Valuing Innovative Technology R&D as a Real Option: Application to Fuel Cell Vehicles

by

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Abstract

This thesis aims to elucidate real option thinking and real option valuation techniques for innovative technology investment. Treating the fuel cell R&D investment as a real option for General Motor's light passenger vehicle fleet, the thesis presents a 3-step approach to value the R&D and its influence on the fleet value, in which the uncertainties and managerial flexibility are proactively accounted for and evaluated.

To comprehensively assess the investment, the thesis includes analyses and discussions on fuel cell technology, industry, and related public policies, as well as illustrations and comparisons of various project valuation techniques. It explains in detail the traditional capital budgeting technique, Discounted Cash Flow, and real option valuation techniques such as the finance-based methods and simulation, including their underlying assumptions, analysis of uncertainties, treatments of flexibility, mechanisms, advantages, and limitations.

The examination of the project valuation techniques and the GM case leads to the proposed valuation approach that (1) utilizes Monte Carlo simulation to model the uncertainties that affect fleet profit; (2) employs constrained optimization by linear programming to find out the annual optimal fleet profit, and (3) applies NPV analysis and Binomial Approximation to project the evolution of the fleet value, as well as to evaluate the optimal exercise time and the optimal value of the real option.

This practical approach captures the complexity in GM's fleet management and offers insight on how its fleet value changes with respect to changes in the product mix of its light passenger vehicle fleet. It also provides an objective justification for a futuristic, highly uncertain investment. The R&D investment alone is estimated to have a negative NPV. However, its payoff essentially lies in the incremental fleet value, which is attributed to the relaxed sales restrictions brought about by commercializing fuel cell vehicles. Possessing and exercising this real option allows GM to market and sell more profitable vehicles within the bounds of production, market, and CAFE constraints. The approach identifies the best commercializing time between 2010 and 2015 in all simulated scenarios and the optimal value of the fuel cell R&D based on a profit-maximizing principle.

Thesis Supervisor : Richard de Neufville
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Table of Contents

List of Tables

List of Figures

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Chapter 1 Introduction

This thesis aims at three main objectives that are to be accomplished in seven chapters: (1) to elucidate for management and engineering students the existing real option concepts and valuation techniques, (2) to illustrate theses concepts and techniques in a case study, the GM fuel cell R&D, and propose a valuation approach that effectively value this program, and (3) to provide an introduction to fuel cell technology and an overview of relevant policies and industry analysis.

The first chapter summarizes the motivation behind and the structure of this thesis, explaining why this thesis is relevant to a firm's investment strategy, and how the above objectives can be attained.

1.1 Innovative Technology R&D

The research and development (R&D) of innovative technologies require substantial capital investments, yet the R&D outcomes may take years to be realized, let along the economic return of the investment. Hence, the proper valuation, selection, and management of the R&D projects are critical to firms' long-term financial health, especially for firms whose survival depends on innovation. For these firms, a realistic and accurate investment valuation allows them to properly allocate the limited resources, as well as to prioritize projects according to their financial returns, all of which aim to mitigate uncertainties and maximize profit.

Investment valuation requires the present and forecasted net cash flows to be discounted to the present time so that all projects' net present values (NPV) are compared on an equal basis. Nevertheless, predicting future cash flows is not a trivial task. The economic success of an R&D venture in innovative technologies is influenced by many uncertain endogenous and exogenous factors, such as reliability, safety, performance, price, consumer preference, the overall economy, competition, time to market, and government policies. The profitability of the venture also depends on how the decision-makers manage the project after it is launched. Overall, R&D projects are inherently risky and require careful valuation and continuous uncertainty management.

The R&D of innovative products is often staged over an extended period of time, between five to twenty years or beyond. The different stages include, but are not limited to, research and development, testing, and commercialization. Obviously, many decisions need to be made throughout a project's life, according to new information received or the latest business dynamics observed so that potential gains could be capitalized and losses, minimized. The flexibility to change is similar to dealing with financial options—exercised only when advantageous to do so. In projects like R&D ventures, the object of change is called a "real option" because this object is a real asset.

1.2 Thesis Structure

This thesis contains both quantitative and qualitative analyses that study innovative technology investment from different angles. The investment project valuation utilizes analytical techniques such as Monte Carlo simulation, Constrained Optimization, and Binomial Approximation. These quantitative analyses are complemented with a qualitative component of fuel cell industry analysis and related government policies, which are equally important to the decisions in fuel cell investments. The qualitative component aims to provide readers a non-economic perspective to better understand the past, present, and future status of fuel cell technology in the U.S. and other parts of the world.

The study of real options and innovative technology R&D is spread among seven chapters in this thesis. Chapter 1 sets forth the required background information and structure and lays out the essential concepts related to uncertainty, risk, and flexibility; all of which are the primary issues to be tackled by real option valuation. Chapters 2, 3, and 4 continue to build a key foundation for understanding project valuation and real option valuation.

Chapter 2 discusses basic capital budgeting concepts such as cost of capital, time value of money, and DCF, along with the limitations of DCF. Chapter 3 reviews fundamental concepts of Financial Option Theory, which is the foundation of the development of the Real Options Concept. Examples are included to illustrate the basic valuation methods: Black-Scholes Options Pricing Model (OPM) and Binomial Approximation. These two methods are commonly borrowed to value real options (flexibility) in real projects or physical assets. In addition, a set of underlying assumptions for these two methods are collected and documented in this chapter, as they are often not mentioned or incomplete in the existing Real Options literature. It is imperative to understand these assumptions as they are quite restrictive conceptually and practically; failure to recognize these assumptions can lead to incorrect models and results.

Chapter 4 formally introduces real options: (1) as flexibility, which is the concept introduced previously in Chapter 1, and (2) as a way of thinking and an analytical tool. An extensive literature survey of real option valuation methods is documented, including Black-Scholes OPM, Binomial Approximation, Decision, Analysis, Decision Analysis and Binomial Approximation Hybrid Model, and Simulation. This chapter also explains the limitations and advantages of these methods. Lastly, this chapter provides an overview of types and applications of real options.

After establishing necessary building blocks in Chapters 2, 3, and 4, Chapter 5 introduces GM fuel cell R&D as a real option and related background information. The objective and problem statement of the quantitative analysis are defined. The last section of this section discusses a critical component in the analysis, the Corporate Average Fuel Economy, or the CAFE standards, as GM's fleet management and fleet valuation is subjected to CAFE laws.

Chapter 6 explains in detail a 3-step approach to value GM's fuel cell R&D. The R&D is treated as an exotic option that could potentially increase GM's total fleet value with respect to cash flows. The last section in Chapter 6 discusses the result and issues in modeling and real option valuation. Finally, Chapter 7 examines the qualitative aspect of fuel cell technology. The characteristics and barriers of fuel cell technology are reviewed, as well as the industry status and related public policies. The thesis ends with a conclusion that summarizes the valuation result and some final remarks about the fuel cell R&D investment.

1.3 The Problem and Proposed Solution

Traditional capital budgeting technique such as Discounted Cash Flow (DCF) method assumes point estimates of future cash flows based on predetermined level of uncertainty over the course of the R&D venture, hence neglects managerial flexibility. The result of the DCF analysis is project's net present value without flexibility; that is, the sum of net cash flows over the project life discounted by an estimated, risk-adjusted discount rate. Nevertheless, as discussed in the previous section, many scenarios can happen throughout a project's life, and how management responds to these scenarios would change the value of the project.

To address the limitations of DCF and to explicitly consider the value of flexibility, this thesis examines investment valuation methods that explicitly identify real options and capture the outcome of exercising managerial flexibility. The products of these methods are a project's net present value with flexibility and an associated decision map for project modifications. The ability to modify a project according to the evolution of project value over time adds value to the project because unfavorable scenarios are avoided.

1.4 Basic Definitions

This section aims to clarify some of the basic terminologies used throughout this thesis.

1.4.1 Profit Maximization

Maximizing the project value is the assumed objective of a firm. The higher the project value, the greater the net profit that is brought to the firm. The overarching purpose in this thesis is to maximize the project value for the project studied.

1.4.2 Uncertainty and Risk

The Oxford English Dictionary defines uncertainty as “the quality of being uncertain in respect of duration, continuance, occurrence, etc.” and risk as “hazard, danger; exposure to mischance or peril.” It is clearly shown in the definitions that risk has a negative connotation while uncertainty is neutral and inevitable.

Indeed, uncertainty and risk are treated as two different concepts in this thesis. In project planning, uncertainties are unavoidable. Cash flows of a project are affected by uncertainties in supply, demand, cost, and organization, and the monetary loss that is the consequence of these uncertainties is risk. Managers must deal with them intelligently so that during the passage of time, uncertainties are mitigated through new information and project revisions. To do this, real option valuation provides a systematic framework that proactively recognizes and incorporates uncertainties in project valuation. The results from real option valuation can serve as a guidance and strategic road map for project selection and management.

1.4.3 Volatility

Mathematically, uncertainties are measured by **volatility**, σ. Luehrman (1998) suggests three ways to calculate the volatility of the underlying asset: (1) make an educated guess. One approach is to examine a range of σ from 30% to 60%, and guess a most appropriate number, (2) gather historical data on investment returns in the same or similar industries, and (3) simulate the project's cash flows and use Monte Carlo Simulation to synthesize a probability distribution for project returns. The volatility (standard deviation) can then be derived from the probability distribution.

In summary, the magnitude of σ has significant impact on the projection of cash flows, which are positively correlated with the value of a project. The greater the volatility, the greater the discount rate is required to compensate investors for bearing the additional risk. It is thus important to carefully examine the business environment and relevant data pertaining to a project, in order to assign a practical level of volatility.

1.4.4 Flexibility

Since uncertainties are explicitly acknowledged and analyzed in project valuation, projects can be modified according to how the value of the project evolves over time. The ability to revise the project, in the context of this thesis, is managerial flexibility. It means that managers and engineers have the ability to abandon, contract, invest, or delay the projects when needed. Without such flexibility, project valuation would only rely on point estimates and management intuition, which could potentially cause projects to be committed sub-optimally.

Besides flexibility to modify projects as a whole, it is worthwhile to mention the concept of flexibility and robustness "in" projects. In the context of technical projects, flexibility and robustness are most often regarded as a system attribute. Evans (1982) defines flexibility and robustness as follows:

> Flexibility is the inherent capability to successfully adapt to unforeseen changes.
> Robustness refers to the ability to ensure such changes.

Evans distinguishes the concepts of flexibility and robustness, while others use them interchangeably (Rosenhead and Wong, 2000), or regard flexibility as one of the desired properties in a robust system (Schillo, et al, 2001). In general, the flexibility "in" projects needs to be built in to the technical system during the design phase, whereas the flexibility "on" projects treats projects as a black box and concerns the valuation but not the design issues (de Neufville, 2003). The concept of flexibility in system and its valuation is discussed in detail in de Weck, et al. (2004) and Wang (2005). Most investment valuation only considers flexibility on project since the main objective is to maximize project value. Value maximization is a required and practical objective for both managers and engineers of a profit-maximizing firm. Financial and technical decisions should both be subjected to project valuation that serves as an objective decision-making rule.

Chapter 2 Basic Valuation Concepts

2.1 Introduction

Project value is defined as the net present value of net cash flows in the life of a 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 (Trigeorgis, 1996). It can also be referred to an analytic procedure that some managers use to value and prioritize a firm's multiyear capital investment projects. Based on the result of capital budgeting, managers choose projects that will generate the greatest amount of net discounted cash flow during the projects' useful lives. Net cash flows are positively correlated with a firm's shareholder wealth. For this reason, capital budgeting decisions can have tremendous impact on firm's long-term financial performance.

Firms utilize different evaluation criteria in capital budgeting depending on their preferences. The criteria include but are not limited to, Discounted Cash Flow (DCF), Internal Rate of Return (IRR), and Cost-Benefit Ratio, and the relatively new real option valuation methods. This thesis is based on the real options concept and applies real option-based valuation methods to capital budgeting decisions; therefore, the IRR and the Cost-Benefit Ratio methods are excluded from this thesis.

Though these criteria are chosen according the firm's objectives and preference, the essence of these methods is the same: Net Present Value Analysis (NPV), in which free net cash flows incurred in the life of a project are discounted to the present with a predetermined discount rate. The rest of this chapter introduces basic concepts in NPV analysis: the cost of capital, time value of money, and the NPV calculation. It concludes by presenting the most common capital budgeting valuation method using the NPV analysis, the Discounted Cash Flow (DCF).

2.2 Cost of Capital by Weighted-Average Cost of Capital (WACC)

In a perfectly competitively market, resources are limited. As a result, firms must select and prioritize projects. Any investment decision should be evaluated against the cost of capital. Hence, the derivation and determination of the cost of capital is one of the most contentious issues in project valuation.

The cost of capital can be obtained from the weighted average return to debt and market-traded equity. This weighted average equals the opportunity cost of capital, and is expressed in the following formula:

$$WACC = r_{equity}(\frac{E}{V}) + r_{debt}(\frac{D}{V}),$$ **Equation 2-1**

where

WACC = r = cost of capital, discount rate for an average project

r_{equity} = expected rate of return on equity, cost of equity

r_{debt} = expected rate of return on debt, cost of debt

E = equity

D = debt

$\frac{E}{V}, \frac{D}{V}$ = weights of equity and debt based on the market value of the firm, V; V = E + D

As can be seen in Equation 2-1, WACC is the average cost of money for a publicly-traded firm and an aggregate measure for a portfolio of all the firm's current assets. In other words, the WACC formula only works for "average" projects, of which the risk profile is similar to that of the firm. WACC is incorrect for the projects that are safer or riskier than the existing assets (Brealey and Myers, 2003, p. 525). For example, an innovative R&D investment certainly bears greater uncertainties than a firm's average projects. Projects like this should require a non-average discount rate that properly compensates for the risk undertaken.

The limitation of WACC and the requirement to consider project risk lead to the use of the Capital Asset Pricing Model (CAPM), which adjusts the discount rate according to level of risk.

2.3 Cost of Capital by Capital Asset Pricing Model (CAPM)

In conventional investment theory, the most commonly used form of assessing risk is the Capital Asset Pricing Model (CAPM). In CAPM, a premium is paid to shareholders beyond the risk-free rate for bearing the systematic (market) risk associated with an industry or sector. This risk-adjusted required rate of return is the opportunity cost that the investor could earn elsewhere in projects with equivalent risk. This rate is then used to discount the operating cash flows of a project (Copeland, 2005, p. 42). CAPM is defined as the following:

$$E(r_i) = r_f + \beta_{im}(E(r_m) - r_f)$$ **Equation 2-2**

Where $E(r_i)$ corresponds to the expected return on the capital asset (investment), r_f is the risk-free rate of interest, and β_{im} (the beta) is the sensitivity of the asset returns to market returns, as defined by the formula:

$$\beta_{im} = \frac{Cov(r_{i,} r_m)}{Var(r_m)}$$ **Equation 2-3**

Where $Cov(r_i, r_m)$ is the covariance between the expected return of the asset (r_i) and the expected return of the market (r_m), measuring the degree to which a set of r_i and a set of r_m move together on average. r_i and r_m can be obtained from the historical data, and the covariance calculation can be done through matrices (an algebraic structure) or Excel spreadsheet with the spreadsheet function = COVAR(asset data set, market data set). Similarly, $VAR(r_m)$ is the variance of the expected return of the market, and can be derived from the spreadsheet function = VAR(market data set). Lastly, *(E(rm) − rf)* is the market premium or risk premium. The calculated value $E(r_i)$ is then applied to the calculation of NPV, which is discussed in Section 2.4, Time Value of Money.

The cost of capital for a project depends on the project and not on the risky profile of the firm financing it. Unless a firm's projects are highly similar, such as McDonald's franchises, individual project should use a different risk-adjusted discount rate to represent its unique level of risk, and not just the weighted average cost of capital.

2.4 Time Value of Money

Time value of money is the next critical concept. A dollar today is worth more than a dollar tomorrow because the dollar can be invested to start earning interest immediately. Therefore, the future payoffs need to be adjusted properly to reflect the time value of money. The formula to discount future payoffs is:

Present Value (PV) = Discount factor x Expected future cash flows

$$Discountfactor = \frac{1}{(1+r_i)^t}$$ **Equation 2-4**

Where

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

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

If a project is perpetual; that is, there is a constant stream of cash flow with no end, a special formula is required for determining the present value of the perpetuity:

$$PV = \frac{CashFlow}{r_i}$$ **Equation 2-5**

The concepts of expected value of the opportunity cost of capital $E(r_i)$ and the time value of money can then be applied to the NPV calculation.

2.5 NPV Analysis

NPV is the most widely used method for discounting cash flows to the present time. The NPV of a project is the present value of its expected future *incremental cash inflows and outflows*. Therefore, most important issues to be addressed are the determination of the expected cash inflows generated by the project, and the expected cash outflows required to implement the project, and the determination of the discount rate to discount future cash flows (Dixit and Pindyck, 1994).

NPV can be expressed in the following formula:

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{E(FCF_t)}{(1+r_i)^t}$$ **Equation 2-6**

where

I_0 = investment at time zero;

$E(FCF_t)$ = expected value of free cash inflows 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* remains constant in each period.

2.6 Decision Rule for Project Selection

As previously stated, project planning and budget allocation are often based on the result of NPV analysis or project value. Intuitively, managers would consider a negative NPV not favorable because it indicates that the project will reduce the value of the company to its shareholders and should not be undertaken. Conversely, a positive NPV indicates that the investment in the project should be made because the project would increase the shareholder value. The sign of the value of NPV is the threshold for a go or no go investment decision.

However, the above dichotomized decision rule might seem too simple. One can argue that the managers might need a more complex set of decision rules on investment decisions to accommodate the different expectations and utilities of the shareholders. Fortunately, this concern is clarified by the Separation Principle in finance (Copeland, 2005, p. 63), which says that the shareholders of a firm are likely to unanimously agree about the following investment decision rule: managers are expected to undertake investments until the marginal return on the last dollar invested is greater than or equal to the market-determined opportunity cost of capital. Therefore, it is appropriate for managers to consider only the overall organizational utility or the sign of the NPV of a project, rather than concerning about the individual shareholder's utility.

2.7 Discounted Cash Flow (DCF)

DCF is the most commonly used capital budgeting technique and rule. Using the same formula as in the NPV analysis, DCF discounts the sum of cash flows of a project to the present time to determine the current project value. Note that most literature uses NPV and DCF interchangeably, but in this thesis, DCF is a type of capital budgeting technique, whereas NPV is simply a necessary arithmetic operation used in all capital budgeting techniques.

By using DCF, managers implicitly assume that the firm holds real assets passively (Brealey and Myers, 2003, p. 432). DCF assumes that the project scope and plan are fixed throughout the project's life, and that the project's value is defined and funding is committed at the project's initial planning stage. However, in reality, project value is not static and the project scope and plan are contingent upon updated information and new decisions.

In addition, as seen in Equation 2-6, the determination of the discount rate would affect the net present value of a project—the discount rate and the net present value are negatively correlated. As a result, the DCF method tends to undervalue projects with high risk since risky projects tend to be assigned a higher discount rate to compensate for the greater volatility their future cash flows. The issue of undervaluation can be avoided if uncertainties are proactively analyzed and flexibility is exercised accordingly.

In Section 1.4.2, the definition of uncertainty indicates neutrality and inevitability, rather than treating it as a negative term. Uncertainties could add value to a project if properly managed. The greater the uncertainty over the future net payoffs of the investment, the greater the value of a project that incorporates flexibility. A firm can choose to design a system that allows configuration modification in the future. Compared to a system whose configuration is fixed from the beginning as DCF assumes, a flexible system can adapt to potential changes in technologies or markets so as to capture promising situations and avoid unfavorable ones.

The true value of a multi-period project fluctuates over time due to varying cash flows. To maximize project value, responsible decision-makers defer, expand, or abandon a project according to new information received or the changing business environment. Real option-based valuation methods provide a mean to value a project with such flexibility. These methods are based on the Option Theory in finance. The next chapter introduces basic concepts in Option Theory.

