equation 6-8. Accordingly, the system of the Chuo Shinkansen must satisfy this relationship.

$$N_{PCS} \geq \frac{L_T}{L_k}$$ **Equation 6-8**

Where N_{PCS}: Necessary number of PCSs per track (i.e., each direction)

L_T: Total length of track between Tokyo and Osaka (= 500km)

Relationship between Operational Requirements and the System Designs

In addition to the results of R&D, the system configuration needs to comply with the operational requirements. More specifically, the system must be equipped with appropriate number of PCSs to be able to simultaneously realize the operational frequency requested and secure the safety of the system.

The sources of the request on the operational frequency will include the requirement from the government and the necessity to serve the demand growth. For example, the government might require that JR Central run at least a certain number of Malgev trains, in order to secure the level of service for passengers, even if there is not enough demand to justify this number of trains. Therefore, the system design will need to be capable of operating this minimum operational frequency. On the other hand, if the demand grows significantly, it will be necessary to run trains more frequently. In this case, JR Central would need to raise the operational frequency to serve the demand.

The system design of the Chuo Shinkansen should be evaluated considering this requirement on the operational frequency. Equation 6-9 expresses this constraint mathematically. Furthermore, this equation is transformed into the constraint of the necessary number of PCSs using Equations 3-1 and 3-2. The transformed formula is shown in Equation 6-10.

$$f \geq f_{requested}$$ **Equation 6-9**

$$N_{PCS} \geq \frac{L_T}{V} f_{requested}$$ **Equation 6-10**

Where f: Operational frequency of the Chuo Shinkansen (trains/hour)

$f_{requested}$: Requested operational frequency

L_T: Total length of track for each direction (=500km for the Chuo Shinkansen)

V: Average speed of a train (= 400km/h for the Chuo Shinkansen[8])

At the same time, the system designers should pay attention to the safety constraint on the system. In order to operate all trains safely, the system must secure the minimum distance between any two trains. In the JR Maglev system, this minimum interval must be at least 6 km because a Maglev train at the top speed requires about 5 to 6 km to stop [10].

In designing the Maglev system for the Chuo Shinkansen, this minimum interval between trains, which is stated above, is interpreted as the minimum allowable coverage of a PCS. In the JR Maglev system, every train requires a dedicated PCS but a different one as it moves along with the route (see Sections 2.3 and 3.1 for detail). Since only one train can be operated in the coverage of a PCS, by setting the coverage larger than the minimum

---

[8] See the footnote on page.53 for more detailed information about the assumption of the average speed.

required distance, the system can maintain the safety of all trains. As a result, the system must satisfy the following equation to secure the safety of the system.

$$L_c \geq L_{\min\_safety} \qquad \textbf{Equation 6-11}$$

Where L_{min_safety}: Minimum distance between PCSs to secure the safety of trains (= 6km for the Chuo Shinkansen)

Using Equation 3-1, the above constraint is transformed into the formula of the number of PCSs:

$$N_{PCS} \leq \frac{L_T}{L_{\min\_safety}} = N_{\max\_safety} \qquad \textbf{Equation 6-12}$$

Where N_{max_safety}: Maximum number of PCSs allowed in the system (= 500/6 = 83 for the Chuo Shinkansen)

Based on Equations 6-8, 6-10, and 6-12, the next section analyzes the potential system designs of the Chuo Shinkansen Project. It also identifies the expansion options of the system that this study evaluates using the hybrid real options analysis.

6.2.2. Possible System Designs in the Chuo Shinkansen Project

In order to identify the possible system designs of a Maglev system, the project designers must first make the assumptions about the R&D outcomes and the requirement of the operational frequency.

For the Chuo Shinkansen Project, this thesis assumes three different results of R&D to extend the coverage of a PCS. These three outcomes are, L_0 = 20km for the case of total failure in R&D, which is approximately the same level as the already established technology, L_1 = 30km as the partial success, and L_2 = 40km for the case of total success.

Chapter 3 provides a detailed explanation as to these assumptions.

With regard to the requirements on the operational frequency, the thesis assumes the following two conditions. First, the thesis assumes that the system must be capable of providing the operational frequency of at least 10 trains per hour at all times. Second, it also assumes that when the demand grows significantly, the system is required to run 15 trains per hour.

The first assumption about the operational frequency (i.e., at least 10 trains/hour) is derived from the system design specifications that the government used when it estimated the cost of the project in 2003 [6]. Because the Chuo Shinkansen Project is planned in accordance with the Nationwide Railway Development Law (NRDL), it is a highly public-related project. Therefore, this thesis assumes that the government will require the system be capable of realizing the frequency of 10 trains/hour, which was used in the government's estimation of cost.

The second assumption (i.e., 15 trains/hour at most) is derived from the operational capacity of the existing terminals of the Tokaido Shinkansen [56]. Obviously, it will be advantageous to operate as many trains as possible if there is enough demand. However, it is not possible to manage a large number of departures and arrivals in a short period of time because the space for the terminals is limited. Since there is little available information about the maximum operational frequency of the Chuo Shinkansen, this thesis simply assumes the same upper limit of frequency as the Tokaido Shinkansen.

Based on the above assumptions about the R&D outcomes and the requirements on the operational frequency, Equations 6-8, 6-10, and 6-12 define the possible system designs. Table 6-3 provides the potential system configurations of the Chuo Shinkansen Project.

Table 6-3: Potential System Designs of the Chuo Shinkansen

Outcomes of R&D Required Frequency	Total Failure 20km (=L_0)	Partial Success 30km (=L_1)	Total Success 40km (=L_2)
Minimum requirement $f_{min\_required}$ = 10 (trains/hour)	25 <= N_{PCS} <= 83	17 <= N_{PCS} <= 83	13 <= N_{PCS} <= 83
Maximum Allowed $f_{max\_constrained}$ = 15 (trains/hour)	25 <= N_{PCS} <= 83	19 <= N_{PCS} <= 83	19 <= N_{PCS} <= 83

From this table, system designers can identify the available options of the expansion of the system. For example, in the case of Total Success of R&D project, the most economical scenario of system development is to build 13 PCSs at the time of construction and to install 6 PCSs later. Therefore, the project can take advantage of the flexibility option to expand the capacity only when it becomes beneficial to do so. In contrast, it is clear that there is no available option in the case of Total Failure; the system designers have to install 25 PCSs in either case of operational frequency. As a result, Table 6-4 summarizes the possible scenarios of system development of the Chuo Shinkansen. This thesis analyzes the value of the Chuo Shinkansen Project in Chapter 7, considering these scenarios of system development.

Table 6-4: Possible Scenarios of System Development

R&D Outcomes		Total Failure: L_0 = 20km	Partial Success: L_1 = 30km		Total Success: L_2 =40km	
Development Scenario		Scenario I (no option available)	Scenario II-1 (option NOT considered)	Scenario II-2 (option available)	Scenario III-1 (option NOT considered)	Scenario III-2 (option available)
Number of PCS (Operational Frequency)	Initial Construction	N_{PCS} = 25 (f = 15)	N_{PCS} = 17 (f = 13)	N_{PCS} = 17 (f = 13)	N_{PCS} = 13 (f = 10)	N_{PCS} = 13 (f = 10)
	After Significant Demand Growth	N_{PCS} = 25 (f = 15)	N_{PCS} = 17 (f = 13)	N_{PCS} = 19 (f = 15)	N_{PCS} = 13 (f = 10)	N_{PCS} = 19 (f = 15)
Additionally Installed Number of PCS		0	0	2	0	6

6.3. Binomial Lattice Model for the Chuo Shinkansen Project

As the third extension of the hybrid real options model, this thesis incorporates capacity constraint into the evaluation of the cash flow of the project. While there are virtually no limitations in the growth of demand for the Chuo Shinkansen, there are ceilings on the actual capacity of the system. The flexibility option to expand the capacity, which the R&D outcomes will enable, also makes the calculation of the cash flow complex because the operational revenues will significantly increase after the option is exercised. Therefore, project evaluators must develop a model that can handle capacity constraints and changes in capacity. This section extends the Binomial Lattice Model of the hybrid real options analysis in order to appropriately evaluate these complexities of capacity constraint. It first explains the extended Binomial Lattice Model with the capacity constraint but without expansion options. Based on this model, this section develops the model, incorporating both the capacity constraint and the expansion option.

6.3.1. Project Value Calculation Model for the Chuo Shinkansen with No Expansion Option

The extension of the Binomial Lattice Model begins with the construction of a normal Lattice Model of demands. In the general Binomial Lattice Model, the structure of demand movement is expressed by Figure 6-2.

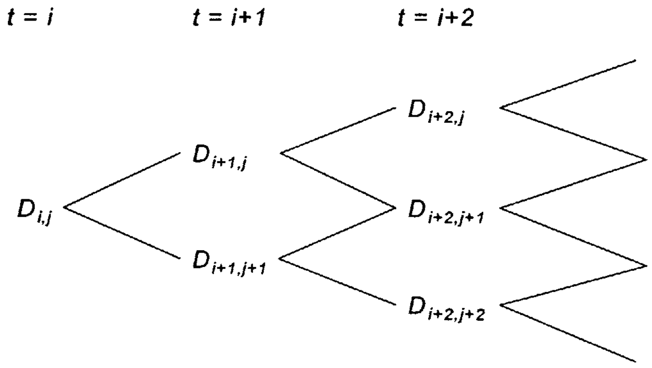


Figure 6-2: Binomial Lattice Structure of Demand Movement. Demand moves in one of only two directions, up or down, and the intermediate branches all recombine.

Using the Binomial Lattice evaluation, project managers can express the relationship among the demands, $D_{i,j}$, $D_{i+1,j}$, and $D_{i+1,j+1}$, by the following figure and equations (see Section 5.1.2 for the detail of Binomial Lattice evaluation).

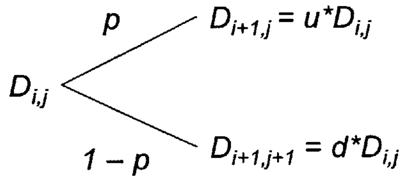


Figure 6-3: Binomial Lattice Evolution of Demand

$$
\begin{aligned}
u &= e^{\sigma\sqrt{\Delta T}} \\
d &= 1/u = e^{-\sigma\sqrt{\Delta T}} \\
p &= \frac{1}{2}\left(1+\frac{\nu}{\sigma}\sqrt{\Delta T}\right)
\end{aligned}
\qquad \textbf{Equation 6-13}
$$

Where σ : Standard Deviation of demand

ν : Growth rate of demand

ΔT : Time length of one period

With this distribution of demand, project managers can calculate the cash flow at each node. This calculation compares the demand and the capacity, and the smaller figure is chosen to represent the constraint of operational capacity.

$$
CF_{i,j} = \min\lfloor D_{i,j}, C_{apa}(f)\rfloor R_{unit\_demand} - C_{ope.}(f) \qquad \textbf{Equation 6-14}
$$

Where $CF_{i,j}$: Annual cash flow at node (i, j) (where demand = $D_{i,j}$) (billion yen)

$D_{i,j}$: Annual demand at node (i, j) (billion people km)

C_{apa} (f): Operational capacity (billion people km)

R_{unit_demand}: Annual revenue per unit demand (yen/km/person)

$C_{ope.}(f)$: Annual Operational Cost (billion yen)

f: Operational frequency (trains/hour)

Note that in this calculation, it is assumed that trains are fully loaded if demand is larger than or equal to the capacity, and that the exceeded demand is ignored. Also, the annual operational cost, $C_{ope.}(f)$, is calculated by Equation 6-1, and the operational capacity, $C_{apa}(f)$, is given by the following equation:

$$C_{apa}(f) = f\left\{C_{apa\_per\_train} \cdot 2 \cdot L_T \cdot H_{daily\_ope.} \cdot 365 \times 10^{-9}\right\}$$ **Equation 6-15**

Where $C_{apa\_per\_train}$: Capacity per train (people)

L_T: Total length of track between terminals for each direction (= 500 km for the Chuo Shinkansen)

$H_{daily\_ope.}$: Daily operational hours (hours/day)

Using Equations 6-1, 6-13, 6-14, and 6-15, project managers can construct the Binomial Lattice of cash flows (Figure 6-4).

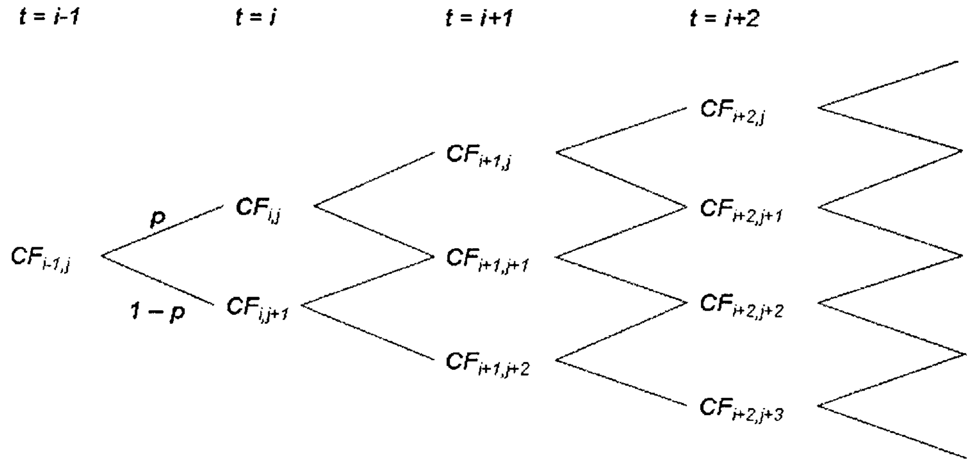
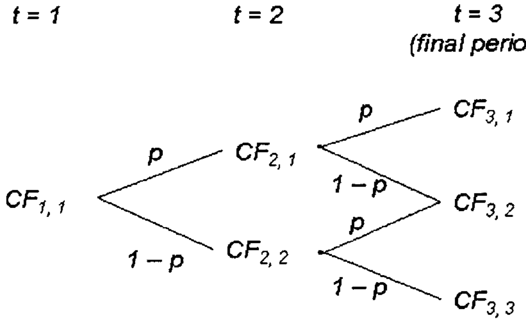


Figure 6-4: Binomial Lattice of Cash Flows of the Chuo Shinkansen Project

Finally, project managers can calculate the expected value of the project by a backward induction process [47]. The following steps describe the process to calculate the value of the cash flow stream of the project, illustrating a case example of a three-stage Binomial Lattice:

Step 1: Calculate the expected value in the final period of the cash flow of the two adjoining nodes that both descend from the same node in the preceding period. Then make the same calculation for all the other adjoining pairs as shown in Figure 6-5.

Example



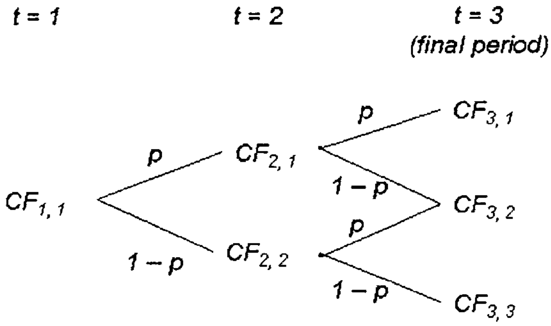
$$EV_{3,1} = p \cdot CF_{3,1} + (1-p) \cdot CF_{3,2}$$

$$EV_{3,2} = p \cdot CF_{3,2} + (1-p) \cdot CF_{3,3}$$

Figure 6-5: Example of the First Step in the Backward Induction Process. The process starts with the calculation of the expected values of cash flow in the final period: $EV_{3,1}$ and $EV_{3,2}$.

Step 2: Discount the expected value of cash flow by an appropriate discount rate (i.e., the risk-free discount rate in the case of risk-neutral valuation) so that the resulting value represents the value at time = *N-1* (where *N* is the final period).

