PLATINUM SUPPLY AND THE GROWTH OF FUEL CELL VEHICLES

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Abstract

This report addresses problems associated with possible U.S. fuel cell vehicle production and a limited platinum supply. Polymer Electrolyte Membrane (PEM) fuel cells, which use a platinum catalyst, could place strain on the platinum market if fuel cell vehicles are widely produced. We developed a dynamic hypothesis, identified causal relationships, and created a system dynamics model in *iThink*. Based on this model, we found platinum prices would likely reach $50,000 per kilogram in 30 years and the cost of platinum for a fuel cell vehicle would be $2,500. At this price, the platinum barrier is surmountable if the cost of other FCV components is drastically reduced. If a world FCV market takes hold, it was concluded that only about 15% global market penetration is feasible.

Acknowledgements

We would like to thank professor Datta and professor Saeed for advising this project.

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Executive Summary

Utilizing hydrogen as an energy carrier is considered to be an environmentally friendly and energy efficient method to generate and consume energy. Fuel cells are a well known application which uses a hydrolysis electrochemical reaction to generate electricity and is an attractive source to replace the internal combustion engine that is currently used in the majority of motor vehicles. Major car companies such as GM and Honda have already introduced hybrid cars in the market and some major projects to build hydrogen infrastructure are underway; these projects include the California Hydrogen Highway and HyNor, a network of hydrogen infrastructure in Norway.

A question arises at this point; why are we not there yet? Fuel cell technology was first discovered about 200 years ago and the principles behind its operation still remain the same today. The first problem is the nature of fuel cell technology which is hindered by some very difficult technical problems such as the necessity of having platinum as a catalyst, degradation of the polymer electrolyte membrane, performance dependency on number of variables, and hydrogen storage and hydrogen production. The second problem is building the infrastructure that can bolster the hydrogen economy and adapt the new technology with a greater efficacy. This requires an enormous investment and the uncertainties involved in such as big investment has caused both the government and the private sectors to hesitate in expediting the progress[1].

The motivation of this project was to evaluate the impeding factors to the development of a hydrogen economy. The first term of the project was used to research many different areas of the hydrogen economy and fuel cells, of which platinum is a key factor. The group, therefore, decided to focus on developing a model to predict the price change of platinum in order to address how the shortage of platinum can impact the feasibility of establishing a stable fuel cell vehicle market. The models currently

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[1] (Helmolt & Eberle, 2007)

available in literatures focus on the relationship between FCV market penetration in the United States and the platinum supply, but their sensitivity to different factors such as platinum loading, supply rate, and platinum recycling rate have imposed some limitations on their usefulness. A model endogenizing these factors with appropriate feedbacks will set a better reference point to analyze how the platinum price will change as fuel cell vehicles (FCVs) take the role as the major method of transportation.

In order to create the model, causal loops were established to represent the relationships among the variables that influence the platinum market. The relationship between demand, supply, recycling, and price were developed and reviewed with proper tests. The model was developed using the system dynamics software, *iThink*.

Three scenarios were proposed to predict the change in platinum price for the different combinations of market penetration, platinum loading, life expectancy of the vehicles, and the recycling efficiency. The results from these scenarios provide the worst, middle-ground, and the best cases possible for the platinum market; the best case resulting in the slowest increase in the platinum price. The current technology has advanced beyond the worst case; the purpose of the worst case was to provide the upper boundary in the range of price change. In developing scenarios, remaining within the viable range of technology improvement was important. In the best case scenario, the platinum loading of 0.020kg/vehicle, life expectancy of 5 years, and fraction wasted of 0.05 (95% recycling efficiency) were used. The 95% recycling efficiency and the life expectancy of 5 years is currently achievable. A platinum loading of 0.020kg/vehicle is projected to be the optimum loading that can be achieved[2].

In addition to the three major scenarios, three special cases were added to the simulation of model. First, instead of fixing the platinum loading, it was assumed to be changing with the price; the logic behind this assumption was that the high price of platinum will drive the technology to develop in order

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[2] (Borgwardt, 2001)

to decrease the platinum loading. The next scenario was to add the assumption of a constant inflow to the platinum reserves; i.e. discovery of new platinum at a rate of 50,000kg/year. The last scenario was a reflection of the power crisis that occurred in South Africa in 2008, which caused an abrupt decrease in mining capability. At the time of crisis, the platinum price increased dramatically for a period of time, and then crashed after mining resumed. This scenario can especially give good insights, since it is a very plausible scenario considering that South Africa is the largest platinum producer.

Thus far, the scenarios were based on the U.S. market. A scenario based on the world market with different penetration percentage (15%-100%) was also analyzed. It was observed that 100% market penetration of FCVs worldwide will not be feasible as the demand of platinum will exceed the supply.

The results from these scenarios cannot be the ultimate measurement of the feasibility of a hydrogen economy. Overall cost analysis of an FCV including the projection of technology advancement in the membrane and hydrogen storage is necessary, where much larger analysis is desired for the hydrogen generation, transportation, and the infrastructure. However, the result from the middle-ground case (the more realistic scenario) shows that the cost of platinum loading per vehicle by year 2038 will be about $2,500 per vehicle. While this is still quite expensive, it may not be a barrier if the prices of other fuel cell components decrease. From this result, it can be concluded that the price of platinum is not an absolute hindrance that will prevent the realization of a partial hydrogen economy. Diversification will of course be a key to this realization.

Chapter 1: Introduction and Background

1.1: Introduction

The modern oil age began in 1859 with Edwin Drake's small oil well in Western Pennsylvania. Compared to today's world production of around 83 billion barrels a day[3], Drake's 69 foot well capable of producing a mere dozen or so barrels a day[4] may not seem like much, but it marked the beginning of an entirely new era. Almost 150 years later, the world is still very much reliant on oil. However, increasing demand, worries over supply, and environmental concerns have lead many to look for ways to decrease the world's dependency on oil.

Oil plays a pivotal role in today's world, accounting for around 36% of worldwide energy use (see figure 1)[5]. Unfortunately, many nations have already reached peak oil production and are now producing less and less oil per year. The United States is an excellent example; in 1970, the U.S. oil production peaked at just below ten million barrels per day[6]. Ever since, the U.S. oil production has been decreasing; in 2007, oil production was just five million barrels per day. While the U.S. is still a significant oil producer, it is also the largest oil consuming nation on Earth. The United States consumed an astonishing 23.9% of the world's supplied oil in 2007; for comparison, China, the second most oil consuming nation, only had 9.3%[7]. While oil production and consumption is a worldwide issue, it is of particular importance to the United States. Consuming nearly a quarter of the world's oil and faced with depleting oil production, energy has become one of the most important problems facing the nation.

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[3] (Energy Information Administration, 2008)
[4] (Pees, 2004)
[5] (British Petroleum, 2006)
[6] (Energy Information Administration, 2008)
[7] (British Petroleum, 2008)

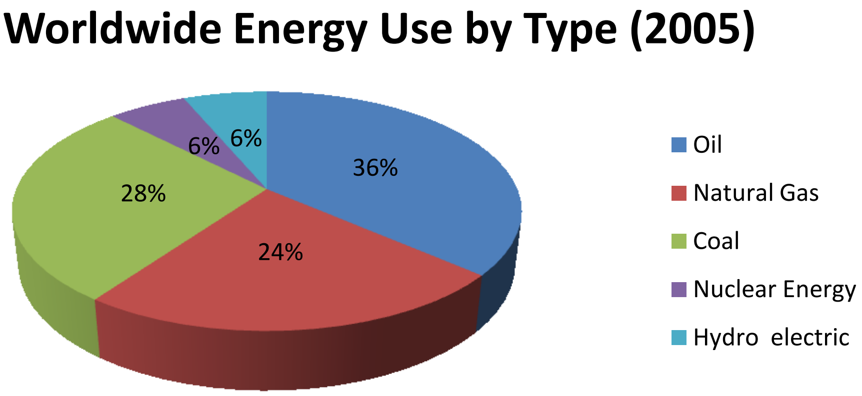

Figure 1: Energy Use by Type[8]

Due to its thirst for oil, the United States has become heavily reliant on foreign oil to meet demand. In 1985, U.S. crude oil and petroleum net imports were about three million barrels per day. By 2006, imports reached about thirteen million barrels per day. Since then, oil imports have slightly declined to about ten million barrels per day[9]. Despite the recent decline in imports, the trend from 1985 to 2006 was a steady increase in foreign oil imports. In addition to the large consumption of oil, decreasing production, and increasing reliance on imports, the United States also faces more competition on the global markets. From 2006 to 2007, Chinese oil consumption increased by 4.1% and Indian oil consumption increased by 6.7%[10]. As developing nations experience rapid growth, the demand for oil will also grow. The growth of the middle class in developing nations adds further competition for oil. In the next 12 years, the middle class is expected to increase by 1.8 billion people[11]. It is the combination of these factors that make it necessary to rethink how the world produces and uses energy. This is especially applicable to the United States as it is, by far, the world's largest oil consumer.

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[8] (British Petroleum, 2006)

[9] (Energy Information Administration, 2008)

[10] (British Petroleum, 2008)

[11] (Naím, 2008)

In addition to concerns over oil dependency, there are environmental issues to consider. One of the largest concerns is the effect of greenhouse gasses on global warming. Carbon dioxide, a major greenhouse gas, is given off through the combustion of hydrocarbons such as gasoline and other oil-based derivatives. In the 2006 U.S. Climate Action Report, it was reported that U.S. CO_2 emissions for 2004 was 7,074.4 Tg (707 million metric tons). This was a 15.8% increase from 1990. The report attributed the rise in emissions to increases in electricity demand, expanding industrial production, and increased travel[12]. With more vehicles on the road emitting carbon dioxide, it is becoming more important to consider the environmental impacts of conventional internal combustion engines.

One plan to reduce oil dependency and our carbon footprint is to replace internal combustion engine vehicles with fuel cell vehicles (FCVs). These vehicles are more efficient (30% wells-to-wheel efficiency compared to a 15% wells-to-wheel efficiency for internal combustion engine vehicles[13]) and they use hydrogen as fuel which can be produced from a vast array of energy sources. Polymer Exchange Membrane (PEM) fuel cells are currently regarded as one of the most viable types of fuel cells for automotive use due to their low operating temperature (only around 80°C[14]). The automotive industry has already begun producing FCVs on a small scale for testing purposes and to raise public awareness. Some manufacturers have gone further; in the summer of 2008, Honda began to lease a small number of FCVs to the public in California. In addition to automotive developments, the infrastructure necessary to support FCV fleets is being established in Norway with the HyNor project and in California with the California Hydrogen Highway Network (CaH_2Net).

While these projects have provided useful information on the small scale development of fuel cell vehicles, many concerns still exist, especially when considering large scale market penetration of FCVs. Some of these concerns are currently being addressed; for example, the storage of hydrogen is

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[12] (U.S. Department of State, 2007)
[13] (Datta)
[14] (Hydrogen, Fuel Cells & Infrastructure Technologies Program, 2008)

improving with stronger tanks capable of storing hydrogen at 10,000 psi[15], the public is becoming increasingly aware of fuel cell technology and the benefits it offers, and infrastructure is being developed in selected areas. However, some concerns still need further investigation.

In particular, a limited platinum supply needs to be taken into account when considering the development of fuel cell vehicles. Currently, fuel cells have a platinum loading of about 0.5 to 0.6 mg/cm^2_{MEA} (on an experimental level, loadings have been as low as 0.25 mg/ cm^2_{MEA}) and a power density around 0.9 W/cm^2_{MEA}[16]. This translates to 0.6 to 0.67 mg/W; from this result, a 100 kW FCV would require 60 to 67 grams of platinum. In November of 2008, the average price of platinum was $844.21 per troy ounce ($24.31 per gram)[17]. For a 100 kW vehicle, the cost of the platinum catalyst *alone* would be $1,600. Other components of the fuel cell, such as the Nafion membrane, will drive the cost even further. To put this in perspective, a *complete* internal combustion engine costs about $2,500 to $3,500[18]. The cost of platinum alone is approximately half the cost of a fully functional internal combustion engine. While the costs for fuel cells may go down due to technological advances that result in a smaller platinum loading, the price of platinum may increase as FCVs are introduced. In addition to price, there are other concerns such as limited platinum reserves. Platinum, being one of the rarest metals on Earth, is difficult to mine. For every 7 to 12 tons of ore mined, only about one ounce of platinum is produced[19]. Due to its extreme rarity, there is the possibility that the amount of mineable platinum could dramatically decrease in the future.

Previous research concerning this problem has provided valuable insights into how the platinum and FCV market might interact but there is also controversy regarding platinum limitations on FCV growth. In a report by Robert H. Borgwardt a computational model was used to determine if platinum was a limit

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[15] (Hydrogen, Fuel Cells & Infrastructure Technologies Program, 2008)
[16] (Mathias, et al., 2005)
[17] (Johnson Matthey, 2008)
[18] (US Department of Energy, 2007)
[19] (United Nations Conference on Trade and Development)

to FCV production. Borgwardt came to the conclusion that U.S. FCV market penetration could require up to 48% of the world's production and take 66 years[20]. However, in a report by R.J. Spiegel a different conclusion was reached. It was concluded that platinum demand from FCVs was relatively small compared to total world reserves. According to Spiegel, only 4% of the world's platinum reserves are needed to maintain FCV production up to 2035[21]. Beyond platinum limitations, Spiegel offered some qualitative insights on how mining companies might be affected.

> "Thus, the issue is not whether there are sufficient world platinum reserves, but whether countries (South Africa and Russia) would be willing to rapidly ramp up to meet peak demand in 2020, and then face the consequences of a bust in the market as demand subsequently dropped."

Using the insights and controversies brought about by previous research, the goal of this project is to expand upon what is known and to arrive at a more conclusive result. One of the greatest limitations of the Borgwardt and Spiegel reports is the use of a computational model. Such models do not take into account important feedback loops and interrelations that result in more robust and realistic model behavior. Instead of using a computational model, a system dynamics model will be developed. This model will be able to take into account the interrelations among variables such as platinum price, production, and consumption.