Chapter 3 Option Theory

3.1 Introduction

Option Theory in Finance provides a critical foundation for identifying, valuing, and exercising Real Options. In finance, an option is a contract giving the buyer the right, but not the obligation, to buy or sell an underlying asset as stock or index, at a specific price on or before a certain date. An option is a security, just like a stock or bond, and constitutes a binding contract with strictly defined terms and properties.

There are many details with regard to trading options such as government regulations on trading, commissions, taxation, margins, and dividends, but the major interest concerning financial option is its pricing. Prior to 1973, the pricing of options was entirely ad hoc. Traders made buying decisions based on intuition and simple calculations. In 1973, Fischer Black and Myron Scholes published a paper proposing what became known as the Black-Scholes Options Pricing Model (OPM), a closed-form solution that yields the theoretical prices of non-dividend paying European options (Black and Scholes, 1973). The Black-Scholes OPM is a solution to the Black-Scholes-Merton differential equation, which must be satisfied by the price of any derivative dependent on a non-dividend-paying stock. Hence, with the ability to set a standardized option price fairly and accurately, the option market has seen revolutionary developments in providing innovative products over the past 25 years.

This chapter introduces basic concepts in the world of options and the pricing approaches employed to value them. The approaches include the seminal Black-Scholes model and Binomial Approximation method when Black-Scholes is not applicable. Binomial Approximation simulates the stochastic behavior of the underlying asset through different approximations, hence avoiding the need to solve the Black-Scholes-Merton differential equation through Ito Process.

3.2 Basic Concepts: Definition, Relationship, and Net Profit

There are two basic types of options. A call options gives the holder the right to buy the underlying asset by a certain date for a certain price. A put option gives the holder the right to sell the underlying asset by a certain date for a certain price (Hull, 2002). Table 3-1 summarizes a list of important terminologies and their definitions.

Table 3-1 Option Terminologies and Definition

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

Note: The definition of options is obtained from the Chicago Board Options Exchange web site and simplified by the author: http://www.cboe.com/LearnCenter/Tutorials.aspx#Basics, last accessed on March 26, 2005

Essentially, the type of option (call or put), the expiration date (American or European), the exercise price, stock price, interest rate, and the volatility of the stock price influence the value of the option. Table 3-2 summarizes the relationship between these factors and the call option price.

Table 3-2 Effect on the Price of a Call Option

If there is an increase in:	The direct change in the call option price is:
Stock price, S	Positive
Exercise price (strike price, K)	Negative
Interest rate (risk-free rate), r	Positive*
Time to expiration, T	Positive
Volatility of the stock price (σ)	Positive*

* Note that the column to the right describes direct change in the call option price. In these two cases, the increase in interest rate and volatility, there might also be indirect effects. For example, an increase in the interest rate could reduce stock price. This in turn could reduce option price. ((Brealey and Myers, 2003, p. 581)

Examples

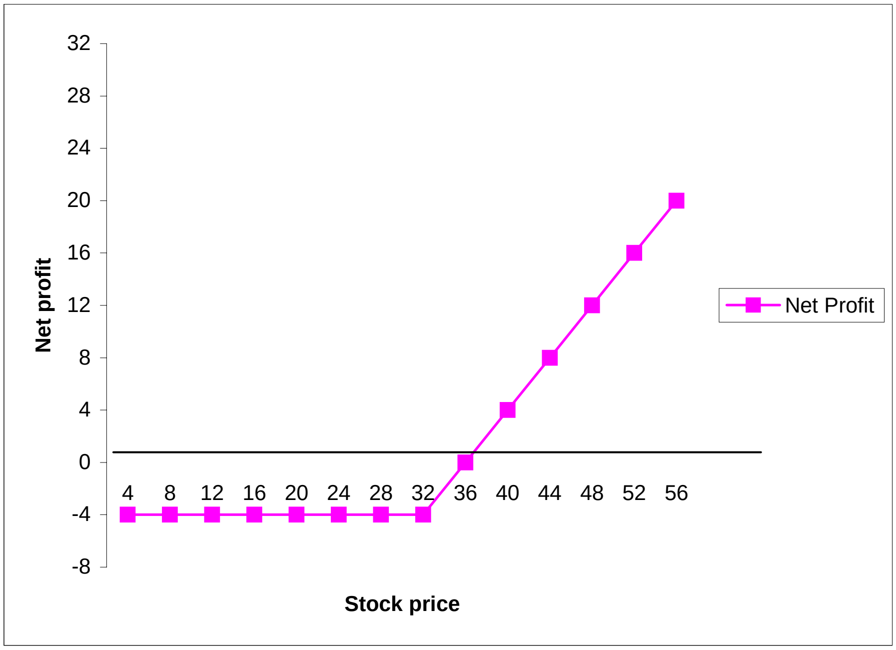
The rest of this section provides two examples to illustrate how options work. The examples use vanilla European options as examples. The American options have the same payoff scheme, except that they can be exercised anytime prior to the expiration date.

Consider an investor who purchases a European call option with a strike price of $32 to purchase 100 GM (General Motors) shares. The current stock price is $35, the expiration date of the option is in six months, and the price of an option to purchase one share is $4.

The initial investment for the above situation is $400. On the expiration date of the option, if the stock price is less than the strike price of $32, the investor will not exercise the option because the market offers a lower price than the contracted price, $32. In this case, the investor loses the initial investment of $400. If the stock price is higher than $32, the investor will exercise the option to make a profit from the difference between the stock price and the strike price. Figure 3-1 shows the net profit or loss to the investor.

Figure 3-1 Profit from One European Call Option on One GM Share

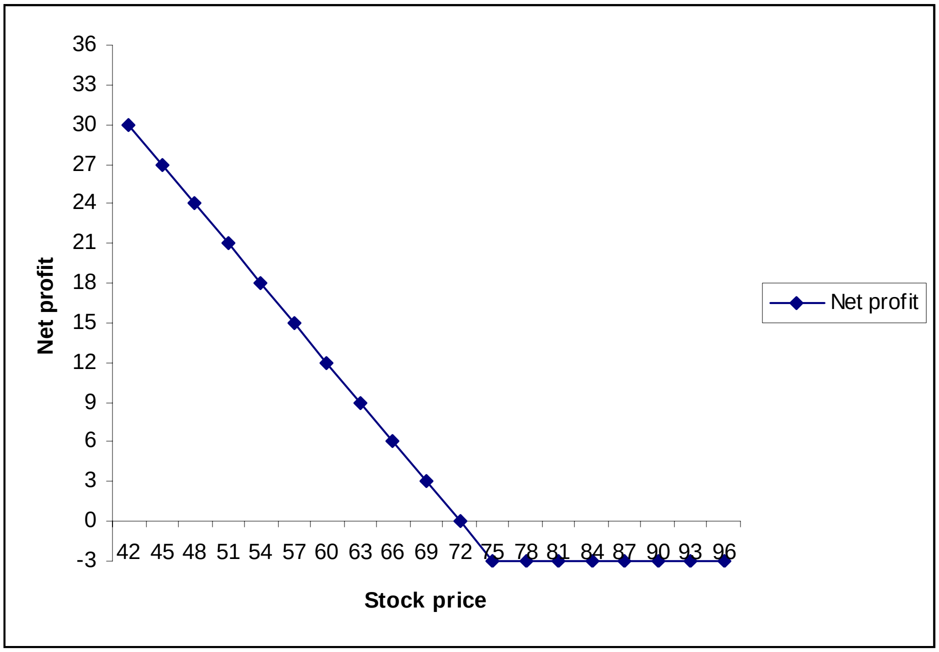
Option price = $4; strike price = $32



Next, consider an investor buying a European put option to sell 100 shares of Toyota stock with a strike price of $75. The current stock price is $70, and the expiration date of the option is in six months. The price of the option is $3 per share, making the initial investment $300. On the day of expiration, the investor will not exercise the option unless the stock price falls below $75, the strike price. Suppose the stock price at expiration is $65, the investor can buy 100 shares for $65 per share and sell the same shares for $75 under the put option contract. In this case, the investor will make a net profit of ($76-$65) x 100 – $300 = $700. If the stock price on the expiration date is above $75, the put option expires worthless, and the loss borne by the investor is $300. Figure 3-2 illustrates the above example.

Figure 3-2 Profit from a European Put Option on One Toyota Share

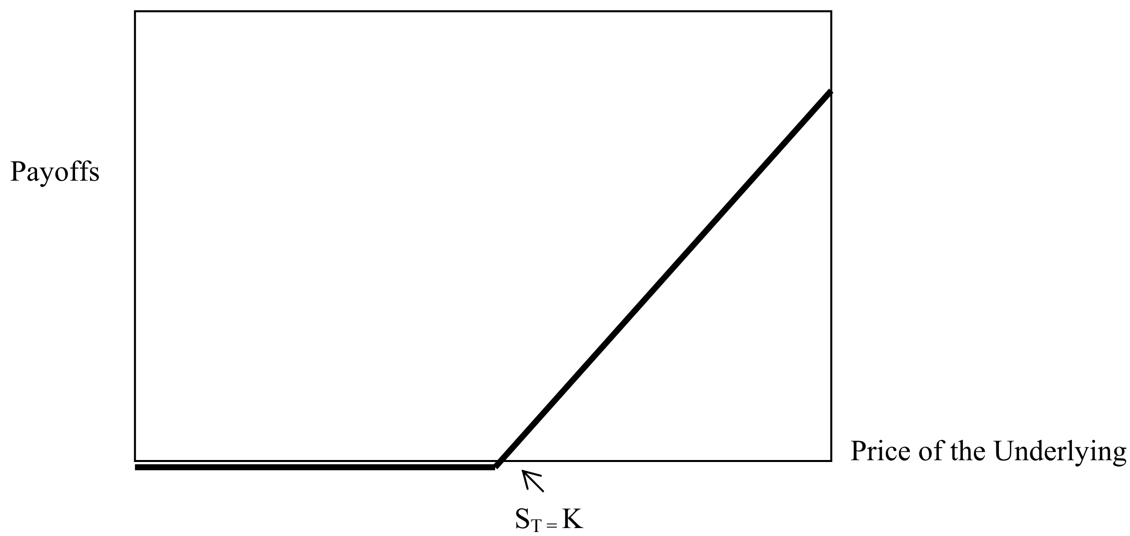
Option price = \$3; strike price = \$75.



3.3 General Payoff Schemes

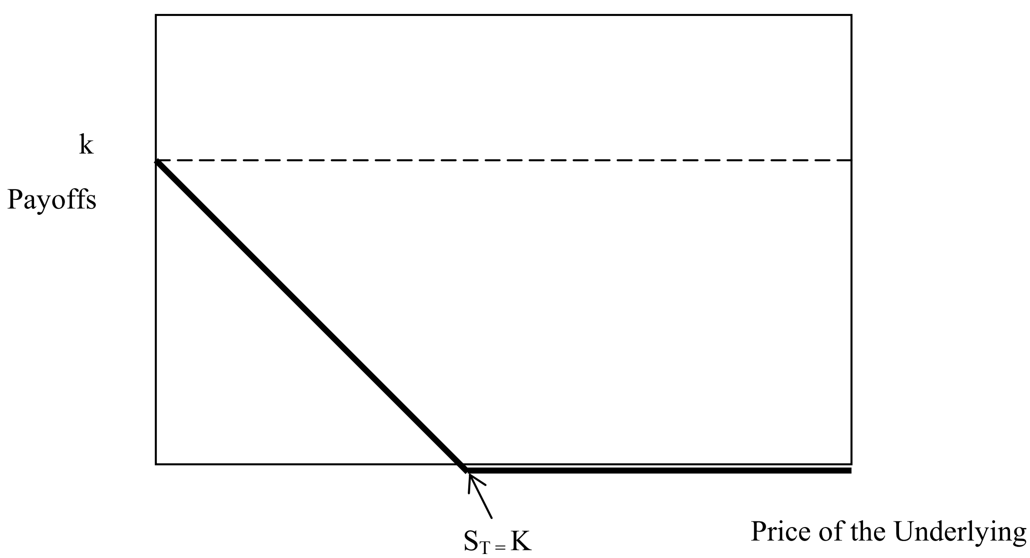
It should be noted that some options literature uses the term “payoff” instead of net profit. The difference between net profit and payoff is as follows: an option’s payoff takes into account only what the holder gets at expiration, rather than considering the total out-of-pocket expense from the holder. Figure 3-3 illustrates the payoff scheme for a European call. Mathematically, the *payoff of European call options = Max (ST – K, 0)*, where *ST* is the stock price at the expiration date, and *K* is the strike price.

Figure 3-3 General Payoff Diagram of a European Call



A diagram for the payoffs from buying European put options is shown in Figure 3-4. Mathematically, the *payoff of European put options = Max (K - ST, 0)*, where *ST* is the stock price at the expiration date, and *X* is the strike price.

Figure 3-4 General Payoff Diagram of a European Put



The payoff diagrams show that option holders will only exercise options when they are advantageous to do so. The payoffs for options are *asymmetric*: the earning potential for call options is unlimited, and for put options, the ceiling is the strike price.

The rest of the chapter lays out the mechanisms and assumptions of two fundamental methods that are used to price call and put options. Keep in mind that there also exist exotic options whose pricing requires variant formulas of these methods. As Luenberger (1998) indicates, there are still cases of exotic options whose pricing still present a serious technical challenge to the investment analysis community (p. 370).

3.4 Black-Scholes Options Pricing Model (OPM)

The first approach is the Black-Scholes OPM, a continuous-time, closed-form solution of the Black-Scholes-Merton Differential Equation. Black-Scholes OPM is capable of pricing European call and put options on a non-dividend paying stock. The formula for the price of a non-dividend paying European call is:

$$c = S_0 N(d_1) - Ke^{-rT} N(d_2)$$ **Equation 3-1**

where

$$d_1 = \frac{\ln(S_0 / K) + (r_f + \sigma^2 / 2)T}{\sigma\sqrt{T}}$$ **Equation 3-2**

$$d_2 = d_1 - \sigma\sqrt{T}$$ **Equation 3-3**

The function $N(x)$ is the cumulative probability distribution function for a standardized normal distribution (with mean zero and standard deviation one).

Other notions are denoted as follows:

S_0 = the price of the underlying stock at time 0

K = the predetermined strike price

rf = the continuously compounded, risk free interest rate

T = the time until the expiration of the option (unit depends on how σ is defined)

σ = the implied volatility for the underlying stock for the time period

Similarly, the solution for the price at time zero of a European put on a non-dividend-paying stock is as follows:

$$p = Ke^{-rT}N(-d_2) - S_0N(-d_1) \qquad \textbf{Equation 3-4}$$

Example

Suppose one share of IBM stock price is $90; the strike price is $85; the volatility is 30%, and the risk-free interest rate is 5% annually; and the time to maturity is one year. What is the price for an IBM European call option?

In the Equations 3-1, 3-2, and 3-3, substitute the stock price, the strike price, the volatility, the risk-free rate, and the time to maturity. A European call option based on the Black-Scholes OPM should be priced at $15.39.

The assumptions of Black-Scholes OPM are explained in Section 3-6. They are highly relevant to the accuracy and plausibility of any real options model and pricing.

3.5 Binomial Approximation by Binomial Lattice

The Binomial Approximation method was first introduced by Cox, Ross, and Rubinstein in their 1979 paper titled *Option Pricing: A Simplified Approach* (Cox, Ross, and Rubinstein, 1979). Binomial Approximation uses *Binomial Lattice* to approximate the price evolution and the payoffs of an underlying asset. The essential trick in pricing options is to set up a package of investment in the stock and a loan that will exactly replicate the payoffs from the option (Brealey and Myers 2003, p. 409).

In Binomial Lattice, the price of an asset is assumed to either move up or move down in a single time period by an *up* multiplier u or a *down* multiplier d--Both u and d are positive, with $u > 1$ and (usually) $d < 1$. Suppose the price of an asset at time 0 is *S0*, it will be either uS or dS at the next time period. It is only necessary to observe two movements if the period length is small. Multiple values can be observed after several short time periods.

There are probabilities associated with the up and down movements. A probability p is defined for the up or down movement; that is, the probability that *S0* will become uS is p. And since there are only two possibilities for the fluctuation of *S0*, the probability of *S0* to become dS is 1- p, since the total probability needs to add up to 1. Figure 3-1 illustrates a stock price fluctuation model based on *S0*, u, d, and p. Notice that *S0* fluctuates in a recombining fashion. Recombining means that the up movement followed by a down is identical to a down movement followed by an up-- S_0ud is the same as S_0du.

Figure 3-1 Three-Period Binomial Lattice

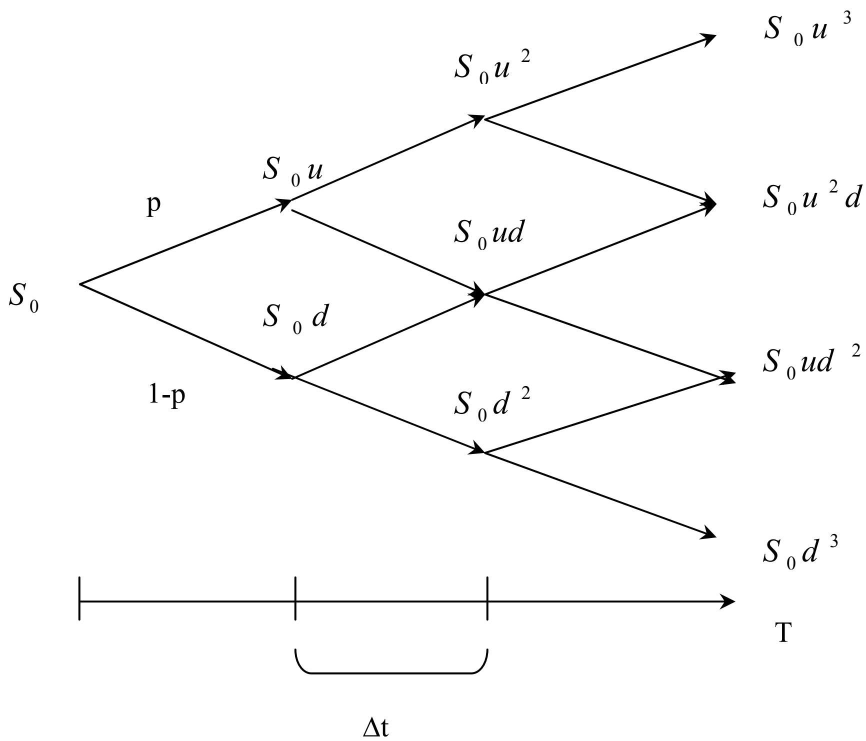


Figure 3-1 shows the stock price evolution for three periods. For any evaluation period to expiration, the period length is $\Delta t = t/n$ if the time to expiration t is divided into n equal periods. The option valuation process is repeated starting at the last period and working backward recursively. The general multiplicative binomial option-pricing formula for n period is:

$$C = \frac{\sum_{j=0}^{n} \frac{n!}{j!(n-j)!} p^j (1-p)^{n-j} \max[u^j d^{n-j} s - k, 0]}{(1+r)^n}$$ **Equation 3-5**

The risk neutral probability, p, derived by Cox, Ross, and Rubinstein, is

$$p = \frac{r - d}{u - d}$$ **Equation 3-6**

$$1 - p = \frac{u - r}{u - d}$$ **Equation 3-7**

where $r = 1 + r_f$, in addition,

$$u = e^{\sigma \sqrt{\Delta t}}$$ **Equation 3-8**

$$d = e^{-\sigma \sqrt{\Delta t}} = \frac{1}{u}$$ **Equation 3-9**

where

σ = volatility of the natural logarithm of the underlying free cash flow returns in percent

Note that as Δt gets smaller, the binomial formula approximates to the continuous Black-Scholes formula.

3.6 Underlying Assumptions for Black-Scholes Options Pricing Model and Binomial Approximation

Black-Scholes Options Pricing Model and Binomial Approximation are the cornerstones of the Option Theory. They are the most widely used methods for fairly and accurately pricing the options on exchange and in the over-the-counter market. This section discusses their assumptions to help students of options and real options understand their applications and limitations.