Example



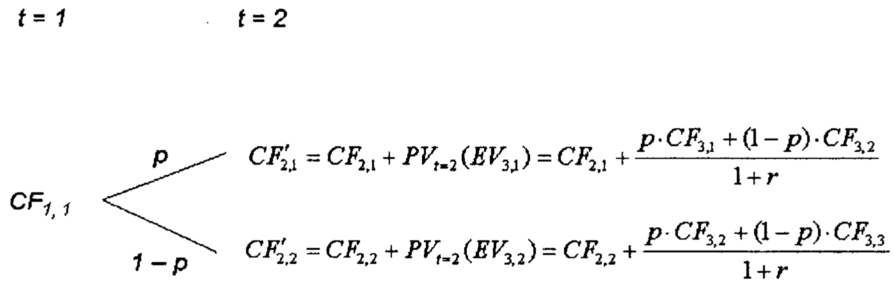
$$PV_{t=2}(EV_{3,1}) = \frac{p \cdot CF_{3,1} + (1-p) \cdot CF_{3,2}}{1+r}$$

$$PV_{t=2}(EV_{3,2}) = \frac{p \cdot CF_{3,2} + (1-p) \cdot CF_{3,3}}{1+r}$$

Figure 6-6: Example of the Second Step in the Backward Induction Process. The expected values calculated in Step 1 are discounted so that they represent the value at $t = 2$.

Step 3: Add the discounted value of the expected cash flow obtained in Step 2 to the cash flow at the preceding node from which the two adjoining nodes both descend. The obtained value represents the expected net present value, at time = N-1, of the project provided that the project reached the node (N-1,j) (j = 1, 2...N). Then replace the cash flow at time = N-1 by the calcuated expected net present value of the project.

Example



$$CF'_{2,1} = CF_{2,1} + PV_{t=2}(EV_{3,1}) = CF_{2,1} + \frac{p \cdot CF_{3,1} + (1-p) \cdot CF_{3,2}}{1+r}$$

$$CF'_{2,2} = CF_{2,2} + PV_{t=2}(EV_{3,2}) = CF_{2,2} + \frac{p \cdot CF_{3,2} + (1-p) \cdot CF_{3,3}}{1+r}$$

Figure 6-7: Example of the Third Step in the Backward Induction Process. The cash flow at t = 2 need to be replaced by the sum of the value obtained in Step 3 and the cash flow at t =2.

Step 4: Repeating Step 1 through 3, make the same calculation with each of the preceding time periods.

The above process of the backward induction can be mathematically summarized by a recurring formula. Equation 6-16 provides the formula for the calculation of the net present value (at time = i) of the cash flow stream descending from the node (i, j). Repeatedly using this equation from the final period to the first period, project managers can calculate the total present value of the project.

$$NPV_i(CFS_{i,j}) = CF_{i,j} + \frac{p \cdot NPV_{i+1}(CFS_{i+1,j}) + (1-p) \cdot NPV_{i+1}(CFS_{i+1,j+1})}{1+r}$$ **Equation 6-16**

Where $CF_{i,j}$: Cash flow at the node (i, j)
$CFS_{i,j}$: Cash flow stream that descend from the node (i, j)
$NPV_i(CFS_{i,j})$: Net present value of the cash flow stream, $CFS_{i,j}$, at time $= i$
r: Discount rate

Finally, combining Equations 6-14 and 6-16, project managers can calculate the net present value of the Chuo Shinkansen Project with consideration of the capacity constraint. The next section explains the process for evaluating the project with options for expansion.

6.3.2. Project Value Calculation Model for the Chuo Shinkansen with Option to Expand Capacity

The option of expanding the capacity of the Chuo Shinkansen affects the Binomial Lattice structure of the cash flow since the cash flow is a function of the capacity. Once the option is exercised, the cash flow stream will become completely different from the one without an option. Therefore, project managers need to prepare two different Binomial Lattice models of cash flow, and they must switch these models at the time of implementation of the option.

In the case of the Chuo Shinkansen Project, the capacity is expressed as the function of the maximum operational frequency (see Equation 6-14). Therefore, if the system is designed with the expansion option of maximum operational frequency from f_1 to f_2, project managers need to construct two Binomial Lattice models using these frequencies, and they also need to calculate the project value using the cash flow stream that corresponds to the actual configuration of the system.

To illustrate, let us assume that the system capacity has been expanded from the frequency of f_1 to f_2 at a certain time that is represented by the node (i, j) (i.e., the node where the demand $= D_{i,j}$) in Figure 6-8 (a). Once the expansion option has been exercised, the cash flow lattice that descends from this node must be calculated using f_2, instead of f_1, while the rest of the lattice structure should remain unchanged (see Figure 6-8 (b)). Therefore, project managers need to switch the cash flow lattice that they use in the calculation of the project value depending on whether or not the option to expand the capacity has been exercised.

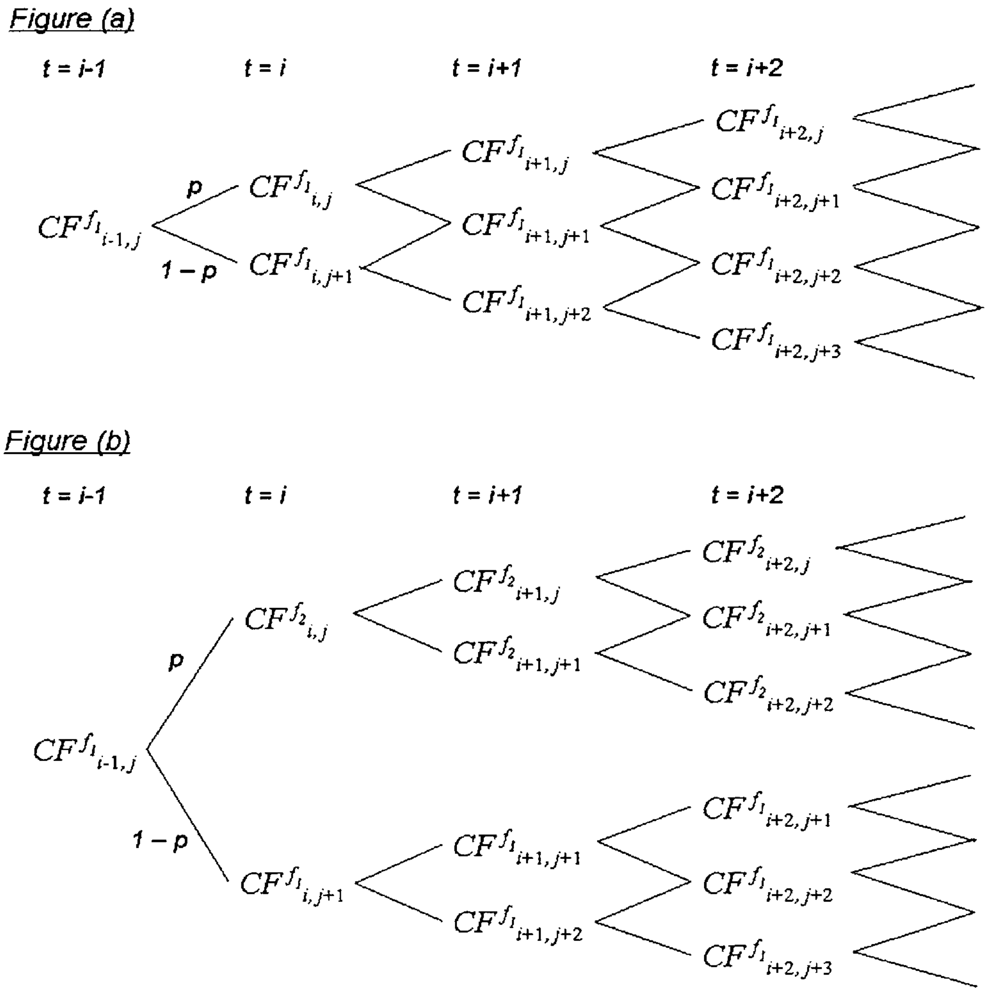


Figure (a)

Figure (b)

Figure 6-8: Cash Flow Lattice for the Chuo Shinkansen System without and with the Expansion of the Capacity (Figures (a) and (b), respectively).
Once the option to expand the capacity (i.e., the option to increase the frequency from f_1 to f_2) has been exercised at the node (i, j), the cash flow lattice from this node needs to be calculated using f_2 instead of f_1 as shown in Figure (b).

Except for the switching of the cash flow lattice, the process of calculating the value of the project with the option is essentially the same as that of the one with no expansion option. Therefore, Equation 6-17, which can be derived from Equation 6-16 for projects with no options, provides the formula that will calculate the total net present value of the project in which the expansion option is exercised at the node (*i, j*).

$$NPV_{project} = NPV_1\left(CFS_{1,1}^{f_1}\right) + \frac{-NPV_i\left(CFS_{i,j}^{f_1}\right) + NPV_i\left(CFS_{i,j}^{f_2}\right) - I_{op.}}{(1+r)^{i-1}} \qquad \textbf{Equation 6-17}$$

Where $NPV_{project}$: Total net present value of the project

$NPV_i\left(CFS_{i,j}^{f_m}\right)$: Value of the cash flow stream, $CFS_{i,j}^{f_m}$, discounted so that it represents the value at time = i

$CFS_{i,j}^{f_m}$: Cash flow stream of the system with the operational frequency f_m, descending from the node (*i, j*)

$I_{op.}$: Implementation cost of the expansion option

r : Discount rate

Using Equation 6-17, project managers can make a rule for deciding whether or not they should exercise the option at the node (*i, j*). The last term of Equation 6-17 represents the difference between the project values which the project managers will earn by exercising the option compared with not exercising it. Therefore, if this value is greater than zero, they should exercise the option; otherwise, it will be advantageous not to implement the option. As a result, project managers can set up the following decision criterion:

<u>Decision Criterion</u>

Exercise the expansion option at the node (*i, j*) if:

$$VOP_{i,j} = \frac{-NPV_i\left(CFS_{i,j}^{f_1}\right) + NPV_i\left(CFS_{i,j}^{f_2}\right) - I_{op.}}{(1+r)^{i-1}} > 0 \qquad \textbf{Equation 6-18}$$

Where $VOP_{i,j}$: Value of exercising the expansion option at the node (*i, j*)

6.4. Selecting the Discount Rate

Finally, the project managers need to consider the choice of an appropriate discount rate. In the general scheme of the hybrid real options analysis, the risk-free rate is used to discount the project cash flows. However, this choice of discount rate is possible only when the following two conditions are satisfied. First, project managers can diversify their investments broadly enough to avoid the project-specific risks. Second, they can appropriately transform the market risks into the risk-neutral distribution of project outcomes by relating the project cash flow driving factor to one or more priced market factors (see Section 5.2). Unfortunately, for the Chuo Shinkansen Project, it seems difficult to satisfy these two conditions and the risk-free rate will not necessarily become the appropriate discount rate.

With regard to the diversification of investments, JR Central does not seem to have enough large projects to avoid the project-specific risk of the Chuo Shinkansen Project. Currently, JR Central operates the Tokaido Shinkansen and several conventional lines. However, these lines have well-established infrastructures and there are not many large projects to improve the profitability of these lines compared to the scale of the Chuo Shinkansen Project. Therefore, it seems inappropriate to imagine that JR Central can avoid the project-specific risks of the Chuo Shinkansen Project by diversifying investments. From this viewpoint, it seems inappropriate to use the risk-free rate for the Chuo Shinkansen Project.

In addition, as explained earlier in this chapter, this thesis uses GDP instead of a market-traded priced factor to estimate the future distribution of demand. Since GDP is not a traded asset and it cannot be used to make a risk-less portfolio, the risk-free rate will not necessarily become the appropriate rate to discount the cash flows of the Chuo Shinkansen Project.

For these reasons, project managers need to consider the method of determining the appropriate discount rate for the Chuo Shinkansen Project, instead of just applying the risk-free rate. Section 4.2 provides three common methods of determining the discount rate:

weighted average cost of capital (WACC), capital asset pricing model (CAPM), and the arbitrage pricing theory (APT). Among these three methods, CAPM is the most widely used model for estimating the cost of equity capital, especially for larger companies [37]. Therefore, this thesis calculates the discount rate for the Chuo Shinkansen Project based on CAPM, and it also conducts sensitivity analyses, changing the value of the discount rate in order to analyze its effect on the project value.

Equation 6-19 provides the formula which calculates the discount rate for the Chuo Shinkansen Project based on the CAPM. All the data that are necessary to calculate the discount rate can be obtained from market information. Based on this equation, this thesis calculates the discount rate and applies the obtained discount rate to evaluating the value of the Chuo Shinkansen Project.

$$r_{CS} = r_f + \beta_{JR-Central} \cdot \left[E(r_m) - r_f \right] \qquad \textbf{Equation 6-19}$$

Where r_{CS}: Discount rate for the Chuo Shinkansen Project (%)

r_f: Risk-free rate (i.e., rate of return on bonds) (%)

$E(r_m)$: Expected rate of return of the market (%)

$\beta_{JR-Central}$: Sensitivity of the stock price of JR Central to the market returns

6.5. Conclusions about the Extension of the Hybrid Real Options Model

In this chapter, this thesis applies the hybrid real options model in an innovative manner considering the following four aspects in order to appropriately evaluate the Chuo Shinkansen Project:

First, the thesis develops a model that estimates the demand for the Chuo Shinkansen, which does not exist yet. By relating the demand for the Tokaido Shinkansen to GDP, the thesis develops a model that calculates the estimated distribution of the demand for the Tokaido Shinkansen. Using the estimated relation between the future demands for the Chuo Shinkansen and the Tokaido Shinkansen, which the government had already developed, the thesis obtains the estimated demand for the Chuo Shinkansen from the demand distribution for the Tokaido Shinkansen.

Second, this chapter introduces a model that transforms the possible coverage of a PCS (i.e., the outcomes of R&D) and the operational requirements such as the minimum frequency of trains into the constraints on the system design. In particular, this thesis develops a model that specifies the number of PCSs needed in the system. Based on the assumptions about the R&D outcomes and the requirement for the operational frequency, this model also identifies the potential scenarios of the system development. In other words, the thesis identifies the expansion options that will increase the value of the project.

Third, this chapter extends the Binomial Lattice Model in order to incorporate into it the capacity constraint of the Chuo Shinkansen system. After developing the formula to calculate the present value of the cash flow lattice for projects with no options, the thesis develops it so that it can calculate the value of the cash flow lattice with expansion options. Using this formula, the thesis also identifies the criterion as to whether or not the project managers should exercise the expansion option.

Finally, the thesis proposes using CAPM for the determination of the discount rate. Since the Chuo Shinkansen Project is a large-scale investment compared to other projects that JR Central holds, it is virtually impossible to avoid project-specific risks by diversifying investments. Therefore, the risk-free rate would not be an appropriate discount rate for this project. In addition, since GDP, to which this thesis relates the demand, is not a traded asset, the resulting distribution of demand cannot be regarded as the risk-neutral distribution. For these reasons, this thesis proposes CAPM to cope with the difficulty of determining the discount rate.

Building upon the models developed in this chapter, the next chapter applies the hybrid real options analysis to the Chuo Shinkansen Project and evaluates the value of the project considering the options to expand the capacity.

Chapter 7 Evaluation of the Chuo Shinkansen Project

This chapter applies the extended hybrid real options model to the evaluation of the Chuo Shinkansen Project. As Chapter 5 explains, the hybrid real options analysis, which is a composite model of the decision analysis and the options method, is an appropriate evaluation model for projects with both market risks and project-specific risks. Chapter 6 develops the hybrid real options model further in order to deal with the difficulties that arise in applying the model to the Chuo Shinkansen Project. Using this extended hybrid real options model, this thesis evaluates the value of the project with considerations of the uncertainty of demand growth and the probability of success of research and development (R&D) activity that influences the flexibility of the system design.