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[20] (Borgwardt, 2001)
[21] (Spiegel, 2004)

1.2: Background

Polymer electrolyte membrane (PEM) fuel cells are regarded as one of the most viable fuel cell technologies to power vehicles. One of the most redeeming features of using PEM fuel cell technology is the low operating temperature (typically between 60 and 80 degrees centigrade). For comparison, molten carbonate fuel cells have an operating range between 600 and 700 °C and solid oxide fuel cells have an operating range between 900 and 1,000 °C[22]. However, there is a price to pay in order to operate at such low temperatures. PEM fuel cells must use platinum as a catalyst; other fuel cell technologies can use cheaper and more readily available catalysts such as nickel.

Platinum has numerous uses, creating strain on the current supply. The most prominent use of platinum is in the automotive industry for catalytic converters. In 2007, about 49% of the platinum supplied was used for autocatalysts[23] (see Figure 2 for platinum usage in past years). Nations such as the United States, Japan, South Korea, members of the European Union have clean air regulations that require autocatalysts on vehicles. In 2000, China also imposed similar regulations. With an emerging middle class and an increase in demand for vehicles, it would be no surprise to see an increase in the amount of platinum used in the autocatalyst industry. Such an increase could inflict more strain on an already strained supply of platinum.

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[22] (S.A. Sherif & Veziroglu, 2005, pp. 71-2)

[23] (Johnson Matthey, 2007)

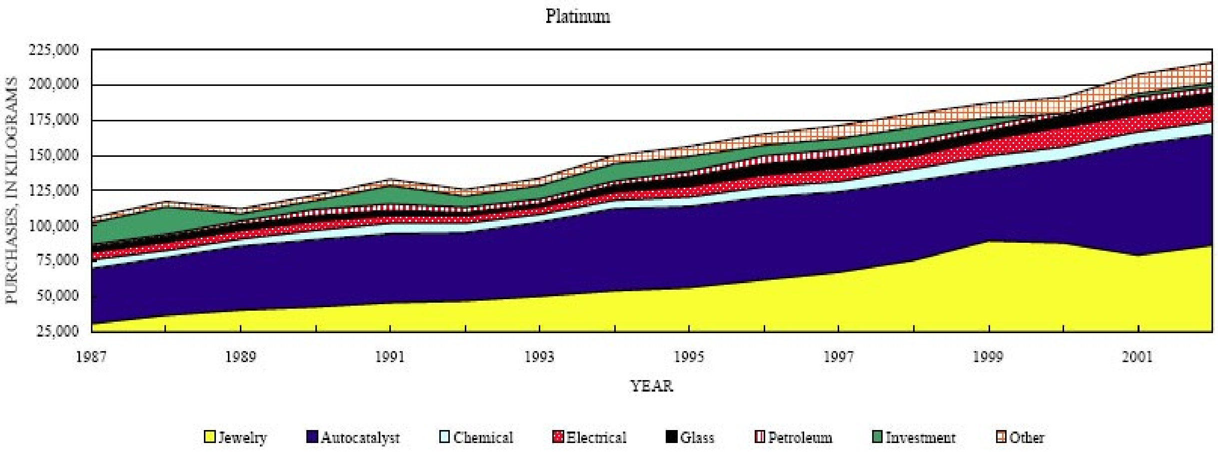

Figure 2: Historical Platinum Use by Type[24]

While platinum prices pose a problem to the development of PEM fuel cells, a more concerning problem could be the limited supply of platinum. In 2006, only 214 tons (6,200,000 troy ounces) of platinum was mined worldwide[25]. In order to grasp how little this is the amount of gold supplied in 2006 was over ten times the amount of platinum. Another grave prospect for the platinum market is the difference between the amount demanded and the amount supplied. In 2007, there was a supply deficit of 412,000 ounces. The predicted 2008 deficit is better, at about 370,000 ounces[26].

Another major concern is the centralized supply of platinum. Approximately 77% of the world's platinum supply is mined in South Africa. The platinum market, therefore, is heavily influenced by the political and economic state of South Africa; if a major catastrophe occurs in South Africa, the platinum supply could plummet and prices would skyrocket. In early 2008, South Africa experienced a major power crisis resulting in many mines shutting down temporarily. Even after the crisis, many mines were limited to operating at 50% normal power capacity. Even today, mines still have a power limit of 90%. This power limit is expected to remain for the next few years until more power plants can be built.

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[24] (Wilburn & Bleiwas, 2004)
[25] (Burgess, 2007)
[26] (Nones, 2008)

Despite these problems, it may be possible to supply enough platinum to meet the current demand and additional demand due to fuel cell vehicles through recycling programs. In 2007, platinum recycling programs have successfully re-obtained 916,000 ounces of platinum[5]. Depending on the growth of the PEM fuel cell market, the amount of recycling may have to increase considerably.

In order to determine how the wide scale production of fuel cell vehicles would affect the supply and demand of platinum, it is necessary to create a model based on several key assumptions and accurate data. In the past there have been studies concerning the effect of fuel cell vehicle production on platinum prices and supply. These studies have often arrived at varying conclusions and it would appear that there is no strong consensus on whether platinum supply could limit the production of fuel cell vehicles.

Many studies on the interrelation between the platinum and the FCVs have concluded that the platinum supply will be sufficient enough to respond to increasing FCV penetration. *TIAX*, a technology processing company, has done extensive research on the prediction of FCV growth with the U.S. Department of Energy. With scenarios based on different level of FCV market penetration, *TIAX* concluded that when 50% of new vehicle sales are occupied by FCVs, the increase in the FCVs demand can be bolstered by the world platinum supply[27]. Industrial experts and the Department of Energy (DOE) suggest that the rate of increase in platinum demand on the order of 12Mg/year is feasible[28]. The increase in demand has been about 6Mg/year for past years since 1988[29], and with the scenario of 50% market penetration by year of 2050, the sharpest increase will occur in 2030, lasting for about 15 years with demand growth rate of

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[27] (Kromer, Rhodes, & Guernsey, 2008)
[28] (Kromer, Rhodes, & Guernsey, 2008)
[29] (Borgwardt, 2001)

12Mg/year[30]. The model predicts that eventually the demand will remain at about 700Mg/year with no increase in the rate of demand growth (see Figure 3).

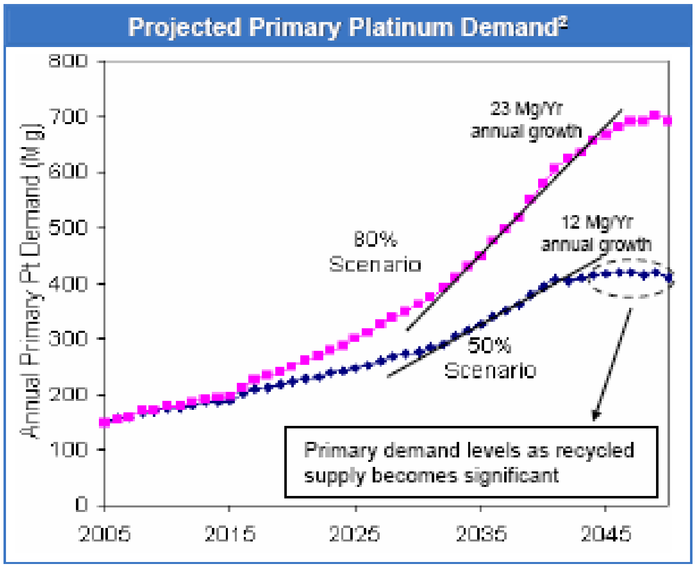

Figure 3: Projected Primary Platinum Demand – *TIAX* Model[31]

The change in price with increasing demand of platinum is also an important aspect of the FCV market prediction. Some studies demonstrate that the highest increase in price change for platinum will not exceed 12.5%[32] as the price will converge back to its nominal values (Figure 4). This model assumes 95% rate of recycling, a platinum loading of 20g per vehicle, and the eventual decrease in platinum demand with the advance of technology. While the experimental results corroborate very high recycling rate from used fuel cells[33], the assumption of significant decrease in demand within less than two decades seems to be overly optimistic. It is known that there is currently no viable alternative to platinum as a

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[30] (Kromer, Rhodes, & Guernsey, 2008)
[31] (TIAX LLC, 2003)
[32] (TIAX LLC, 2003)
[33] (Lafon, Girold, & Russello, 2006)

catalyst for fuel cells in vehicles[34]. Palladium may be able to substitute some portion of platinum demand, but it offers little advantage in terms of cost of availability[35].

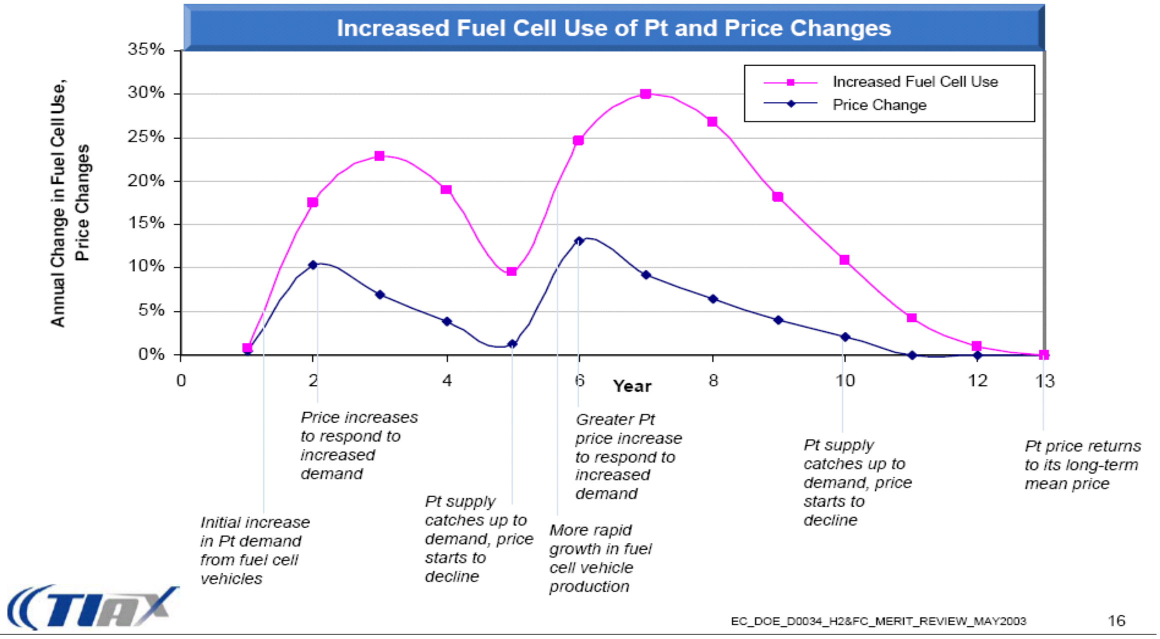

Figure 4: Effect of Pt Demand on FCV Price – *TIAX* Model[36]

Some literature point out the invalidity of these models due to their assumptions based on very optimistic scenarios. In fact, most analysis based on practical information reflecting current level of technology show that the supply may not be sufficient to meet worldwide platinum demand if more realistic alternative assumptions are used. The alternative assumptions include:[37]

- South African supply (80% of world platinum production) can only be increased by 4% per annum instead of 5%.
- Jewelry demand grows at more than 2% per annum – it is either assumed to remain constant or decrease as the platinum demand by FCV increases.

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[34] (Platinum and hydrogen for fuel cell vehicles)
[35] (Platinum and hydrogen for fuel cell vehicles)
[36] (TIAX LLC, 2003)
[37] (Platinum and hydrogen for fuel cell vehicles)

- Fuel cell stacks require more than 20g Pt/vehicle – this is less than half of the amount that is currently being used.
- The demand for cars grows by more than 55% per decade, instead of 45-50%.

The high sensitivity of the results from current models is due to the absence of feedback loops within the model. Without important feedbacks, the model can't respond to changes within the system, resulting in high sensitivity. With these models, results have largely been inconclusive, with large variations in results among different studies. It should be noted, however, that many models make conclusions based on relaxed constraints, despite the sensitivity of the model to those constraints. Also, most of analysis does not reflect practical market penetration, as they do not include the response of FCV production to platinum prices. The uncertainties presented due to the relaxation of constraints suggest that the future research should focus on assessing costs associated with increasing Platinum Group Material (PGM) production and PGM market dynamics[38].

The system dynamics model used in this report was proposed to predict the price change of platinum as the growth of the FCV market fluctuates. The dynamics of the model are created by the interrelationships among important variables, such as how the price of platinum affects the platinum mining and FCV production, which are related to each other in feedback loops that were carefully developed, correlating the effect of variables from one to the other.

Given platinum's unique position as a severely limited material needed for a PEM fuel cell vehicle, it is crucial to understand how the platinum market will react to the development of a large FCV fleet and how this reaction will affect FCV development. Without this understanding, unintended consequences are bound to occur, possibly causing major setbacks or even the complete failure of the emerging FCV market.

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[38] (Tonn.B.E. & Sujit.D., 2002)

In a 2001 study from the US Environmental Protection Agency, authored by Robert H. Borgwardt[39], it was estimated that platinum could dramatically inhibit the production of fuel cell vehicles. The report also found that it would take an estimated 66 years and a total 10,800 tons of platinum to convert the entire US fleet to fuel cell powered vehicles. This conclusion was based on the assumption that US platinum consumption was at 48% of the worldwide supply. If US platinum consumption was at 16% (the percentage consumed in 2001) then it was concluded that it would take 146 years for complete conversion. In a 2004 study[40], also from the US Environmental Protection Agency, a different conclusion was reached. Under the authorship of R.J. Spiegel, the study found that only 4% of the world's platinum supply is needed to meet fuel cell vehicle demand until 2035.

While these studies are informative and supply valuable data and predictions, the large variation among studies prevents one from arriving at any solid conclusion about platinum supply and fuel cell vehicle production. In addition, since 2001 and 2004, more up-to-date information has become available. Using new information, we hope to establish a more accurate model that can be developed to obtain a better understanding of how platinum supply may or may not limit the production of fuel cell vehicles.

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[39] (Borgwardt, 2001)
[40] (Spiegel, 2004)

Chapter 2: Methodology and Analysis

Modeling complex problems, such as the issue of platinum limitations in an emerging FCV market, requires a model that considers feedback effects and how these effects reverberate through the model. System dynamics takes important feedback loops and interrelations into account, resulting in a more realistic model.