Some option literatures omit the discussion of assumptions, while some only mention the most fundamental assumptions: arbitrage-enforced pricing and that the stock price evolution follows Geometric Brownian Motion with constant volatility. The following is a comprehensive list of assumptions that are mentioned in various literatures:

- **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 asset exists 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.

- Option price and stock price depend on the same underlying uncertainties.

- **There is a continuum of stock prices**. This seems unrealistic since the trading is not continuous, but Black-Scholes as a continuous-time model performs quite well in the real world where stocks trade only intermittently with price jumps.

- **Stock prices fluctuate randomly in a complete, efficient market**. Paul Samuelson proves in his 1965 paper, "Proof that Properly Anticipated Prices Fluctuate Randomly," that even though there may be a known seasonal pattern in the current price of a commodity, the future price will fluctuate randomly (Samuelson, 1965). Therefore, **in a short period of time, stock price jump is**

characterized by a normal or lognormal probability distribution--this means that the logarithm of 1 plus the rate of return follows a normal or bell-shaped curve. Changes in the magnitude of the jump are described by Geometric Brownian Motion (GBM)**,** where the logarithm of the underlying variables follow generalized Wiener process (Hull, 2002, p. 219).

- **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. Baxter and Rennie (1996) show that the existence of any arbitrage opportunities enforces the price of the option. Therefore, a portfolio of the stock and the stock option with a same risk profile can be set up so that the payoffs of the option exactly replicate the payoffs of the stock, hence the stock and the option should be traded a the same price. Since there is no risk involved in setting up such a portfolio, the investor's risk attitude is not a factor in pricing the option. The "arbitrage-enforced" pricing concept leads to the next assumption.

- **A risk-free rate is used to discount future cash flows**. The arbitrage-enforced pricing permits no consideration of investor's risk attitude. This risk-free rate is constant throughout the option life.

In addition, Binomial Lattice has the following assumptions for the asset price evolution:

- The price evolution is **stationary over time**.

- Each state leads to two other states over one time period (or a time step). The intermediate branches are all **recombining**.

- The paths to a state are independent of each other.

The many assumptions seem restrictive, but Black-Scholes and Binomial Approximation have proven to be two solid and rigorous methods that produce correct prices for financial options. More importantly, the assumptions such as the stock price behavior and arbitrage-enforced pricing apply well to financial instruments, for which the historical and observable market data are readily available.

Chapter 4 Real Options

4.1 Real Options as a Way of Thinking

Buying financial options is the right, but not the obligation, to take an action (to buy or sell options) at a predetermined cost, now or in the future. "Real options" shares similar flexibility—they represent opportunities to modify projects through built-in flexibility in the design (so as to expand, to switch, or to defer the project) or through management action (so as to abandon, to switch, or to contract the project). This flexibility allows decision-makers to capture upside potential and limit downside loss. In contrast to options functioning as contracts, the options are "real" because they deal with real projects (de Neufville, fall 2004).

Real options are often embedded in capital investment projects. They can occur naturally or, at some additional expense, may be built into investment opportunities. Building real options into an investment opportunity may be preferable if the present value of the cost of modifications that may be required later is greater than the additional cost of designing flexibility into the investment opportunity at the outset. Given the increase in variability in both product and financial markets, firms that recognize real options in projects or systems are more likely to be at a significant advantage in the future, relative to companies that fail to take account of options in the design and evaluation of capital projects.

Real Option thinking reflects how value is created in an uncertain environment, and how the firms can strategically design and execute flexibility in project management. Contrasting to the mentality of "avoiding all risks if possible," Real Option thinking provides much insight into project management because it educates engineers and managers how to deal with uncertainties proactively and add value to projects accordingly.

4.2 The Identificatin of Real Options

Learning the types of real options is fundamental to real options valuation. Practitioners must be able to recognize real options in or on projects before identifying appropriate valuation methods. Table 4-1 summarizes the types of real options (Trigeorgis 1987).

4.3 Real Option Valuation

Since MIT Professor Stewart Myers (1977) first used the term "real options", there have been many interpretations and debates on their definitions, scopes, and valuation methods. The lack of consensus in Real Options community is understandable--just as there are various types of financial options, real options are vastly different in their behaviors, timings, and applications.

This section offers an overview of the many applications of real options and the methods used to value these real options, including (1) Black-Scholes OPM that approximates the resulting partial differential equations, and (2) Binomial Approximation and Monte Carlo Simulation that approximate the underlying stochastic processes directly (Trigeorgis,1996). In addition, Decision Analysis, and a hybrid Decision Analysis-Binomial Lattice model are also discussed. Methods (1) and (2) are borrowed from the Option Theory in Finance; the detailed calculations can be found in Chapter 3.

Table 4-1 Types of Real Options

Source: Lenos Trigeorgis. 1993. Real Options and Interactions with Financial Flexibility. Financial Management, Autumn.

Option	Description	Example
Deferral options	The firm postpones the investment to gather information or wait for the best entry time to the market.	All natural resource extraction industries; real estate development; farming; paper products
Abandonment options	If market conditions decline severely, the firm can abandon current operations permanently and realize the resale value of capital equipment and other assets in secondhand markets.	Capital intensive industries, such as airlines and railroads; financial services; new product introductions in uncertain markets.
Staged investments; sequential options	The firm partitions investment as a series of outlays, creates the option to abandon the enterprise in midstream if new information is unfavorable. Each stage can be viewed as an option on the value of subsequent stages, and valued as a compound option.	All R&D intensive industries, especially pharmaceuticals; long-development capital-intensive projects, e.g., large-scale construction or energy-generating plants; start-up ventures
Scaling options	The firm can expand, contract, or temporarily shut down.	Natural resource industries such as mine operations; facilities planning and construction in cyclical industries; fashion apparel; consumer goods; commercial real estate.
Growth options; barrier options	As early investment is a prerequisite or a link in a chain or interrelated projects. The early entry and associated knowledge gained allow the firm to capture future opportunities.	All infrastructure-based or strategic industries, especially high-tech, R&D, or industries with multiple product generations or applications
Multiple interaction options; compound options	The firm holds multiple real options in a project. The collection of options, both upward-potential enhancing calls and downward-protection put options present in combination. Their combined option value may differ from the sum of separate option values, i.e., they interact. They may also interact with financial flexibility options.	Real-life projects in most industries discussed above.

4.3.1 Black-Scholes OPM

Here is a quick review for Black-Scholes OPM: the Nobel Prize-winning Black-Scholes Options Pricing Model is a continuous time model that values a European call or put. This means that there will not be dividend payouts, and that options can only be exercised at a predetermined time in the future. In addition, Black-Scholes is built on the assumptions that the underlying follows Geometric Brownian Motion, and that it is solved through risk neutral valuation by establishing a replicating portfolio.

Nevertheless, with respect to physical assets and projects, it is unlikely to find a replicating portfolio. Moreover, dividends are distributed as cash outflows, and real options are exercised during the life of the project. Consequently, many variants of OPM have been developed to model more complex scenarios. The OPM-based variants aim to accommodate cases to which OPM does not apply: Trigeorgis and Mason value real options in manufacturing plant (1987); Pindyck values project cost (1993); Grenadier and Weiss value real options in investment technologies (1997); Chen, et al. value flexible manufacturing switching options (1998); and Benaroch and Kauffman value IT investment decisions (1999).

4.3.2 Binomial Approximation

In contrast to Black-Scholes OPM, Binomial Approximation is a discrete-time model, using simple algebra to model the price volatility with the historical return distribution of the replicating portfolio. Binomial Approximation is flexible and can model most types of real options. In addition to the limited applicability, Black-Scholes cannot value real options that are exercised prior to a predetermined expiration date, like American options. Hence, real options that possess American option-like property can be modeled using Binomial Approximation. For example, using Binomial Approximation, Luenberger values a gold mine (1998); Kelly values a mining property initial public offering (1998); Copeland and Antikarov value a new Internet venture (2003); Ho and Liu value architecture and construction technology (2003).

Binomial Approximation is more intuitive than continuous-time models and it requires less mathematical background and skill to actually develop and use. However, at the same time, it shares the same limitation as those of in OPM: the difficulty in finding a replicating portfolio and consequently hinders the risk neutral valuation. Copeland and Antikarov (2003) propose using the project's own NPV as the underlying. If the NPV has a well-defined market value, it can be used as an underlying (Brealey and Myers, 2003).

4.3.3 Decision Analysis

Decision analysis is a structured approach to aid decision-making by systematically examining the alternatives for a decision or a sequence of decisions over a period of time, as well as the uncertainty associated with each outcome. The analysis utilizes a tree-like construct to model each alternative and choose the best decision according to the expected value of each alternative:

$$E(X) = \sum_{1}^{i} p_i x_i$$ **Equation 4-1**

E(X) is the expected value of an alternative. x_i and p_i are the discrete outcomes and the associated probabilities of occurrences. Ranking the expected value from high to low, best scenario is selected and flexibility can be exercised accordingly. In summary, Decision Analysis leads to three results: (1) structuring the problem, which could otherwise be confusing due to the many uncertainties and contingent decisions, (2) defining optimal choices for any period through the expected value calculation, and (3) identifying an optimal strategy over many periods of time (de Neufville, 1990).

Smith and Nau (1995) demonstrate that in a complete market, a "full decision analysis" (traditional Decision Analysis plus a utility function to model time and risk preferences) can yield comparable results as the real options pricing methods do, and these two approaches can be can be integrated to extend option pricing methods to incomplete markets.

Ramirez (2002) uses Decision Analysis to value infrastructure development. Brandao, Dyer, and Hahn (2004) propose a "generalized approach" to solve real option valuation based on the previous work of Smith and Nau (1995). The assumptions of this "generalized approach" are similar to those of Market Asset Disclaimer of Copeland and Antikarov (2003). Instead of using Binomial Lattice, they use off-the-shelf Decision Analysis software but admit that additional coded algorithms are required to enhance computational efficiency since the proposed approach is computationally intense.

4.3.4 Hybrid Model Decision Analysis-Binomial Approximation

Two of the assumptions of OPM and Binomial Approximation are the existence of a replicating portfolio and arbitrage-enforced pricing. Borison comments on a hybrid approach that some have taken to avoid such restrictive assumptions:

> *"…they suggest that the classic finance-based real options approach can be applied where these assumptions apply (namely replicating portfolio and no-arbitrage), and that management science-based approaches such as dynamic programming and decision analysis be applied where they do not. Real options should be used where investments are dominated by market-priced or public risks, and dynamic programming/decision analysis should be used where investments are dominated by corporate-specific or private risks" (2003, p.17).*

In summary, some practitioners claim that there are two types of risks associated with an investment, namely private and public risks. Therefore, a hybrid approach should be adopted to model these two risks separately.

Dixit and Pindyck (1994) elaborated extensively on this hybrid approach. Smith and Rau (1995), and Smith and McCradle (1998) integrated a finance-based options valuation approach with Decision Analysis. Both suggest that OPM can be used to simplify Decision Analysis when some risks can be hedged by trading, and conversely, Decision Analysis techniques can be used to extend option pricing techniques to problems with incomplete securities markets. Furthermore, Amram and Kulatilaka (1999) used the hybrid approach to value investments in pharmaceutical R&D. Neely (1998) propose a hybrid real options valuation model for risky product development projects in his MIT PhD dissertation. He argues that, for financial derivatives, OPM and other extension models are extremely pertinent, but their applicability to real options projects is less obvious, for reasons including practicality and information availability. Therefore, the market risk can be modeled using the finance-based methods, and the technical risk should be modeled using Decision Analysis.

4.3.5 Monte Carlo Simulation

Simulation refers to a variety of analytical approaches in different disciplines, but fundamentally, it is an analytical method meant to imitate the behavior a system, especially when other analyses are too mathematically complex or too difficult to reproduce. Models of a real-life system can be built by FORTRAN, C, or by custom simulation software, to capture the interactions of actors in the system. In the context of this thesis, Monte Carlo Simulation is used to generate the distribution and characteristics of the possible values of an output (Y), by repeatedly sampling from probability distributions of the inputs ($x_1, x_2 ... x_k$). Specifically, spreadsheet software such as Excel will be used to perform Monte Carlo Simulation.

In general, the simulation follows the following general steps:

1) Model the variables through a set of mathematical equations and identify the interdependencies among variables and across different time periods.

2) Specify probability distributions for the variables.

3) Draw a random sample using Excel random number generator and then plugged back into an inverted cumulative distribution function to generate another random variants. (The most basic form of randomness can be modeled using the Excel worksheet function **rand()**, which returns an evenly distributed random number greater than or equal to 0 and less than 1.)

4) Repeat (3) many times (e.g., 500 times for every single variable in this thesis) and calculate statistics of the sample results, such as mean and standard deviation to obtain the estimate.

Merck used simulation to value its R&D investments in the 1980's (Nicols, 1994), Tufano and Moel used it on mining property bidding process (2000), and Schwartz used simulation to value pharmaceutical patents and R&D (2003).

In conclusion, the methods discussed above are ways to model the real world. A closed-form equation like Black-Scholes formula is too simplistic and is not sufficient to reflect the complexity involved in real projects. However, a more sophisticated method might require many more assumptions and computational steps to better reflect the reality. Consequently, the complex methods might not be robust due to many assumptions. The computation could also become cumbersome and challenging to practitioners. Practitioners indeed face many trade-offs when choosing a valuation approach. Table 4-2 is a summary of the real option valuation methods discussed in this chapter. This table only serves as a guideline; a most appropriate valuation method is one that is chosen based on extensive study of the macro business environment and the circumstances of the project.

Table 4-2 Advantages and Potential Issues of Real Option Valuation Methods

Methods	Advantages	Potential Issues in Real Options Valuation
Black-Scholes OPM	Uses risk-free rate, does not need to estimate risk-adjusted discount rate Is easy to use through a closed-form solution Provides quick estimate to one European put and call	Restrictive to one European put and call on non-dividend paying stocks Difficult to explain as closed-form solution is like a black box
Binomial Approximation	Generally models all types of options; ability to approximate values of options when B-S is not applicable Uses risk-free rate, does not need to estimate risk-adjusted discount rate Clear decision roadmap in each time period	Difficult to find a replicating portfolio Timing of exercise may not yield optimal project value Unable to handle "path-dependent" options Risk neutral valuation is not intuitive
Decision Analysis	Allows multiple decisions and uncertainties over time	Decision trees can be messy Needs to adjust discount rate for each period Choice of chance probabilities subjective
Hybrid Model (Binomial Approximation + DA)	Separates technical and economic uncertainties; uses DA and Binomial Approximation to model different risks, respectively	Difficult to separate uncertainties and their timings Multi-functional team is required to estimate technical risks, otherwise statistical analysis needed to estimate technical uncertainties Advanced modeling is required Could be confusing to either side of experts
Simulation	Relaxes replicating portfolio, GBM requirements Models path-dependent cash flows	Requires significant modeling effort Difficult to maintain a balance between reality and succinctness Difficult to debug, verify, and validate complex models

Chapter 5 GM Fuel Cell R&D

This chapter introduces the GM fuel cell R&D program and uses it as a case study to demonstrate how an innovative technology R&D program could be valued in a highly uncertain environment.

5.1 About GM

GM is the world's largest automaker in terms of sales and revenue, followed by Ford and Toyota. Founded in 1908, GM employs about 317,000 people around the world. It has manufacturing operations in 32 countries and its vehicles are sold in 200 countries. In 2004, GM sold nearly 9 million cars and trucks globally, of which 2 million light passenger vehicles were sold in the U.S. (Ward's Communications, 2004, GM, 2005,).

GM started to develop fuel cell vehicular and stationary applications in the late 1990's, and has made significant strides since then. A chronology of GM's fuel cell R&D can be found in Appendix A, which shows GM's commitment to fuel cell-powered vehicles. Between 1996 and 2005, GM spent $1 billion on the fuel cell R&D project. GM has predicted that they could mass produce fuel cell vehicles by 2010—by working with thousands of researchers and engineers in government, academia, and private labs in 14 countries (Fahey, 2005).

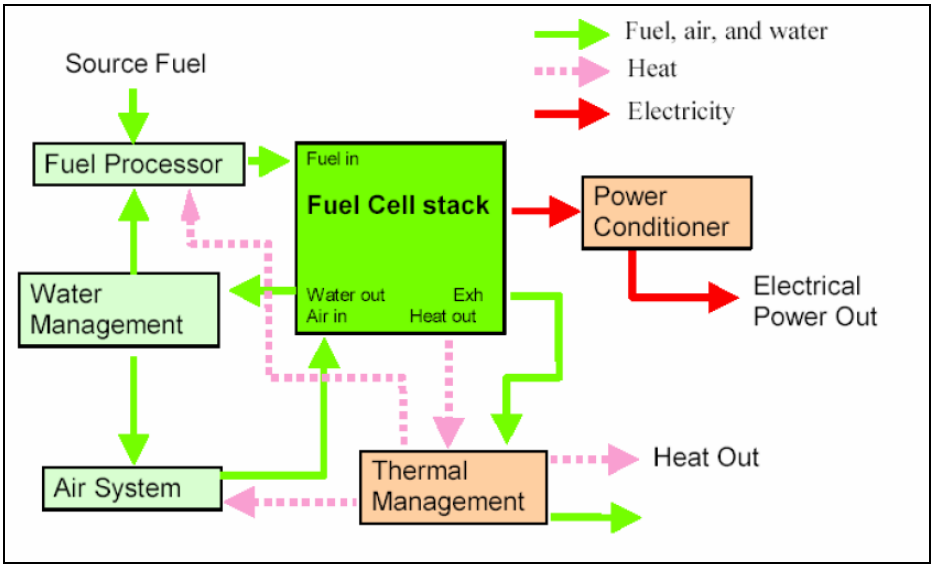
The next section introduces basic characteristics of fuel cells and fuel cell vehicles. Additional information such as challenges and policy implications of fuel cell investments is discussed and summarized in Chapter 7.

5.2 Fuel Cell Basics

A fuel cell is an electrochemical device which converts the energy of a chemical reaction directly into electricity. By combining hydrogen fuel with oxygen from air, electricity is formed without combustion of any form. The source of the hydrogen fuel could come from fossil fuels, biomass, or pure hydrogen. Fuel cells produce zero or low emissions, depending on the fuel used. When the input is pure hydrogen, the exhaust consists of water vapor. If hydrocarbon fuels are used, the exhaust is water and carbon dioxide.

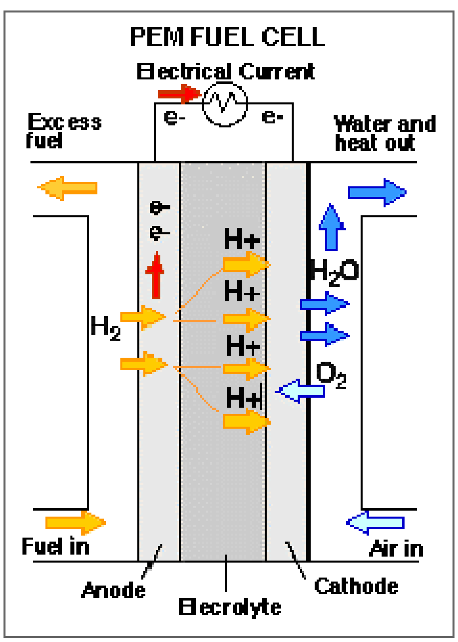
A fuel cell system consists of a fuel processor system, fuel cells and stacks, and a power management system, including storage and infrastructure. (For vehicle applications, the fuel cell stack and fuel processor are together described as the fuel cell engine.) Figure 5-1 depicts the schematic of a fuel cell system. A major component is the fuel cell stack that contains fuel cells. A fuel cell consists of membrane electrode assembly packed between two electrodes—anode and cathode. A catalyst in the anode separates hydrogen atoms into protons and electrons. The membrane in the center transports the protons to the cathode, leaving the electrons behind. The electrons flow through a circuit to the cathode, forming an electric current to provide power. In the cathode, the protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat (EERE, 2003). Figure 5-2 illustrates how a Proton Exchange Membrane (PEM) fuel cell works.