7.1. Project Data Collection

In the hybrid real options analysis, project managers first need to identify the major uncertainties associated with the project and to collect the data necessary for evaluating these uncertainties. Chapter 3 has already identified the major uncertainties associated with the Chuo Shinkansen Project: the uncertainty of demand as the market risk and the uncertainty of R&D outcomes as the project-specific risk. The following sections explain the data necessary to evaluate these uncertainties.

7.1.1. Data for Estimating Demand

For the Chuo Shinkansen Project, demand will be the *project cash flow driving factor* that primarily influences the cash flows of the project. Therefore, appropriately estimating the demand is essential for the accurate appraisal of the project.

Furthermore, Chapter 6 develops a model that relates the demand for the Chuo Shinkansen to the Gross Domestic Product (GDP), in order to make the estimation of the future demand possible (see Section 6.1). Accordingly, the project managers need to collect the data of

GDP; in particular, they need to analyze the average growth rate of GDP and the volatility of the growth rate to calculate the Binomial Lattice distribution of the demand.

The average annual growth rate of GDP, ν, and the volatility of the growth rate, σ, can be estimated from the data of GDP in the past. The following equations provide the estimates of these values [9]:

$$\nu = \frac{1}{\Delta t} \cdot \sum_{t=1}^{N-1} \ln \frac{GDP(t+\Delta t)}{GDP(t)} \Big/ (N-1) \qquad \textbf{Equation 7-1}$$

$$\sigma = \sqrt{\frac{1}{\Delta t} \cdot \sum_{t=1}^{N=1} \left\{ \ln \frac{GDP(t+\Delta t)}{GDP(t)} - \nu \right\}^2 \Big/ (N-2)} \qquad \textbf{Equation 7-2}$$

Where ν : Average annual growth rate of GDP

σ : Volatility (standard deviation) of the growth rate of GDP

N : Number of GDP data

ΔT : Length of incremental time period

Using Equations 7-1 and 7-2 and the GDP data shown in Table 7-1, ν and σ are calculated to be 2.71% and 11.5%, respectively.

Table 7-1: Japan' GDP Data from 1980 through 2004

time	GDP(t) (billion yen)	time	GDP(t) (billion yen)
1st quarter/1980	75,102.0	1st quarter/1993	121,018.0
2nd quarter/1980	74,100.8	2nd quarter/1993	114,284.4
3rd quarter/1980	78,483.2	3rd quarter/1993	119,563.8
4th quarter/1980	85,454.0	4th quarter/1993	127,324.3
1st quarter/1981	77,137.3	1st quarter/1994	117,174.0
2nd quarter/1981	76,482.2	2nd quarter/1994	118,394.4
3rd quarter/1981	81,292.7	3rd quarter/1994	123,033.4
4th quarter/1981	87,413.7	4th quarter/1994	128,917.9
1st quarter/1982	78,889.5	1st quarter/1995	118,956.5
2nd quarter/1982	79,149.3	2nd quarter/1995	120,885.7
3rd quarter/1982	83,336.5	3rd quarter/1995	124,755.4
4th quarter/1982	89,860.8	4th quarter/1995	132,378.5
1st quarter/1983	80,308.5	1st quarter/1996	122,959.0
2nd quarter/1983	80,092.6	2nd quarter/1996	125,053.7
3rd quarter/1983	85,057.7	3rd quarter/1996	128,490.2
4th quarter/1983	91,116.2	4th quarter/1996	137,543.8
1st quarter/1984	82,131.0	1st quarter/1997	128,201.1
2nd quarter/1984	82,569.7	2nd quarter/1997	127,850.8
3rd quarter/1984	88,175.8	3rd quarter/1997	129,826.3
4th quarter/1984	94,196.1	4th quarter/1997	137,999.4
1st quarter/1985	86,720.0	1st quarter/1998	126,701.5
2nd quarter/1985	86,491.7	2nd quarter/1998	126,013.9
3rd quarter/1985	91,946.9	3rd quarter/1998	128,910.7
4th quarter/1985	99,553.6	4th quarter/1998	136,529.4
1st quarter/1986	89,665.7	1st quarter/1999	125,847.6
2nd quarter/1986	88,927.0	2nd quarter/1999	127,162.2
3rd quarter/1986	94,939.6	3rd quarter/1999	128,824.6
4th quarter/1986	101,970.6	4th quarter/1999	136,783.1
1st quarter/1987	92,234.1	1st quarter/2000	128,992.0
2nd quarter/1987	91,498.9	2nd quarter/2000	130,061.1
3rd quarter/1987	98,621.5	3rd quarter/2000	133,052.2
4th quarter/1987	107,398.6	4th quarter/2000	141,414.6
1st quarter/1988	99,439.4	1st quarter/2001	133,341.8
2nd quarter/1988	97,912.8	2nd quarter/2001	131,659.4
3rd quarter/1988	105,500.0	3rd quarter/2001	132,522.9
4th quarter/1988	113,267.0	4th quarter/2001	138,398.6
1st quarter/1989	106,704.1	1st quarter/2002	128,802.8
2nd quarter/1989	102,369.2	2nd quarter/2002	130,590.6
3rd quarter/1989	109,891.2	3rd quarter/2002	133,421.7
4th quarter/1989	119,171.1	4th quarter/2002	140,412.5
1st quarter/1990	110,181.7	1st quarter/2003	132,246.2
2nd quarter/1990	109,437.7	2nd quarter/2003	133,193.6
3rd quarter/1990	117,282.2	3rd quarter/2003	136,355.2
4th quarter/1990	124,023.6	4th quarter/2003	144,821.8
1st quarter/1991	117,169.7	1st quarter/2004	140,282.6
2nd quarter/1991	112,992.6	2nd quarter/2004	138,793.3
3rd quarter/1991	119,369.3	3rd quarter/2004	141,178.1
4th quarter/1991	126,837.8	4th quarter/2004	146,851.0
1st quarter/1992	118,835.2		
2nd quarter/1992	114,248.8		
3rd quarter/1992	120,596.8		
4th quarter/1992	127,318.9		

Source: Cabinet Office, Government of Japan [55]

7.1.2. Assessing the Difficulty of R&D

The other major uncertainty associated with the Chuo Shinkansen Project is the results of R&D to extend the coverage of a Power Conversion System (PCS). Chapter 3 explains that the success in R&D of the PCS technology is the key for the flexible development of the Chuo Shinkansen system; unless R&D succeeds in extending the coverage, the Chuo Shinkansen must be constructed with many PCSs alongside the route, which means a large operational capacity, regardless of the actual size of the demand it will serve. Therefore, in order to appropriately evaluate the project, managers of the Chuo Shinkansen Project need to analyze the technical uncertainty of R&D.

The hybrid real options analysis incorporates the uncertainty of R&D into the project evaluation by using decision analysis. In other words, project managers need to assume discrete outcomes of R&D and the associated probabilities. For the discrete results of R&D, this thesis assumes three levels of coverage of a PCS. These are: 20km for the total failure case (the current situation), 30km for the partial success case, and 40km as the case of total success (see Section 3.1.2 for the reasons for these assumptions). Accordingly, project managers need to estimate the probabilities of these assumed R&D outcomes.

However, estimating the probability of the results of R&D is not easy, especially for the Chuo Shinkansen Project. This is because currently there are not many Magnetically Levitated Linear Motor Vehicle (Maglev) systems that are under development; there is not much available information about the probabilities of success with regard to the R&D of Maglev technology, still less for the Chuo Shinkansen which utilizes the superconducting Maglev technology.

Owing to the lack of data, managers of the Chuo Shinkansen Project will need to develop other methods of probability assessment. They might be able to obtain the probabilities by surveying subjective expert-opinions about the R&D, or by assuming a form of distribution, estimating the means and standard deviation, and developing discrete estimates using the distribution. Nevertheless, developing these methods of assessment is a substantial research topic in itself and is beyond the scope of this thesis. Therefore, for the sake of simplifying the analysis, this thesis simply assumes arbitrary probabilities for the results of R&D, and it analyzes the sensitivity of the project value against these probabilities.

Table 7-2 summarizes the three sets of probabilities of R&D outcomes assumed for sensitivity analyses. Among these three sets of probabilities, Case 1 can be interpreted as a pessimistic attitude toward the success of R&D, because in this case the probability for Total Failure is assumed to be higher than that for Total Success. On the other hand, Case 3 represents an optimistic attitude; the probability for Total Success is set to be higher than that for Total Failure. As the representation of a moderate perspective, Case 2 uses the same probability for Total Failure and Total Success. This thesis calculates the value of the project and examines the effect of the probability on the value of the project using these three sets of probabilities.

Table 7-2: Assumed Probabilities for R&D Outcomes

Probability	P_0	P_1	P_2
	(Total Failure)	(Partial Success)	(Total Success)
	L_0=20km	L_1=30km	L_2=40km
Case 1	0.4	0.5	0.1
Case 2	0.3	0.4	0.3
Case 3	0.1	0.5	0.4

With regard to the validity of the assumptions of probabilities shown in Table 7-2, there is not much information available to examine how reasonable these assumptions are. However, the technology of covering 30km of track has been already established in the Shanghai Maglev system, though the German Transrapid technology which the Shanghai Maglev system utilizes is not the same as the Japanese Maglev technology [57][58]. Therefore, it would be reasonable to assume the highest probability for Partial Success, which corresponds to 30km of coverage, and a higher probability for Total Success than that for Total Failure. In this sense, Case 3 will be a more realistic assumption than other two cases.

In addition to the above sensitivity analyses, this thesis demonstrates how the evaluation model developed in this thesis can be used to analyze the probabilities of R&D outcomes that would make the investment in R&D neither attractive nor unattractive. To conduct this "break-even" analysis, this study makes assumptions about the relationship between probabilities of the three outcomes of R&D and the amount of investment in R&D, $I_{R\&D}$, as shown in Table 7-3.

Table 7-3: Assumed Relationship between Probabilities of R&D Outcomes and the amount of investment in R&D, $I_{R\&D}$, for the Break-even Analyses.

Probability	P_0	P_1	P_2	Comment
	(Total Failure)	(Partial Success)	(Total Success)	
	L_0=20km	L_1=30km	L_2=40km	
Case I	P_0	$(1-P_0)/2$	$(1-P_0)/2$	P_0 is the independent variable
Case II	$(1-P_1)/2$	P_1	$(1-P_1)/2$	P_1 is the independent variable
Case III	$(1-P_2)$	0	$P_2=\dfrac{I_{R\&D}}{I_{R\&D}+1}$	P_2 is an independent variable but depends on the amount of R&D investment.

The three cases in Table 7-3 have different expectations about the probabilities of R&D. Case I assumes that Total Success in R&D and Partial Failure are equally likely. On the other hand, Case II expects that Total Success and Total Failure will occur equally. Unlike these two cases, Case III only considers two extreme results of R&D, Total Failure and Total Success, and ignores Partial Success; instead, Case III assumes that the success of R&D depends on the amount of money invested in R&D[9]. In particular, Case III assumes that the probability of Total Success in R&D approaches zero as the amount of money invested in R&D, $I_{R\&D}$, decreases, and that the probability approaches one as $I_{R\&D}$ increases. By using these relationships of the probabilities shown in Table 7-3, this study calculates the probabilities of R&D outcomes that would yield the break-even point in the investment in R&D.

---

[9] The assumption that the probability of R&D success increases in accordance with the budget of R&D would be reasonable in many R&D projects. Though this thesis analyzes only a simple function of the relationship between the probability of R&D success and the R&D budget as shown in Table 7-3, it is suggested, in the future works, that other form of functions of the probability and the budget are also examined.

7.1.3. Calculation of the Discount Rate

Managers of the Chuo Shinkansen Project also need to collect data that are necessary for calculating the discount rate. In order to calculate the discount rate based on the Capital Asset Pricing Model (CAPM), the following three values are needed: the risk-free rate of interest, r_f, the sensitivity of the Central Japan Railway Company's (JR Central's) stock price to the market return, $\beta_{JR-Central}$, and the expected rate of return of the market, $E(r_m)$.

In the calculation of these three values, this thesis uses the interest rates of the 30-year Japanese national bonds and the market data of the Tokyo Stock Exchange (TSE), where the stocks of JR Central are traded. The thesis collects these data between 1998 through 2005 (except for the bond whose data are available only from 1999 [59]) because JR Central's stocks have been publicly traded in the TSE First Section since October, 1997. Table 7-4 summarizes the annual interest rates of the national bonds and the annual increase rates of the Tokyo Stock Price Index (TOPIX) during this period. TOPIX is "a free-float adjusted market capitalization-weighted index that is calculated based on all the domestic common stocks listed on the TSE First Section [60]"; therefore, TOPIX indicates the growth of the entire market [61]. From this table, the average risk-free rate and the average expected return of the market are calculated as 2.32% and 7.74%, respectively.

Table 7-4: Risk-free Rate and the Expected Rate of Return of the Market. TOPIX indicates the growth of the entire market [61].

Year	Annual Average Interest Rate of 10-year Bond	Tokyo Stock Price Index (TOPIX)		
		Start-Value	End-Value	Annual Increase Rate
1998		1175.93	1086.99	-7.56%
1999	2.84%	1083.17	1722.2	59.00%
2000	2.60%	1726.21	1283.67	-25.64%
2001	2.34%	1294.61	1032.14	-20.27%
2002	2.07%	1040.02	843.29	-18.92%
2003	1.60%	851.8	1043.69	22.53%
2004	2.41%	1055.08	1149.63	8.96%
2005	2.42%	1147.24	1649.76	43.80%
Ave.	2.32%			7.74%

Source: JP Actuary Consulting Co., Ltd. [62] and Yahoo Japan Finance [63]

$\beta_{JR-Central}$ can be also calculated using the data of TOPIX and the data of JR Central's stock price. Table 7-5 provides the data of these values, and as shown in this table, $\beta_{JR-Central}$ is calculated to be 0.190.