The first step in establishing a system dynamics model is to create a reference mode. A reference mode captures the predicted behavior of a key variable within the model. A reference mode serves many purposes, such as further establishing the problem and offering a mean to compare if the results of the model fit the expected behavior. For this model, platinum supply will serve as the reference mode.

After establishing the reference mode, the next step is to formulate a dynamic hypothesis. The dynamic hypothesis explicitly shows important feedback loops and how these loops influence the main variables. Part of the dynamic hypothesis includes creating a Causal Loop Diagram (CLD). The CLD depicts the feedback structure in terms of causal links that are either denoted as positive or negative. Positive links connect variables that share the same behavior. For example, a positive link would be placed from “Price of Platinum” to “Platinum Production”; as the price of platinum increases, platinum production also increases. A negative link is established when increase in a variable causes another variable to decrease. Many of these causal links form feedback loops, giving the model its behavior. Feedback loops can be either reinforcing or balancing. Reinforcing loops “explode”, causing growth. Balancing loops display goal-seeking behavior by trying to reach equilibrium.

With a reference mode and a dynamic hypothesis, a simulation model can be created. Qualitative relationships expressed in the dynamic hypothesis can be quantified through research and it is often unfeasible to do experiments, so research will be heavily relied upon to quantize causal relationships. Testing will be completed during and after the creation of the simulation model. The results of the model will be compared with the computational model (reference mode). Parameters and relationships will be adjusted to increase the robustness of the model.

After satisfactory testing, sensitivity analysis can help determine which variables have the most effect on the model. This can help on establishing policies that can mitigate or solve the problems. The next step is to test how the policies influence the model and to derive conclusions from the results. Finally, it is important to iterate each step as need be, in order to optimize the validity of the model. As progress is made, changes to the policies, simulation model, and even the dynamic hypothesis will be inevitable.

2.1: Establishing Reference Modes: The Computational Model

2.1.1: Assumptions

Quantifying possible scenarios concerning platinum supply limitations involves establishing numerous assumptions. These assumptions must take many factors into account, such as the predicted number of FCVs to be produced within the next few decades, the platinum loading per vehicle, and efficiency of platinum recycling programs.

In order to determine the extent that platinum supplies limit FCV production, several assumptions need to be established. The first assumption concerns the annual growth rate of the U.S. vehicle fleet. As of 2006, there were approximately 250 million vehicles on the road[41]. Data of US vehicle sales were available from 1990 to 2007 by the U.S. Bureau of Transportation Statistics. For 2007, approximately 8 million passenger vehicles were sold in the United States[42]. This value will provide the market saturation point for FCVs.

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[41] (Research and Innovative Technology Administration, 2008)

[42] (Bureau of Transportation Statistics, 2008)

The second assumption concerns the annual growth rate of platinum production. From 1985 to 2003, the supply of platinum has increased by an average of 6,150 kg per year[43]. The U.S. Geological Survey has developed some estimates on future trends. These trends were published by the USGS and can be seen below.

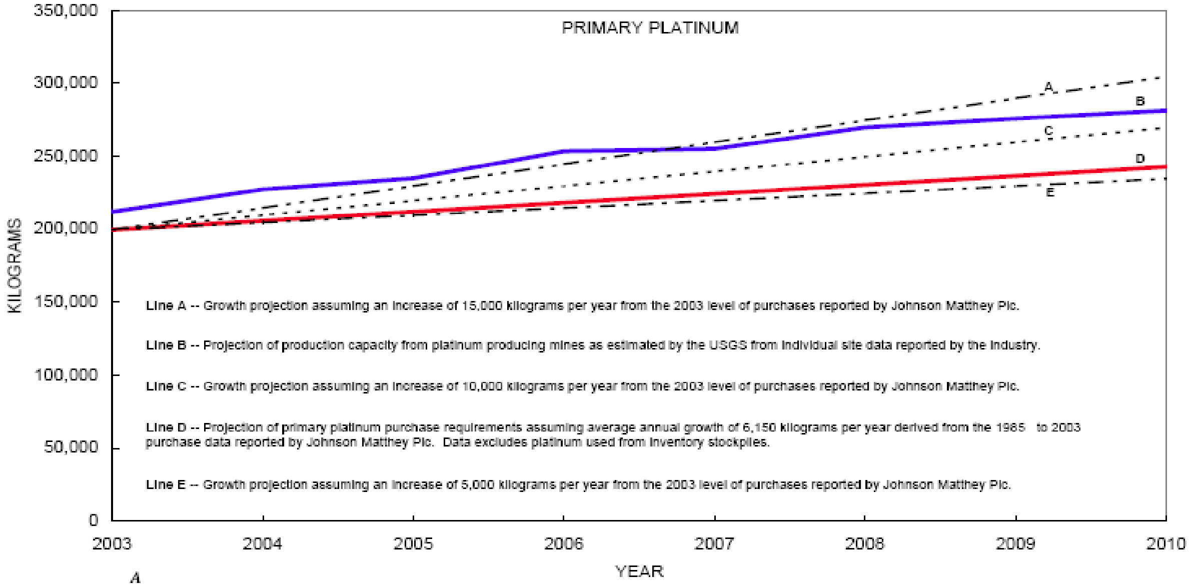

Figure 5: Predicted US Platinum Supply until 2010[44]

The USGS estimated that the platinum supply could increase anywhere between five and fifteen thousand kilograms per year (see Figure 5). In addition to these constant changes in supply, the USGS also estimated future supplies based on projected production capacities for platinum mining sites. However, these estimates are only valid under the assumption that mining facilities are operating under full capacity. Due to South Africa's power supply crisis, South African mines (which mine around 77% of the world's supply) have been operating well under full capacity. Even today, mining facilities in South Africa are limited to 90% full power. This restriction is expected to continue for months or even years until more power plants can be established. Considering these limitations, the estimates based off

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[43] (Wilburn & Bleiwas, 2004, p. 77)
[44] (Wilburn & Bleiwas, 2004, p. 147)

projected mining capacities are probably higher than reality. For this model, three different supply production estimates will be used. Supply will either increase by 5, 10, or 15 thousand kilograms per year starting at a base line of 200,000 per year.

The third assumption is an estimate of the future market penetration of fuel cell vehicles. The estimates that will be used for our modeling purposes will be the HyTrans model, developed by the U.S. Department of Energy in 2005. Unlike many previous models, the HyTrans model incorporates significant hindrances to the development of hydrogen fuel cell technology. The model takes into account factors such as the lack of a strong market for hydrogen fuel technology, the expensive price of fuel cells, and the need for development of economies of scale in vehicle production. The model itself is based on a collection of more specific models. These models include the DOE H2A Model for hydrogen production and delivery, PSAT & ASCM Vehicle Performance and Cost Estimates model, ORNL Vehicle Choice model, ORNL Advanced Vehicle Manufacturing Cost model, GREET GHG Emissions model, and the NEMS AEO 2006 model[45]. Considering that the HyTrans model is quite extensive and thorough, it seems appropriate to use data from HyTrans for our assumption about future market penetration.

Three scenarios, which were analyzed by the Oak Ridge National Laboratory, will be used in our model. The three scenarios can be seen in Figure 6.

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[45] (Greene, Leiby, & Bowman, 2007, p. 3)

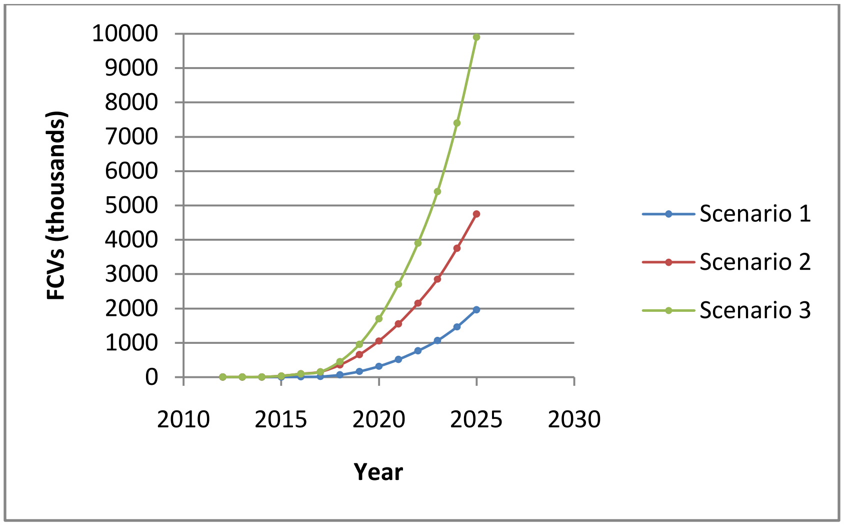

Figure 6: Predicted Number of FCVs in U.S. using HyTrans Model[46]

The final assumptions concern platinum loading for fuel cell vehicles, the efficiency of platinum recovery programs, and the average life of a fuel cell vehicle. In an article by Mark F. Mathias et al[47] in the fall of 2005, it was reported that platinum loadings of 0.25 mg/cm^2 were achieved on an experimental level. In addition to breakthroughs in platinum loadings, power density has increased. The article cites power densities of about 0.9 W/cm^2. Using this information, it was determined that the average amount of platinum per automobile would be about 22 g (for an 80 kW vehicle). In a report by Stephen Grot and Walther Grot of Ion Power Inc. in conjunction with the US Department of Energy[48], a method of platinum recycling was found to recover about 95% of platinum from a fuel cell. Articles published by Robert H. Borgwardt[49] and R.J. Spiegel[50] use an average FCV lifespan of 15 years. This value far exceeds the current lifespan of about 5 years[51] but is used in the ideal case where FCV life expectancy is increased through technological breakthroughs. The average lifespan of a fuel cell vehicle is taken to be

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[46] (Greene, Leiby, & Bowman, 2007, p. 8)
[47] (Mathias, et al., 2005, p. 24)
[48] (Grot & Grot, 2007)
[49] (Borgwardt, 2001)
[50] (Spiegel, 2004)
[51] (Total, 2007)

15 years for the computational model. For the simulation model, this value can be changed to account for less than ideal conditions.

2.1.2: Computational Model Results

Using the assumptions discussed in the previous section, a rudimentary model was developed to give a better estimate of platinum demand for FCVs in the future. The first step in developing this model was to establish a qualitative extension of the HyTrans model (see Figure 7). While the HyTrans model offered valuable insights into FCV growth up to 2025, the model needed to be extended to the point where most of the US vehicle fleet would be made up of FCVs. The three scenarios developed by the HyTrans model were extended until 2075 using a logistic curve. While the curve is not very accurate, it captures the basic behavior of the predicted FCV growth. Initially, growth is slow as FCV technology is still being developed and the public is reluctant to adopt the new technology. However, as the population of FCVs increases, its growth starts to explode. Eventually, growth slows down as most of the population has accepted the technology.

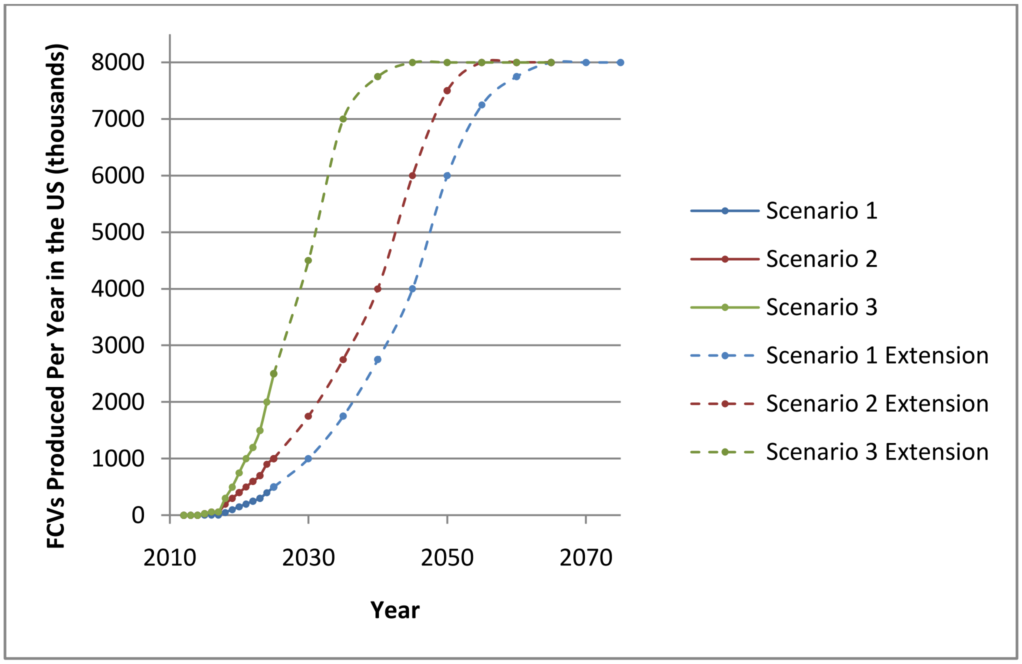

Figure 7: Predicted Number of FCVs in U.S. Extended Until 2065 based on HyTrans Model

With the predicted FCV growth established, the next step was to determine how much platinum is needed per year to satisfy the demand due to FCVs. Using the assumptions that the average FCV will use 22 grams of platinum, will last 15 years, and 95% of the platinum will be recovered after its lifespan, it was possible to determine how much platinum will be needed from primary sources (e.g. mining). Using various estimates, the world's supply of platinum was predicted. Comparing the platinum demand for FCVs with the world supply of platinum gave an estimate on how much platinum was needed as a percentage of the world's supply. The results of the model are displayed in figures 8 through 10.