Figure 5-1 Fuel Cell System



(Drake, 2005)

Figure 5-2 Fuel Cell Illustrated



(Graphic adapted from DOE and Cornell Fuel Cell Institute)

The electricity generated by fuel cells can be used for stationary power, vehicle power, household appliances, and consumer electronics. Fuel cell applications are quiet with longer operating time. In addition, the maintenance is simpler because there are only few moving parts in a fuel cell system.

5.3 R&D as a Real Option

Fuel Cell R&D possesses option-like characteristics: large capital investment is required up-front; commercial value is futuristic and highly uncertain. Generally speaking, capital investments are like a call option when a company commits to invest, or a put option when a company decides to discontinue the investment. However, it is important to recognize that real options involved in capital investments actually behave in various ways. As described in Table 4-1, call and put-like real options are not the only types of options since investments can be managed in diverse terms.

The mere recognition that fuel cell R&D projects can be treated like financial options gives managers and engineers the ability to value the program realistically, as well as to exercise flexibility strategically in a highly uncertain environment. GM's Fuel Cell R&D program is a real option by itself or can be treated as containing compound real options as stages of R&D. These real options allow GM to develop capabilities to sell fuel cell vehicles if they need to or when they want to, in response to tightened environmental policies, mandatory sales of alternative-fueled vehicles, market demand for fuel cell vehicles, breakthrough of fuel cell technology, or strategic fleet management. GM has the right, but not an obligation, to abandon, defer, expand, switch, contract, or exercise these real options either on or by the option expiration date.

5.4 Problem Set-up

The objective of the analysis is to find out the option value of the fuel cell program. Based on literature review, GM has already purchased the option in late 1990's, and it is aiming the exercise time of 2010. The targeted exercise year infers that the R&D program can be treated as a European option. However, other manufacturers are predicting a commercialization time of 2015; MIT's Sloan Automotive Laboratory predicts it to be 2020. Therefore, this thesis assumes that GM can exercise this option anytime between 2010 and 2015. Assigning a restricted exercise period adds more complexity to this problem, but treating the option as an exotic option reflects greater reality and possibly increases the robustness of the model. The valuation process could also provide clearer insight toward the behavior of the option.

The GM fuel cell R&D resembles the characteristics similar to those of a type of exotic option called Bermudan option. In this option, the allowable exercise times are restricted within a specific period (Luenberger, 1998, p. 368). Given the above assumption, the notable characteristics of this fuel cell R&D are:

- It is a non-dividend paying exotic option
- The evaluation time is 2005
- The earliest exercise time is 2010 and the latest exercise time is 2015

In addition, two important assumptions underlie the subsequent analyses: it should be assumed that by 2010, there should be (1) infrastructure in place for hydrogen distribution and refueling, and (2) fuel cell vehicles are cost-effective to be made and reliable in real-world driving. Currently, the major setbacks in commercializing fuel cell vehicles are the high cost of materials, as well as safety and reliability issues in daily street-driving, otherwise the assembly is easy since there are much fewer parts in a fuel cell vehicle than those of in conventional cars. These two assumptions are required for a meaningful, plausible analysis and they appear realistic according to the literature review on the progress of fuel cell technology, as described in Chapter 7.

This thesis looks into two questions of interest:

- What is the reasonable, realistic price to pay for this R&D program?
- How would the commercialization of fuel cell vehicles affect GM's total fleet profitability?

The initial investment incurred in the 1990's is considered sunk cost and is irrelevant to the current valuation. There is also a strike price and payoff associated with possessing this real option, and they are described in detail in the subsequent analyses. Note that the aim of the first question is to find out the value of the real option, and the aim of the second question is to find out the option strike price and payoff.

A critical insight on the GM program is that its value is positively correlated with the **incremental net profit** of GM's light passenger vehicle fleet after fuel cell vehicles are commercialized. The R&D as a real option, if valued independently, is unprofitable; however, it does not mean that this real option is worthless. Fuel cell vehicles enable GM to relax the sales restrictions that previously prevent them from marketing and selling as many high-profit models as they would like to.

Per experts at MIT Laboratory for Energy and Environment (LFEE), auto manufacturers evaluate profit based on fleet as a unit, rather than any individual model program. The fleet profit is constrained by the Corporate Average Fuel Economy (CAFE) standards, whose formulas are of fleet basis. Without CAFE, manufacturers could potentially produce and market high volume of high-profit and low-fuel economy vehicles, but CAFE forces the manufacturers to produce and sell low-profit, high-fuel economy vehicles, in order to comply with the standard. In addition, there is also a strategic consideration in selling low-profit, high fuel economy vehicles. Selling low-profit models help establish brand loyalty from first-time buyers. As these buyers advance into higher annual income brackets, they are more likely to upgrade to the mid-sized or luxury models of the same manufacturers (Sudhir, 2001).

The introduction of fuel cell vehicles to the fleet will relax the CAFE requirement for high-profit, low-fuel economy models. Fuel cell vehicles are inherently efficient; in addition, CAFE offers special "bonus" treatment for alternative fuel in its calculation. As a result, though a highly uncertain investment by itself, fuel cell R&D's value should be viewed as how this real option contributes to the overall fleet profitability—the difference between the fleet values is precisely the payoff of the option. If fleet value without fuel cell vehicles in 2010 is greater than the value of the fleet with fuel cells, GM should choose to defer the commercialization to a later time. If the analysis shows that fleet value with fuel cell vehicles in 2010 is greater than the value of the fleet without fuel cell vehicles, then GM can base its strategic decision on this objective result.

5.5 Corporate Average Fuel Economy (CAFE)

An overview of CAFE is presented here before the real option valuation. CAFE is the main reason why the valuation of GM fuel cell R&D is solved through a 3-step approach.

5.5.1 Definition

CAFE is "the sales weighted average fuel economy, expressed in miles per gallon (mpg), of a manufacturer's fleet of passenger cars or light trucks with a gross vehicle weight rating (GVWR) of 8,500 lbs. or less, manufactured for sale in the United States, for any given model year" (NHTSA, 2005). Fuel economy is defined as the average mileage traveled by an automobile per gallon of gasoline consumed as measured in accordance with the testing and evaluation protocol set forth by EPA.

5.5.2 Classification

The National Highway Transportation Safety Administration (NHTSA) established vehicle classifications for the purposes of calculating CAFE was delegated. The definitions are as follows:

- Passenger Car – any 4-wheel vehicle not designed for off-road use that is manufactured primarily for use in transporting 10 people or less.

- Truck – a 4-wheel vehicle which is designed for off-road operation (has 4-wheel drive or is more than 6,000 lbs.

5.5.3 Formula

As described in the definition, CAFE is the fleet-wide average fuel economy of a manufacturer. The averaging method used is a harmonic mean, which is the number of passenger automobiles manufactured by the manufacturer in a model year; divided by the sum of the fractions obtained by dividing the number of passenger automobiles of each model manufactured by the manufacturer in that model year by the fuel economy measured for that model—in the regulatory language. The mathematical formula is:

$$\frac{TotalProductionVolume}{\frac{\#ofVehicleA}{FuelEconomy}+\frac{\#ofVehicleB}{FuelEconomy}+\frac{\#ofVehicleC}{FuelEconomy}} = AveragePassengerCarFleetFuelEconomy$$

Equation 5-1

In addition, the following formula uses the weighted average method to combine the different fuel economy of city and freeways (http://www.epa.gov):

Average fuel economy = 1 / ((.55 / city fuel economy) + (.45 / hwy fuel economy)) **Equation 5-2**

5.5.4 Current Standard

Passenger car standards were established for manufacturing year (MY) 1978, 18 mpg; MY 1979, 19 mpg; MY 1980, 20 mpg; and for MY 1985 and thereafter, 27.5 mpg. After MY 1990, CAFE has remained at the 27.5 mpg level. Civil penalties are imposed for noncompliance. European manufacturers regularly pay the penalties ranging from less than $1 million to more than $20 million annually. Asian and domestic manufacturers, on the other hand, have never paid a civil penalty.

5.5.5 Treatment for Alternative Fuel Vehicles

The CAFE law provides for special treatment of vehicle fuel economy calculations for dedicated alternative fuel vehicles and dual-fuel vehicles. The fuel economy of a dedicated alternative fuel vehicle is determined by dividing its fuel economy in equivalent miles per gallon of gasoline or diesel fuel by 0.15. For example, a 15 mpg dedicated alternative fuel vehicle would be rated as 100 mpg.

The above calculation provides a great incentive for manufacturers to introduce high fuel-efficient vehicles into their fleet. Having a product mix that contains high fuel-efficient vehicles offers much leeway for the production and sales of low fuel-efficient vehicles, which are usually more expensive, have higher markups, and less sensitive price elasticity (Berry, et al., 1995). Next, the thesis explores a valuation framework that considers a 3-step approach to value GM R&D as an exotic option.

Chapter 6 Real Option Valuation

6.1 An Overview of the 3-Step Approach

The main objective of this chapter is to elucidate a 3-step approach to value GM's fuel cell R&D as a real option. Before elaborating on the input requirements, note that in the model and in this thesis, "production", "deliveries", and "sales" are used interchangeably. The auto market is assumed to be in equilibrium, in which the supply and demand are balanced—GM will always have enough capacity to produce the market demand and at the same time this capacity is not grossly under-utilized either. As a reference, the average capacity utilization for motor vehicle manufacturers is about a steady 80% from 1990 to 2001 (Ward's Communications, 2004).

The proposed approach follows the following three steps:

1) Utilizes Monte Carlo simulation to model the uncertainties that affect the fleet profit,

2) Employs constrained optimization by linear programming to find out the annual optimal fleet profit, with and without fuel cell vehicles, and

3) Calculates the fleet value from the stream of net fleet profit using the Discounted Cash Flow principle, models the evolution of the fleet value projecting from 2005 to 2015 in an underlying lattice, compares the fleet value with fuel cell vehicles and fleet value without fuel cell vehicles and exercises the option only when the latter is greater than the former, identifies optimal times to exercise managerial flexibility by working backward recursively along the option valuation lattice, and obtains the optimal value the R&D in 2005.

The difference between the values before and after the commercialization of fuel cell vehicles is the payoff of the option. The strike price is the expected fleet value with fuel cell vehicles from the following two scenarios:

- A Breakthrough scenario in which the technology experiences a breakthrough that disruptively makes fuel cell a much superior alternative than other engine technologies.

- A Revolution scenario in which the technology is advancing at a slow, gradual pace. This is a more probable scenario given the past history and present status of fuel cell technology.

The difference in these two scenarios is the state of technology through the modeling of its various costs. For example, in Breakthrough scenario, fuel cell vehicles are highly profitable because the material cost, a difficult hurdle to overcome, is drastically reduced, whereas in Revolution scenario, the material cost sill poses significant challenge for fuel cell vehicles to be competitive. The maturity of technology is assumed to affect the net profit per fuel cell vehicles and their demand. The next section offers detailed explanation on the forecasted sales and profitability of vehicle models.

6.2 Uncertainty Identification and Monte Carlo Simulation

As discussed previously, the option value is positively correlated to the difference in net fleet profit before and after the commercialization of fuel cell vehicles. Hence, the estimation of the net fleet profit (net cash flows of the fleet) is an important element for the analysis.

The net fleet profit in turn is influenced by uncertainties in, but not limited to sales volume, price, and cost. The behaviors of these uncertainties can be modeled using Monte Carlo simulation. The rest of the section describes how Monte Carlo simulation models the major source of uncertainty, car sales. Equations 6-1 and 6-2 are the "seeds" for simulation; they describe the relationship between car sales and total fleet profit:

Variable profit per model = Net profit per vehicle x Model sales, **Equation 6-1**

where

Net profit per vehicle = Net profit multiplier x the manufacturer's suggested retail price (MSRP);

Equation 6-2

therefore,

$$\sum Variable\ profit\ per\ model = total\ fleet\ profit$$ **Equation 6-3**

As can be seen in Equation 6-2, MSRP and net profit per vehicle are two other sources of uncertainties. The net profit per vehicle is derived from a net profit multiplier, which is the percentage of profit per MSRP (Vyas, et al., 2000). Theoretically, the MSRP should be autocorrelated with itself over time, the net profit per vehicle should be correlated with vehicle production quantity, and the sales should be negatively correlated with MSRP. The rest of this section discusses how these uncertainties are modeled and their relationships. The results of the analysis are required for the subsequent linear program.

6.2.1 Demand Forecast for Existing Models

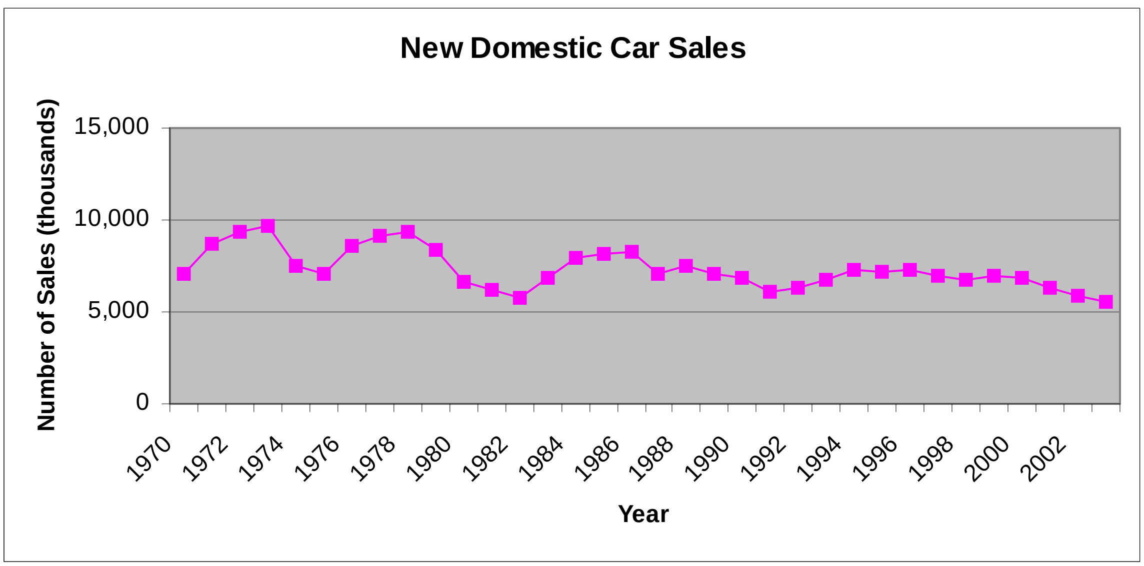
Monte Carlo simulation is used to introduce uncertainties in demand forecast. The model in this thesis assumes two major categories of uncertainties: demand volatility of each year and forecasting errors. The demand forecast for existing models is based on the past sales performance. GM has seen a declining trend in its light passenger fleet sales. As a matter of fact, the overall sales for light passenger vehicles have been decreasing due to market saturation and the growing demand for SUVs and trucks. Table 6-1 provides statistics of GM's past sales; Figure 6-1 shows the overall sales trend for light passenger vehicles.

Table 6-1 GM Sales Trend

Year	GM total sales	% change
1998	2,456,018	
1999	2,591,420	5.51%
2000	2,531,734	-2.30%
2001	2,272,480	-10.24%
2002	2,069,205	-8.95%
2003	1,959,018	-5.33%

(http://www.gm.com, % change calculated by author)

Figure 6-1 Domestic New Passenger Car Sales



(Davis and Diegel, 2004)

The demand model in this thesis still assumes sales of existing models to be constant despite of the decreasing trend and the correlation with the MSRP. The assumption is that the U.S. population growth, income growth, new models, and improved technologies would compensate for the declining sales.

With respect to demand's correlation with MSRP, the thesis assumes it to be negligible. The overall new vehicle pricing has shown insignificant changes. In addition, vehicle cost data (Table 6-3) have shown that manufacturers receive low profit margin. The maturing vehicle technologies, competition, and market segmentation have prevented manufacturers to improve sales significantly through manipulating the MSRP. Therefore, the sales for existing models are assumed to be constant, but they experience volatility each year and forecasting errors, and are autocorrelated with time

The treatment for demand forecast follows the above simplified assumptions since the purpose of the analysis is to supply sales figures for the subsequent analysis. The objective is to capture the annual volatility and forecasting errors, rather than devise a demand forecast model (which, would be another thesis all by itself). This thesis focuses on the outcome of the sales forecast but not the causes of the demand fluctuation.

Method

The demand for a single model (except fuel cells vehicles) before 2011 follows the following formula:

Demand for current year = demand for previous year x (1 – uncertainty factor) + (uncertainty factor x 4 x demand for previous year) **Equation 6-4**

The uncertainty factor is set to be 20% in the analysis. In 2012, the demand is assumed to reach perpetuity with a 2% growth from the 2011 demand. (The assumption of perpetuity is a more plausible assumption than assuming a specific year when GM cars are not going to be sold anymore.) After the random demand for a model for current year is obtained, they are summed up to obtain the total sales figure for that year. This total sales figure is recorded and simulated 500 times using the "Data Table" analysis tool in Excel to generate 500 random samples. The mean of these 500 random samples is then used in the optimization model as the total sales constraint (to be discussed in detail in next section), as well as a reference for market segmentation constraints. The results from Monte Carlo simulation are summarized in Table 6-2.

Table 6-2 Demand Forecast from Monte Carlo Simulation

Code	Example Model	2005	2006	2007	2008	2009	2010	2011	Perpetuity
1	Cavalier	360,635	294,965	242,161	236,067	221,908	256,058	219,457	202,861
2	Sunfire	32,397	30,575	32,666	32,481	27,864	28,366	24,151	26,273
3	ION Sedan	190,364	187,568	216,743	223,582	235,232	235,830	223,570	225,855
4	Vibe	77,720	89,749	102,496	85,992	100,457	104,164	113,216	136,504
5	Malibu	167,592	134,983	139,619	128,955	104,503	101,675	120,770	139,415
6	Century	64,179	53,975	62,486	50,709	55,147	49,233	39,879	42,850
7	Monte Carlo	76,181	62,437	57,966	59,567	69,176	78,725	75,927	61,856
8	Impala	313,259	294,858	282,623	251,239	291,581	317,994	291,554	263,496
9	Grand AM	107,958	110,957	114,587	115,361	122,386	141,193	113,511	122,268
10	LaCrosse	11,246	12,629	12,220	10,941	11,490	10,684	9,989	8,455
11	Grand Prix	190,404	167,033	193,952	197,217	224,519	256,155	257,928	250,939
12	Alero	29,463	30,094	31,614	27,255	27,677	29,154	31,822	33,564
13	LeSabre	98,131	90,065	104,218	98,844	93,136	105,825	86,850	88,351
14	Bonneville	27,855	31,088	33,941	31,460	27,248	29,930	33,387	30,471
15	CTS	48,709	51,023	55,083	63,723	68,480	81,287	93,997	85,417
16	GTO	13,135	15,330	17,898	15,241	16,827	19,318	17,755	18,974
17	Park Avenue	16,033	17,607	15,446	12,884	11,151	11,636	10,374	8,427
18	STS	14,187	11,692	13,479	10,941	11,436	12,111	12,413	12,735
19	Corvette	52,821	44,716	36,633	30,845	27,188	30,194	33,617	37,543
20	DeVille	88,208	89,501	105,327	117,339	135,502	123,951	103,131	93,851
	Compact Total	828,708	737,840	733,684	707,076	689,963	726,093	701,164	730,908
	Mid-size Total	918,676	853,136	893,609	842,594	922,358	1,018,893	940,847	902,250
	Luxury Total	233,093	229,869	243,866	250,973	270,585	278,497	271,285	256,948
	Total	1,949,103	1,820,845	1,871,159	1,800,644	1,882,906	2,023,483	1,913,296	1,890,105

The calculated compact-, mid-size-, and luxury-model totals serve as an indication of the respective market size. The long-term average sales of compact models are 39% of the total GM sales, 49% for the mid-size models, and 13% for the luxury models.