Table 7-5: TOPIX, JR Central's Stock Price, and $\beta_{JR\text{-}Central}$

Month, Year	TOPIX (A(t))	JR Central Stock Price (B(t))	C(t) = A(t)/A(t-1)-1	D(t) = B(t)/B(t-1)-1	Month, Year	TOPIX (A(t))	JR Central Stock Price (B(t))	C(t) = A(t)/A(t-1)-1	D(t) = B(t)/B(t-1)-1
Jan., 1998	1,267.51	394,000			Jan., 2002	971.77	740,000	-0.05849	-0.12736
Feb., 1998	1,272.45	408,000	0.00390	0.03553	Feb., 2002	1,013.80	727,000	0.04325	-0.01757
Mar., 1998	1,251.70	429,000	-0.01631	0.05147	Mar., 2002	1,060.19	740,000	0.04576	0.01788
Apr., 1998	1,222.98	454,000	-0.02294	0.05828	Apr., 2002	1,082.06	733,000	0.02063	-0.00946
May, 1998	1,221.49	508,000	-0.00122	0.11894	May, 2002	1,120.08	763,000	0.03514	0.04093
Jun., 1998	1,230.38	513,000	0.00728	0.00984	Jun., 2002	1,024.89	730,000	-0.08499	-0.04325
Jul., 1998	1,262.04	587,000	0.02573	0.14425	Jul., 2002	965	721,000	-0.05844	-0.01233
Aug., 1998	1,106.49	586,000	-0.12325	-0.00170	Aug., 2002	941.64	765,000	-0.02421	0.06103
Sept., 1998	1,043.57	577,000	-0.05686	-0.01536	Sept., 2002	921.05	773,000	-0.02187	0.01046
Oct., 1998	1,035.60	598,000	-0.00764	0.03640	Oct., 2002	862.24	741,000	-0.06385	-0.04140
Nov., 1998	1,143.50	600,000	0.10419	0.00334	Nov., 2002	892.71	766,000	0.03534	0.03374
Dec., 1998	1,086.99	598,000	-0.04942	-0.00333	Dec., 2002	843.29	739,000	-0.05536	-0.03525
Jan., 1999	1,125.26	598,000	0.03521	0.00000	Jan., 2003	821.18	720,000	-0.02622	-0.02571
Feb., 1999	1,120.03	614,000	-0.00465	0.02676	Feb., 2003	818.73	720,000	-0.00298	0.00000
Mar., 1999	1,267.22	615,000	0.13142	0.00163	Mar., 2003	788	709,000	-0.03753	-0.01528
Apr., 1999	1,337.12	637,000	0.05516	0.03577	Apr., 2003	796.56	774,000	0.01086	0.09168
May, 1999	1,297.19	638,000	-0.02986	0.00157	May, 2003	837.7	822,000	0.05165	0.06202
Jun., 1999	1,416.20	614,000	0.09174	-0.03762	Jun., 2003	903.44	860,000	0.07848	0.04623
Jul., 1999	1,478.93	610,000	0.04429	-0.00651	Jul., 2003	939.4	835,000	0.03980	-0.02907
Aug., 1999	1,457.02	710,000	-0.01481	0.16393	Aug., 2003	1,002.01	823,000	0.06665	-0.01437
Sept., 1999	1,506.83	710,000	0.03419	0.00000	Sept., 2003	1,018.80	904,000	0.01676	0.09842
Oct., 1999	1,563.89	705,000	0.03787	-0.00704	Oct., 2003	1,043.36	962,000	0.02411	0.06416
Nov., 1999	1,641.53	640,000	0.04965	-0.09220	Nov., 2003	999.75	875,000	-0.04180	-0.09044
Dec., 1999	1,722.20	641,000	0.04914	0.00156	Dec., 2003	1,043.69	926,000	0.04395	0.05829
Jan., 2000	1,707.96	660,000	-0.00827	0.02964	Jan., 2004	1,047.51	976,000	0.00366	0.05400
Feb., 2000	1,718.94	674,000	0.00643	0.02121	Feb., 2004	1,082.47	946,000	0.03337	-0.03074
Mar., 2000	1,705.94	621,000	-0.00756	-0.07864	Mar., 2004	1,179.23	926,000	0.08939	-0.02114
Apr., 2000	1,648.87	580,000	-0.03345	-0.06602	Apr., 2004	1,186.31	902,000	0.00600	-0.02592
May, 2000	1,522.84	600,000	-0.07643	0.03448	May, 2004	1,139.94	891,000	-0.03909	-0.01220
Jun., 2000	1,591.60	600,000	0.04515	0.00000	Jun., 2004	1,189.60	929,000	0.04356	0.04265
Jul., 2000	1,453.15	596,000	-0.08699	-0.00667	Jul., 2004	1,139.30	895,000	-0.04228	-0.03660
Aug., 2000	1,511.44	618,000	0.04011	0.03691	Aug., 2004	1,129.55	912,000	-0.00856	0.01899
Sept., 2000	1,470.78	633,000	-0.02690	0.02427	Sept., 2004	1,102.11	866,000	-0.02429	-0.05044
Oct., 2000	1,379.96	665,000	-0.06175	0.05055	Oct., 2004	1,085.43	858,000	-0.01513	-0.00924
Nov., 2000	1,362.66	720,000	-0.01254	0.08271	Nov., 2004	1,098.79	841,000	0.01231	-0.01981
Dec., 2000	1,283.67	703,000	-0.05797	-0.02361	Dec., 2004	1,149.63	837,000	0.04627	-0.00476
Jan., 2001	1,300.23	677,000	0.01290	-0.03698	Jan., 2005	1,146.14	839,000	-0.00304	0.00239
Feb., 2001	1,241.48	698,000	-0.04518	0.03102	Feb., 2005	1,177.41	900,000	0.02728	0.07271
Mar., 2001	1,277.27	772,000	0.02883	0.10602	Mar., 2005	1,182.18	918,000	0.00405	0.02000
Apr., 2001	1,366.46	777,000	0.06983	0.00648	Apr., 2005	1,129.93	863,000	-0.04420	-0.05991
May, 2001	1,310.81	780,000	-0.04073	0.00386	May, 2005	1,144.33	875,000	0.01274	0.01390
Jun., 2001	1,300.98	775,000	-0.00750	-0.00641	Jun., 2005	1,177.20	857,000	0.02872	-0.02057
Jul., 2001	1,190.31	737,000	-0.08507	-0.04903	Jul., 2005	1,204.98	809,000	0.02360	-0.05601
Aug., 2001	1,103.67	730,000	-0.07279	-0.00950	Aug., 2005	1,271.29	846,000	0.05503	0.04574
Sept., 2001	1,023.42	835,000	-0.07271	0.14384	Sept., 2005	1,412.28	884,000	0.11090	0.04492
Oct., 2001	1,059.37	856,000	0.03513	0.02515	Oct., 2005	1,444.73	987,000	0.02298	0.11652
Nov., 2001	1,050.22	809,000	-0.00864	-0.05491	Nov., 2005	1,536.21	1,030,000	0.06332	0.04357
Dec., 2001	1,032.14	848,000	-0.01722	0.04821	Dec., 2005	1,649.76	1,130,000	0.07392	0.09709
							β = LINEST(D(t), C(t)) =	**0.190**	

Source: Yahoo Japan Finance [63][64]

Using the identified values of the r_f, $E(r_m)$, and $\beta_{JR-Central}$, and CAPM, project managers can calculates the discount rate for the Chuo Shinkansen Project as shown in Equation 7-3.

$$r_{CS} = r_f + \beta_{JR-Central} \cdot \lfloor E(r_m) - r_f \rfloor$$

$$= 2.32 + 0.190\,(\,7.74 - 2.32\,) = 3.35\ (\%) \qquad \textbf{Equation 7-3}$$

7.1.4. Estimating Other Miscellaneous Data

In order to conduct the hybrid real options analysis, project managers need to collect data in addition to those analyzed thus far in this thesis. These "miscellaneous" data include such data as the length of the construction period, length of operation (N years), length of the incremental time of the Binomial Lattice (ΔT years), the estimated cost of one Maglev car, and the estimated cost of R&D.

Some of these data, such as the cost of one Maglev car, can be estimated from the publicly accessible data of the government, JR Central, and *the Conference of Scholars along the Chuo Shinkansen*. Other data can be basically determined by the management's decision. For example, N and ΔT are parameters that project managers can choose.

Although the choice of these data will affect the value of the project, to simplify the analysis, this thesis uses constant values for these data. As a result, all the "miscellaneous" data are considered constants in this analysis and Table 7-6 provides the list of these "miscellaneous" data.

Table 7-6: Miscellaneous Data used in the Analysis of the Chuo Shinkansen Project

No.	Item	Value	Unit	Comment
1	Construction period	10	years	Source *1 Assume equally distributed construction cost during this period.
2	Procurement period of Maglev trains	3	years	Assumption.
3	Cost of one Malgev car	0.8	billion yen	Source *1
4	Number of cars in one train	16	cars	Source *2
5	Operational revenue per unit demand	30.8	yen/passenger/km	Estimated from the data of Tokaido Shinkansen. Source *1, *3
6	Operational cost per train per one-way trip between Tokyo and Osaka	5.56	million yen	Assume the same cost as Tokaido Shinkansen. Source *3, *4
7	Average travel distance per passenger of the Tokaido Shinkansen	300	km	Source *5, *6
8	Length of operational period	40	years	Assumption.
9	Length of the incremental time of the Binomial Lattice	1	year	
10	Operational hours per day	16.5	hours	Assumption.
11	Dwelling time at terminals	5	minutes	Assumption.
12	Initial value of GDP	535 = 4.57	trillion yen trillion US$	Calculated from the data of MLIT (source *6) and Equation 6-5. at the rate of US$1 = 117 yen
13	Project commencement year	2010		Assumption.
14	Cost of R&D (planned)	320 = 2.74	billion yen trillion US$	Source: *7 at the rate of US$1 = 117 yen

Sources, *1: Tatematsu (2006) [6], *2: JR Central [32], *3: JR Central [65], *4: JR Central (2006) [2],
*5: Conference of Scholars along the Chuo Shinkansen (2001) [1],
*6: East Japan Linear Motor Train Promotion Conference [54],
*7: JR Central [66][10].

---

[10] According to the JR Central's announcement, the project to extend the Yamanashi Maglev Test Line is expected to cost about 320 billion yen including the renewal of the existing facilities, which is not necessarily required for the R&D of the PCS technology [66]. However, since the detailed information is unavailable, this thesis assumes this cost as the cost of R&D.

7.2. Calculation of Demand based on Project Data

In the second step of the hybrid real options analysis, project managers need to use the project data to calculate the distribution of the demand. This calculation can be done using the Binomial Lattice evaluation (see Section 5.1.2) as well as the growth rate and the volatility of GDP.

As explained in Section 7.1.1, the growth rate and the volatility of GDP in Japan are calculated to be 2.71% and 11.5%, respectively. Using these data and the data in Table 7-6, the distribution of GDP can be obtained as follows.

$$GDP(t=0) = 570{,}000 \quad \text{(billion yen)}$$

$$u = e^{\sigma\sqrt{\Delta T}} = e^{0.115} = 1.122$$ **Equation 7-4**

$$d = 1/u = 0.891$$

$$p = \frac{1}{2}\left(1+\frac{\nu}{\sigma}\sqrt{\Delta T}\right) = \frac{1}{2}\left(1+\frac{0.0271}{0.115}\sqrt{1}\right) \fallingdotseq 0.618$$

This distribution of GDP can be further transformed into the distribution of annual demand of the Chuo Shinkansen, using the following equation which is derived from Equation 6-5.

$$\begin{aligned} D_{annual}(t) &= D_{daily}(t)\cdot k_t \cdot 365\times10^{-6} \\ &= 0.72\cdot\{47.84+6.17\times10^{-4}\cdot GDP(t)\}\times300\times365\times10^{-6} \\ &= 3.77+4.86\times10^{-5}\cdot GDP(t) \quad \text{(billion people km)} \end{aligned}$$ **Equation 7-5**

Using the above formula, project managers can calculate the distribution of the demand for the Chuo Shinkansen. Table 7-7 shows this distribution of demand and the distribution of probabilities for the first 15 years of operation.

Table 7-7: Binomial Lattice Distribution of Demand for the Chuo Shinkansen and the Distribution of Probabilities. Only the distributions of the first 15 years are shown.

Year														
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Annual Demand														
29.7964	32.9681	36.5264	40.5183	44.9967	50.021	55.6575	61.981	69.0752	77.034	85.9627	95.9796	107.217	119.825	133.968
	26.9692	29.7964	32.9681	36.5264	40.5183	44.9967	50.021	55.6575	61.981	69.0752	77.034	85.9627	95.9796	107.217
		24.4492	26.9692	29.7964	32.9681	36.5264	40.5183	44.9967	50.021	55.6575	61.981	69.0752	77.034	85.9627
			22.2029	24.4492	26.9692	29.7964	32.9681	36.5264	40.5183	44.9967	50.021	55.6575	61.981	69.0752
				20.2007	22.2029	24.4492	26.9692	29.7964	32.9681	36.5264	40.5183	44.9967	50.021	55.6575
					18.4159	20.2007	22.2029	24.4492	26.9692	29.7964	32.9681	36.5264	40.5183	44.9967
						16.8251	18.4159	20.2007	22.2029	24.4492	26.9692	29.7964	32.9681	36.5264
							15.407	16.8251	18.4159	20.2007	22.2029	24.4492	26.9692	29.7964
								14.143	15.407	16.8251	18.4159	20.2007	22.2029	24.4492
									13.0164	14.143	15.407	16.8251	18.4159	20.2007
										12.0121	13.0164	14.143	15.407	16.8251
											11.1169	12.0121	13.0164	14.143
												10.319	11.1169	12.0121
													9.60771	10.319
														8.97372
Probability														
1	0.61783	0.38171	0.23583	0.1457	0.09002	0.05562	0.03436	0.02123	0.01312	0.0081	0.00501	0.00309	0.00191	0.00118
	0.38217	0.47223	0.43764	0.36051	0.27842	0.20642	0.14878	0.10505	0.07302	0.05013	0.03407	0.02296	0.01537	0.01022
		0.14606	0.27071	0.33451	0.34445	0.31921	0.2761	0.22745	0.18067	0.13953	0.10536	0.07811	0.05704	0.04111
			0.05582	0.13795	0.21307	0.26328	0.28465	0.28139	0.26077	0.23016	0.19552	0.16107	0.12936	0.10172
				0.02133	0.0659	0.12214	0.17608	0.21757	0.24196	0.24915	0.24189	0.22417	0.20005	0.17304
					0.00815	0.03022	0.06535	0.10767	0.14967	0.18494	0.20948	0.22187	0.22275	0.21407
						0.00312	0.01348	0.0333	0.06172	0.09533	0.12958	0.16012	0.18372	0.19863
							0.00119	0.00589	0.01636	0.0337	0.05725	0.0849	0.11364	0.14042
								0.00046	0.00253	0.00782	0.01771	0.03282	0.05272	0.076
									0.00017	0.00107	0.00365	0.00902	0.01812	0.03134
										6.6E-05	0.00045	0.00167	0.00448	0.00969
											2.5E-05	0.00019	0.00076	0.00218
												9.7E-06	7.8E-05	0.00034
													3.7E-06	3.2E-05
														1.4E-06

7.3. Calculation of the Total Project Value

The next step of the analysis is to calculate the total value of the project. In doing so, managers of the Chuo Shinkansen Project first need to calculate the total value of the project for each of the development scenarios identified in Table 6-4. Using the results, they can construct and analyze a decision tree and calculate the total expected value of the project.

7.3.1. Project Value of Each Development Scenario

Using the distribution of demand, which is obtained in Section 7.2, and using Equations 6-13 through 6-16, project managers can obtain the value of the Chuo Shinkansen Project. Table 7-8 shows the calculated net present value of each of the identified scenarios of the system development.

Table 7-8: Net Present Value of Each Development Scenario of the Chuo Shinkansen Project. NPV values exclude the cost of R&D.

Result of R&D		Total Failure	Partial Success		Total Success	
Development Scenario		Scenario I (no option available)	Scenario II-1 (option NOT considered)	Scenario II-2 (option available)	Scenario III-1 (option NOT considered)	Scenario III-2 (option available)
Number of PCS (Operational Frequency)	Initial Construction	$N_{PCS} = 25$ ($f = 15$)	$N_{PCS} = 17$ ($f = 13$)	$N_{PCS} = 17$ ($f = 13$)	$N_{PCS} = 13$ ($f = 10$)	$N_{PCS} = 13$ ($f = 10$)
	After Significant Demand Growth	$N_{PCS} = 25$ ($f = 15$)	$N_{PCS} = 17$ ($f = 13$)	$N_{PCS} = 19$ ($f = 15$)	$N_{PCS} = 13$ ($f = 10$)	$N_{PCS} = 19$ ($f = 15$)
NPV of Project Value excluding R&D cost (Triilion yen)		7.28	8.04	8.34	8.36	9.37
Optimal Timing of Implementing Option		N/A	N/A	21st year in operation	N/A	18th year in operation

By comparing the results of Scenario II-1 and Scenario II-2, which are both calculated from the case of Partial Failure of R&D, project managers can observe that the option to expand the capacity increases the value of the project. This benefit of the option can also be confirmed in the case of Total Success from the results of Scenarios III-1 and III-2.

The optimal timing to implement the option for Scenarios II-2 is calculated to be not the first year in operation but the 21st year in operation. From this fact, it can be concluded that increasing the system capacity later is more advantageous than building the system with maximum capacity at the beginning of operation. The same conclusion can be obtained for the case of Total Success from the result of Scenario III-2.

Combining the observations described above, project managers can conclude that the flexible development strategies are more beneficial than the development scenarios with fixed capacity (i.e., fixed number of PCSs). By developing the flexibility of the system, project managers can increase the value of the Chuo Shinkansen Project at time = 0, even if the option to expand the capacity may never be exercised in the future.