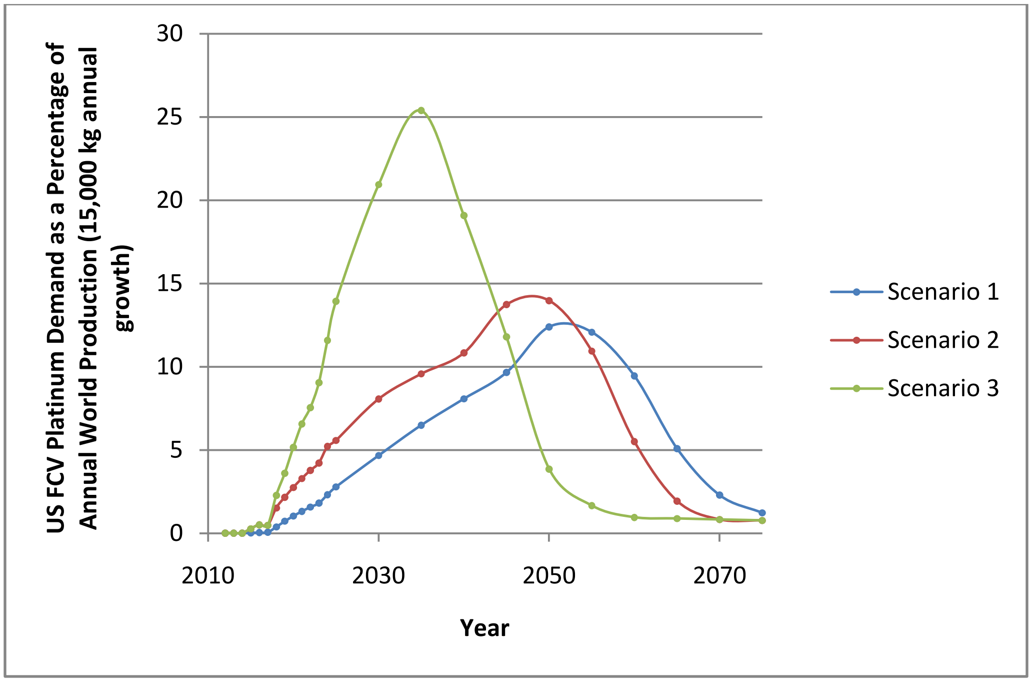

Figure 8: US FCV Platinum Demand as a Percentage of Annual World Production (15,000 kg annual growth)

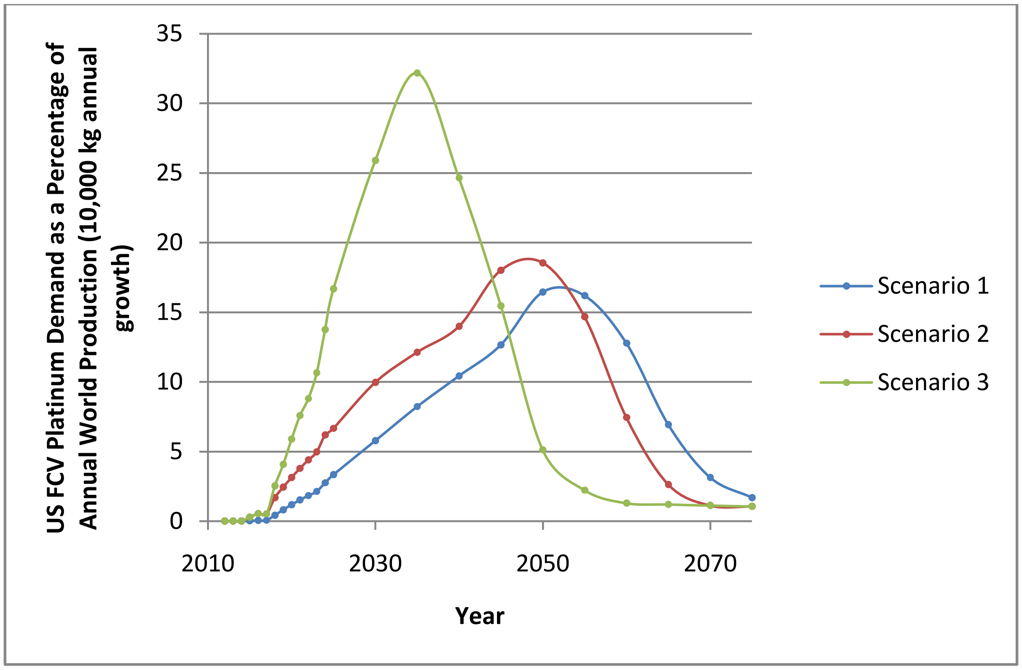

Figure 9: US FCV Platinum Demand as a Percentage of Annual World Production (10,000 kg annual growth)

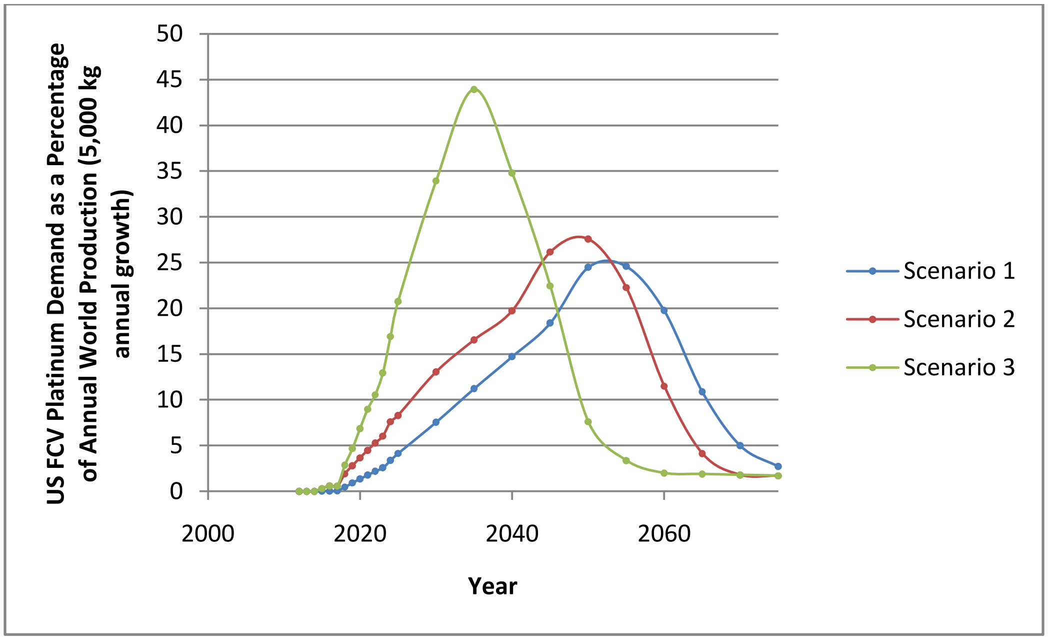

Figure 10: US FCV Platinum Demand as a Percentage of Annual World Production (5,000 kg annual growth)

2.1.3: Conclusions from the Computational Model

The computational model suggests that platinum demand will increase dramatically at the beginning. However, as recycling of platinum from old FCVs begins to take hold, the demand for platinum would quickly decrease. Depending on the annual growth of the global platinum supply, US FCV platinum demand could peak at 12 to 44% of world-wide platinum demand.

While the computational model does offer some insight on the problem at hand, there are some limitations to what can be extracted from the results. Firstly, many of the assumptions are based on ideal conditions. For example, the FCV life that was used for the computational model (15 years) greatly exceeds the current life expectancy of 5 years, but it was used under the assumption that the lifespan of FCVs would increase over time. Another weakness of the computational model is that it does not take into account feedback structures that could dramatically affect the outcome of the model. In this model, annual world production is assumed to increase at a constant rate. In reality, world production is strongly dependent on platinum demand. If there's a large demand for platinum, world production could decrease dramatically. If demand suddenly falls, so could world production. These causal links, which have been neglected for the purpose of the computational model, will be an integral part of the system dynamics model.

2.2: Formulation of Dynamic Hypothesis

Using the reference mode and research that has already been done, it is possible to establish a dynamic hypothesis. From the reference mode, it appears that recycling will play an important role in the model. If recycling is prominent enough, it could cause a "boom and bust" scenario for platinum mines. There's the initial mining boom due to increased consumption, but as old FCVs are recycled, secondary platinum is introduced into the market causing a bust for the platinum mining industry. These two competing forces form two of the model's most important feedback loops, seen in figure 11.

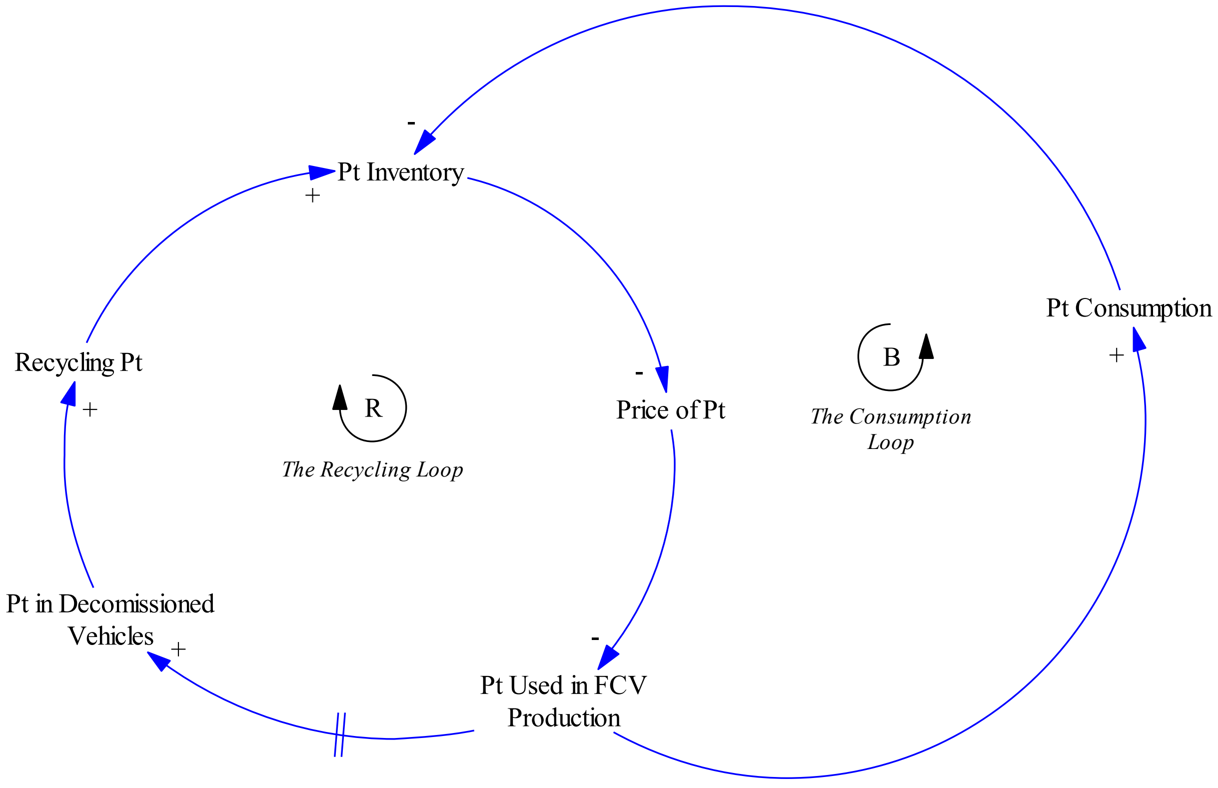

Figure 11: The Recycling and Consumption Feedback Loops

Internal combustion engine vehicles are also considered. As FCVs are introduced, platinum will be extracted from the catalytic converter in decommissioned ICEVs. Since FCVs do not have a catalytic converter, there will be a gain in the platinum supply from ICEVs. Other variables and their relation in the model can be seen in Figure 12.

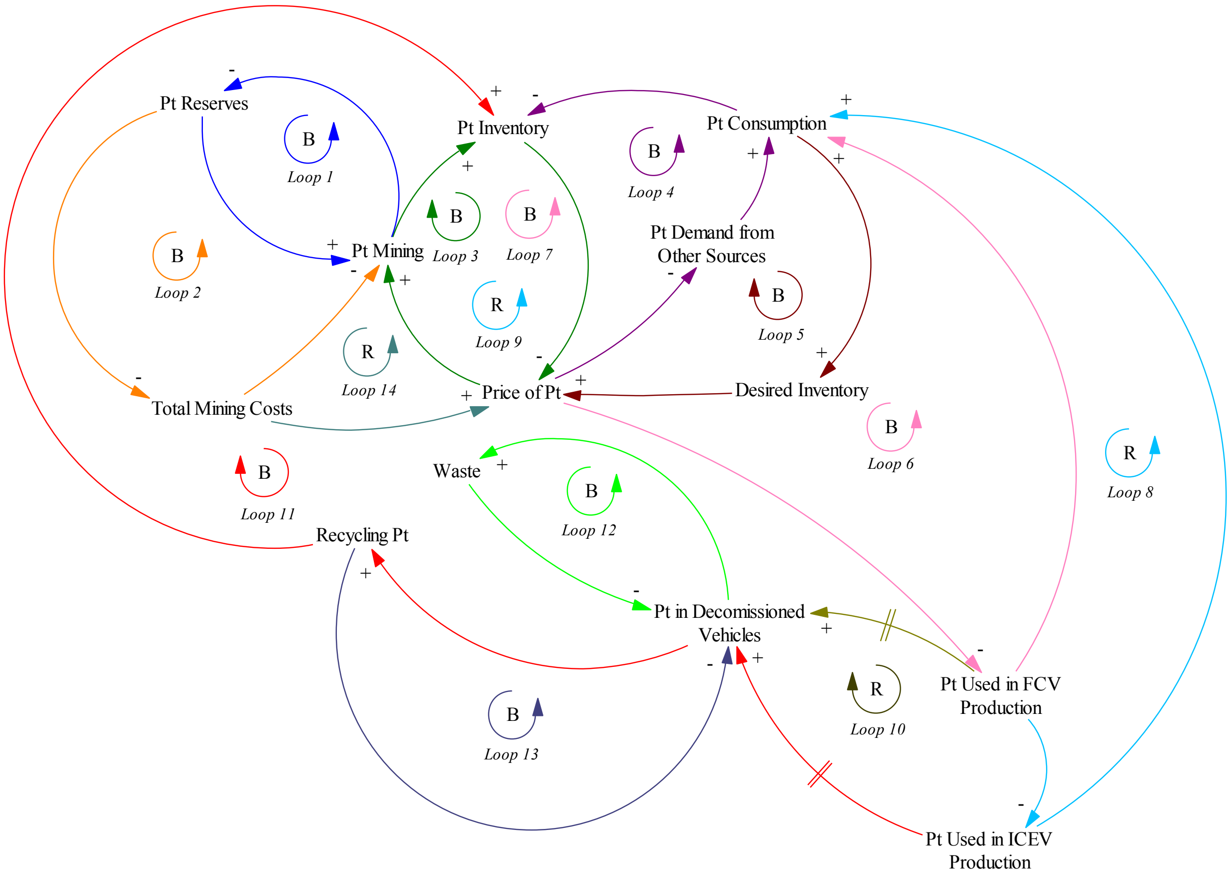

Figure 12: Vensim Causal Loop Diagram

This causal loop diagram takes into account a variety of relationships that could influence both the FCV and platinum market. Loop 1 is a simple relationship between the platinum reserves and mining; as mining continues the platinum reserves are depleted making it more difficult to mine. This forms the first balancing loop. Loop 2, also a balancing loop, describes similar behavior. As the reserves shrink, not only is it more difficult to mine, total mining costs increase as more ore needs to be processed to get the same amount of platinum.