6.2.2 Net Profit per Existing Model

Table 6-2 provides baseline, static data of vehicle model for simulation. All MSRP and fuel economy data are obtained from http://www.gm.com, and the net profit per vehicle estimates are derived from simulated net profit multipliers (Vyas et al. 2000). MSRP, fuel economy, and profit margin are inputs for the constrained optimization model.

There are about 27 current models presented on the GM web site. Models with similar pricing and fuel economy levels (for example, the Cavalier 4-door sedan and the 2-door coupe of same model) are consolidated to reduce redundancy. In the end, light passenger vehicle fleet has a product mix of 20 representative vehicle models including 4-door sedans and 2-door coupes. These 20 models are coded from 1 to 20. This specific code for any single vehicle model should be viewed as a representation of “desired set of attributes” or “specific market demand for similar kinds of attributes.” All manufacturers roll out new designs or even revamp vehicle specifications every few years. It is unrealistic to assume, for example, that GM will continue to manufacturer Grand Prix for the next 30 years. However, it is reasonable to assume that even when GM stops selling Grand Prix, the replacement will have similar attributes even when the model name is changed. It is assumed that there is always demand for each code during the evaluation period.

Table 6-3 Baseline Fleet Information

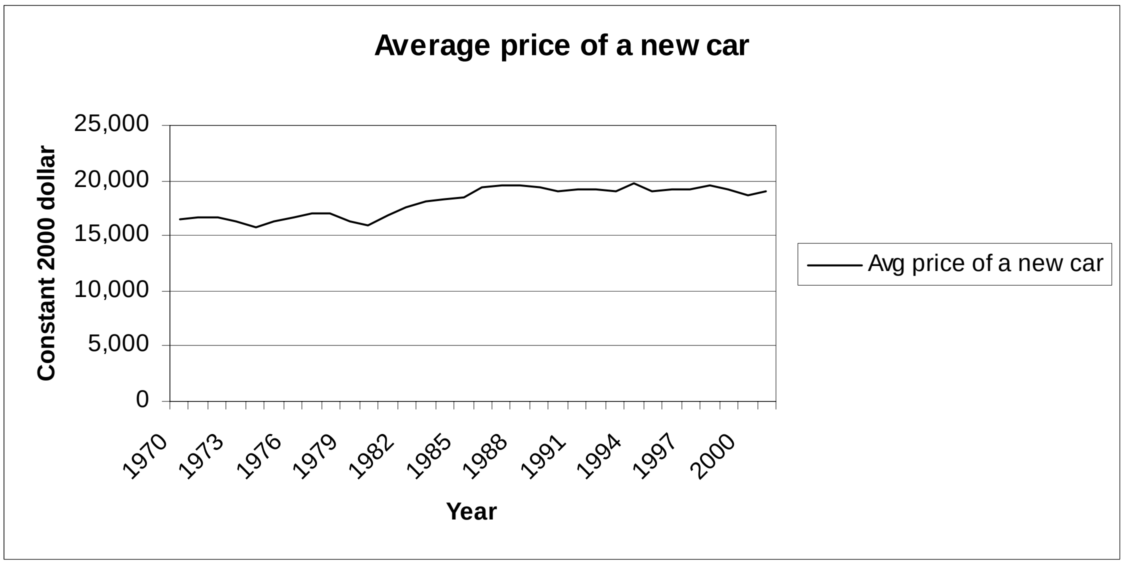
Code	Example Model	MSRP	Avg MPG - City	Avg MPG - Hwy	Total average MPG	Net Profit per Vehicle	Profit Margin
1	Cavalier	10,592	25.5	34.8	29.70	0.010	106
2	Sunfire	11,460	25	35.0	29.50	0.015	172
3	ION Sedan	11,995	24.5	32.0	27.88	0.015	180
4	Vibe	17,690	27.5	33.5	30.20	0.015	265
5	Malibu	20,563	22.25	31.5	26.41	0.015	308
6	Century	22,700	20	30.0	24.50	0.025	568
7	Monte Carlo	22,940	20	30.0	24.50	0.025	574
8	Impala	23,010	20	30.0	24.50	0.025	575
9	Grand AM	23,125	22.5	31.5	26.55	0.025	578
10	LaCrosse	23,459	19.5	28.0	23.33	0.025	586
11	Grand Prix	23,720	19	28.5	23.28	0.025	593
12	Alero	23,960	19	28.5	23.28	0.025	599
13	LeSabre	27,450	20	29.0	24.05	0.025	686
14	Bonneville	27,910	18.5	26.5	22.10	0.025	698
15	CTS	33,135	17.5	27.0	21.78	0.030	994
16	GTO	34,295	17	25.0	20.60	0.030	1,029
18	STS	41,220	16.5	24.0	19.88	0.030	1,237
19	Corvette	44,510	18	27.0	22.05	0.030	1,335
20	DeVille	46,480	17.5	25.0	20.88	0.030	1,394

(Note: net profit per vehicle is derived from Vyas, et al., 2000.)

Next, the net profit per vehicle needs to be determined for the variable profit per model. The net profit of each vehicle is positively correlated, at an increasing rate, with the manufacturer's suggested retail price (MSRP).

Hence, MSRP needs to be defined first so that the profitability as a percentage to MSRP can be calculated accordingly. The current MSRP figures, ranging from $9995 to $55000, are obtained from http://www.gm.com. For years beyond 2001, vehicle price is assumed constant--its variability is assumed negligible. The historical sales data show that the new car price has remained quite constant from 1988 (Davis and Diegel, 2004). Factors such as competition, sales campaigns, and cost reduction strategies have all contributed to the stagnant price. Figure 6-2 shows the average price of a new car from 1970 to 2001 in constant 2000 dollar, adjusted by the Consumer Price Inflation Index.

Figure 6-2 Average Price of a New Car



(Note: figure constructed by author; data obtained from Davis and Diegel, 2004)

For existing models, the following are the three observed, general characteristics regarding to the relationship among vehicle price, profit, and fuel economy: (1) the net profit per vehicle monotonically increases with price at an increasing rate, (2) the price and fuel economy are negatively correlated, and (3) the high-profit vehicles do not generate highest variable profit (*demand x net profit*) for the fleet. The reasons are that high-profit vehicles do not have as much demand as the low-profit and medium-profit models; another factor is that the manufacturers limit their production of high-profit vehicles due to the CAFE constraint.

After determining the MSRP trend, profit margin is obtained from this simple formula: *net profit multiplier x MSRP* for existing models. Net profit multiplier is obtained from Vyas, et. al (2004). They examine the commonly used multipliers from three national research labs, which range from an average of 2% to 8.5% of the MSRP. This average figure is adjusted to reflect different markets in this thesis; that is, the multiplier for compact vehicles is smaller than that of mid-size vehicles; the multiplier for mid-size vehicles is smaller than that of luxury vehicles. This is a rational assumption, in the context of this thesis, that compact, mid-size, and luxury models indeed have different profit margins. The adjustment ratio references the mark-up ratio proposed for different market segments in Berry, Levinsohn, and Pakes (1995).

6.2.3 Demand Forecast for Fuel Cell Vehicles

The potential demand for fuel cell vehicles also needs to be estimated. Even though the total sales of the fleet have been determined, the introduction of fuel cell vehicles will affect sales of other models within the bound of the total sales, and consequently affect the fleet profit. Note that the forecast of fuel cell vehicles represents an aggregate figure for all fuel cell models. GM could market different models of fuel cell vehicles, but the estimates in this thesis do not differentiate model types.

The demand forecast for fuel cell vehicles is more complex since there is no historical data to extrapolate from. Theoretically, there are many ways to predict demand for new technologies such as fuel cell vehicles: (1) Quantitatively, *trend analysis or extrapolation* can be applied using other similar technologies as a reference, and (2) Qualitatively, *Delphi Process (or Expert Opinions)* involves setting up committees or structured questionnaires to get expert advice. The logic is that the experts are often years ahead of day-to-day practice so they could have a good grasp of how technologies are going to evolve. The obvious disadvantage of this approach is that the result from the experts could be suspected of subjectivity or organizational agendas.

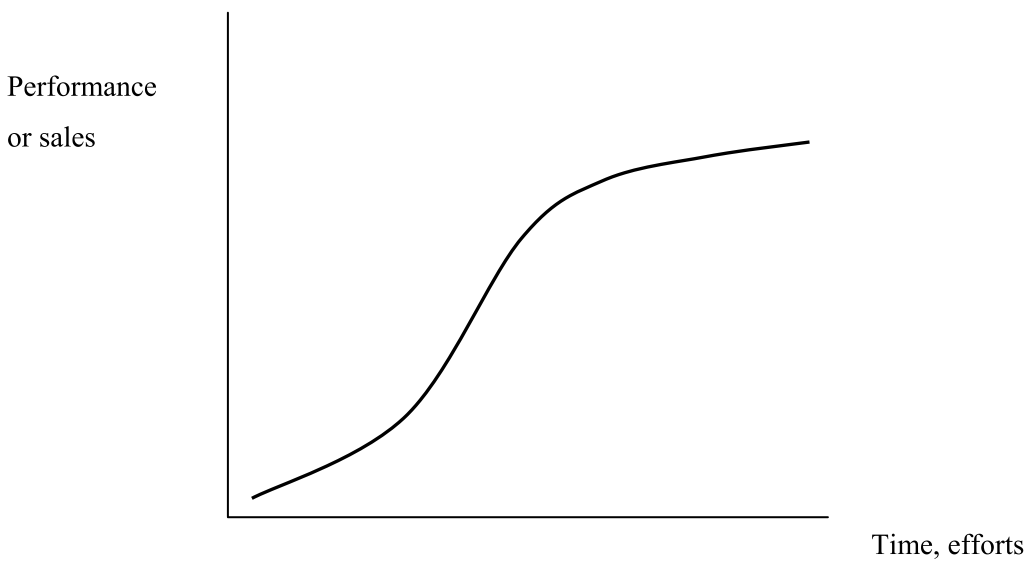
Method

A combination of the above methods is used to forecast the fuel cell vehicle demand. First, expert opinions are taken to assume fuel cell vehicles' cannibalization of existing models in the Evolution scenario. In Breakthrough scenario, fuel cell vehicle sales not only cannibalize the existing GM models, but also win market share from other auto manufacturers.

Secondly, the first year demand uses the first year sales of Toyota Prius as a proxy. For sales throughout fuel cell vehicles' product life, time series analysis is used to extrapolate future demand. The analysis fits linear and nonlinear curves into time series and then extrapolating future values.

Specifically, a stochastic S-Curve is chosen to represent the growth pattern of fuel cell vehicle sales. Stochastic S-Curves is a type of stochastic process that can be used to model sales of fuel cell vehicles over the amount of time and efforts involved. (Stochastic process is a statistical process involving a number of random variables depending on a variable parameter, which is usually time.) Other common stochastic processes include Brownian Motion, which is discussed previously in this thesis to model stock price volatility, or Poisson Process, which is often used to model the queuing process.

Figure 6-3 S-Curve as a Demand Growth Model for Innovative Technologies



The S-curve shows that when the technology first enters the market, the demand growth is slow (Moser, 2004). As time progresses, the demand increases faster than time but eventually reaches its limit.

The S-curve model is based on the following formula:

$$demand(t) = demand(\infty) - \alpha e^{-\beta t}$$ **Equation 6-5**

Where

$$\alpha = demand(\infty) - demand(0)$$ **Equation 6-6**

$$\beta = \frac{-\ln\left(\frac{demand(\infty) - demand(t)}{\alpha}\right)}{t}$$ **Equation 6-7**

Method

Based on the above formula, Monte Carlo simulation is performed to randomize the calculated demand. The sales for compact cars are previously estimated and are used as a seed to estimate the fuel cell vehicle sales. The random number generation is based on Table 6-4:

Table 6-4 Static Inputs for Fuel Cell Vehicle Demand Forecast

Inputs	Value	Notes
FC Demand in 2010	5,000	Use Prius as a proxy
Compact demand in 2050	792,659	Previously simulated value
FC demand as % of compact	50%	2050 assumed to be the mid-life of the technology
FC demand in 2050	396,329	=792,659 x 50%
Demand limit	792,659	Previously simulated value (total compact) in 2080
Initial demand volatility	20%	Volatility to be used in simulation; can be adjusted
2050 demand volatility	40%	
demand limit volatility	50%	
Annual volatility	2%	

The above inputs are randomized using Monte Carlo simulation, based on the formulas specified in Table 6-5:

Table 6-5 Randomized Inputs for Fuel Cell Vehicle Demand Forecast

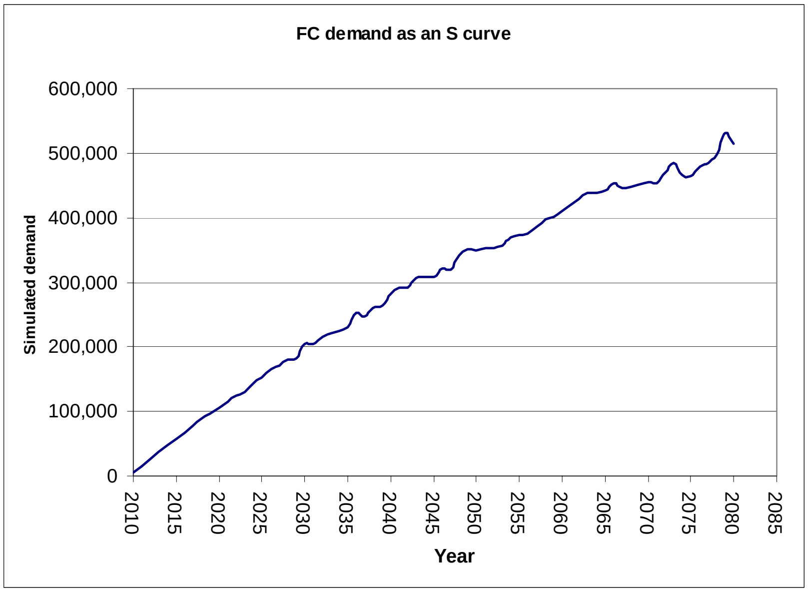
Randomized values	Value	Notes (Excel formulas)
Realized demand in 2010	4817	= (1 - initial demand volatility)(FC demand in 2010) + 2(FC demand in 2010)(initial demand volatility)(rand())
Realized demand in 2050	345,845	= (1 - 2050 demand volatility)(FC demand in 2050) + 2(FC demand in 2050)(2050 demand volatility)(rand())
Realized demand limit	865,452	= (1 - demand limit volatility)(FC demand limit) + 2(FC demand limit)(demand limit volatility)(rand())
alpha	860,635	Equations 6-6 & 6-7
Beta	0.0126	

The randomized inputs are then plugged back to the S-curve formula, adding annual forecast of 2%, Table 6-6 shows the forecasted demand for fuel cell vehicles from 2010 to 2080 based on an S-curve growth. Some intermediate years in the above table are omitted to save space. The forecasted sales depict an S-curve characteristic: the growth pattern as having a slower growth rate after 2050.

Table 6-6 Forecasted Fuel Cell Vehicle Demand in Evolution Scenario

Year	Demand projection	Demand Growth projection	Random draw from standardized normal distribution	Realized Growth	Realized Demand
2010	4,817				4,817
2011	15,606	224.0%	-0.371903012	223.2%	15,570
2012	26,259	68.3%	0.242739309	68.8%	26,335
2013	36,779	40.1%	-0.377339858	39.3%	36,581
2014	47,167	28.2%	0.7656158	29.8%	47,730
2015	57,425	21.7%	-0.42112641	20.9%	57,028
2016 - 2025					
2026	162,119	5.8%	0.902297749	7.6%	164,883
2027	170,935	5.4%	0.09470718	5.6%	171,243
2028	179,642	5.1%	0.203287063	5.5%	180,337
2029	188,239	4.8%	-1.975970717	0.8%	181,139
2030	196,728	4.5%	2.168902695	8.8%	204,894
2031-2049					
2050	345,845	1.9%	0.561223391	3.1%	349,653
2051	352,359	1.9%	0.198491293	2.3%	353,732
2052	358,791	1.8%	-0.789830843	0.2%	353,225
2053	365,142	1.8%	-1.165256229	-0.6%	356,781
2054	371,414	1.7%	-0.271815744	1.2%	369,429
2055	377,607	1.7%	-0.492732221	0.7%	373,947
2056-2074					
2075	486,390	1.0%	-2.262370665	-3.5%	464,600
2076	491,142	1.0%	-1.13623727	-1.3%	480,089
2077	495,835	1.0%	-1.040100818	-1.1%	485,618
2078	500,468	0.9%	-0.200067071	0.5%	498,484
2079	505,043	0.9%	2.673482279	6.3%	531,803
2080	509,561	0.9%	0.552036454	2.0%	515,137

Figure 6-4 Fuel Cell Vehicle Demand as an S-Curve



The above figure shows an important S-curve characteristic: growing sales at a diminishing rate. For the GM case, the S-curve shows a much smoother growth during the initial years because the author slightly adjusted the formula for β --instead of dividing the negative natural logarithm by 50 (as t = 50 in this case), the denominator was 40 to create a greater β that would result in a slower growth in demand. The purpose of doing so is to mimic the growth rate of Toyota Prius, whose first year demand serves a proxy in this case. Without the adjustment, the S-curve model could have potentially assigned a 400 to 500% growth rate by the second year. This is simply not realistic given that the auto market has been saturated for the past ten years. In addition, the curve shows up-and-down volatility along the growing trend because in addition to the different uncertainty level modeled in the forecast, the sales is subjected to an additional 2% annual volatility to compensate for forecasting errors.

The above demand forecast illustrates the Evolution scenario of fuel cell technology. For Breakthrough scenario, it is assumed that fuel cell vehicles not only cannibalize existing models, but also captures 5% additional market share in the compact passenger vehicle market and ultimately 10% additional market share when the technology reaches its peak. The modeling steps are the same as those of in Evolution scenario, except that Breakthrough scenario uses (the same) compact sales plus

5% and 10% additional sales for 2050 and demand limit, respectively. The sales forecast in Breakthrough scenario can be seen in Table 6-10. Section 6.2.4 discusses the last optimization inputs that utilize Monte Carlo simulation.

6.2.4 Net Profit per Fuel Cell Vehicle

Net profit for fuel cell vehicles are adjusted from the following costing structure proposed by Borroni-Bird (1996), which is comparable to the costing structure used at the Argonne National Laboratory (Cuenca et al. 2000; Vyas et al. 1998).

Table 6-7 Vehicle Cost Structure

Type of Cost	Vehicle	Manufacturing	Fixed Cost		Selling		Net Profit
	Material Cost	Assembly Labor and Other Manufacturing Costs a	Transportation, Warranty	Amortization and Depreciation, Engineering R&D, Pension and Health Care, Advertising, and Overhead	Price Discounts	Dealer Markup	
Conventional vehicles	0.425	0.065	0.045	0.215	0.05	0.175	0.025

The above cost structure is adjusted for fuel cell vehicles for Evolution scenario and Breakthrough scenario:

Table 6-8 Estimated Profit Margin per Fuel Cell Vehicle

	Vehicle	Manufacturing	Fixed Cost		Selling		Net Profit
	Material Cost	Assembly Labor and Other Manufacturing Costs a	Transportation, Warranty	Amortization and Depreciation, Engineering R&D, Pension and Health	Price Discounts	Dealer Markup	
Conventional vehicles	0.425	0.065	0.045	0.215	0.050	0.175	0.025
FC 2010 - 2020 (evolution scenario)	0.630	0.033	0.045	0.323	0.100	0.105	-0.235
FC 2010-2020 (breakthrough scenario)	0.340	0.020	0.045	0.215	0.025	0.105	0.251

The adjustments are explained below:

- *Materials* - In Evolution scenario, the material cost is assumed to be 50% higher than that of the conventional vehicles. This is due to the high cost of platinum used in fuel cell stacks. In Breakthrough scenario, the material cost is 80% of the conventional vehicles.

- *Assembly and manufacturing* - The assembly and manufacturing cost are assumed to be 50% and 30% of the conventional vehicles for the evolution and breakthrough scenario. This is due to the significantly fewer parts required in fuel cell vehicle manufacturing and assembly.