Using the project values obtained in Table 7-8, the next section constructs the decision tree and analyzes the value of the project considering the probabilities of the R&D outcomes.

7.3.2. Decision Analysis

The decision tree for the Chuo Shinkansen Project can be constructed in the same way as shown in Figure 5-6. Using the net present values of project shown in Table 7-8 and the cost of R&D shown in Table 7-6, the decision tree of the Chuo Shinkansen Project can be obtained as in Figure 7-1.

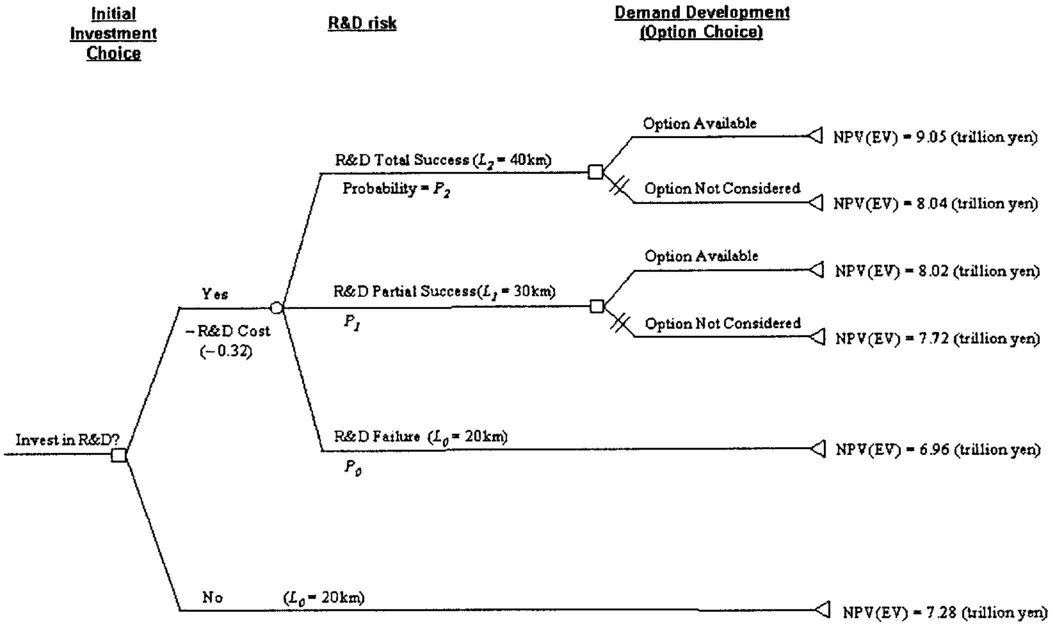


Figure 7-1: Decision Tree of the Chuo Shinkansen Project

Note that, in this case, the project managers should take advantage of the expansion option whenever it is available, because they can increase the value of the project by enabling the option.

Provided that the project managers decide to invest in R&D, the value of the project can be calculated, using the probabilities of three R&D outcomes, P_0, P_1, and P_2 (Equation 7-6).

$$NPV(EV)_{invest} = 6.96P_0 + 8.02P_1 + 9.05P_2 \qquad \textbf{Equation 7-6}$$

Based on this equation and the sets of probabilities shown in Table 7-2, project managers can decide whether it is beneficial for them to invest in R&D or not. Table 7-9 summarizes the results of comparison of the expected values of the project.

Table 7-9: Comparison of the Expected Net Present Value of the Chuo Shinkansen Project with and without R&D Investment

Probability	P_0 (Total Failure) L_0=20km	P_1 (Partial Success) L_1=30km	P_2 (Total Success) L_2=40km	Expected NPV of Project (trillion yen) with R&D investment	Expected NPV of Project (trillion yen) w/o R&D investment	Better Decision
Case 1	0.4	0.5	0.1	7.700	7.28	Invest in R&D
Case 2	0.3	0.4	0.3	8.011	7.28	Invest in R&D
Case 3	0.1	0.5	0.4	8.330	7.28	Invest in R&D

As is clear from this table, the best decision is to invest in R&D for any of the three cases of probabilities assumed in Table 7-2. Even with a low probability of 0.1 of R&D Total Success, the project managers can expect a higher value of the project with R&D investment than without R&D.

Equation 7-6 can be also used to calculate the maximum financial benefit, the maximum loss, or a "reasonably expectable" benefit that the managers of the Chuo Shinkansen Project will receive by investing in R&D. For example, by setting $(P_0, P_1, P_2) = (0, 0, 1)$, which is the extreme case of guaranteed best outcome in R&D of Total Success in Table 7-9, project managers will obtain 9.05 trillion yen of NPV of the Chuo Shinkansen Project. The difference between this NPV and the NPV of the project without R&D investment (i.e., 9.05 – 7.28 = 1.77 trillion yen) is interpreted as the maximum benefit project managers can receive by investing in R&D.

On the other hand, by setting the probabilities as $(P_0, P_1, P_2) = (1, 0, 0)$, which is the worst scenario of R&D, project managers will obtain NPV of the project of 6.96 trillion yen. Therefore, the difference of NPVs with and without R&D investment (i.e., 6.96 – 7.28 = – 0.32 trillion yen) can be interpreted as the maximum loss that project managers need to expect as the worst result of R&D. Finally, the probability set of $(P_0, P_1, P_2) = (0, 1, 0)$, which only considers Partial Success, will yield NPV of the project of 8.02 trillion yen and 0.74 trillion yen of the benefit of R&D. Since Partial Success seems more likely than other results of R&D (see Section 7.1.2), this benefit of R&D could be interpreted as a reasonable expectation of the benefit of R&D investment. To summarize, Equation 7-6, which expresses the NPV of the Chuo Shinkansen Project as the function of probabilities of R&D outcomes, is useful for project managers to calculate the maximum benefit, the maximum loss, and a reasonable expectation of the benefit that may occur as the result of R&D investment.

As a conclusion of the decision tree analysis, it can be said that the flexible system development strategy, which R&D success enables, is likely to increase the value of the Chuo Shinkansen Project, as far as the probabilities in Table 7-2 are concerned. Also, the formula that calculates NPV of the project based on the probabilities of R&D outcomes, which can be obtained as the result of decision tree analysis, will be useful for project managers in examining the expectable benefits and losses of R&D investment.

7.4. Sensitivity Analyses

Finally, project managers should conduct sensitivity analyses since these results are obtained based on many assumptions. For this purpose, this thesis analyzes the sensitivity of the project value to the followings: GDP growth rate, volatility of GDP growth, the discount rate, and the probability of R&D success or failure.

7.4.1. NPV of Project and GDP Growth Rate

Figure 7-2 shows the NPVs of the Chuo Shinkansen Project calculated by using different GDP growth rates. This figure shows that the expected NPV of the Chuo Shinkansen Project is highly sensitive to the change of the GDP growth rate. Therefore, it can be concluded that precisely analyzing the GDP growth rate is important for the accurate estimation of the value of the Chuo Shinkansen Project.

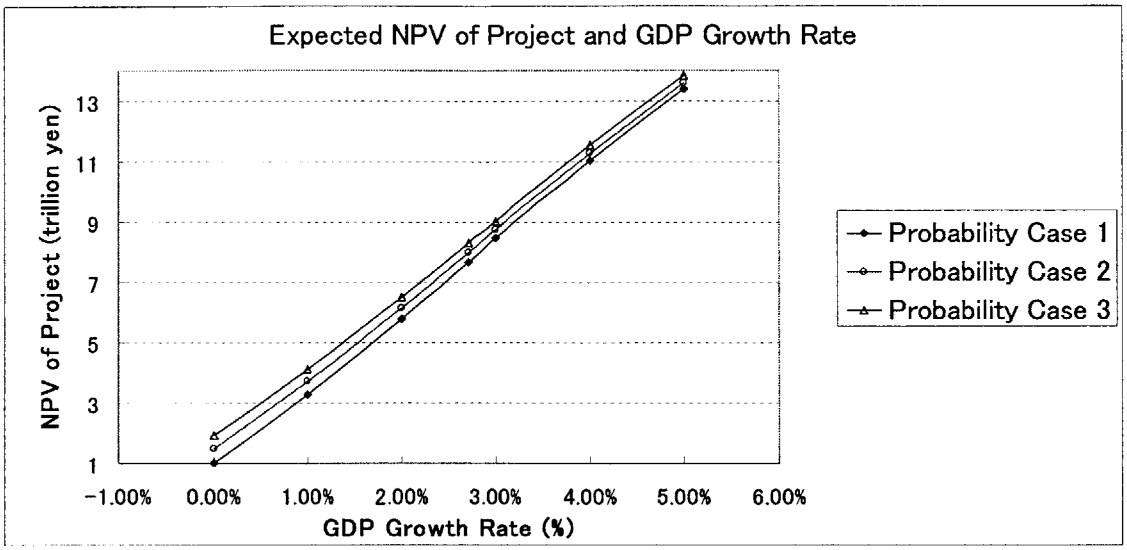


Figure 7-2: Expected NPV of the Chuo Shinkansen Project and GDP Growth Rate.
Three results correspond to the sets of probabilities shown in Table 7-2, Case1, Case2, and Case 3, respectively.

Figure 7-2 has another interesting implication for project managers; it seems that the expected net present value of the project has an almost linear positive correlation with the GDP growth rate. In applying the hybrid real options analysis, this thesis relates demand to GDP using a linear regression model (see Section 6.1). In addition, in the Binomial Lattice Model, the probability of up-movement of GDP is also a linear function of the growth rate. Therefore, the changes in the growth rate of GDP linearly affect the demand. Although non-linear calculations are used in the transformation of the demand into the project value (see Equations 6-14 and 6-18), Figure 7-2 suggests that the project value increases almost linearly in accordance with the increase of GDP growth rate.

In order to clarify how the change of GDP growth rate affects the possible financial benefit of the flexible development strategies, this thesis defines a non-dimensional parameter, NPV^*, as shown in Equation 7-7. As can be seen from the form of Equation 7-7, NPV^* represents how much R&D investment increases the value of the project compared to the project value without R&D investment. Therefore, NPV^* can be regarded as the relative benefit of the flexibility of the system. Using this parameter of NPV^*, the thesis then analyzes the relationship between GDP growth rate and NPV^* (Figure 7-3).

NPV^* = NPV of Project with R&D / NPV of Project without R&D **Equation 7-7**

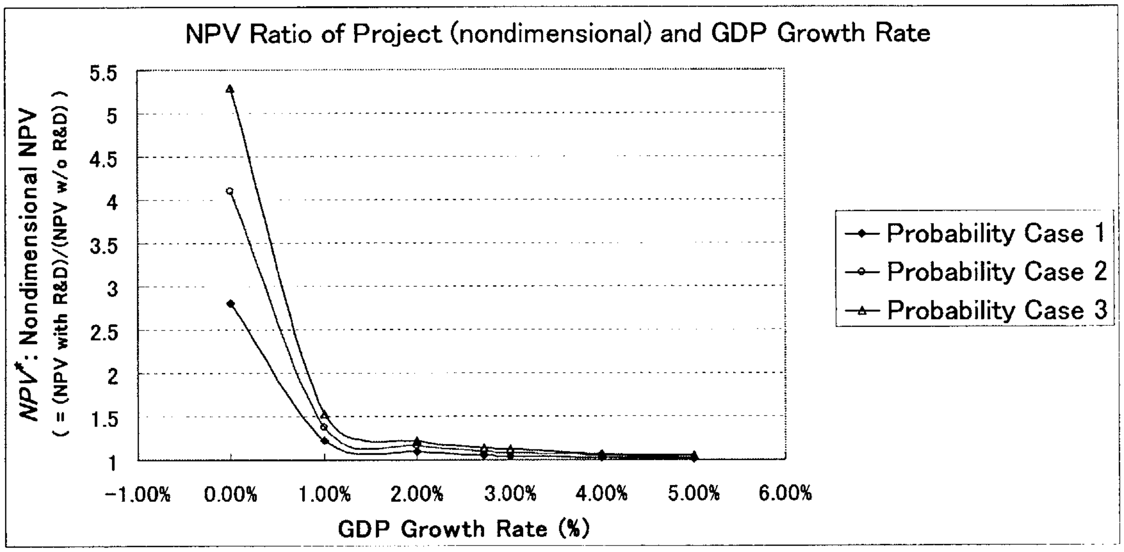


Figure 7-3: Non-dimensional NPV of the Chuo Shinkansen Project and GDP Growth Rate. Non-dimensional NPV of Project is defined as NPV of Project with R&D investment divided by NPV of Project without R&D investment.

Figure 7-3 indicates a decreasing relative benefit of the flexibility as GDP growth rate increases, because all the NPV^* decrease with the increase of GDP growth rate. This behavior seems to be explained in the following way. First, let I_0 and I_0' denote the initial construction costs of the Chuo Shinkansen Project with a large capacity and a small capacity, respectively ($I_0 > I_0'$). Then, the cost of expanding the capacity later from the small capacity to the large capacity (i.e., the cost of implementing the option to expand capacity) can be expressed by $\Delta I = I_0 - I_0'$. Since the financial benefit of the option is the time value of this difference of costs, the NPV of the option can be expressed as:

$$\underline{\text{NPV of Financial Benefit of Option}} = \frac{\Delta I}{(1+r)^{t_1}} - \frac{\Delta I}{(1+r)^{t_2}}$$

$$= \frac{\Delta I\{(1+r)^{t_2} - (1+r)^{t_1}\}}{(1+r)^{t_1}(1+r)^{t_2}}$$ **Equation 7-8**

Where ΔI : Construction cost of the expanded capacity
(i.e., the difference of the initial construction costs of
the large-capacity system and the small-capacity system)
r : Discount rate
t_1 : Time of initial construction
t_2 : Time of expanding capacity ($t_2 > t_1$)

Now, let us consider the effect of large GDP growth rate on the NPV of the benefit of option. The larger the GDP growth rate is, the more likely large demands become to occur. Because the probability of large demand is large, it becomes more likely that project managers exercise the option to expand the capacity at an early period (i.e., the probability of small t_2 becomes large). Finally, the sooner the option is exercised (i.e., $t_2 \rightarrow t_1$), the smaller the NPV of the financial benefit of option becomes (i.e., NPV of option in Equation 7-8 approaches zero). As a result, the relative benefit of the option decreases in accordance with the increase of GDP growth rate.

7.4.2. NPV of Project and the Volatility of GDP Growth

Contrary to the results of changes in GDP growth rate, changes of GDP growth volatility have non-linear effects on the NPV of the project because the factors of up and down movement of GDP and their probabilities are described by non-linear functions of the volatility. As a result, the NPV of the Chuo Shinkansen Project proved to be not as sensitive to the GDP volatility compared to its sensitivity to the GDP growth rate (Figure 7-4).