The first two loops explained the mining/reserves relationship. The next series of relationships primarily illustrate the interconnectedness of platinum price, mining, and consumption. In Loop 3, an increase in platinum mining will result in a larger inventory. In turn, the larger inventory will decrease the price of platinum as supply increases relative to demand. The increase in price will decrease platinum mining, closing the balancing loop. Loops 4 and 7 depict the demand aspect of the platinum market. As platinum consumption increases, the platinum inventory decreases. The decrease in the platinum inventory will increase the price of platinum as demand increases relative to supply. The higher price will decrease the demand from FCVs (Pt from New FCV Production) and it will decrease the demand from other sources. Loops 5 and 6 act in a similar manner to 4 and 7, but instead of consumption influencing price through inventory, consumption influences price through a desired inventory.

Loops 8 and 9 represent how ICEV production influences platinum consumption, how that consumption influences desired inventory (loop 8) or actual inventory (loop 9), and how those inventory effects influence price. Unlike FCVs, the price doesn't directly influence ICEV demand. Since the platinum loading in catalytic converters is relatively small (around 2 to 3 grams for most vehicles[52]), it is assumed that platinum prices will have a negligible effect on ICEV demand. However, FCV demand does have a large effect on ICEV demand. As FCVs penetrate the market, ICEV demand begins to decline as people start buying FCVs instead. As a result, Loops 8 and 9 follow a similar path as Loops 4 through 7, however, due to the inverse relationship between ICEV and FCV production, Loops 8 and 9 are reinforcing, not balancing.

Loops 10 and 11 are very important. These two loops represent the influence of recycling on the system. After FCVs or ICEVs are produced, there is a delay (due to the lifespan of the vehicle) before they are decommissioned and the platinum is extracted. However, not all platinum is extracted; recycling is not 100% efficient and some platinum is lost. After being recycled, the platinum re-enters the market and acts as a second source of platinum. The influx of platinum to the market decreases the price of platinum. The decrease in price will increase FCV production, forming a reinforcing loop (Loop 10). The

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[52] (World Health Organization, 2000)

decrease in price will have the opposite effect for ICEV production since more FCVs are being produced; this will form a balancing loop (Loop 11).

2.3: Creating the Simulation Model

The next step in developing this model is to translate the qualitative representation of the problem seen in the Causal Loop Diagram to a quantitative representation that uses mathematical equations to represent causal links and the transportation of ideas and materials through the system. The simulation model structure can be seen in Figure 13.

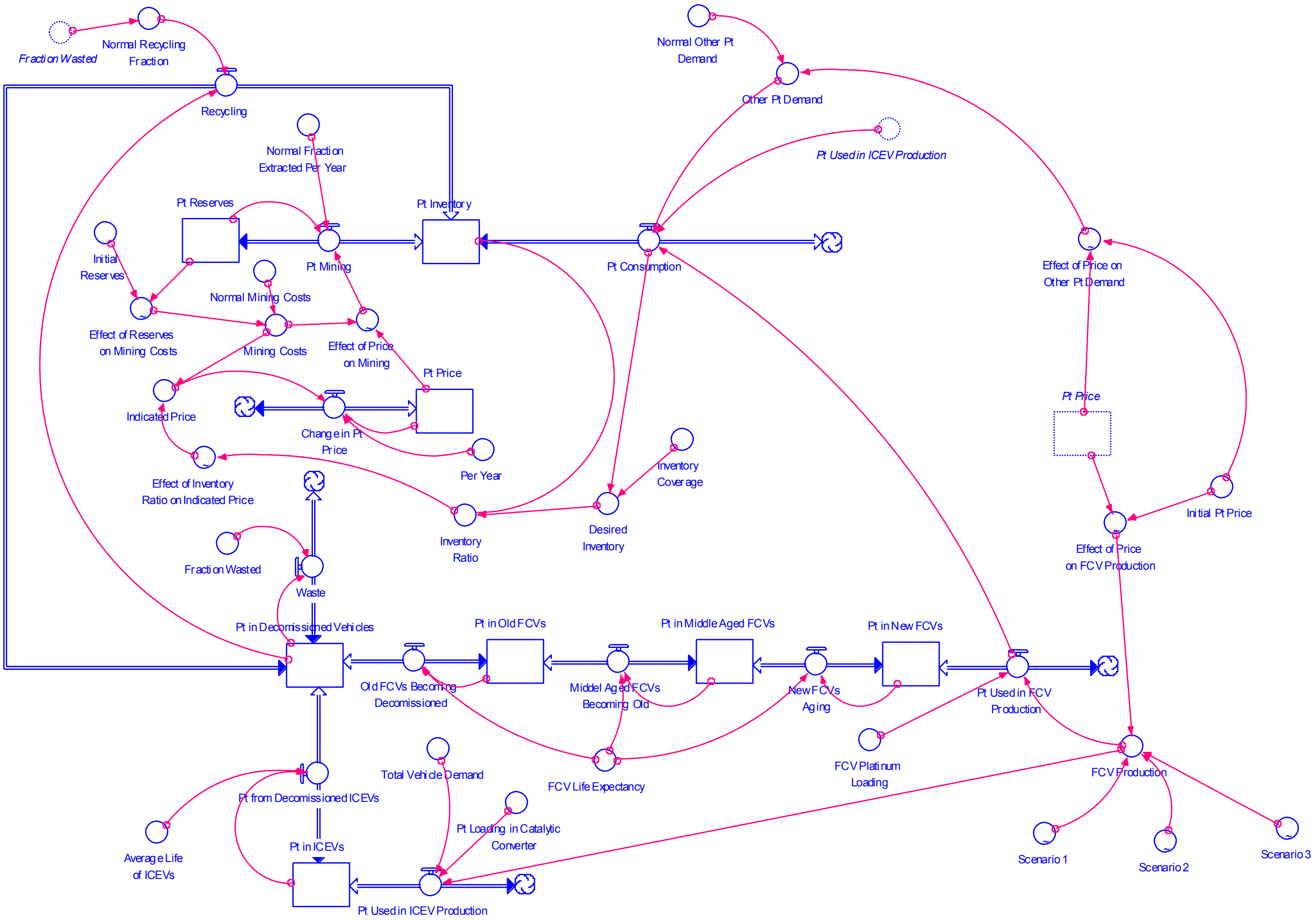

Figure 13: The iThink Model

The first flow, “Pt Used FCV Production” is defined by FCV Production and platinum loading. FCV Production is defined by three different scenarios which are in the form of graphical functions and it is affected by price through a graphical function; this function is a representation of elasticity of demand for FCVs. These three scenarios are based off past research; in particular uses results from the HyTrans model (see Table 3) and fits the data with a Gompertz function. These three scenarios capture different levels of FCV market penetration (half a million, one million, and 2.5 million per year by 2025 for each scenario respectively). FCV platinum loading is multiplied by FCV Production to give the amount of platinum used in FCVs per year. The next three stocks and their respective flows represent the lifecycle of an FCV. It is expanded as a third-order material delay in order to achieve a more discrete delay.

After the lifecycle of the FCV is completed, the FCV is recycled for valuable material. In this model, the interest is only with the platinum recycle. However, not all the platinum can be recycled. Some of it is lost due to inefficiencies during the recycling process. This is represented by “Fraction Wasted”. In addition to FCVs, there is also ICEVs to consider. ICEV production is modeled as a function of Total Vehicle Demand and FCV Production. As established in the computational model, Total Vehicle Demand is assumed to remain at about 8 million vehicles per year. ICEV production is this value minus the FCV production (for each FCV produced, there is one less ICEV that would have been produced). The FCV and ICEV platinum loadings are used to convert the number of ICEVs to an equivalent value in kilograms of platinum. Due to the small amount of platinum in catalytic converters, the delay due to lifespan is just represented as a first-order delay. For this model, the average lifespan for ICEVs was assumed to be 12 years[53].

Recycle is determined simply by subtracting the Fraction Wasted from 1. In addition to the recycle entering the inventory, there is the platinum from mining and the initial value for the platinum

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[53] (Garland, 2007)

inventory. For 2007, approximately 200,000 kg of platinum was mined[54]; this value was used for the initial platinum inventory. Platinum mining is a function of the reserves and price. Price effects mining through a graphical function and models the elasticity of supply. The auxiliary “Normal Fraction Extracted per Year” is the fraction extracted relative to the reserves. The initial value for the reserves is based on a report in the South African Journal of Science by R.G. Cawthorn that estimates 48,000,000 kg of platinum exists worldwide[55]. Using the initial values for the platinum inventory and reserves, the normal fraction extracted per year was determined to be 0.00417. In addition to the effects of price, mining is defined as the reserves multiplied by the normal fraction. Since the reserves have no inflow (limited by what’s in the Earth), the depleting reserves reduce the amount mined as time goes by.

Platinum is added to the inventory through recycling and mining; it is removed through consumption. Platinum consumption is defined as the summation of platinum for FCV production, for ICEV production, and for all other sources. It is important to note that FCV and ICEV production is for the U.S. only while other platinum demand is global (including ICEV production other than the U.S.). Other platinum demand is defined by a normal demand and an elasticity of demand represented by a graphical function. The normal demand is assumed to be 190,000 kg per year. This is slightly less than the 200,000 kg produced because U.S. ICEV platinum demand is considered separately. The platinum for ICEV production is not influenced by price directly since catalytic converters have a small platinum loading when compared to fuel cells.

One of the most vital components of the model is price. The initial value of price is set to $35,000 per kg, based on a 5-year historical price[56]. It’s worth noting that mining costs are also initially set at $35,000 in order to start in equilibrium. The actual mining costs are very close to this value, around $33,000 for the

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[54] (Johnson Matthey PLC, 2008)

[55] (Cawthorn, 1999)

[56] (Johnson Matthey, 2007)

Anglo Platinum mining company based in South Africa[57]. Price is influenced by indicated price, which is simply the mining cost multiplied by a graphical function of inventory ratio. The inventory ratio is the inventory divided by the desired inventory. The desired inventory is defined as platinum consumption multiplied by inventory coverage. This models mining companies trying to maintain an inventory based on current consumption. The inventory ratio acts as a goal-seeking mechanism. If the desired inventory is greater than the actual inventory, prices will increase until the actual inventory is the same as the desired inventory. If the desired inventory is less than the actual inventory, prices will decrease until to the goal (actual equals desired) is reached. However, the inventory does not directly influence price. The ratio influences the indicated price through a graphical function. The indicated price minus the actual price will be the change in price. By having platinum consumption and the platinum inventory influence price through this mechanism, oscillations in price will be smoothed out, making the results clearer to see.

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[57] (Anglo Platinum, 2007)

Chapter 3: Results and Discussion

3.1: Model Limitations

One of the most important simplifying assumptions of this model is that the platinum market operates under pure competition. The inventory mechanism that is used in the model is effective at emulating supply and demand behavior but it does have limitations. The mechanism establishes goal-seeking behavior that results in equilibrium when platinum price equals cost (where the cost includes a normal profit). Under these conditions, an economic profit is never sustained. In other words, the mechanism replicates a purely competitive market. Unfortunately, the platinum market is not likely to be purely competitive. Only a few mining companies operating in South Africa are responsible for the majority of the world's platinum production. With so few companies having such a large market share, it is likely that a cartel could develop. Instead of a purely competitive market, the market is most likely to be dominated by an oligopoly of platinum mining firms. Increasing platinum demand due to FCVs may result in these companies participating in price fixing schemes to increase profits. This is one of the larger weaknesses of the model and could be improved upon in future work.

3.2: Sensitivity Analysis

Sensitivity analysis was performed in the following variables; FCV platinum loading, FCV life expectancy, and the fraction wasted in the recycling process. The model was the most sensitive to the variation of platinum loading. Platinum loading directly influences the demand of platinum, so it is logical that it impacts the price change more significantly than the other two variables. The results from the sensitivity analysis are shown in Figure 14.

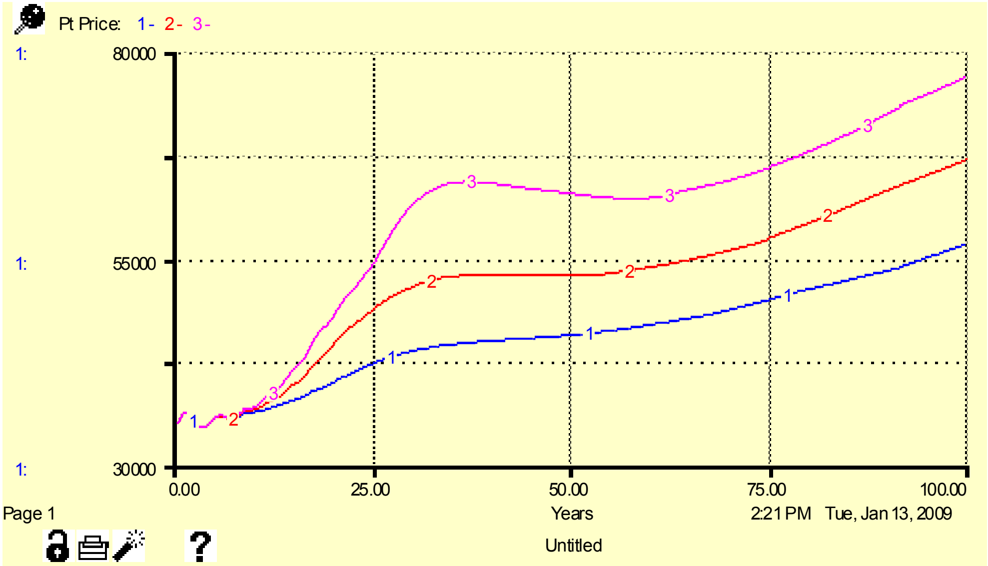

Figure 14: FCV Platinum Loading Sensitivity Analysis

Legend: Line 1: 0.02 kg Pt/FCV Line 2: 0.06 kg Pt/FCV Line 3: 0.10 kg PT/FCV

The desired platinum loading for competitive pricing is about 0.02kg per 100 kW FCV.[58] The current platinum loading is 0.06 kg per 100 kW FCV[59], and the difference of 0.04 kg/FCV in loading will affect the price change significantly in the first quarter of a century. Although the sensitivity to the platinum loading decreases as time progresses, the high increase in the price at the early years may reduce, or even terminate the demand of FCVs. For FCVs to progress as the main land vehicles, it is critical that the platinum loading is reduced to as low as possible.