- *Transportation and warranty* – The cost are assumed to be the same.

- *Amortized R&D and administration cost* – In Evolution scenario, the cost is 50% higher than that of the R&D and administrative expenses in conventional vehicles. The cost is assumed to be the same in Breakthrough scenario.

- *Price discount* – The price discount is assumed to be 50% higher than that of for the conventional vehicles. Consider Evolution scenario in which the technology is not in its prime, GM is assumed to cut back the price to stimulate sales. On the other hand, the discount in Breakthrough scenario is smaller than that of for the conventional vehicles since the technology is superior.

- *Dealer markup* – In general, dealers are assumed to charge less mark-up for fuel cell vehicles. It is assumed that they only charge 60% of the mark-up of the conventional vehicles.

Based on these adjustments, net profit per each fuel cell vehicle is estimated for each scenario. The figures can be found in Table 6-9 for Evolution scenario and Table 6-10 for Breakthrough scenario. Note that the MSRPs for fuel cell vehicles are estimated and randomized based on the MSRPs for 2005 Ford Escape Hybrid for Evolution scenario and 2005 Honda Civic CVT for Breakthrough scenario. All figures are in 2005 constant dollar.

Table 6-9 Fuel Cell Break-Even Analysis for Evolution Scenario

Year	Simulated demand	Randomized Price	Annual Revenue (2005 $)	Annual Cost (2005 $)	Loss/Profit	Net Loss/Net Profit per Vehicle	Additional Sales to Break-Even	Required Break-Even Sales
2,010	4,817	28,330	117,725,077	145,390,471	-27,665,393	-5,743	977	5,794
2,011	15,570	28,004	365,166,191	450,980,246	-85,814,055	-5,511	3,064	18,635
2,012	26,335	28,006	599,690,566	740,617,849	-140,927,283	-5,351	5,032	31,367
2,013	36,581	26,611	768,458,888	949,046,726	-180,587,839	-4,937	6,786	43,367
2,014	47,730	26,683	976,102,758	1,205,486,906	-229,384,148	-4,806	8,597	56,327
2,015	57,028	26,822	1,138,166,310	1,405,635,393	-267,469,083	-4,690	9,972	67,000
2,016	67,313	28,152	1,368,984,233	1,690,695,528	-321,711,295	-4,779	11,428	78,741
2,017	78,094	27,087	1,483,645,821	1,832,302,589	-348,656,768	-4,465	12,872	90,965
2,018	89,184	28,491	1,730,253,159	2,136,862,651	-406,609,492	-4,559	14,272	103,455
2,019	95,957	27,829	1,765,445,371	2,180,325,033	-414,879,662	-4,324	14,908	110,865
2,020	105,332	28,348	1,916,567,666	2,366,961,068	-450,393,402	-4,276	15,888	121,220
2,045	307,655	17,271	1,628,892,407	2,011,682,122	-382,789,716	-1,244	22,164	329,819
2,046	321,015	18,014	1,721,112,353	2,125,573,756	-404,461,403	-1,260	22,453	343,468
2,047	318,692	17,811	1,640,197,780	2,025,644,258	-385,446,478	-1,209	21,641	340,333
2,048	342,231	18,633	1,788,965,808	2,209,372,773	-420,406,965	-1,228	22,562	364,794
2,049	351,623	18,754	1,796,112,994	2,218,199,547	-422,086,553	-1,200	22,506	374,130
2,050	349,653	18,360	1,697,598,624	2,096,534,301	-398,935,677	-1,141	21,729	371,382
2,051	353,732	17,381	1,578,470,937	1,949,411,607	-370,940,670	-1,049	21,342	375,074
2,052	353,225	18,186	1,601,175,116	1,977,451,268	-376,276,152	-1,065	20,690	373,915
2,053	356,781	18,100	1,562,762,578	1,930,011,784	-367,249,206	-1,029	20,290	377,071
2,054	369,429	18,742	1,626,757,675	2,009,045,729	-382,288,054	-1,035	20,397	389,826
2,055	373,947	18,688	1,594,085,439	1,968,695,517	-374,610,078	-1,002	20,045	393,992
2,056	374,506	17,713	1,469,104,028	1,814,343,474	-345,239,447	-922	19,491	393,997
2,075	464,600	17,981	1,055,085,385	1,303,030,450	-247,945,065	-534	13,789	478,390
2,076	480,089	18,395	1,082,876,098	1,337,351,982	-254,475,883	-530	13,834	493,923
2,077	485,618	18,638	1,077,491,148	1,330,701,568	-253,210,420	-521	13,586	499,203
2,078	498,484	18,749	1,080,219,183	1,334,070,691	-253,851,508	-509	13,539	512,023
2,079	531,803	17,577	1,048,916,742	1,295,412,177	-246,495,434	-464	14,024	545,827
2,080	515,137	17,683	992,400,803	1,225,614,992	-233,214,189	-453	13,189	528,326

Table 6-10 Fuel Cell Break-Even Analysis for Breakthrough Scenario

Year	Simulated demand	Randomized Price	Annual Revenue (2005 $)	Annual Cost (2005 $)	Loss/Profit	Net Loss/Net Profit per Vehicle
2,010	5,779	19,685	98,138,064	73,554,479	24,583,585	4,254
2,011	20,546	19,853	341,615,185	256,040,581	85,574,604	4,165
2,012	34,614	20,093	565,508,132	423,848,345	141,659,787	4,093
2,013	48,966	19,173	741,113,795	555,464,789	185,649,006	3,791
2,014	65,974	19,415	981,691,809	735,778,011	245,913,798	3,727
2,015	78,594	20,369	1,191,209,194	892,811,291	298,397,903	3,797
2,016	92,710	19,908	1,333,348,037	999,344,354	334,003,683	3,603
2,017	108,684	19,135	1,458,635,771	1,093,247,511	365,388,261	3,362
2,018	121,039	19,198	1,582,325,239	1,185,952,767	396,372,472	3,275
2,019	130,674	19,358	1,672,352,447	1,253,428,159	418,924,288	3,206
2,020	145,052	18,960	1,765,236,627	1,323,044,852	442,191,775	3,049
2,045	436,316	17,416	2,329,490,148	1,745,952,866	583,537,282	1,337
2,046	443,195	17,782	2,345,573,592	1,758,007,407	587,566,185	1,326
2,047	441,318	18,305	2,334,305,173	1,749,561,727	584,743,446	1,325
2,048	458,923	18,416	2,371,018,399	1,777,078,290	593,940,109	1,294
2,049	471,865	18,203	2,339,499,343	1,753,454,757	586,044,585	1,242
2,050	477,977	18,622	2,353,736,225	1,764,125,301	589,610,924	1,234
2,051	512,582	18,301	2,408,384,075	1,805,083,864	603,300,211	1,177
2,052	497,539	17,166	2,128,855,947	1,595,577,532	533,278,415	1,072
2,053	516,275	18,278	2,283,613,760	1,711,568,513	572,045,247	1,108
2,054	537,680	16,233	2,050,683,240	1,536,987,088	513,696,152	955
2,055	548,833	15,749	1,971,659,933	1,477,759,120	493,900,813	900
2,056	547,394	15,374	1,863,754,161	1,396,883,743	466,870,417	853
2,075	703,687	16,230	1,442,422,423	1,081,095,606	361,326,817	513
2,076	719,272	15,813	1,394,647,251	1,045,288,115	349,359,136	486
2,077	682,933	16,136	1,311,878,157	983,252,678	328,625,478	481
2,078	731,393	15,362	1,298,616,913	973,313,376	325,303,537	445
2,079	702,000	15,767	1,242,029,351	930,900,999	311,128,353	443
2,080	732,768	16,682	1,331,749,819	998,146,489	333,603,330	455

The estimated demand and net profit can then be plugged into the linear program to find out the optimal fleet profit.

6.3 Constrained Optimization by Linear Programming

The valuation of this real option involves solving a constrained optimization problem. The optimization model would allow GM to study the interactive effect of fuel cell vehicles with other models. After the commercialization of fuel cell vehicles, GM could potentially market and sell more high-profit vehicles, not only because fuel cell vehicles have low fuel economy, but also because they are given a special, favorable formula in CAFE (as explained in Section 5.5). A constrained optimization model can help GM properly allocate its resources to the various vehicle programs since a by-product of the model is the optimal sales volume for each vehicle model in the fleet. The result of the optimization is the maximized fleet profit for one year.

The optimization model needs to be repeated for the evaluation years because the optimization result, optimal fleet profit, is only a point estimate for respective year. This annual fleet profit should be simulated for several years and then become perpetuity. (The assumption of perpetuity is a more plausible assumption than assuming a specific year when fuel cell vehicles are not going to be sold anymore.)

6.3.1 Formulation

The optimization model for GM is a linear program that maximizes total fleet profit. Algebraically, let q_n be the sales (or production) of vehicle *n*, p_n be the profit margin of vehicle *n*, and f_n be the average fuel economy of vehicle model *n*, $n = 1,\ldots, 20$. The formulation is:

Max: $\sum_{1}^{n} q_n p_n$, $n = 27$ **Equation 6-8**

S.T. $\sum q_n$ = total sales (currently it is the average sales from 2001-2004)

Equation 6-9

$q_n >= 10{,}000$ **Equation 6-10**

$\sum_{1}^{10} q_n <= totalsales * 39\%$, **Equation 6-11**

$\sum_{11}^{19} q_n <= totalsales * 48\%$, **Equation 6-12**

$\sum_{20}^{27} q_n <= totalsales * 13\%$, **Equation 6-13**

$27.5 \sum_{1}^{27} \frac{q_n}{f_n} = totalsales$, **Equation 6-14**

$q_n <= highestsalesfigurebetween 1999 and 2003, n = 2,6,7,9,10,12,13,15,19$

Equation 6-15

Table 6-11 describes the above equations:

Table 6-11 Formulation of the Linear Program

Equation #	The Objective Function
7-8	Max. Total Fleet Profit
	Constraints
7-9	Total production per year (Total capacity)
7-10	Minimum production requirement
7-11	Market segmentation of low-, medium-, and high-mark up vehicles
7-12	
7-13	
7-14	CAFE
7-15	Sales cap/constraints for Sunfire, LaCrosse, Alero (phased out), and certain high-profit margin vehicles such as Century, Monte Carlo, Grand AM, and Corvette

6.3.2 Inputs: Independent Variables, Coefficients, and Constraints

The independent variables required to run the program are estimates of:

- Fuel cell demand for both the Evolution and Breakthrough scenarios (Tables 6-9 and 6-10)
- Existing model sales (Table 6-2)

The coefficients are:

- Profit margins of existing models and of fuel cell vehicles (Tables 6-7 and 6-8)
- Average fuel economy for each model (Table 6-3)

Lastly, the rest of this section describes the rationales for the constraints, summarized in Table 6-11.

- *Total sales* – the annual sales must be less or equal to the sales forecast.

- *Minimum production* - the model assumes a minimum production of 10,000 for each car model so that the production lines achieve economies of scale and are not under-utilized. This is to prevent the optimization from allocating unrealistic low production to vehicles that are relatively "unfavorable" to the model; that is, the vehicles that have low profit margin and low fuel economy. For some low-profit models such as Cavalier and Saturn ION, the minimum production is higher than 10,000 simply because they have the market demand that is much greater than 10,000 per year. In cases like this, the minimum production is set to be the lowest annual sales from 1998 to 2003.

- *Market Segmentation* - a sales cap for each market segment should be placed in the model. For example, the sales of luxury cars are only estimated to be 13% of the total new vehicle sales (Bresnahan, 1987). If the market constraints are not enforced, the model will seek to produce as many luxury cars as possible since they are highly profitable compared to compact cars. The ratio of compact, mid-sized, and luxury cars has been quite constant over the past five years (Ward's Communications, 2004), and it is assumed to be the same every year until 2012, two years after the fuel cell vehicles are commercialized. After that, these constraints are gradually relaxed since GM could be marketing more high-profit cars and consumer behaviors are slowly modified through sales campaigns. Therefore, the model is devised to following the above market segmentation as shown in formulation.

- *CAFE* - the model assumes that GM always complies with CAFE since the Japanese and American manufactures have never been fined since CAFE was written into law in 1975 (NHTSA, 2003). The current standard is used, which is 27.5 mpg as an average passenger car fleet fuel economy.

- *Maximum sales cap* - each segment the sales of each model is examined and the cap is enforced to prevent unrealistic production volume of some highly profitable models. For example, a market cap needs to be placed on Corvette, in addition to its market segment constraint. Without this cap, the model would have designated the overwhelmingly majority of sales to Corvette instead of other luxury models since Corvette's specifications are relatively "favorable" to the model. In cases like this, the cap is the highest annual sales among these years.

Figure 6-5 A Snapshot of the Linear Program

		Vibe	Malibu	Century	Monte Carlo	Impala	Alero	LeSabre	Bonneville	CTS	Corvette	DeVille			
		4	5	6	7	8	12	13	14	15	19	20			
Product Mix	Op. Quantity	10,000	147,415	40,000	40,000	556,630	10,000	127,487	10,000	48,193	32,365	82,589			
Capacity Constraint	Production Coefficient	1	1	1	1	1	1	1	1	1	1	1	1,489,036	<=	1,938,351
Market Constraint	Sunfire	0	0	0	0	0	0	0	0	0	0	0	10,000	<=	36,095
Market Constraint	LaSabre	0	0	0	0	0	0	1	0	0	0	0	127,487	<=	127,487
Market Constraint	Corvette	0	0	0	0	0	0	0	0	0	1	0	32,365	<=	35,000
Market Constraint	Compact Segment	1	1	0	0	0	0	0	0	0	0	0	290,914	=	710,658
Market Constraint	Mid-size Segment	0	0	1	1	1	1	1	1	0	0	0	1,004,117	=	1,004,867
Market Constraint	Luxury Segment	0	0	0	0	0	0	0	0	1	1	1	194,005	=	222,826
Environ. Constraint	CAFÉ	0.911	1.042	1.122	1.122	1.122	1.182	1.143	1.244	1.263	1.247	1.317	1,659,187	=	1,938,351
Min. Production	Production Coefficient	0	0	0	0	0	0	0	0	0	0	0	250,000	>=	251,917
Min. Production	Production Coefficient	0	0	0	0	0	0	0	0	0	0	0	10,000	>=	10,000
Min. Production	Production Coefficient	0	0	0	0	0	1	0	0	0	0	0	210,000	>=	10,000
Min. Production	Production Coefficient	0	0	0	0	0	0	1	0	0	0	0	127,487	>=	10,000
Min. Production	Production Coefficient	0	0	0	0	0	0	0	1	0	0	0	10,000	>=	10,000
Min. Production	Production Coefficient	0	0	0	0	0	0	0	0	0	0	1	82,589	>=	68,860
	Profit Margins	3715	4318	5675	5735	5753	5990	6863	6978	9941	13,353	13,944	9,353,827,909		

(Note: (1) the shaded bars are also part of the program. They are omitted car models and their constraints, truncated to fit the entire screen shot onto this page, (2) the mpg information for fuel cell vehicles is obtained from Demirdoven and Deutch (2004) plugged into the special formula given to alternative fuels in CAFE (Section 5.5.5 in this thesis), and (3) The 3rd row from the top represents the optimization results, which are the optimal production quantity for each car model. The box at the bottom left corner is the optimal fleet profit for the respective year.)

6.3.3 Results from Solving the Linear Program

The linear program is simulated for years between 2010 and 2015 and for both Evolution and Breakthrough scenarios with corresponding inputs, and for a single year 2050 for both scenarios. The net profits in both scenarios for years between 2015 and 2050 are extrapolated from the optimization outputs. Tables 6-12 and 6-13 describe the optimization results:

Table 6-12 GM Fleet Value with Fuel Cell Vehicles in Evolution Scenario

Year	2010	2011	2012	2013	2014	2015		Perpetuity
Influence on Fleet	Cannibalize Other Cars in the Fleet							
FC Vehicle Profit Margin	-5,529	-5,663	-5,169	-4,989	-4,844	-4,813	→	-1118
FC Demand	4817	15,570	26,335	36,581	47,730	57,028	*2,016*	349,653
Simulated Demand other than fuel cell Vehicles (Mean from 500 Trials)	2,023,483	2,092,840	2,105,313	1,941,166	1,908,435	2,027,022	*to*	2,100,000
Total Fleet Demand	2,028,300	2,108,410	2,131,648	1,977,747	1,956,165	2,084,050	*2,049*	2,449,653
Total variable profit	882,362,548	901,281,345	1,151,986,386	1,084,752,931	1,286,614,651	969,660,976		1,455,730,337
Sum of Discounted Net Profit from Respective Year to 2049 (A) (in billions)	7.80	7.97	8.13	8.07	8.07	7.86	→	
Perpetuity Value Discounted to Respective Year (B) (in billions)	0.07	0.08	0.09	0.10	0.12	0.13		10.86
Value in Respective Year (sum of A & B) (in billions)	7.87	8.05	8.22	8.17	8.18	7.99		

Table 6-13 GM Fleet Value with Fuel Cell Vehicles in Breakthrough Scenario

Year	2010	2011	2012	2013	2014	2015		Perpetuity
Influence on Fleet	95% FC Sales Cnnibalize Other Cars in GM Fleet; 5% Increase in GM Market Share							
FC Vehicle Profit Margin	4,161	4,234	3,951	3,966	3,683	3,713	→	1,178
FC Demand	5779	20,546	34,614	48,966	65,974	78,594	2016	477,977
Simulated Demand other than fuel cell Vehicles (Mean from 500 Trials)	2,023,483	2,126,791	2,255,668	2,124,521	2,260,392	2,323,220	to	2,100,000
Total Fleet Demand	2,029,262	2,147,337	2,290,282	2,173,487	2,326,366	2,401,814	2049	2,577,977
Total variable profit	957,767,695	1,146,028,592	1,339,877,426	1,657,661,196	1,731,873,582	1,926,482,174		2,106,342,333
Sum of Discounted Net Profit from Respective Year to 2049 (A) (in billions)	12.30	12.99	13.58	14.06	14.29	14.47	→	
Perpetuity Value in Respective Year (B) (in billions)	0.10	0.12	0.13	0.15	0.17	0.19		15.72
Value in Respective Year (sum of A & B) (in billions)	12.40	13.10	13.71	14.21	14.46	14.66		

The last rows of each table are the fleet value for each respective year. These numbers are to be used in the subsequent real option valuation. The value of Breakthrough Scenario is about 50-60% higher than that of Evolution scenario, and the 2005 value in Evolution scenario is a little higher than the 2005 fleet value without fuel cell vehicles (Table 6-14). Note that the perpetuity value ranges from 7% to 19% of the total fleet value. It is intuitive that the perpetuity value decreases as it is discounted to earlier years. Even when it seems to be a small 7% of the total fleet value as in the case of 2010 Evolution scenario, it means a $70 million-dollar discounted net profit to GM. The inclusion of perpetuity value shows how assumptions could affect the final analysis results--it is really up to the modeller to decide the length of the analysis period. This thesis has argued previously that it seems more plausible to assume GM would exist for a long period of time than having to arbitrarily predict the end of GM's life.

6.4 Binomial Approximation

The last step is to use Binomial Lattice to value the real option; the following section explains the steps. As suggested by Hull (2002, p. 436), nonstandard American options can usually be valued using a binomial tree. The underlying is the NPV of GM's fleet value without fuel cell vehicles, obtained by discounting the stream of net profit back to 2010.

6.4.1 Discount Rate

The discount rate is used to adjust future cash flows to the present. The choice of discount rate is an important issue in valuation and should first be settled for discounting the net profit figures from optimization. The CAPM is employed to find out the average expected rate of return for GM projects. Since the net profit is derived from the evaluation of the entire GM light passenger vehicle fleet, it is justifiable to use CAPM, rather than finding a project-specific discount rate that reflects the project's unique level of risk. The CAPM formula is as follows:

$$E(r_i) = r_f + \beta(E(r_m) - r_f)$$ **Equation 6-16**

Where $E(r_i)$ corresponds to the expected return on the capital asset (investment), r_f is the risk-free rate of interest, and β_{im} (the beta) the sensitivity of the asset returns to market returns. The beta for GM is 1.4 (http://www.finance.yahoo.com, July 27, 2005); therefore,

$E(r_i) = 5\% + 1.4\ (11\%-5\%) = 13.4\%$

Where the risk-free rate is the treasury bonds expected return, 5% (Department of Treasury Bureau of Public Debt , http://www.publicdebt.treas.gov/), and the market return is set to be 11%, consistent with long-term historical average (Seigel, 1998).