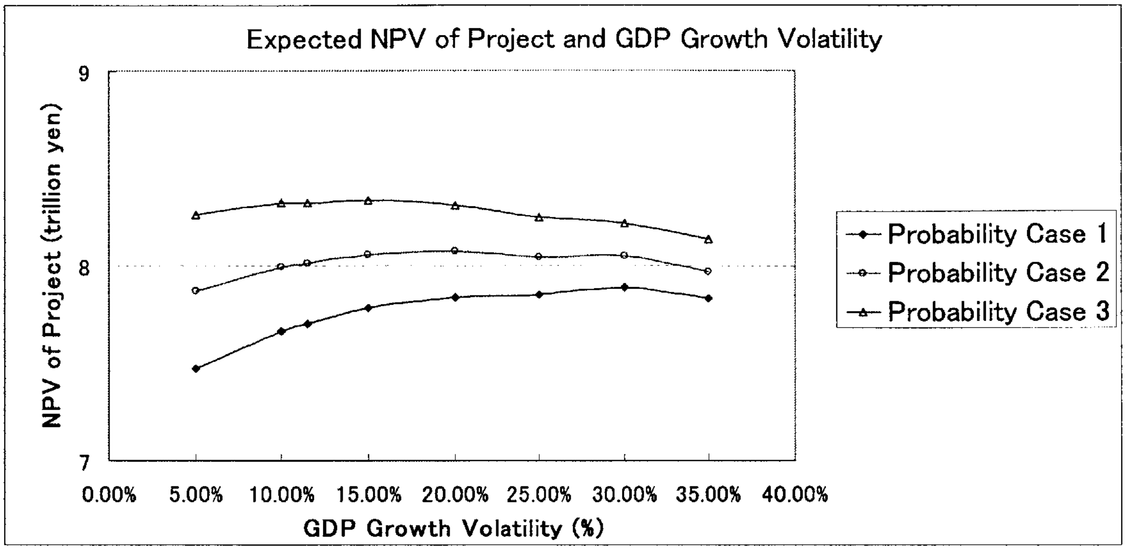


Figure 7-4: Expected NPV of the Chuo Shinkansen Project and Volatility of GDP Growth

From this graph, it seems that the higher the volatility is, the less attractive the benefit of the flexible strategy becomes because the three lines approach each other as the volatility increases. This tendency can be confirmed by the relation between *NPV** and the volatility (Figure 7-5).

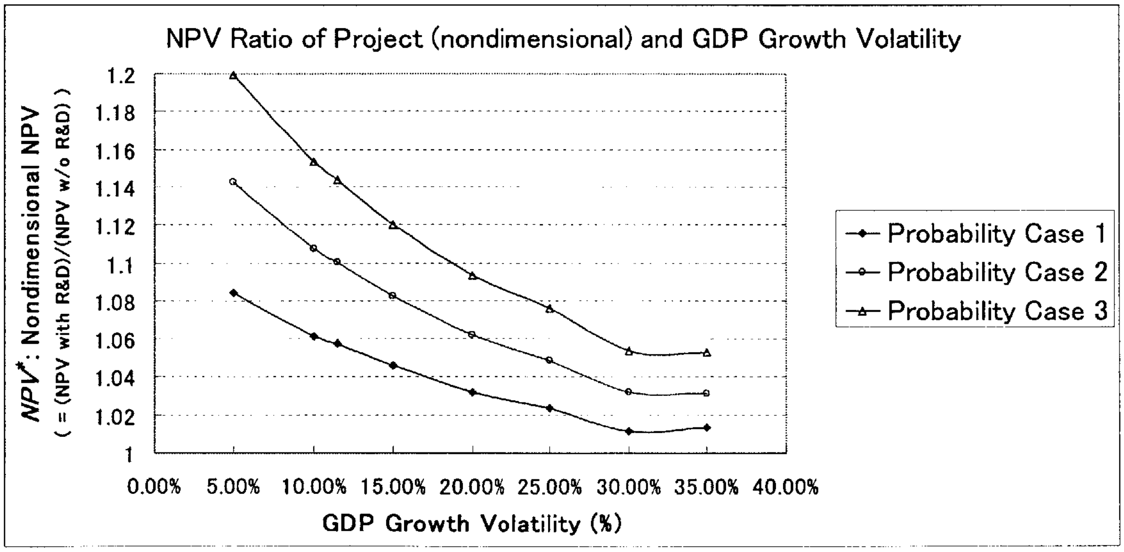


Figure 7-5: Non-dimensional NPV of the Chuo Shinkansen Project and the Volatility of GDP Growth

Similarly to Figure 7-3, Figure 7-5 shows a decreasing benefit of the flexible strategy; the relative benefit of the expansion option decreases in accordance with the increase of the volatility. This decreasing tendency of the relative benefit arises because, as the volatility increases, the range of distribution of demand expands making a large demand more likely. Accordingly, it becomes more likely that the system needs to offer the maximum operational frequency. As a result, the option to expand capacity tends to be exercised early, leading to the decrease of the benefit of the option that defers the investment in capacity.

7.4.3. NPV of Project and the Discount Rate

Project managers will also be interested in how changes of the discount rate will affect the value of the Chuo Shinkansen Project. In general, the value of projects decreases as the discount rate increases. While the operational profits of the project, which generally occur in the later period of projects, diminish because of the large discounting factor, the initial investment cost remains not discounted significantly. As a result, the contribution of the operational benefits to the project value become relatively small, and the effect of the initial cost becomes relatively influential. This general tendency can be also confirmed in the Chuo Shinkansen Project from the result of sensitivity analysis of the project value against the discount rate (see Figure 7-6).

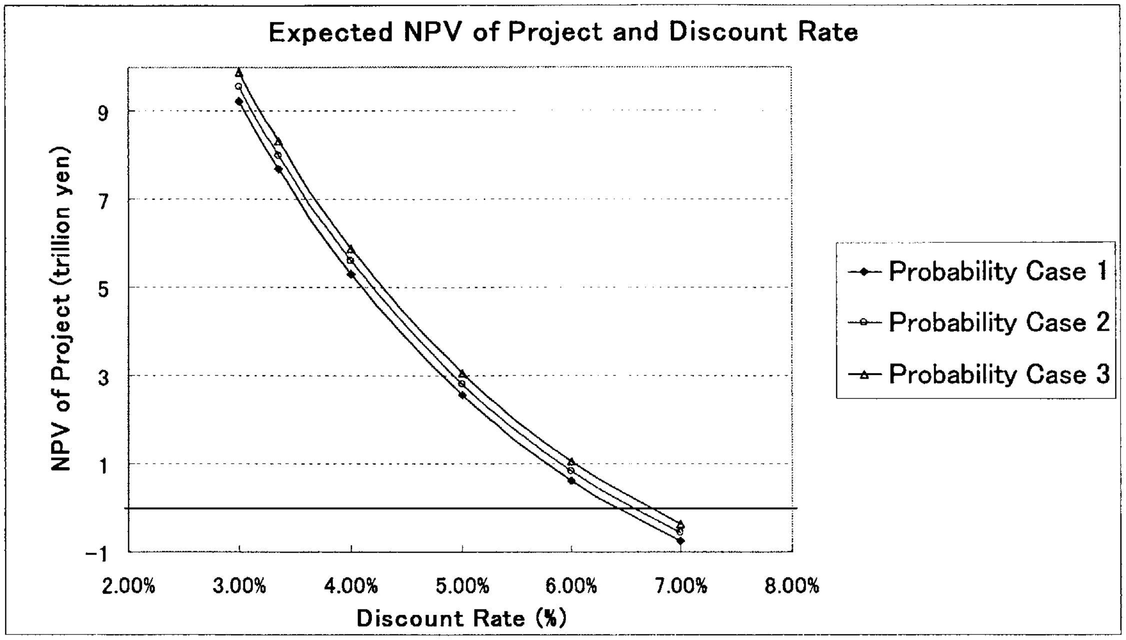


Figure 7-6: Expected NPV of the Chuo Shinkansen Project and the Discount Rate

As is clear from this figure, the expected NPV of the Chuo Shinkansen Project is very sensitive to the changes of the discount rate. With a large discount rate, it will be difficult to make profits from the Chuo Shinkansen Project, and the project may not be implemented at all. For example, with the discount rate of seven percent, the NPV of the project are calculated to be negative with any of the three cases of probabilities; the project will be abandoned unless the societal benefits, such as the increased redundancy of inter-metropolis transportation and the formation of the "extra huge" economic zones (see Section 2.2), are considered. In this sense, appropriately choosing the discount rate is critical for analyzing the viability of the Chuo Shinkansen Project.

With regard to the relative benefit of the expansion option, Figure 7-7 provides the result of the sensitivity analysis of the relative benefit of the flexibility based on several discount rates. From this figure, project managers can see that, when the NPV of the project is positive (i.e., with a discount rate of six percent or less in this analysis), the relative benefit of the flexibility of the system increases in accordance with the increase of the discount rate, because the lines in Figure 7-7 go up as the discount rate increases. This increase seems to occurs because, the higher the discount rate is, the more advantageous it becomes to reduce the cost of the initial investment. Since the expansion option offers the flexibility to defer the cost of investment for the maximum capacity, the benefit of the option seems to grow as the discount rate increases.

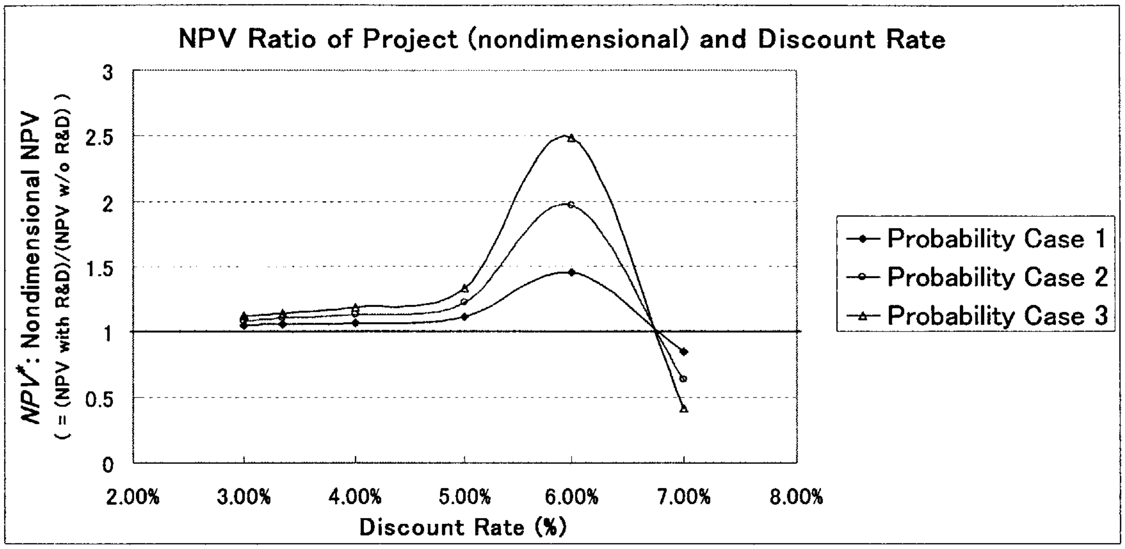


Figure 7-7: Non-dimensional NPV of the Chuo Shinkansen Project and the Discount Rate

Note that, even with the relatively high discount rate of seven percent, with which NPVs of the project become negative, the expansion option increases the project value compared to the value of the project without expansion option. When the NPV of the project becomes negative, the smaller the absolute value of the NPV is (i.e., the smaller the magnitude of the deficit is), the better the project becomes from the financial point of view. Therefore, in this case, an NPV^* (the non-dimensional NPV) of less than one means that the project managers can reduce the deficit by enabling the option to expand the capacity. Since all the NPV^* are below one, as shown in Figure 7-5, the expansion option increases the value of the project even with the relatively high discount rate of seven percent.

7.4.4. NPV of Project and the Probability of R&D Success

Finally, this thesis analyzes the sensitivity of NPV of the Project against the probability of R&D success. By looking into Figures 7-2 through 7-7, project managers can see that the higher the probability of R&D success is, the larger the NPV of the project becomes. This tendency is reasonable because project managers can be more likely to take advantage of the option to expand the capacity, as the probability of R&D success increases.

A more important implication of the sensitivity analyses about the probability of R&D success is that all the results of above analyses indicate the advantage of investing in R&D. Figures 7-3, 7-5, and 7-7 show that NPV^*, which is the ratio of the NPV of the project with R&D to that of the project without R&D, always exceeds one as long as the NPV of the project remains positive. This fact indicates that investing in R&D increases the expected value of the project. Furthermore, when the NPV of the project turns to be negative (i.e., the project goes into debt), NPV^* falls below one. This fact means that the magnitude of the deficit can be reduced by investing in R&D. Based on all the above observations, it can be said that investing in R&D improves the value of the project, as far as the results of the above analyses are concerned.

However, it can also be imagined that with a very low probability of R&D success, it will not be advantageous to invest in R&D. In order to demonstrate how project managers can utilize the evaluation model developed in this study to analyze the conditions with which it becomes unattractive to invest in R&D, this thesis conducts break-even analyses assuming the relationship between the probabilities of R&D outcomes as shown in Table 7-3.

Break-even Analysis Case I

The first case for the break-even analysis, which is shown as Case I in Table 7-3, assumes the following relationship between the probabilities of R&D outcomes.

$$P_1 = P_2 = \frac{1 - P_0}{2}$$ **Equation 7-9**

Where P_0: Probability of Total Failure in R&D
P_1: Probability of Partial Success in R&D
P_2: Probability of Total Success in R&D

Project managers can combine the relationship of Equation 7-9 with the decision criterion as to whether or not to invest in R&D, which is expressed by Equation 7-10, to obtain the formula that expresses the range of probability of Total Failure in R&D with which it becomes advantageous to invest in R&D (Equation 7-11).

$$\begin{aligned} & NPV(EV)_{invest} = 6.96P_0 + 8.02P_1 + 9.05P_2 \\ & > NPV(EV)_{No-investment} = 7.28 \end{aligned}$$ **Equation 7-10**

$$\begin{aligned} & 6.96P_0 + 8.02\left(\frac{1-P_0}{2}\right) + 9.05\left(\frac{1-P_0}{2}\right) > 7.28 \\ & \Leftrightarrow P_0 < 0.80 \end{aligned}$$ **Equation 7-11**

As can be seen from Equation 7-11, project managers will be able to increase the value of the project by investing in R&D, as long as Equation 7-9 is satisfied and the probability of Total Failure in R&D is less than 0.80 (Figure 7-8) given assumed cost of R&D.

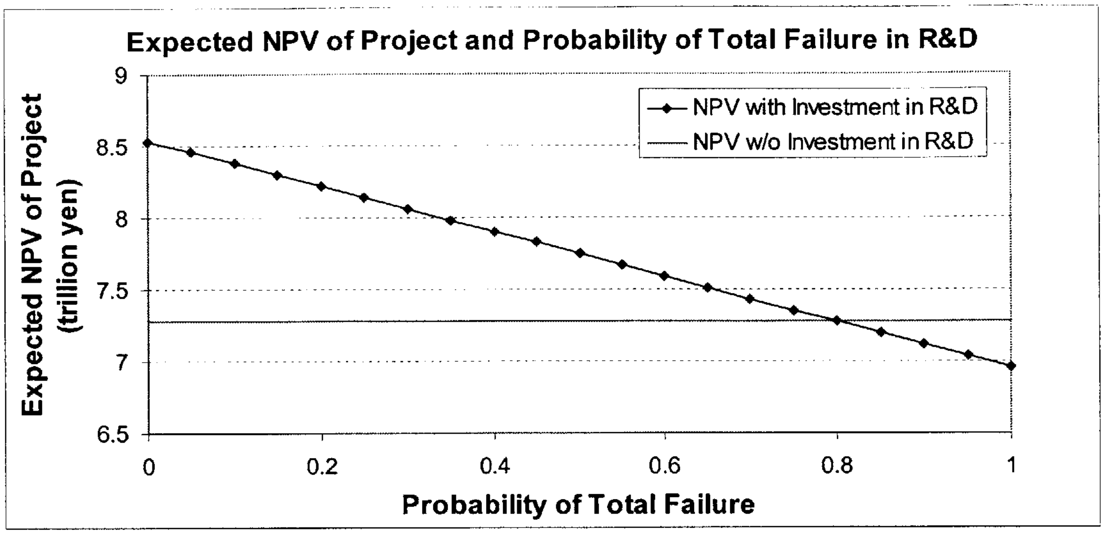


Figure 7-8: Expected NPV of Project and the Probability of Total Failure in R&D

Break-even Analysis Case II

For the second case of the break-even analysis, this thesis assumes that Total Failure and Total Success in R&D are equally likely to occur. Accordingly, the thesis assumes the relationship between the probabilities of R&D outcomes as shown in Equation 7-12:

$$P_0 = P_2 = \frac{1-P_1}{2}$$ **Equation 7-12**

Where P_0: Probability of Total Failure in R&D
P_1: Probability of Partial Success in R&D
P_2: Probability of Total Success in R&D

In the same way as the analysis of Case I, the range of the probability of Partial Success which makes the investment in R&D attractive, can be calculated as shown in Equation 7-13.

$$NPV(EV)_{invest} = 6.96P_0 + 8.02P_1 + 9.05P_2$$
$$> NPV(EV)_{No-investment} = 7.28$$
$$\Leftrightarrow 6.96\left(\frac{1-P_1}{2}\right) + 8.02P_1 + 9.05\left(\frac{1-P_1}{2}\right) > 7.28$$
$$\Leftrightarrow P_1 > -48.333$$

Equation 7-13

From the above equation, it can be seen that it is advantageous to invest in R&D as long as P_1 is greater than –48.333. However, this condition is always satisfied because no probabilities can become negative. As a result, project managers can conclude that as long as they can expect the same probability for both Total Failure and Total Success in R&D, it is always advantageous to invest in R&D at assumed R&D cost.