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[58] (TIAX LLC, 2003)

[59] (Mathias, et al., 2005)

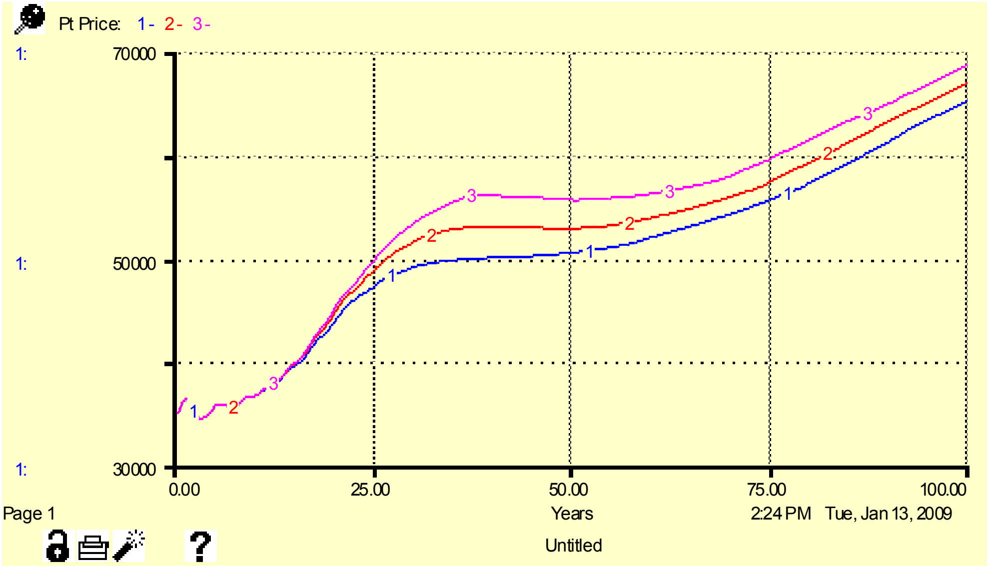

Figure 15: FCV Life Expectancy Sensitivity Analysis

Legend:	Line 1: 5 years	Line 2: 8 years	Line 3: 11 years

The results from the FCV life expectancy analysis seems to be counterintuitive, as one would assume that the longer the life expectancy of the vehicle, the less the price should increase. The results shown in Figure 15 are due to the influence from recycling; when the life expectancy of FCVs is longer, it takes longer time for the platinum to be recycled. While the recycle is delayed proportionally to the life expectancy of FCVs, the annual production of FCVs remain relatively constant or increases, which increases the depletion rate of platinum. The result brings about an interesting point; leasing the vehicles rather than selling them will decrease the price of platinum, since the life expectancy would be shorter with more frequent remodeling of the car.

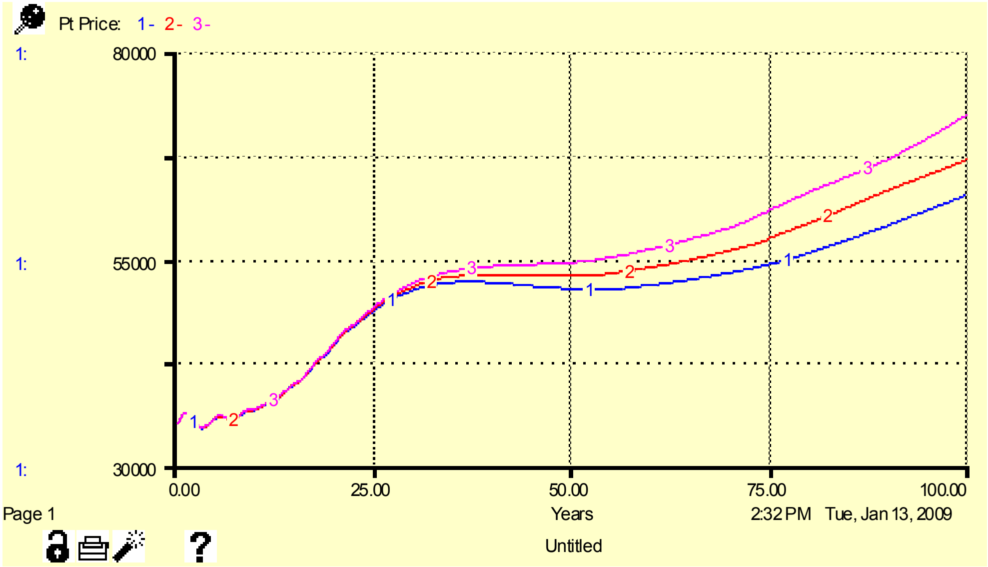

Figure 16: Fraction Wasted in Recycle Sensitivity Analysis

Legend: Line 1: 0.05 Line 2: 0.10 Line 3: 0.15

Variation in the fraction wasted had little effect in the early stages of FCV growth. This is due to the fact that there is little recycling during the period of time (most FCVs are still on the road). However, as time continues, the efficiency of recycling starts to have a more significant impact on price as shown in Figure 16.

3.3: Extreme Value Testing

Extreme value testing is useful in determining how robust the model is under a wide variety of conditions. It's good for determining any flaw in model logic that might have gone unnoticed if extreme values were not tested.

3.3.1: Fraction Wasted

For this test, fraction wasted was set to 100%. While highly unrealistic, the model still should behave logically. The results of this test can be seen in Figures 17 and 18.

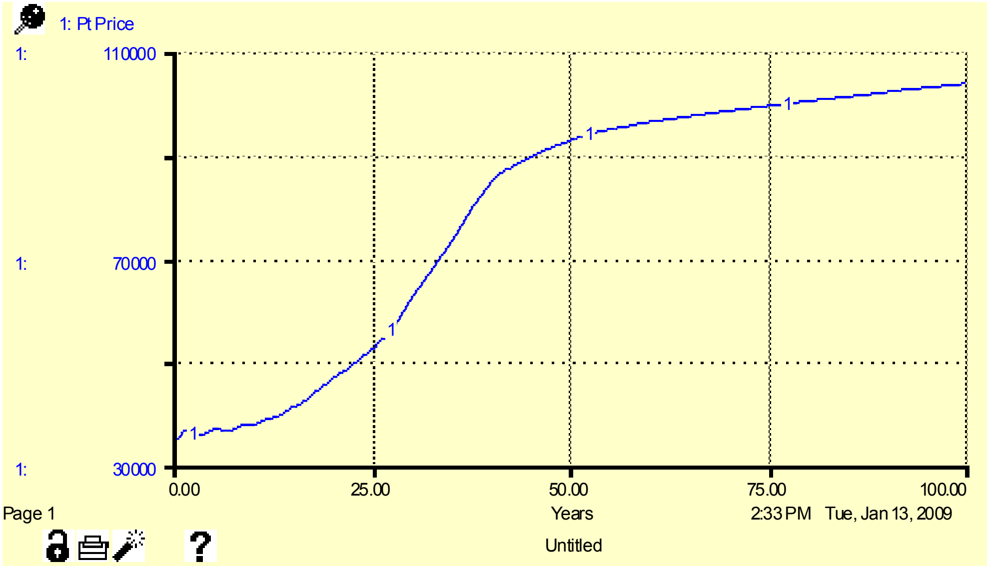

Figure 17: Graph of Pt Price with no recycling

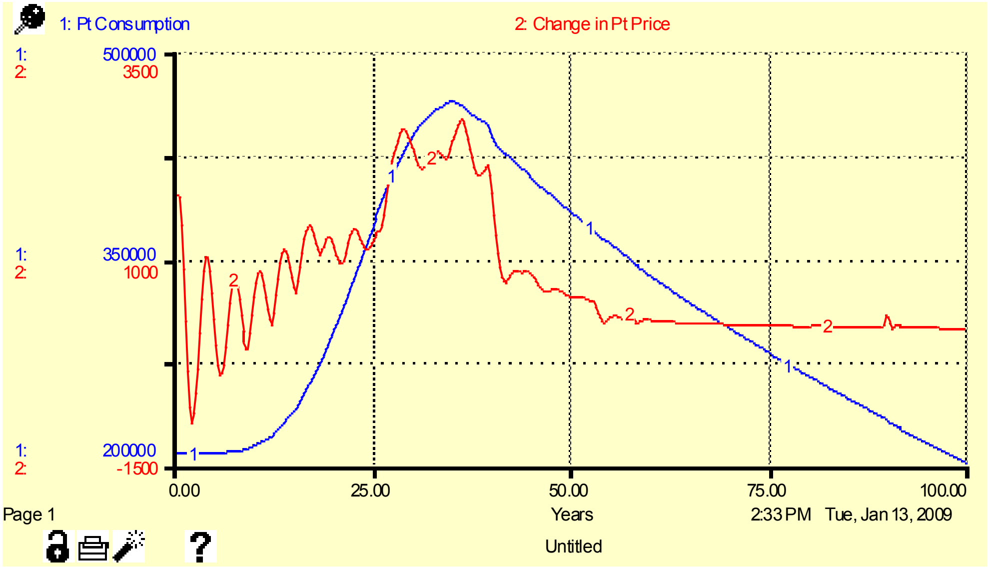

Figure 18: Pt Consumption and Change in Pt Price with no recycling

The results confirm that the model functioned logically. Without any recycle, the price of platinum quickly increases as the only source of platinum is from mining. The sudden jump in price in Figure 17 is followed by a drastic drop in consumption in Figure 18 due to a lack of demand at this high price point.

With the fall in demand, price begins to level off, but still remains extremely expensive at about $104,000 per kg by the year 100.

3.3.2: No FCV Production

With no FCVs being produced, the price of platinum should increase steadily due to depleting platinum reserves. However, there should be no dramatic price increases/decreases as platinum demand from other sources remains constant (one of our simplifying assumptions). The results of Figure 19 reflect this behavior:

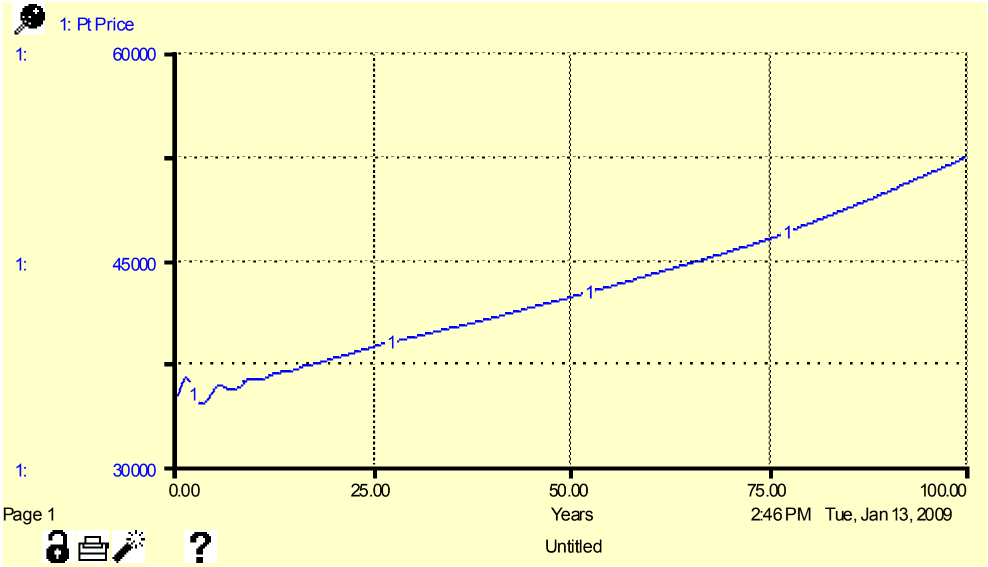

Figure 19: Pt Price at no FCV Production

3.4: Scenario Analysis

After the sensitivity analysis and extreme value testing, the development of possible scenarios can begin. Three scenarios were tested: the “worst” case, “best” case, and “middle ground” case. The values for all three scenarios are summarized in Table 1.

Table 1: Scenario Analysis

	Worst Case	Middle Ground	Best Case
Normal Change in FCV Population	Scenario 3 (rapid growth)	Scenario 2 (steady growth)	Scenario 1 (slow growth)
FCV Platinum Loading	0.100 kg	0.050 kg	0.020 kg
FCV Life Expectancy	12 years	8 years	5 years
Fraction Wasted	0.15	0.10	0.05

It's worth noting that the "best" and "worst" case scenarios are defined as the best and worst case scenarios for platinum prices. For example, the "best" case has an average FCV lifespan of only 5 years. Looking at the bigger picture, such a short lifespan is bad. However, in terms of platinum price, a short lifespan means a shorter time before the platinum is recycled; this reduces the price of platinum. While the best and worst case scenarios are not very realistic, they proved a lower and upper bound on platinum price.