6.4.2 The Underlying and Underlying Lattice

The underlying is GM's fleet value without fuel cell vehicles. This value is derived from the NPV analysis from 2005 until perpetuity. The stream of net profit from 2005 to 2011 comes from the optimization. After 2011, GM is assumed to receive a roughly constant profit every year to perpetuity (see Section 7.2.1). The calculation for perpetuity as of year n is:

$Vn = Net\ Profit_{\ n+1} / E(r_i)$ **Equation 6-17**

According to Equation 6-17, perpetuity after 2011 is:

$V_{2011} = V_{2012}$ / 13.4% = 994,044,228 / 13.4% = 7,418,240,507,
V_{2005} = 7,418,240,507 / (1+13.4%)^6 = 3,488,370,316

Therefore, the NPV of perpetuity after 2012, combined with NPV from 2005 to 2011, is approximately $7.8 billion dollars.

Table 6-14 Annual Fleet profit and Fleet NPV

Year	2005	2006	2007	2008	2009	2010	2011	Perpetuity
Net Profit	0.99	0.93	0.98	0.95	1.02	1.08	1.02	0.99
NPV from 2005 to 2011	4.31							
NPV from Perpetuity	3.49							
NPV of GM Fleet without Fuel Cell	7.80							

$7.8 billion is used as an underlying in a Binomial Lattice to model the value trajectory of current state of the system. Table 6-15 summarizes the inputs and calculated inputs required to construct an underlying lattice. The formulas for u, d, r, and p are discussed in detail in Chapter 3, as in Equations 3-6 to 3-9.

Table 6-15 Required Inputs for an Underlying Lattice

Inputs		Calculated Parameters	
Annual risk free rate	5%	Up movement per step	1.73
Current Value of Underlying (Fleet NPV w/o Fuel Cell)	7.80	Down movement per step	0.58
Exercise price, X	Variable	Risk free rate	5%
Annual standard deviation	54.85%	Risk neutral probability (up)	0.41
Number of steps per year	1	Risk neutral probability (down)	0.59

Note that the annual standard deviation is derived from taking the standard deviation of GM monthly adjusted close price from 1990 to July of 2005 (http://www.finance.yahoo.com). The calculated monthly standard deviation for this time period is 9.14%. The annual standard deviation is simply the product of the monthly standard deviation and the square root of 12, which is 54.85%. The stock price volatility is used as a proxy for the up and down movement of the fleet value.

Table 6-16 shows an underlying lattice, which projects the possible values of NPV without fuel cell vehicles from 2005 to 2015:

Table 6-16 The Evolution of NPV without Fuel Cell Vehicles

(All figures are in billion dollars)

Current State of Underlying											
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Time period	0	1	2	3	4	5	6	7	8	9	10
0	7.80	13.50	23.36	40.43	69.97	121.10	209.58	362.72	627.74	1086.40	1880.18
1		4.51	7.80	13.50	23.36	40.43	69.97	121.10	209.58	362.72	627.74
2			2.60	4.51	7.80	13.50	23.36	40.43	69.97	121.10	209.58
3				1.50	2.60	4.51	7.80	13.50	23.36	40.43	69.97
4					0.87	1.50	2.60	4.51	7.80	13.50	23.36
5						0.50	0.87	1.50	2.60	4.51	7.80
6							0.29	0.50	0.87	1.50	2.60
7								0.17	0.29	0.50	0.87
8									0.10	0.17	0.29
9										0.06	0.10
10											0.03

6.4.3 Strike Price and Payoff

This section discusses another important element in GM's real option valuation, which is the strike price. Strike price is a tricky issue in GM's case and should not be strictly interpreted as its conventional definition in a financial option contract, which is, "the stated price per share for which the underlying security may be purchased (in the case of a call) or sold (in the case of a put) by the option holder upon exercise of the option contract" as defined in Table 3-1.

In a financial call or put option, holder of the option will only exercise when strike price is lower than the stock price in a call, and higher, in a put--the holder essentially compares the strike price against the stock price. Similarly, in the case of GM's fuel cell R&D as an exotic option, GM would also compare two values: the values of its fleet with fuel cells and without fuel cells. Readers can think of the fleet value with fuel cell vehicles as GM's strike price. Under a rational, profit-maximizing assumption, GM will and should only commercialize fuel cell vehicles only if the fleet value increases with fuel cell vehicles in the product mix. If GM's fleet value with fuel cell vehicles does not exceed GM's fleet value without fuel cell vehicles, GM is better off waiting to see the progress of technology, the direction of government policy, or the strategy of competitors. On the other hand, if the fleet value with fuel cell vehicles is predictably profitable, GM should commercialize fuel cell R&D to immediately capture the cash flows.

Unlike the fixed, pre-determined strike price in options trading, GM's strike price is obviously a dynamic value that changes annually. The bottom rows of Tables 6-12 and 6-13 are GM's fleet value with fuel cell vehicles from 2010 to 2015 as GM is assumed to exercise this option within this time frame. The computation of the strike price for any given year involves taking the expected value between the value in Evolution scenario and Breakthrough scenario.

Method

It is assumed that there are certain probabilities associated with Breakthrough and Evolution scenarios. The fleet values in each scenario are discrete variables, and the corresponding probabilities of each scenario add up to 1. The expected value for fleet value of any given year, E(X), can be computed as described in Equation 4-1. Take year 2010 as an example:

E(fleet value of 2010) = (Probability of Breakthrough scenario in 2010 x Fleet value in Breakthrough scenario in 2010) + (Probability of Evolution scenario in 2010 x Fleet value in Evolution scenario in 2001) **Equation 6-18**

The *E(Fleet value of 2010)* is thus the strike price for 2001. The last thing that is left to do is to estimate the probabilities for the two scenarios. The extended Pearson-Tukey method approximates the continuous distribution shown with a discrete distribution. It utilizes the 0.05, 0.50, and 0.95 fractiles (5th, 50th, and 95th percentiles) from the underlying continuous distribution as the three possible values in the approximating discrete distribution and assigns them probabilities of 0.185, 0.630, and 0.185. Using this method as a guide, this thesis assumes, in 2010, the probability of Breakthrough scenario is 0.185, whereas the probability of Evolution scenario is 0.815 (0.630 + 0.185). The probability of Breakthrough scenario increases as time progresses. The first row in Table 6-17 indicates the probabilities, the fleet values, and the variable strike prices for the evaluation years.

Table 6-17 Probabilities of Scenarios and Projected Strike Prices

	Scenarios	2010	2011	2012	2013	2014	2015
Probabilities	Breakthrough	0.185	0.185	0.185	0.37	0.37	0.45
	Evolution	0.815	0.815	0.815	0.63	0.63	0.55
Optimal Fleet Values (in billions)	Breakthrough	12.40	13.10	13.71	14.21	14.46	14.66
	Evolution	7.87	8.05	8.22	8.17	8.18	7.99
Strike Prices (in billions)	Expected Fleet Values	8.71	8.98	9.24	10.41	10.50	10.99

The strike prices listed in Table 6-17 are based on the annual fuel cell vehicle demand projection and the associated fleet profit. The forecast of demand and profit is estimated based on the current GM fleet sales (see Sections 6.2.3 and 6.2.4) and thus represents some most probable business scenarios. Consequently, the strike prices in Table 6-17 are assumed to be the results from these business scenarios.

However, as the underlying lattice shown in Table 6-16, GM fleet value as underlying is projected to have ten potential values in 2015, meaning that business for GM could span from highly profitable to highly unprofitable. As a result, the strike price needs to be adjusted to reflect this wide range of situations. The fleet value with fuel cell vehicles (strike prices) should be correlated with the fleet value without fuel cell vehicles. If in 2015 GM is doing extremely well with its existing car models, GM might not have a great incentive to continue to invest in fuel cell R&D let along sell them. On the other hand, if in 2015 GM suffers an extraordinary poor performance, its value with fuel cell vehicles should not be valued as much. The exact level of correlation is difficult to predict and define with certainty, but it is reasonable to assume that GM's launch policy should be related to how their light passenger vehicle fleet performs.

Therefore, an option exercise policy according to GM's future performance can be devised with the following steps. The methodology is simplified by categorizing future performance to three scenarios per year and calculating the three corresponding strike prices:

1) Examine the underlying lattice every year and assign each business scenarios a high, medium, or low business scenario.

2) Calculate the average fleet value for each business scenario for each year. Note that the average fleet value in the medium scenario corresponds to the strike price obtained from the linear program.

3) Start from the high business scenario. Find out the ratio between the average values in the high business scenario and medium business scenario. Calculate a strike price for the high business scenario according to the ratio.

4) Repeat step (3) for the low business scenario.

5) Repeat steps (1) to (4) from years 2010 to 2015.

Following these steps, Table 6-18 lists the indicators for GM's option-exercise policy according to different business scenarios in different years. In conclusion, each strike price is derived based on the two scenarios for fuel cell vehicle sales: Breakthrough and Evolution, as well as the business scenario in the respective evaluation year.

Table 6-18 Strike Prices for High, Medium, and Low Business Scenarios

	Year	2010	2011	2012	2013	2014	2015
Revised	High	39.12	80.57	114.73	129.24	282.26	384.01
Strike	Medium	8.71	8.98	9.24	10.41	10.50	10.99
Prices	Low	0.70	0.72	0.34	0.30	0.30	0.14

6.4.4 Option Valuation Lattice

Working backward recursively from the last period in the underlying lattice, the strike prices shown in Table 6-18 are used to compare the value of fleet without fuel cell vehicles in each year and the respective business scenarios. If the strike price is greater than the value of underlying, then exercise the option; if the strike price is lower than the value of underlying, then do not exercise the option and the option value is thus zero. The derivation of the option valuation lattice is explained in detail in Chapter 3.

Table 6-19 contains (1) an underlying lattice that shows the evolution of the fleet value without fuel cell vehicles from 2005 to 2015, (2) variable strike prices for years 2010 to 2015, the time period that GM could commercialize the fuel cell R&D, and (3) an option valuation lattice that shows a decision road map with respect to the optimal time to commercialize the fuel cell R&D in all scenarios. The value $3.21 billion dollars in the far left of the 2nd lattice is the value of the real option.

6.4.5 Valuation by Discounted Cash Flow

Having obtained the optimal real option value based on the 3-step approach, what is the value of the R&D if evaluated alone by itself, irrespective of its effect on the sales of other models, the CAFE standard, and the overall fleet value? Consider the column "Loss/Profit" in Tables 6-9 and 6-10. These two columns list the estimated cash flows from 2010 to 2080 (cash flows from perpetuity is negligible since they are very small) in Evolution scenario and Breakthrough scenario. Use the NPV formula (Equation 2-6) described in Chapter 2 and the same discount rate, 13.4%, as that of in real option valuation, the NPV for Evolution scenario is negative $2.1 billion dollars; for Breakthrough scenario, $2.3 billion dollars. Using probabilities of 0.185 for Evolution scenario and 0.815 for Breakthrough scenario as estimated in Table 6-17, the expected value of fuel cell R&D shows a $1.27 billion-dollar loss. ((-2.1 x 0.815) + (2.3 x 0.185) = - 1.27).

Table 6-19 Option Valuation in Evolution Scenario

(Shaded areas indicate the high and low business scenarios. All figures are in billion dollars)

Current State of Underlying		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	
	Time period	0	1	2	3	4	5	6	7	8	9	10	
Business Scenarios	0	7.80	13.50	23.36	40.43	69.97	121.10	209.58	362.72	627.74	1086.40	1880.18	
	1		4.51	7.80	13.50	23.36	40.43	69.97	121.10	209.58	362.72	627.74	High
	2	a		2.60	4.51	7.80	13.50	23.36	40.43	69.97	121.10	209.58	
	3			b	1.50	2.60	4.51	7.80	13.50	23.36	40.43	69.97	
	4					0.87	1.50	2.60	4.51	7.80	13.50	23.36	
	5						0.50	0.87	1.50	2.60	4.51	7.80	Medium
	6							0.29	0.50	0.87	1.50	2.60	
	7								0.17	0.29	0.50	0.87	
	8									0.10	0.17	0.29	
	9										0.06	0.10	Low
	10											0.03	
					Strike Price	**High**	**39.12**	**80.57**	**114.73**	**129.24**	**282.26**	**384.01**	
						Medium	**8.71**	**8.98**	**9.24**	**10.41**	**10.50**	**10.99**	
						Low	**0.70**	**0.72**	**0.34**	**0.30**	**0.30**	**0.14**	
Option Valuation Lattice													
	Time period	0	1	2	3	4	5	6	7	8	9	10	
Business Scenarios	0	**3.21**	**4.76**	**7.33**	**11.84**	**19.84**	**32.91**	**50.35**	**64.54**	**55.15**	**0.00**	**0.00**	
	1		**2.40**	**3.39**	**4.82**	**7.30**	**12.45**	**23.61**	**44.77**	**76.52**	**98.08**	**0.00**	High
	2	e		**1.92**	**2.68**	**3.51**	**4.34**	**5.77**	**10.92**	**26.54**	**68.04**	**174.43**	
	3				**1.56**	**2.34**	**3.23**	**3.71**	**2.68**	**1.01**	**0.00**	**0.00**	
	4					**1.15**	**1.92**	**3.17**	**4.73**	**4.07**	**1.80**	c **0.00**	
	5						**0.72**	**1.22**	**2.35**	**4.18**	**6.00**	**3.19**	Medium
	6							**0.43**	**0.54**	**1.28**	**3.27**	**8.39**	
	7								**0.18**	**0.07** d	**0.00**	**0.00**	
	8									**0.20**	**0.13**	**0.00**	
	9										**0.24**	**0.04**	Low
	10											**0.10**	

Excel Formulas:

a) 7.80, first derived in Table 6-14, is the NPV of GM fleet without fuel cell vehicles.

b) 2.60 = 7.8 x (0.58^2) = the underlying of 2005 x (down movement ^2), is one of the three possible values in 2007.

c) The formula for the 0 in the far right of the second lattice = "max [(Strike price of 2015 (which is 10.99) – Su5d5 (which is 23.36)), 0]"

d) 0.07 = max [(0.30 – 0.29), ((0 x 0.41 + 0.13 x 0.59)/1.05)]. 0.41 and 0.59 are the up and down risk neutral probabilities shown in Table 6-15. 1.05 = 1+ 5%, the risk free rate. This formula compares the payoff between exercise and deferral.

e) The option value is simply: 3.21= (4.76 x 0.41 + 2.40 x 0.59)/1.05. From 2005 and 1009, the option is deferred because the earliest exercise time is 2010.

6.4.6 Results

Following the 3-step approach using Monte Carlo simulation to model uncertainties, constrained optimization to find out the optimal profit stream and Binomial Approximation to calculate the option value, the option value of GM's fuel cell R&D is **$3.21** billion dollars. If fuel cell R&D is only valued by itself, the value calculated by traditional DCF analysis is negative $1.27 billion dollars, which represents an undervaluation of $4.5 billion dollars.

The option payoffs are the figures in the option valuation lattice shown in Table 6-19. In 2015, the payoff is MAX [strike price – value of fleet without fuel cell vehicles, 0]. This means that GM should only exercise the option when the fleet value with fuel cell vehicles is greater than the value without fuel cell vehicles. If not, than the option value is simply zero—the commercialization of fuel cell R&D is of no value to GM since GM is better off without it. Between 2011 and 2014, the payoff of the option is the maximum value between exercise and deferral.

A survey of the option valuation lattice indicates that fuel cell R&D indeed is worthwhile to invest as it would increase fleet value in most of the business scenarios. It, however, brings less profit to GM if GM sales do not perform well as shown in the low business scenario. In a couple of extreme business scenarios in 2015 where GM is doing exceptionally well, fuel cell R&D does not add value to GM's fleet and according to the option-exercise policy, the R&D should not be commercialized.

6.5 Remarks on Real Option Valuation

The section offers some thoughts on the mechanics and concepts of the 3-step approach.

6.5.1 Thoughts on Modeling

A model is a representation of the real world, which encompasses different actors, changing business climate, and complex decision rules. A simple model is easy to understand; it takes less time and modeling effort. However, it might not be a realistic representation of the problem to be solved. On the other hand, a complex, detailed model requires significant modeling time and effort but at the same time sacrifices flexibility and robustness.

The 3-step approach presented in this thesis strives to maintain a balance between simplicity and complexity, between reality and robustness. GM has an unconventional, futuristic, and complex exotic option that requires a combination of modeling techniques to best represent the situation and to value the option correctly. The many steps required to accomplish the valuation task might seem cumbersome, but they are straightforward and require only basic-to-intermediate modeling skills. The proposed approach can be done using Excel, which offers the following benefits to the approach: (1) Excel is more transparent than most of the simulation and decision-making commercial software, which often offers build-in functions. The automation could very likely obscure errors and assumptions, (2) students and practitioners are likely to be familiar with Excel; therefore, they will not face a steep learning curve to learn the software and the modeling concepts, and (3) Excel does not cost as much as the simulation and decision-making commercial software.

Excel, however, requires intensive modeling efforts. For example, the optimization needs to be run for every single year, and due to the nature of the fuel cell business, this task must be repeated for tens of years with respective inputs. These repetitions could possibly be avoided if using MATLAB or FORTRAN.

6.5.2 Value, Not Cash Flow

The overarching purpose of real option valuation is to evaluate the "value" of real options, not the "cash flows" of them. It is important to recognize the difference between cash flow and a net present value. The 3-step approach in this thesis requires an NPV analysis after executing the linear program. The optimization result is recorded and later used as a net cash flow per year for the NPV calculation. It is tempting to be satisfied with the optimization results and base one's decision on cash flow, but cash flow is only a point estimate and not a decision-making guide. Let's revisit the optimization results from 2010 to 2015.

Table 6-20 GM Fleet Profit with Fuel Cell Vehicles

Year	2010	2011	2012	2013	2014	2015
Total Fleet Profit (in Billions)	0.99	0.93	0.98	0.95	1.02	1.08

(Note: data extracted from Table 6-14)

Suppose a group of managers or engineers go through the exercise proposed in this thesis, using Monte Carlo simulation to simulate demand and net profit per vehicle and using constrained optimization to find out the fleet profit, and they run the optimization model from 2010 to 2015. If they want to know when best to discontinue fuel cell vehicles, it would be naïve and wrong to base their decision on either the decreasing profit in 2013 and 2014, unless the forecasted demand demonstrates a continuing decreasing trend, but it is not the case here.

Lastly, as shown in this thesis, using NPV as a reference does not mean that the analysis stops here, and if it does, then the analysis repeats the pitfall of the traditional capital budgeting technique of DCF. The essence of real option valuation is to capture possible projections of an underlying throughout the years, and such a revolution can be modeled in a Binomial Lattice. The Binomial Lattice model recognizes real options and allows flexibility in project valuation, and this is why real option valuation is a superior model than DCF.

6.5.3 The Choice of Underlying

The choice of underlying in real option valuation has generated many debates due to the difficulty in finding a replicating portfolio. In this case, the underlying is the NPV without fuel cell vehicles. NPV can be used as an underlying in this case because (1) the objective of the analysis is to observe how the fleet NPV behaves after the commercialization of fuel cell vehicles, (2) NPV before launching fuel cell vehicles has similar risk profile with that of after the launch. After all, fuel cell vehicles are selling only as much as 2% of the total light passenger sales, and (3) GM is a publicly traded company and when the unit of evaluation is entire fleet, it is relatively easy to calculate the volatility of the project. The stock market has determined the volatility through the fluctuation of GM share price.