Project managers can derive another useful implication about the effect of the probability of Partial Success in R&D on the value of the project from this analysis. By transforming Equation 7-13, project managers can obtain the following equation, which expresses the value of the project as the function of P_1, the probability of Partial Success in R&D.

$$NPV(EV)_{invest} = 6.96P_0 + 8.02P_1 + 9.05P_2$$
$$= 6.96\left(\frac{1-P_1}{2}\right) + 8.02P_1 + 9.05\left(\frac{1-P_1}{2}\right)$$
$$= 8.005 - 0.015P_1 \qquad \text{(trillion yen)}$$

Equation 7-14

Since the range of value that P_1 can take is from zero to one, project managers can calculate the possible range of NPV of the project as:

$$NPV_{\min} = 7.99 \le NPV(EV)_{invest} \le 8.02 = NPV_{\max} \qquad \text{(trillion yen)}$$
$$0.996 \le \frac{NPV(EV)_{invest}}{NPV_{\max}} \le 1$$

Equation 7-15

From Equation 7-15, project mangers can expect that even when P_1 is zero, the expected NPV of the project decreases by only 0.4% compared to the NPV with $P_1=1$. In the same way as shown in this analysis, it is possible for project managers to calculate how influential the probabilities of R&D outcomes on the NPV of the project.

Break-even Analysis Case III

Finally, this thesis considers a case in which only extreme results of Total Failure and Total Success are possible and the probability of Total Success depends on the amount of money spent on R&D. Equation 7-16 provides the mathematical expression of the assumptions for this break-even analysis.

$$P_0 = 1 - P_2$$

$$P_1 = 0 \qquad \textbf{Equation 7-16}$$

$$P_2 = \frac{I_{R\&D}}{I_{R\&D} + 1}$$

Where $I_{R\&D}$: Amount of investment in R&D

As can be seen from the form of Equation 7-16, it is assumed that the probability of Total Success in R&D, P_2, depends on the amount of money invested in R&D, $I_{R\&D}$, and that the probability of Total Failure, P_0, is dependent on P_2. Furthermore, it is assumed that P_2 approaches one when $I_{R\&D}$ increases and zero as $I_{R\&D}$ decreases.

Using Equation 7-16 and the NPV data (excluding R&D cost) of the Total Failure scenario and the Total Success scenario shown in Table 7-8, project managers can obtain the formula that defines the range of the cost of R&D with which it becomes advantageous to invest in R&D (Equation 7-17).

$$NPV(EV)_{invest} = 7.28P_0 + 9.37P_2 - I_{R\&D} > NPV(EV)_{No-investment} = 7.28$$
$$\Leftrightarrow 7.28\left(1 - \frac{I_{R\&D}}{I_{R\&D}+1}\right) + 9.37\left(\frac{I_{R\&D}}{I_{R\&D}+1}\right) - I_{R\&D} > 7.28$$
$$\Leftrightarrow I_{R\&D}\left(I_{R\&D} - 1.09\right) < 0$$
$$\Leftrightarrow 0 < I_{R\&D} < 1.09 \qquad \text{(trillion yen)} \qquad \textbf{Equation 7-17}$$

Equation 7-17 suggests that it is advantageous for the project managers to invest in R&D as long as the cost of R&D is less than 1.09 trillion yen. However, this result may seem unrealistic because the upper boundary is very large. Therefore, it is also suggested that the accuracy of data and the assumptions used in this analysis be improved to increase the reliability of the results of this analysis. Nevertheless, it could be concluded that the evaluation model developed in this thesis can be used to analyze the range of the cost of R&D with which it will become advantageous to invest in R&D.

7.5. Conclusions about the Evaluation of the Chuo Shinkansen Project

This chapter demonstrates that the evaluation model developed in this thesis can be used to estimate the value of the Chuo Shinkansen Project considering the uncertainty of demand and the project-specific risk of R&D in a consistent quantitative analytic model. Using the various data about the Chuo Shinkansen Project estimated and collected in Chapter 6 and Chapter 7, the thesis calculates the expected net present value of the project. As a result, as long as the data of the Chuo Shinkansen Project collected in this thesis are used and the probabilities of R&D outcomes in Table 7-2 are concerned, it can be concluded that it is advantageous to invest in R&D of the PCS technology that will enable the option to expand capacity.

The thesis also conducts several sensitivity analyses and break-even analyses to investigate the effects of the changes in the following parameters: the growth rate of GDP (which drives demand growth), the volatility of GDP growth (which drives the volatility of demand growth), the discount rate, and the probabilities of R&D outcomes. As the result of these analyses, the following four conclusions are obtained.

First, the GDP growth rate and the discount rate prove to be influential in calculation of the expected net present value of the Chuo Shinkansen Project. Therefore it is critical to estimate these parameters correctly in order to calculate the value of the project accurately.

Second, the volatility of the GDP growth does not affect the net present value of the Chuo Shinkansen Project as significantly as the GDP growth rate or the discount rate. Therefore, it can be said that estimating the GDP volatility is not as essential for an accurate evaluation of the project, compared to the calculation of other parameters.

Third, the results of the sensitivity analyses and the break-even analyses about the probabilities of R&D outcomes suggest that it is likely to be advantageous to invest in R&D, as far as the data of the Chuo Shinkansen Project estimated in this thesis are concerned including assumed R&D cost. In particular, if the same probability is expected for both Total Success and Partial Success in R&D, the availability of the option to expand the capacity increases the value of the project as long as the probability of Total Failure in R&D remains less than 0.80. Furthermore, the investment in R&D proves to be always advantageous as long as Total Failure and Total Success in R&D are equally likely to occur. By making the expansion option possible through R&D, project managers are likely to be able to improve the value of the project.

Finally, this thesis demonstrates how the evaluation model developed in this thesis can be used to analyze the effects of the probability of success in R&D in relation to its cost. In the real-world R&D projects, it seems reasonable to assume the amount money spent on R&D influences the likeliness of success in R&D. Using a simple function as an example relationship to relate the investment in R&D and the probability of success, this study demonstrates that project managers can calculate the range of R&D budget with which it becomes advantageous to invest in R&D. This demonstration of evaluation of R&D will be a useful guide for managers of the Chuo Shinkansen Project.

To summarize, project managers can calculate the value of the Chuo Shinkansen Project using the extended hybrid real options model that this thesis has developed. By conducting sensitivity analyses and break-even analyses as demonstrated in this chapter, they can examine which parameters are influential for the project value and with what ranges of the parameters it will be advantageous to invest in R&D.

The next chapter provides conclusions of this thesis, summarizing the model developed in this thesis, the results of analyses, and the implications obtained from the analyses with regard to the strategies for the development of the Chuo Shinkansen Project.

Chapter 8 Conclusions

8.1. Conclusions about the Application of Hybrid Real Options Model to the Chuo Shinkansen Project

The Chuo Shinkansen Project in Japan is expected to construct an ultra-fast link between Tokyo and Osaka, by way of Kofu, Nagoya, and Nara, with the Superconducting Magnetically Levitated Linear Motor Vehicle (Maglev) system. As a large-scale, high-speed railway project, the Chuo Shinkansen includes various uncertainties associated with the project. Among them, this thesis identifies two major factors that primarily affect the system design and the expected net present value of the project: the uncertainty of demand and the probability of success of research and development (R&D) activities.

Because each Maglev train requires a dedicated Power Conversion System (PCS) but a different one as it moves along the route, managers of the Chuo Shinkansen Project are required to estimate the future demand accurately in order to determine the number of trains to operate simultaneously; in other words, they are required to determine the necessary number of PCSs to design the system. However, it is difficult to accurately forecast the future demand of transportation projects. Therefore, project managers should take the uncertainty of demand into account when evaluating the value of the project.

At the same time, R&D to advance the technologies of the PCS has the possibility of improving the value of the project by enabling staged flexible development strategies. By constructing the line with a small number of PCSs (which reduces initial construction cost but leads to a small operational capacity) and installing additional PCSs later (i.e., expanding the capacity later) only when the demand grows sufficiently, project managers can defer the cost of the increased capacity until it is needed; they may even be able to save this cost if the demand does not grow enough to justify it. However, the magnitude of success of R&D is also uncertain. Therefore, it is important for the project mangers to evaluate the value of the project with consideration of the probability and magnitude of success of R&D.

In light of the above background, this thesis aims to develop a quantitative analytical model that is appropriate for evaluating the flexible development strategies of the Chuo Shinkansen Project, with considerations of uncertain demand and R&D outcomes. To accomplish this purpose, the thesis sets up three objectives. First, by applying the hybrid real options model in an innovative way, this thesis proposes an evaluation model that can quantitatively analyze the uncertainty of R&D and the associated system designs, as well as the uncertainty of the demand in the future. Second, this study applies the proposed method to the evaluation of the Chuo Shinkansen Project. Third, this thesis provides suggestions as to the best development strategy of the project. The rest of this section explains the accomplished works toward these objectives.

Objective 1: Propose an evaluation model that can quantitatively analyze the uncertainty of R&D, the associated system designs, and the uncertainty of the demand in the future

In response to the first objective, this thesis first introduces the hybrid real options model developed by Neely (1998) [9] and fundamental concepts necessary for understanding the model. The hybrid real options analysis is a composite model of decision analysis, which is suitable for evaluating R&D risks, and real options analysis, which is appropriate for analyzing the uncertainty of demand. Because R&D and demand are the major uncertainties of the Chuo Shinkansen Project, the hybrid real options analysis can be considered the appropriate model for evaluating the project.

Furthermore, this thesis uses the hybrid real options model. In order to appropriately evaluate the Chuo Shinkansen Project, we needs to apply it in an innovative manner. More specifically, this thesis applies the model considering the following four aspects.

Aspect 1: This thesis develops a model that estimates the distribution of demand for

the Chuo Shinkansen based on the growth rate of GDP and its volatility. Demand is considered the factor that primarily influences the value of the Chuo Shinkansen Project. However, because the Chuo Shinkansen does not exist yet, it is not possible to estimate the demand from its data in the past; instead, it is needed to forecast the demand from other sources of information.

In order to estimate the demand of the Chuo Shinkansen, this thesis adopts a two-step approach. First, the thesis analyzes the relationship between the demands for the Tokaido Shinkansen and the Chuo Shinkansen. Second, the thesis evaluates the distribution of the future demand for the Tokaido Shinkansen based on the GDP data and the demand data of the Tokaido Shinkansen in the past. By combining the results of these two steps, the thesis develops a model that estimates the distribution of the future demand of the Chuo Shinkansen from the data of GDP.

Aspect 2: This thesis develops a model that analyzes the potential system designs based on both the results of R&D and the operational requirements. For the Chuo Shinkansen Project, determining the number of PCSs to construct is critical in designing the system. Various factors will influence this number of PCSs. Among them, this thesis identifies three principal factors that are essential in determining the number of PCSs in the Chuo Shinkansen system: the results of R&D, the required operational frequency (for maintaining the level of service for passengers), and the minimum distance between trains required to secure safety. By analyzing the relationship between the number of PCSs needed in the system and these factors, the thesis identifies possible system designs and the development scenarios (i.e., the possible options to expand the capacity) of the system.

Aspect 3: This study develops a Binomial Lattice evaluation model that handles the capacity constraints and the expansion of the capacity of the system. The future distribution of the demand for the Chuo Shinkansen can be obtained using a Binomial Lattice evaluation, which is one of the common models of real options analysis, and the growth rate and the volatility of GDP. When project managers transform this demand distribution into the distribution of cash flow of the project, they need to incorporate the constraints of capacity into calculation because there will be limitation of actual capacity of the Chuo Shinkansen. Furthermore, project evaluators must handle the changes of capacity that will occur if the expansion option is implemented. Therefore, in order to appropriately evaluate the Chuo Shinkansen Project, this thesis develops formulas that can calculate the net present value of a project with these constraints and changes of capacity.

Aspect 4: Finally, this thesis incorporates the Capital Asset Pricing Model (CAPM) into the analysis in order to calculate the risk-adjusted discount rate. The risk-free discount rate is usually used to discount the cash flow of a project in real options analyses including the hybrid real options model. However, the use of the risk-free rate is possible only when the investors can avoid the project-specific risks by broadly diversifying investments. Unfortunately, it is difficult for the managers of the Chuo Shinkansen Project to avoid the project-specific risks because this project is quite large compared to other projects they have. Accordingly, the risk-free discount rate may not necessarily become the appropriate rate with which to discount the Chuo Shinkansen Project. Therefore, this thesis extends the hybrid real options model and proposes using CAPM, which is the most widely used model for estimating the cost of equity capital, to calculate the risk-adjusted discount rate for the Chuo Shinkansen Project.

Building upon above extensions, this thesis develops an evaluation model that can analyze the value of the Chuo Shinkansen Project with considerations of the uncertainty of demand and the flexible development strategies that will become possible as the result of R&D.

Objective 2: Apply the proposed method to the evaluation of the Chuo Shinkansen Project

Using the extended hybrid real options model, this thesis evaluates the Chuo Shinkansen Project, assuming different levels of R&D outcomes (with their associated probabilities) and the Binomial Lattice distribution of demand. Three levels of R&D outcomes are assumed in this thesis; 20km of track-coverage of a PCS (which is almost the same level as the current technology) as the case of Total Failure, 30km of coverage for the case of Partial Success as the median value of the cases of Total Failure and Total Success, and 40km of coverage (which is derived from the plan to extend the Maglev test line) for Total Success case.

Based on the assumptions of probabilities for these R&D outcomes as well as other assumed reasonable estimates of R&D costs, demand growth, demand volatility, and the discount rate, the thesis first calculates the net present values of the project for each of the development scenarios of the Chuo Shinkansen system identified earlier in this thesis. Based on the obtained project values of each scenario, the thesis constructs a decision tree and calculates the expected net present value of the project to point out that it will be advantageous to invest in R&D as far as the above data are concerned.

Objective 3: Provide suggestions as to the best development strategy for the project

In addition to the above evaluation, this thesis conducts sensitivity analyses in order to obtain suggestions with regard to the strategies of the system development. The thesis evaluates the sensitivity of the project value against four factors: the growth rate of GDP, the volatility of GDP growth rate, the discount rate, and the probability of the R&D success.

With regard to the sensitivity to these four factors, this thesis finds that the value of the Chuo Shinkansen Project is very sensitive to the growth rate of GDP, which then means the growth of demand, and the discount rate. Therefore, correctly estimating these factors is essential for the accurate evaluation of the Chuo Shinkansen Project.

At the same time, this study examines the sensitivity of the project value against the changes in probabilities of R&D outcomes. The results of these analyses suggest that the project managers are likely to be able to increase the value of the Chuo Shinkansen Project by enabling the flexible development strategies. In particular, if the same probability is expected for both Total Success and Partial Success in R&D, the flexible system development strategy will increase the value of the project as long as the probability of Total Failure in R&D remains less than 0.8. In addition, the results of analyses indicate that it will be always advantageous for the project managers to invest in R&D as long as they can expect the same probability for both Total Failure and Total Success in R&D. From these analyses, it can be concluded that, by making the flexibility to expand the capacity later possible through R&D, project managers are likely to increase the value of the project.