The results from the simulations show quite a large difference between the worst and best case scenarios (see Figure 20). Under the worst case scenario, prices skyrocket to $78,724 per kg in the first 30 years. Afterwards, recycling begins to kick in, resulting in a dip. Prices start to increase again as reserves diminish and it becomes more difficult to mine. The best case scenario has very little impact on the price. Instead of jumping to nearly $79,000, the price gradually rises to $41,967 in the first 30 years. Then the price rises even more gradually, starting to approach the "No FCV Production" line. The middle ground scenario has a noticeable increase in price by the year 30. At this point, the price is $50,146. For comparison purposes, the "No FCV" case has a platinum price of $39,433 per kilogram at year 30.

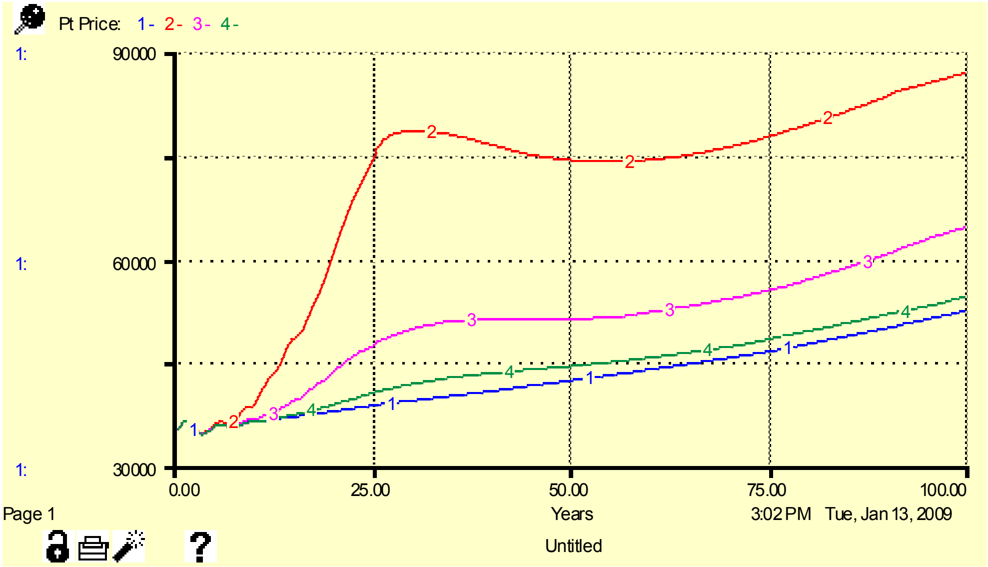

Figure 20: Platinum Price at Best through Worst Cases

Legend: Line 1: No FCV Production Line 2: Worst Case Line 3: Middle Ground Line 4: Best Case

3.5: Other Scenarios

Four other scenarios were tested using this model. The scenarios are as follows: improvements in platinum loading as price rises, the discovery of new platinum reserves, a limitation on platinum mining, and a worldwide FCV population.

3.5.1: Improvements in Platinum Loading

This scenario operates under the assumption that as prices increase, there is more incentive to develop technologies that can reduce the amount of platinum needed per vehicle. In other words, as the price of platinum increases, the amount of platinum needed per vehicle decreases. This will decrease the demand of platinum and decrease the price of platinum, forming a balancing loop. The scenario parameters are seen in Table 2.

Table 2: Improvements in Platinum Loading

Variable	**Value**
Normal Change in FCV Population	Scenario 2
FCV Platinum Loading	Initially set at 50 grams (0.05 kg)
FCV Life Expectancy	8 years
Fraction Wasted	0.10

The results of the simulation can be seen in Figure 21. Price has little effect on the platinum loading during this period. However, as platinum prices continue to rise due to platinum reserves' depletion, the loading should become much smaller.

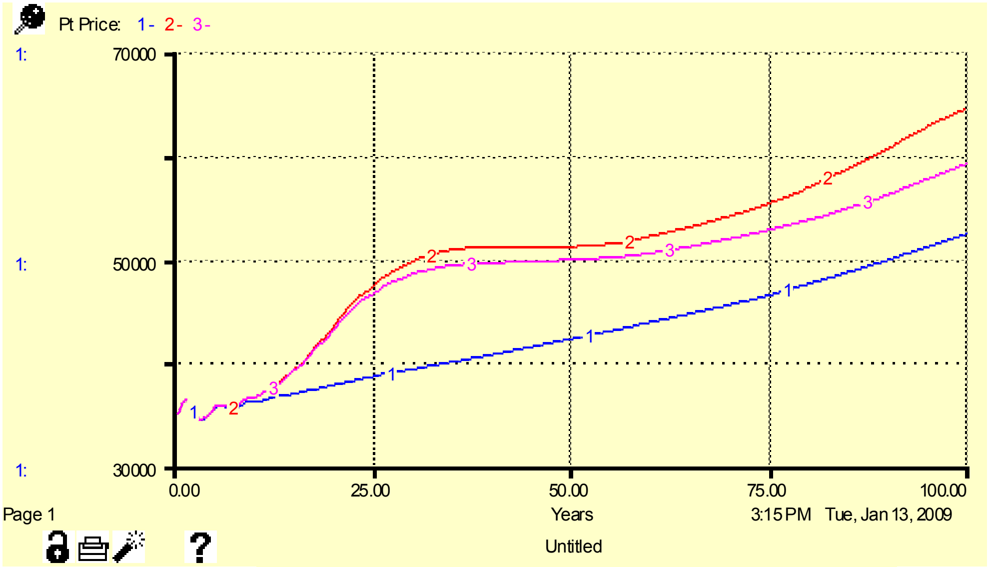

Figure 21: Platinum Price when Pt Loading Decreases with Price

Legend: Line 1: No FCV Production Line 2: Constant FCV Loading (0.05 kg Pt)
Line 3: Price/Loading Relation (0.05 kg initial loading)

3.5.2: The Discovery of New Platinum Reserves

In this scenario, new platinum reserves are discovered. The parameters for this scenario are the same as the previous scenario except that FCV platinum loading remains constant at 50 grams. It is assumed that

50,000 kg of platinum will be discovered per year. As can be seen from the results of Figure 22, when new Pt discoveries are made, the price is increases less dramatically.

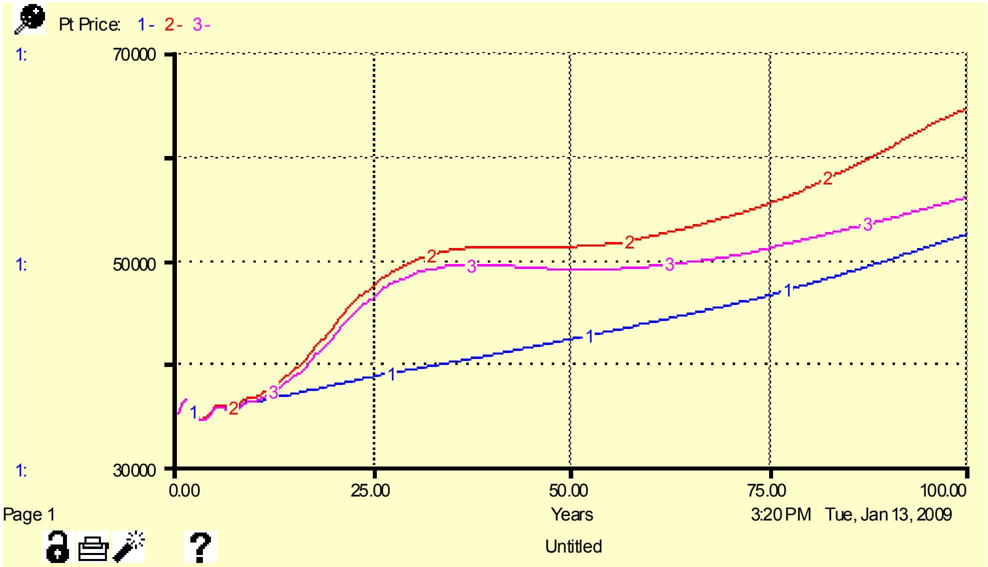

Figure 22: Effect of New Constant Yearly Reserve Discoveries on Pt Price

Legend: Line 1: No FCV Production Line 2: No Reserve Discovery
Line 3: Reserve Discovery

3.5.3: Limitations on Platinum Mining

In January of 2008, a major power crisis hit South Africa. South Africa's state-owned power supply company could not meet the electricity demand of the nation. As a result, many platinum mines were operating way below operating capacity or even not producing for extended periods of time. The result was a skyrocketing platinum price (see Figure 23).

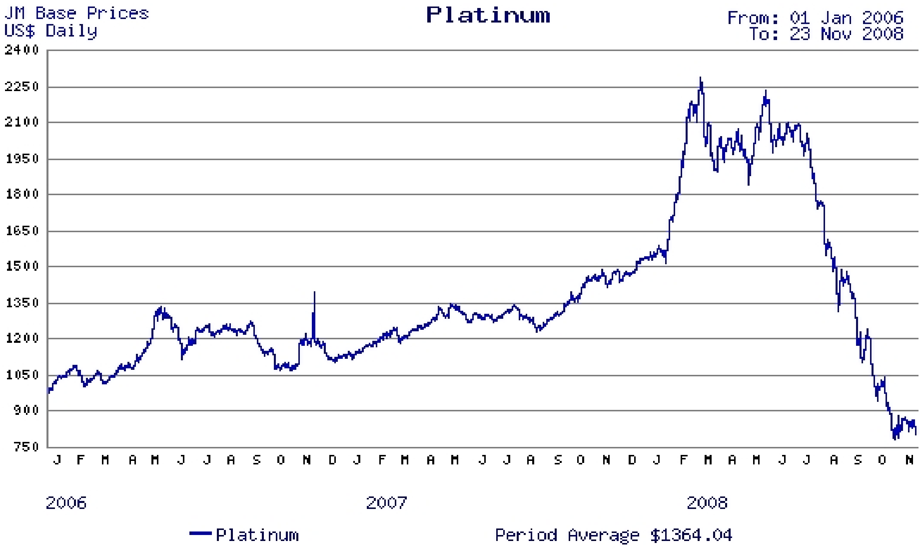

Figure 23: Platinum Price since 2006[60]

Since then, prices have leveled off and then dramatically declined. However, what would happen if there was another power crisis (or any crisis that produced similar results)? What would happen if this crisis were to occur during peak FCV production? This is the focus of the next simulation.

In order to simulate a drastic drop in production and then a drastic increase in production once the crisis is resolved, two step functions were used in an auxiliary (called “Capacity Utilization”). The auxiliary is seen below:

$$Capacity\ Utilization = 1 - [STEP(0.5,10) - STEP(0.5,12)]$$

The auxiliary was then multiplied by the Pt Mining stream. This results in a sudden decrease to half the normal capacity utilization for two years. At the end of the two years, capacity utilization jumps back to normal.

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[60] (Johnson Matthey, 2007)

The results of the model show similar results to real life. When production was drastically reduced in January of 2008, prices soon shot up. A few months later, in July, the price began to fall as platinum mines began to utilize more of their capacity. The resulting flux of platinum on the market reduced prices. The model shows a similar spike in prices. After this initial jump, the price oscillates until it eventually follows the case where there was no crisis. In the long run, such an event would not have a significant impact on price, however, in the short run, there are dramatic price fluctuations. The results from the model can be seen in Figure 24.

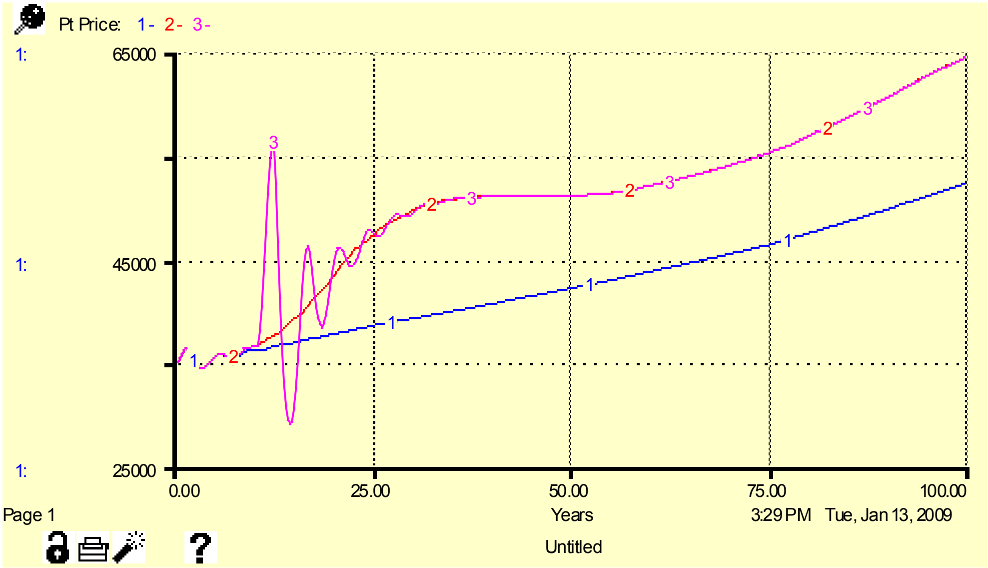

Figure 24: Pt Price as a Consequence of a Platinum Crisis

Legend: Line 1: No FCV Production Line 2: No Limits on Production
Line 3: Two Year Crisis Resulting in Half the Normal Production

3.5.4: Worldwide FCV Population

The previous scenarios operated under the assumption that only the United States will adopt Fuel Cell technology, which based on population constitutes only 4.6% of the entire world population. In reality, it is likely that other nations will use fuel cell technology. To consider worldwide demand of FCVs, slight alterations to the model were made. The total vehicle demand was changed from 8 million vehicles per year to 53 million vehicles per year[61].

With the model adjusted for a worldwide scenario, five different runs were considered. It was noticed that the platinum price would increase dramatically the first 25 years and then it would level off as soon as the recycling feedback begins to gain strength. These results are shown in Figure 25.