Copeland and Antikarov (2003) use NPV as the underlying in their proposed method, Market Asset Disclaimer (MAD). Stewart Myers, the MIT Finance professor who first introduced the term real options, also supports the use of NPV as underlying in Brealey and Myers (1998). Both of them attest that if the project has a well-defined market value, then NPV can legitimately be used (per interviews with Professor Copeland on February 23, 2005 and with Professor Myers on July 29, 2005).

It is not to say that the practitioners should always use NPV as the underlying regardless of the case to be evaluated. Practitioners should carefully evaluate, based on their understanding of their specific problem, what underlying best describes the risk and payoff structure of the option. After all, the choice of underlying is not only difficult but contentious; it seems that none of the choices of underlying are completely justifiable. For example, as discussed in Chapter 4, practitioners have used Gold price or electricity price as the underlying for a Gold mine or a large dam. However, can the price of Gold and the price of electricity be a representative indication of the risk level of these projects? Gold price and electricity price are readily observable, but they do not seem to represent the many technical and organizational risks involved in mining or infrastructure projects.
Contrary to the stock or commodity price, NPV or the value of a project is not observable nor is it obvious.

The analysis presented in this thesis shows the underlying evolution in a Binomial Lattice. It is a projection given the assumed volatility observed from **today**. When the time reaches 2010, and the underlying lattice shows six possible scenarios, the practitioners will not know which of the six states that the project is in, unless they perform the NPV analysis again in 2010. As long as NPV is computable, it is quite all right if it is not readily observable. This is because when the time reaches 2010 or anytime in the future, the evolution of the underlying is highly likely to change unless the original lattice is a completely accurate prediction of the future. No one can guarantee a perfectly error-free prediction. During the passage of time, new information could arrive, the world will certainly change, and so does the volatility of the project. The analysis results provided in this thesis serve as a decision tool for GM and allow GM to better understand the fuel cell investment, given today's volatility and demand estimation. It would have been desirable to have a super computer that calculates the fleet values with and without fuel cell vehicles everyday and informs the management when to exercise the option. Without this kind of computing power, practitioners should repeat the same analysis in the future at the time of decision.

6.5.4 No Cookie-Cutter Solution

In conclusion, there is not a cookie-cutter method for all real options problem. Real option models are only as good as the method used and the data fed. In an ever-changing environment and with ever-updating information, it is unrealistic to expect or claim an absolutely accurate real option method or valuation, if it could be verified at all. After all, the process of examining the problem, collecting the data, and modeling the problem is significant to managers and engineers. Valuable insights are gained on the technology and its value dynamics; managerial flexibilities could be exercised accordingly for project value maximization.

Chapter 7 Fuel Cell Technology

Technology investment decisions are not solely based on quantitative analysis alone, but also require comprehensive examination of the technology and circumstances. This chapter summarizes the status of fuel cell technology, as well as the relevant industry analysis and policy implications to complement the quantitative work.

7.1 Challenges

Fuel cells were first invented in 1839, and were first used in practical applications in the 1960s to provide electricity on spacecraft in the Gemini and Apollo space programs. During the 1970s, fuel cell technology was developed for systems on earth. However, fuel cells are still considered a novel technology for mass production. There are several challenges that prevent the mass production of fuel cell-powered applications (DOE, 2004). This section focuses on barriers in the vehicular application:

- *Cost* - the cost of fuel cell power systems must be reduced before they can be competitive with conventional technologies. Currently the costs for automotive internal combustion engine power plants are about $25-$35/kW; for transportation applications, a fuel cell system needs to cost $30/kW for the technology to be competitive. For stationary systems, the acceptable price point is considerably higher ($400-$750/kW for widespread commercialization and as much as $1000/kW for initial applications). In addition, the present day cost estimates for natural gas steam reformer stations are near $1.5 million per station, but costs could drop to less than $250,000 per station if mass-produced. Sufficient infrastructure for mass-production would therefore require between $3 billion and $15 billion in capital investment.

- *Durability and reliability* - the durability of fuel cell systems has not been established. For transportation applications, fuel cell power systems will be required to achieve the same level of durability and reliability of current automotive engines, i.e., 5,000 hour lifespan (150,000 miles equivalent), and the ability to function over the full range of vehicle operating conditions (40°C to

80°C). For stationary applications, more than 40,000 hours of reliable operation in a temperature at -35°C to 40°C will be required for market acceptance.

- *System size* - the size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. This applies not only to the fuel cell stack, but also to the ancillary components and major subsystems (e.g., fuel processor, compressor/expander, and sensors) making up the balance of power system.

- *Improved heat recovery systems* - the low operating temperature of PEM fuel cells limits the amount of heat that can be effectively utilized in combined heat and power (CHP) applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems and improved system designs that will enable CHP efficiencies exceeding 80%. Technologies that allow cooling to be provided from the low heat rejected from stationary fuel cell systems (such as through regenerating desiccants in a desiccant cooling cycle) also need to be evaluated.

7.2 Fuel Cell Industries

In 2002, Fuel Cells Canada, a government-industry-academia consortium, and PricewaterhouseCoopers, predicted that the global demand for fuel cells could reach $30 billion by 2011, with a market potentially exceeding $1.7 trillion by 2021. GM CEO Rick Wagoner took a similar, optimistic view, "…the fuel cell heralds really massive changes, changes that amount to a new industrial revolution that will impact the big oil companies and half the companies in the Fortune 100" (Palmer, 2002). This section explains why; despite of the long R&D gestation period, the investors and governments still think positively about the future of fuel cell technology. This section also provides an overview of the fuel cell industries including the major players and applications.

7.2.1 Emphasis on Future Value

A salient characteristic of the fuel cell industry is the forward thinking mentality that places tremendous future value on innovative technologies and their earning potentials. In the U.S. and Canada, the top four companies whose primary business is fuel cell R&D and manufacturing have a total market capitalization close to $2 billion, but not one of them is near net positive earnings. Nevertheless, the expectation of future gain is significant in terms of how a company evaluates its capital investments, and consequently the value of the company perceived by the investors. Table 7-1 shows that investors continue to bet on fuel cell technology. Moreover, companies are developing different applications based with R&D capabilities at hand to hedge the risks involved in any single application.

Table 7-1 North American Fuel Cell Companies

Major Manufacturers	Major Applications	Stock Quote on 4/13/15	Market Cap (in Millions)
Ballard Power Systems Burnaby, B.C., Canada	Vehicular applications, stationary power generation	BLDP: 4.71	559.4
Plug Power Latham, NY	Portable power for residential and commercial use	PLUG: 5.99	436.12
FuelCell Energy Danbury, CT	Large-scale fuel cell power plants	FCEL: 9, 4	433.67
Hydrogenics Mississauga, Ontario, Canada	Power products, hydrogen generation, system integration	HYGS:4.34	280.48
United Technologies Corp Hartford, CT	Vehicular applications, power plants from UTC Fuel Cell Division	UTX: 98.20	50.30 (Billion)

Note: fuel cell technology is only a small part of UTC

7.2.2 Current Status of Vehicular Applications

This section summarizes the recent notable progress in transportation applications. In 2005, the European Commission is allocating €18.5 million to the CUTE (Clean Urban Transport for Europe) demonstration project, to support nine European cities in introducing hydrogen into their public transport system: Amsterdam (Netherlands), Barcelona (Spain), Hamburg (Germany), London (United Kingdom), Luxembourg, Madrid (Spain), Oporto (Portugal), Stockholm (Sweden) and Stuttgart (Germany) (Europa, 2005). In North America, Chicago, Washington, D.C., Santa Clara, and Vancouver are currently running bus demonstration programs on regular routes on a daily basis. Contrary to EU's centralized program, the demonstration programs in North America are often funded through public-private partnerships in different cities. The collaborative demonstration programs include stakeholders such as the federal and state Department of Transportations, Department of Energy, bus manufacturers, fuel cell manufacturers, and regional public agencies.

For private passenger vehicles, all major car manufacturers already have prototypes on the road as of 2005: GM's HydroGen3 in Washington D.C., Toyota's FCHV in Tokyo and Yokohama, Ford's Focus FCV in Vancouver, B.C., and Honda's FCX in Geneva and Las Vegas.

The commercialization of fuel cell-powered transit buses could be realized sooner than that of light-duty vehicles. Buses are primarily refueled centrally at the depots; therefore, hydrogen storage and refueling is less of an issue for buses. The refueling and storage requirements of fuel cell vehicles expose a check-and-egg problem (Eisenmann and Willis, 2004, p.2). Fuel cell vehicles would have few buyers if refueling stations were not readily available. The refueling stations would be not built until fuel cell vehicles were widely adopted.

7.3 Public Policies

Government policies have tremendous impact on the diffusion of fuel cell technology.
This section of the thesis focuses on reviewing the current environmental and energy policies that could affect the progress of fuel cell R&D and commercialization.

7.3.1 The Kyoto Protocol

The Kyoto Protocol is a declaration and collaboration of the international community to address emissions and global climate change issues. In 1992, countries that participated in Earth Summit joined an international treaty, the United Nations Framework Convention on Climate Change, to begin to consider what could be done to reduce harmful emissions in related to the rising temperature. In 1997, the participating governments agreed to an addition to the treaty, called the Kyoto Protocol, which set the legally binding measures (UNFCC, 2005).

To meet the reduction targets set by the protocol by 2010, countries that produce more emissions than their quota can purchase emission credit from countries that produce below their quota. The former will continue to do so until the cost of developing new technologies is less than purchasing emission credit from others. Alternatively, countries can start to develop new technologies, such as fuel cell power generation system, as a long-term solution. In the U.S., DOE funded, tested, and constructed a 32.3-million-fuel-cell power generation plant in Indiana and a fuel cell-gas turbine hybrid power generation in California in 2002 (DOE, 2002).

The U.S. signed but did not ratify the Kyoto Protocol, meaning that it is non-binding to the U.S. unless ratified (UNFCC, 2005). Nevertheless, in June 2002, the U.S. Environmental Protection Agency (EPA) released the "Climate Action Report 2002," and some observers have interpreted this report as being supportive of the protocol. In 2004, nine Northeastern and Mid-Atlantic US states formed Regional Greenhouse Gas Initiative (RGGI), which is a multi-state cap-and-trade program with a market-based emissions trading system. RGGI is considered to be a supporter of Kyoto on a regional scale and expected to attract more states to join their program (http://www.RGGI.org, 2005).

Unlike fuel-cell power generation, vehicular applications have minimal direct correlation with Kyoto Protocol's emission trading program. The Kyoto Protocol however demonstrates the international community's awareness and commitment to reduce emissions and to maintain the health of the ecosystem. For example, according to a new letter sent by the Japanese Prime Minister Junichiro Koizumi on February 18, 2005, since the adoption of Kyoto Protocol, the Japanese government has advanced environmental technologies such as fuel cells and low-emission vehicles, and has already succeeded in switching all official government vehicles to low-emission vehicles over a three-year period. Kyoto Protocol is significant to this thesis because it drives technologies and policies on a global basis, as oppose to other national or regional policies of smaller scale. Since fuel cell applications have the potential to reach a global market, it is vital for firms to closely monitor the mandates and progress of Kyoto Protocol.

7.3.2 U.S. Policies

The Hydrogen Program and the Hydrogen, Fuel Cells, and Infrastructure Technologies Program of the U.S. Department of Energy are the lead Federal groups for directing and integrating activities in hydrogen and fuel cell R&D. These groups aim to address several major challenges facing America today: dependence on petroleum imports, poor air quality, and greenhouse gas emissions (EERE, 2005). Specifically, in a 2002 workshop led by the experts from these groups, fuel cells are predicted to enter the commercial market between 2010 and 2020 (http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf).

Indeed, supporting policies and legislations are necessary to make the hydrogen economy a reality. Several federal laws have pushed the U.S. along the path leading to a potential hydrogen economy; their history and current policies could provide industries and government agencies some insights toward the evolution of fuel cell-related policies. The United States Congress passed the Clean Air Act in 1963 with amendments and extensions in 1966, 1970, 1977, and 1990. The United States Environmental Protection Agency (EPA) was asked to develop and enforce regulations to protect the general public from exposure to airborne contaminants from mobile sources. Numerous state governments and local governments have enacted similar legislation, either by implementing federal programs or filling in locally important gaps in federal programs. The 1990 Amendments specifically address the mandatory requirements for auto manufacturers to sell clean-fuel cars in California, a big market and trendsetter, and for agencies and government to purchase clean-fuel fleets. Moreover, in 1975, the Energy Policy Conservation Act established the Corporate Average Fuel Economy (CAFE) standards for passenger cars and light trucks. CAFE requires manufacturers to meet a standard for each of their fleets, and noncompliance will result in penalty. Since 1983, manufacturers have paid more than $590 million in CAFE civil penalties (NHTSA, 2005). Noncompliance costs millions of dollars to manufacturers, but is also one of the reasons that the manufacturers strive to improve fuel efficiency technologies and to introduce high fuel efficiency models into a fleet. Finally, the Energy Policy Act of 1992 (EPAct) also has direct impact on fuel cell R&D. It includes provisions that address all aspects of energy supply and demand and requires certain fleets to acquire alternative fuel vehicles.

7.4 Summary

Knowing the current policies and looking forward to the future, a question worth asking is, would hydrogen economy come to pass? The answer would not only affect GM, but also the U.S. economy, environment, and the general public. Any definitive answer would be considered a bold statement, but any definition answer has a possibility. The government and industries want to be prepared, just as what GM is investing in fuel cell technology. A superior technology could very likely drive the passing of favorable policies and legislations. The firm that possesses such a technology could reap the benefits from regulatory capture and first-mover’s advantages.

It is undeniable that U.S. government and businesses have recognized the potential of fuel cells and established plans to pursue their commercialization. However, much still needs to be done, and continuous financial support from the government and businesses is imperative to see progress in the technologies. As previously noted, DOE has actively involved in fuel cell R&D, and spent $240 million for hydrogen-related initiatives in 2004, but the DOE spending on fuel cell only accounted for 0.5% of the agency’s annual budget. In addition, the $240 million spending was only 10% of federal government subsidies paid that year to U.S sugar producers, direct economic aid to the Jordanian government, or one-half day’s expenditure on the occupation and reconstruction of Iraq (Eisenmann and Willis, 2004, p. 8).

How much more investment is required, and how long does it take for fuel cell vehicles to become a reality? From public agencies' perspective, much of the debate regarding to fuel cell R&D is concerned with how much appropriation is reasonable and how the government should allocate funding to the different fuel cell applications, in order to make the commercialization practical. From businesses' perspective, their bottom-line is at stake, and yet the technology investment does not guarantee positive payoffs. There are simply too many uncertainties involved in fuel cell R&D, but through systematic examination and analytical valuation of this program as presented in this thesis, managers and engineers could better understand the uncertainties involved and the optimal timing for managerial flexibility.

Specifically, this thesis applies a 3-step approach to value the fuel cell R&D program as a real option. Fuel cell vehicles' high-fuel economy and CAFE benefit would allow GM to market and sell greater volume of high-profit, low-fuel economy vehicles that are previously restricted by the CAFE constraint. The value of the R&D program should not be evaluated by itself, which is predicted to be negative; rather, the value and the payoff of the R&D program are positively correlated to the incremental value of the fleet brought about by selling fuel cell vehicles in the product mix of the fleet. The approach identifies the best commercializing time between 2010 and 2015 in all scenarios; the analysis result is the optimal value of the fuel cell R&D as uncertainties are proactively quantified and managerial flexibility is exercised based on a profit-maximizing principle.

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Appendix A The Chronology of GM fuel cell R&D

((Reuters, 2005)

Year	Month	Development
2001	January	GM and Toyota reached a multi-year technology agreement on the fuels used for fuel cell vehicles. The standards are a clean hydrocarbon fuel in the short- to medium-term, and hydrogen in the long term. In Japan, natural gas in conjunction with a clean hydrocarbon fuel will be considered. The fuel standards will be achieved through separate research agreements with ExxonMobile.
	August	The Wall Street Journal reported that GM is developing fuel-cell-powered electric generator, which would become available sooner than would a fuel-cell-powered automobile.
	October	GM announced a strategic partnership with Hydrogenics Corporation, a developer and commercializer of Proton Exchange Membrane (PEM) fuel cell systems. As part of the agreement, GM will receive more than 11 million shares of Hydrogenics common stock, or 24% of Hydrogenics's outstanding shares. Hydrogenics will also issue GM warrants to acquire an additional 2.4 million Hydrogenics common shares, bringing GM's stake to 28% of outstanding equity.
	October	GM and Suzuki announced an agreement to collaborate in fuel cell R&D
	October	GM and Giner, Inc., a privately held researcher and developer in electrochemistry and related areas, agreed to expand their fuel cell R&D to include applications beyond the transportation field including hydrogen generation for refueling systems and regenerative fuel cell units for stationary power.
2002	April	GM shipped first fuel cell demonstration vehicle to California.
	July	GM opened a new Fuel Cell Development Center in Honeoye Falls, NY.
2003	March	GM and Royal Dutch's Shell Hydrogen agreed to work together on building hydrogen station by October 2003 with GM's commitment to use Shell's hydrogen at the Shell retail gas station in Washington D.C.
	May	The Dow Chemical Company agreed to use GM fuel cells in fuel cell transaction. Tests would be done during the 4th quarter of 2003 to the end of 2005, with plans to commercialize in 2006. If the tests are successful, Dow could eventually use up to 35 megawatts of power generated by 500 GM fuel cell units on an ongoing basis.
2004	October	GM and Shanghai Automotive Industry Corporation agreed to jointly pursue the R&D and commercialization of hybrid and fuel cell vehicles in China.
2005	January	GM to provide 13 fuel cell-powered vehicles in the NYC in 2006 under the US DOE's Infrastructure Demonstration and Validation Project. The NY fleet is part of the 40 vehicles that GM is building under the DOE program. GM will also introduce fleets in California and the Detroit Metro and expand the Washington D.C. fleet. Shell will installed hydrogen pumps at their gas stations in the above-mentioned cities.
	March	GM and DOE signed a five-year, $88-million agreement to build a 40-vehicle fuel cell fleet and further develop the technology. They will split the $88-million cost.
	April	GM delivers first fuel cell truck to U.S. army.

Appendix B Specifications and Prices of 2005 Hybrid Vehicles

(Davis and Diegel, 2003)

The Honda Insight, Civic Hybrid and Toyota Prius are the three advanced technology vehicles which are currently available to the public in the U.S. The Ford Escape Hybrid will be available in the Fall of 2004. They are hybrid vehicles, using both electricity (from batteries) and mechanical power (from a small internal combustion engine). Learn more about hybrid vehicles at: www.fueleconomy.gov/feg/hybrid_sbs.shtml.

Sales and Specifications of Available Advanced Technology Vehicles

	Fuel Economy (city/hwy)	Emissions Rating	Passenger Capacity	Cargo Capacity	Price ($)
2005 Honda Insight CVT	57/56	SULEV-2	2	16.3 ft3	21,380
2005 Toyota Prius CVTa	60/51	AT-PZEV	5	16.1 ft3	20,875
2005 Honda Civic Hybrid CVT SULEVa	48/47	ULEV	5	10.1 ft3	19,800
2005 Ford Escape Hybrid					
2WD	36/31	AT-PZEV	5	27.6 ft3	26,380
4WD	33/29				28,005
2005 Chevrolet Silverado Hybrid					
2WD	18/21	ULEV	5	56.9 ft3	30,345
4WD	17/19				31,835
2005 GMC Sierra Hybrid					
2WD	18/21	ULEV	5	43.5 ft3	28,132
4WD	17/19				

	Calendar Year Sales in the U.S.				
	1999	2000	2001	2002	2003
2005 Honda Insight CVTa	17	3,788	4,726	2,216	1,168
2005 Toyota Prius CVTa	0	5,562	15,556	20,119	24,627

Sources:

Manufacturer's web sites: www.hondacars.com and www.toyota.com. Insight and Prius sales data - Ward's Communications, Inc., Wards Automotive Reports, Southfield, MI, 2004.

Note: SULEV = Super ultra low emission vehicle.

a. Specifications are for the model containing a continuously variable transmission (CVT).

b. Sales through October 2004.