Finally, this thesis demonstrates how the evaluation model developed in this thesis can be used to analyze the effects of the probability of success in R&D in relation to its cost. Using a simple function, as an example, to relate the investment in R&D and the probability of success, this study shows that project managers can calculate the range of the R&D cost with which it becomes advantageous to invest in R&D. Practically, it seems reasonable to assume that the success in R&D depends on the money spent on it. Therefore, the method of evaluation of R&D demonstrated in this analysis will be a useful guide for managers of the Chuo Shinkansen Project in analyzing the benefit of R&D.

In summary, this thesis develops a quantitative model for the appraisal of the Chuo Shinkansen Project, integrating the evaluation of the uncertainties of demand and R&D into a consistent framework of analysis. Using this model and assuming reasonable estimates of R&D costs, probability of success in R&D project, demand growth, the volatility of demand, and the discount rate, this study demonstrates that the managers of the Chuo Shinkansen Project are likely to be able to increase the value of the project by investing in R&D of flexible system development strategies. This thesis also demonstrates how project managers can utilize the evaluation model to analyze the effect of changes in R&D cost that will influence the probability of R&D success.

8.2. Future Works

For the sake of further improvement of the evaluation methodology which this thesis proposes, the author suggests the following three directions of research:

First, the accuracy of the data used in this thesis needs to be improved. This thesis uses rough estimates of the data of the Chuo Shinkansen Project. Therefore, it is necessary to increase the accuracy of the data of the Chuo Shinkansen Project used in this thesis in order to improve the reliability of the results of this evaluation.

Second, the methods of calculating the discount rate should be further studied. Although not examined in this thesis, different approaches to estimating the discount rate will yield different values of the rate. Though this thesis uses the Capital Asset Pricing Model (CAPM) because it has been widely used in evaluating projects, the Arbitrage Pricing Theory (APT) is considered more robust since APT applies to any subset of assets and does not require the existence of an efficiently diversified market portfolio. However, the calculation of APT is more complicated than that of CAPM, and APT seems to have not been generally accepted. Therefore, it is hoped that a well-accepted robust method of estimating the discount rate is developed.

Finally, project managers are also encouraged to analyze the effect of changes in those data that are fixed in this thesis. Although the thesis uses fixed values for some miscellaneous parameters that can be changed by management's decision (see Section 7.1.4), it is possible that they have substantial effects on the project value. Therefore, it is important to examine the sensitivity of the project value to these parameters in order to develop a competitive project plan.

Finally, the author expresses sincere gratitude for the readers of this thesis. It will be the author's greatest pleasure if this thesis contributes to their better understanding of project evaluation methodologies, and to the further development of research in this field.

Abbreviation and Terminologies

APT:	Arbitrage Pricing Theory
BCA:	Benefit-Cost Analysis
CAPM:	Capital Asset Pricing Model
CEF:	Chubu Economic Federation
DCF:	Discounted Cash Flow
DCS:	Drive Control System
EHEZ:	“Extra Huge” Economic Zone
EU:	European Union
FESS:	Flywheel Energy Storage System
GBM:	Geometric Brownian Motion
GDP:	Gross Domestic Product
IRR:	Internal Rate of Return
JNR:	Japanese National Railways
JR:	Japan Railway
JR Central:	Central Japan Railway Company
LSM:	Linear Synchronous Motor
Maglev:	Magnetically Levitated Linear Motor Vehicle
MLIT:	Ministry of Land Infrastructure and Transportation
NEDO:	New Energy and Industrial Technology Development Organization
NPV:	Net Present Value
NRDL:	Nationwide Railway Development Law
OPM:	Option Pricing Model
PCS:	Power Conversion System
PV:	Present Value
R&D:	Research and Development
RTRI:	Railway Technical Research Institute
SCM:	Superconducting Magnet
TGV:	Train a Grande Vitesse
TOPIX:	Tokyo Stock Price Index
TSE:	Tokyo Stock Exchange
WACC:	Weighted-Average Cost of Capital
YMTL:	Yamanashi Maglev Test Line

References

[1] Conference of Scholars along the Chuo Shinkansen, *Linear Chuo Shinkansen Changes Japan*, (Chiyoda-ku, Tokyo: PHP Institute, 2001).

[2] Central Japan Railway Company, "Central Japan Railway Company Annual Report 2006," Nagoya, Aichi, (2006).

[3] Central Japan Railway Company, "The Superconducting Maglev Review," Nagoya, Aichi, (2006).

[4] Chubu Economic Federation, "The Benefit of Linear Chuo Shinkansen and the Regional Development," (2003). <http://www.chukeiren.or.jp/katudou/teigen/15/pdf/rinia.pdf>

[5] K. Sawada, "Development of Magnetically Levitated High Speed Transport System in Japan," *IEEE Transactions on Magnetics*, Vol. 32, No. 4, July (1996): 2230-2235.

[6] N. Tatematsu, "The Present Condition of Linear Chuo Express and the Future Challenges," (2006). Suzuka International University web site; <http://www.suzuka-iu.ac.jp/campana/jp/15.pdf>

[7] M. Ono, S. Koga, and H. Ohtsuki, "Japan's Superconducting Maglev Train," *IEEE Instrumentation & Measurement Magazine*, March, (2002): 9-15.

[8] K. Hodota, "R&D and Deployment Valuation of Intelligent Transportation Systems: A Case Example of the Intersection Collision Avoidance Systems," M.S. Thesis in Master of Science in Transportation, Massachusetts Institute of Technology, Cambridge, MA, (2006).

[9] J. Neely, "Improving the Valuation of Research and Development: A Composite of Real Options, Decision Analysis and Benefit Valuation Frameworks," Ph.D. Dissertation in Technology, Management and Policy, Massachusetts Institute of Technology, Cambridge, MA, (1998).

[10] Railway Technical Research Institute, "Superconducting Magnetically Levitated Vehicle," <http://www.rtri.or.jp/rd/maglev/html/maglev_frame_J.html> Last accessed on Feb. 14, 2007.

[11] Central Japan Railway Company, "Central Japan Railway Company Data Book 2004," Nagoya, Aichi, (2005).

[12] Japanese Ministry of Transport (now Ministry of Land, Infrastructure and Transport), "White Paper on Transport in Japan," (1995).

[13] Gifu Prefecture Residents Committee, "Report of Gifu Prefecture Residents Committee Meeting," (2005).
<http://www.pref.gifu.lg.jp/pref/soutenken/sangyoukeizai/2kai/file1.pdf>

[14] S. Tsuchiya, Y. Tadano, and N. Okada, "Economic Loss Assessment Caused by Lessened Transportation Network Function at a Great Earthquake", *Annals of Disaster Prevention Research Institute, Kyoto University* No. 47B, (2004).

[15] Japanese Ministry of Land, Infrastructure and Transport, "White Paper on Transport in Japan," (2006).

[16] Nikkei Business Publications, Inc., "Airline Industry," (2006).
< http://www.nikkeibp.co.jp/style/biz/feature/industry/060601_airline/index.html >

[17] A. Chandra and E. Thompson, "Does public infrastructure affect economic activity? Evidence from the rural interstate highway system," *Regional Science and Urban Economics*, Vol. 30, (2000): 457-490

[18] E. Kim, "Economic Gain and Loss from Public Infrastructure Investment," *Growth and Change*, vol. 29, (1998): 445-469

[19] B. Petkova, "Future Plans and Policy Issues for the Portuguese Railways: New National and International Challenges," *MIT-Portugal Program Transportation Systems Focus Area Working Paper Series, 6*, Nov. (2006).

[20] United Nations, "World Urbanization Prospects, the 2003 Revision," (2003).
< http://www.un.org/esa/population/publications/wup2003/2003WUPHighlights.pdf >

[21] United Nations, United Nations Statistics Division web site:
< http://unstats.un.org/unsd/cdb/cdb_help/cdb_quick_start.asp >

[22] Thomas Cook Publishing, "European Rail Timetable Summer 2006 Japanese Edition," (Shibuya-ku, Tokyo: Diamond Inc. 2006).

[23] Falcon System Consulting Company web site:
< http://www.harenet.ne.jp/shinkansen/shiryo/8-p3.PDF >

[24] Cabinet Office of Japan, "White Paper on the National Lifestyle," (1991). < http://wp.cao.go.jp/zenbun/seikatsu/wp-pl91/wp-pl91-02101.html>

[25] R. Prud'homme, "Urban Transport and Economic Development," *Keynote speech for the 7th conference on the Development and Planning of Urban Transport in Developing Countries*, New Delhi, Feb. 12, (1996). <http://www.regionetdeveloppement.u-3mrs.fr/pdf/R5_Prud'homme.pdf>

[26] IOL Technology web site: <http://www.ioltechnology.co.za/article_page.php?iSectionId=2890&iArticleId=3600247> Last accessed on Feb. 13, 2007.

[27] New Energy and Industrial Technology Development Organization, "Technology Strategy Map," (2006). < http://www.nedo.go.jp/roadmap/2006/all.pdf >

[28] M. Kubota et al. "Characteristics of superconducting magnetic bearings for 50kWh-class flywheel system," *Proceedings of the 19th International Conference on Magnetically Levitated Systems and Linear Drives,* (2006).

[29] Y. Yamauchi et al. "Development of 50 kWh-class Superconducting Flywheel Energy Storage System," International Symposium on Power Electronics, Electrical Drives, Automation and Motion (2006)

[30] B. Flyvbjerg, M. K. Skamris Holm, and S. L. Buhl, "How (In)accurate Are Demand Forecasts in Public Works Projects?" *Journal of the American Planning Association, Vol. 71, No. 2*, Spring (2005): 131-146.

[31] Niigata Nippo web site: <http://www.niigata-nippo.co.jp/rensai/n10/n10h5k7m1.html> Last accessed on Mar. 6, 2007.

[32] Central Japan Railway Company web site: < http:// jr-central.co.jp/eng.nsf/ english/ chuo_shinkansen> Last accessed on Mar. 28, 2007

[33] L. Trigeorgis, *Real Options*, (Cambridge: MIT Press, 1996).

[34] M. Tsui, "Valuing Innovative Technology R&D as a Real Option: Application to Fuel Cell Vehicles," M.S. Thesis in Master of Science in Technology and Policy and in Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, (2006).

[35] R. de Neufville, *Applied Systems Analysis*, (New York: McGraw-Hill Publishing Company, 1990).

[36] R. A. Brealey, and S. C. Myers, *Principles of Corporate Finance*, (New York: McGraw-Hill Book Company, 1988).

[37] S. P. Pratt, *Cost of Capital*, (New York: John Wiley & Sons, Inc., 1998).

[38] Tokyo Legal Mind K.K. web site: < http://www.lec-jp.com/denno/shouken/pdf/ sample.pdf > Last accessed on Mar. 30, 2007.

[39] J. R. Canada et al., *Capital Investment Analysis for Engineering and Management*, (Upper Saddle River, NJ: Pearson Education Inc., 2005)

[40] J. Broyles, *Financial Management and Real Options*, (West Sussex, England: John Wiley & Sons Ltd., 2003).

[41] A. K. Dixit and R. S. Pindyck, *Investment under Uncertainty*, (Princeton, NJ: Princeton University Press, 1994).

[42] J. R. Graham and C. R. Harvey, "The Theory and Practice of Corporate Finance: Evidence from the Field," *Journal of Financial Economics*, (2001).

[43] J. Hull, *Options, Futures, and Other Derivatives*, (Upper Saddle River, NJ: Prentice Hall, 2002).

[44] J. C. Cox, S. A. Ross and M. Rubinstein, "Option Pricing: A Simplified Approach," *Journal of Financial Economics*, (1979).

[45] L. Trigeorgis, "Real Options: An Overview," *Real Options and Investment under Uncertainty, E. S. Schwartz and L. Trigeorgis*, (Cambridge, MA: MIT Press, 2001).

[46] F. K. Reilly and K. C. Brown, *Investment Analysis and Portfolio Management*, (Mason, OH: Thomson South-Western, 2006).

[47]R. de Neufville, Lecture notes from MIT *ESD.71: Engineering Systems Analysis for Design* (Fall 2005).

[48]G. M. Jabbour, M. V. Kramin, and S. D. Young, "Two-State Option Pricing: Binomial Model Revisited," *The Journal of Futures Markets,* Vol. 21, No.11, (2001): 987-1001.

[49]E. S. Schwartz and L. Trigeorgis, "Real Options and Investment under Uncertainty: An Overview," *Real Options and Investment under Uncertainty, E. S. Schwartz and L. Trigeorgis*, (Cambridge, MA: MIT Press, 2001).

[50]P. Samuelson, "Proof that Properly Anticipated Prices Fluctuate Randomly," *Industrial Management Review*, (1965): 41-49.

[51]T. Wang, "Real Options "in" Projects and Systems Design – Identification of Options and Solution for Path Dependency," Ph.D. Dissertation in Engineering Systems, Institute of Technology, Cambridge, MA, (2005).

[52]R. McDonald and D. Siegel, "Option Pricing When the Underlying Asset Earns a Below-Equilibrium Rate of Return: A Note," *Journal of Finance*, Mar., (1984): 261-265.

[53]J. E. Neely, R. de Neufville, "Hybrid real options valuation of risky product development projects," *International Journal of Technology, Policy and Management*, Vol. 1, No. 1, (2001): 29-46.

[54]East Japan Linear Motor Train Promotion Conference web site:
< http://www.h2.dion.ne.jp/~linear/topics0403.htm#kennsetuhi > Last accessed on Mar. 18, 2007.

[55]Cabinet Office, Government of Japan web site:
< http://www.esri.cao.go.jp/jp/sna/qe052-2/gdemenujb.html > Last accessed on Jan. 26, 2007.

[56]Kyoiku-Shuppan Co. Ltd. web site:
< www.kyoiku-shuppan.co.jp/kousha/ns.pdf/ns7-02.pdf> Last accessed on Mar. 19, 2007.

[57] S. Onoda, "World's First Commercial Superspeed Maglev in Shanghai," *The Journal of The Institute of Electrical Engineers of Japan*, Vol. 125, No. 5, (2005): 280-283.

[58] The Pennsylvania High Speed Maglev Project web site: <http://www.maglevpa.com/propul.html> Last accessd on May 10, 2007.

[59] Ministry of Finance, Japan web site: < http://www.mof.go.jp/jouhou/kokusai/siryou/result.xls > Last accessed on Apr. 11, 2007.

[60] Tokyo Stock Exchange web site: < http://www.tse.or.jp/english/market/topix/index.html> Last accessed on Apr. 2, 2007.

[61] Toyota Financial Services Securities Corporation web site: < http://www.toyota-fss.com/fund/01311889_prom1.html > Last accessed on Apr. 2, 2007.

[62] JP Actuary Consulting Co., Ltd. web site: < http://www.jpac.co.jp/bond/index.html > Last accessed on Mar. 30, 2007.

[63] Yahoo Japan Finance web site: < http://table.yahoo.co.jp/ t?c=1997&a=10&b=1&f=2006&d=3&e=31&g=m&s=998405.t&y=0&z=998405.t >
Last accessed on Mar. 30, 2007.

[64] Yahoo Japan Finance web site: < http://table.yahoo.co.jp/ t?c=1997&a=10&b=1&f=2006&d=3&e=31&g=m&s=9022.t&y=0&z=9022.t
Last accessed on Mar. 30, 2007.

[65] Central Japan Railway Company web site: Accounting Statement, < http://jr-central.co.jp/co.nsf/CorporateInfo/co_0420 > Last accessed on Mar. 30, 2007.

[66] Central Japan Railway Company web site: News Release, < http://jr-central.co.jp/co.nsf/news/nws2006925-191710 > Last accessed on Setp. 29, 2006.