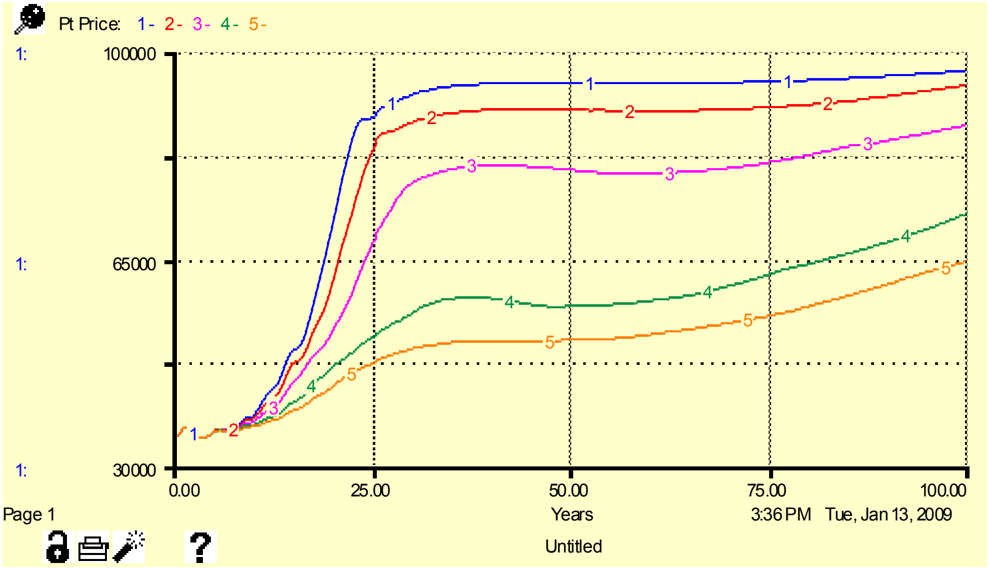

Figure 25: Pt Price based on different percentages of worldwide technology adoption

Legend:
Line 1. 100% worldwide adoption.
Line 2. 75% worldwide adoption.
Line 3. 50% worldwide adoption.
Line 4. 25% worldwide adoption.
Line 5. 15% worldwide adoption.

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[61] (2007 Production Statistics, 2007)

Chapter 4: Conclusions and Recommendations

Six different scenarios were tested using the model. These scenarios varied from generic “best” and “worst” case scenarios to specific circumstances and events that may have an effect on platinum and FCV market. It is important to note that the worst and best case scenarios do not reflect realistic outcomes; instead, they determine the maximum and minimum price range that can be expected. Depending on the conditions, it may or may not be feasible to develop fuel cell vehicles in the United States.

4.1: Worst Case

In the worst case scenario, there is a large platinum loading (100 grams) and an inefficient recycling process (85% efficient). In addition, the lifespan of FCVs is assumed to be just as long as ICEVs (12 years). This creates a longer delay before recycling begins to flood the platinum market. As a result, prices stay higher for a longer period of time. Finally, it is assumed that the growth of the FCV market is quite rapid. Under these extreme conditions, the price of platinum rises quite dramatically to nearly $79,000 per kg by the year 30 (2038). The price then falls due to recycling. However, by 2060, prices begin to rise again due to a shrinking reserve. Platinum reserves decrease from 48 million kg to around 17.2 million kg over the course of 100 years. In addition, the price of platinum reached $85,000 per kg by the year 100 (see Figure 26).

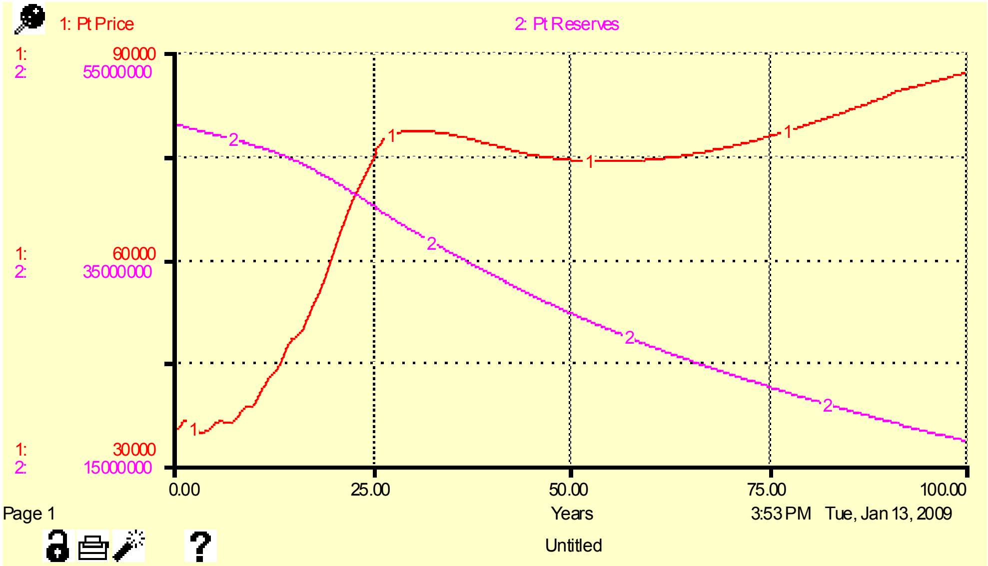


Figure 26: Platinum Price and Reserves based on the Worst Case Scenario

By 2038 (30 years), with the price of $78,724 per kg of platinum and a loading of 100 grams, the cost of platinum for a fuel cell vehicle would be $7,872. This is around three times the cost of a complete internal combustion engine. The costs due to platinum alone would inhibit the development of fuel cell vehicles. The decrease in reserves is also concerning. Within 100 years, the platinum reserves would be depleted by 64% from 2008. However, most of the depletion would be caused by other sources of demand since FCV recycling would largely be self-sustaining. The worst case scenario is infeasible; the cost of platinum is too high and there is a large decrease in platinum reserves.

4.2: Middle Ground

In the middle ground scenario, there is a platinum loading of 50 grams per vehicle, a more realistic lifespan of 8 years, a 90% efficient recycling process, and steady market growth. Compared to the worst case scenario, the price of platinum is only about $50,146 by 2038 instead of $78,724 (see Figure 27). At this price and at a loading of 50 grams per car, the cost of platinum per vehicle would be $2,507. This cost is comparable to a complete internal combustion engine. While it is still expensive, it is much more feasible than the worst case scenario. If the other components of the fuel cell, particularly the Nafion membrane, decrease in price due to increased production efficiency, then it could be possible to overcome the platinum price barrier. The reserves also depleted less quickly than the worst case scenario. Instead of decreasing to 17.2 million kg, the reserves decreased to 24 million kg. However, in 100 years, the price of platinum is quite high, near $65,000 per kg. By then, however, new technology could dramatically change the nature of FCVs or there could be a completely different alternative to FCVs. Overall, the middle ground scenario is feasible only if the other components of an FCV have dramatic reductions in price.

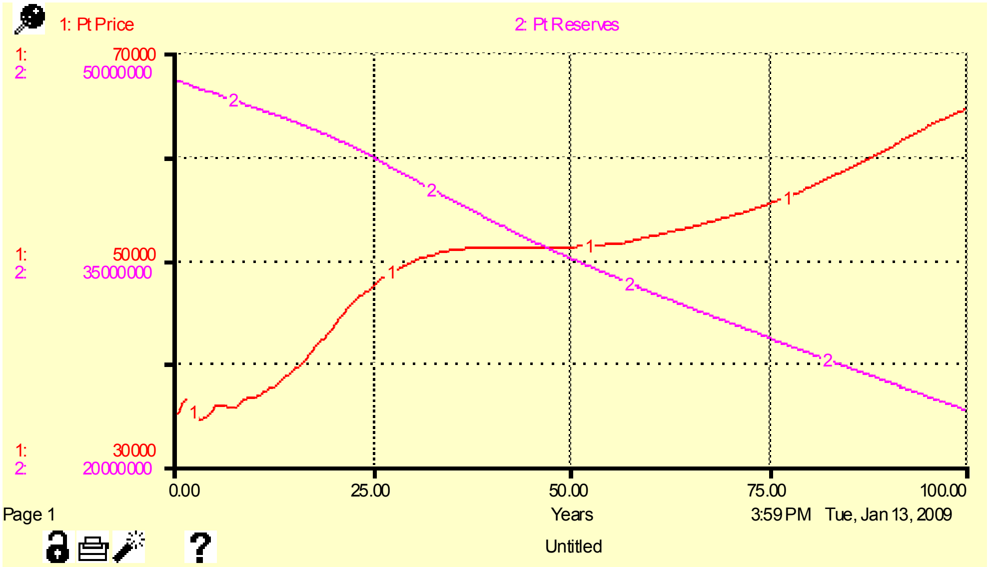


Figure 27: Platinum Price and Reserves based on the Middle Ground Scenario

4.3: Best Case

For the best case scenario, the platinum loading is only 20 grams per vehicle, recycling is efficient at 95%, the lifespan of FCVs is short, resulting in a smaller delay before recycling takes effect, and FCVs are slowly introduced to the market. With these parameters, the price of platinum only reaches about $42,000 by 2038 (see Figure 28). Using the 20 gram loading, the cost of platinum per FCV is only $840. While still a significant component of the cost, it probably won’t inhibit the development of FCVs, especially when considering likely price reductions in Nafion. The platinum reserves decreases to 28 million kg within 100 years; this difference is not as significant as the difference between the worst case and middle ground, but it is still worth mentioning. In 100 years, the price of platinum would be about $54,500. At a 20 gram loading, the price per vehicle is still reasonable at $1090. The best case scenario is feasible at these conditions.

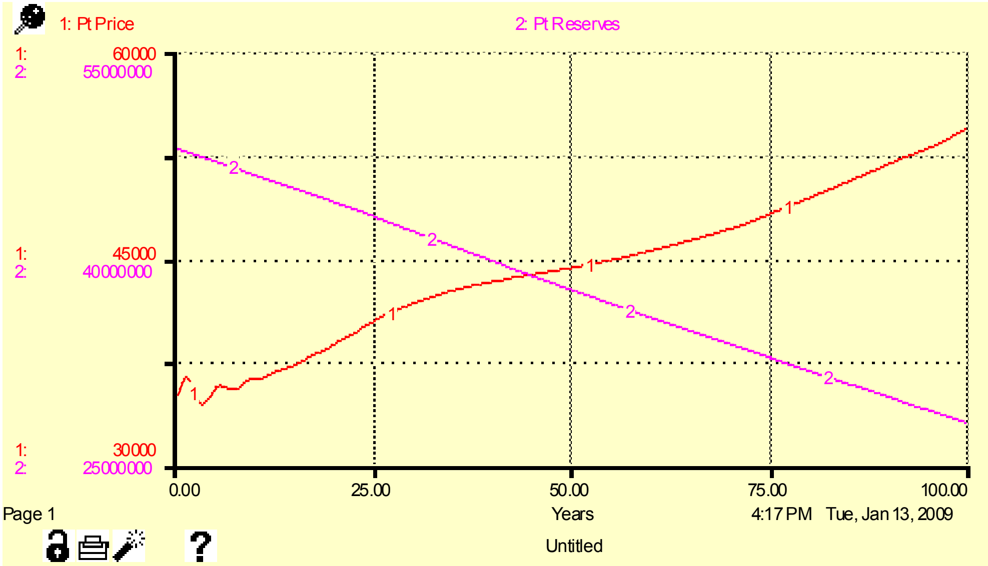


Figure 28: Platinum Price and Reserves based on the Best Case Scenario

4.4: Other Scenarios

In addition to the best through worst case scenarios, a few other scenarios were looked at. The model was modified to take these scenarios into account (see Appendix B, Figure 35). These scenarios include improvements in platinum loading with price, the discovery of new platinum reserves, and a supply crisis where platinum mines only produce half normal output due to a disaster.

Improvements in platinum loading with price are based on the notion that the higher the price of platinum, the more incentive there is to develop technology that reduces the platinum required. This scenario is largely dependent on defining factors such as the elasticity of technological breakthroughs and imposing technological limits: after a certain point, it becomes impossible to make improvements due to physical constraints. For this model, a graphical function was defined so that when the price of platinum is twice its initial cost, the platinum loading will be reduced by almost half. The effect of this scenario is noticeable but not very dramatic.

The discovery of new platinum reserves has a large impact on the model. In particular, the discovery of new reserves would significantly reduce the depletion of the reserves. Assuming a constant discovery of 50,000 kg per year, the reserves would only be reduced to 28.6 million kilograms after 100 years (see Figure 29). This is comparable to the "best case" scenario, where the reserves were depleted to 28 million. The platinum price by 2038 would be $49,000 which is a little less than the middle ground scenario. A steady discovery of new reserves would result in a more sustainable scenario.

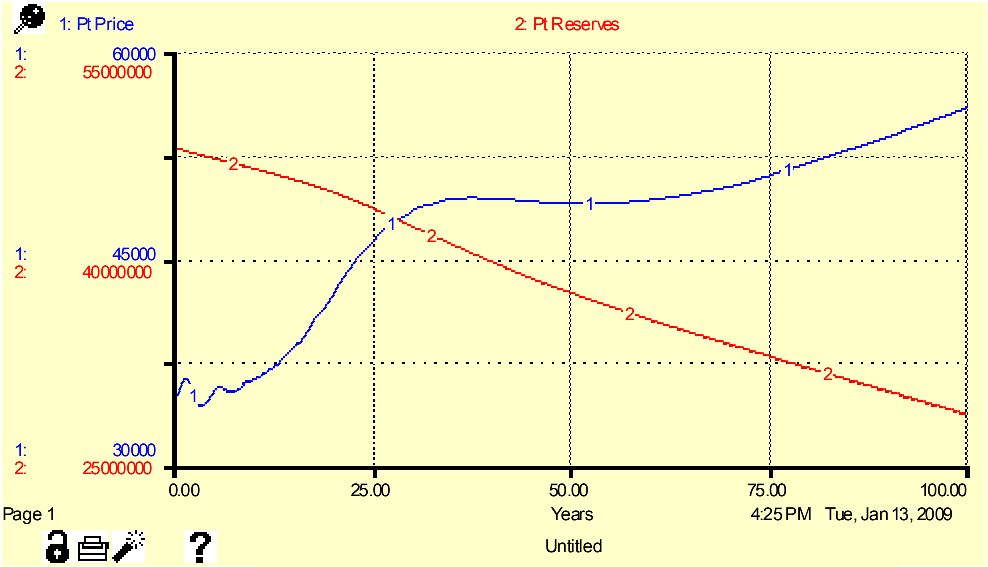


Figure 29: Platinum Price and Reserves Considering the Discovery of New Reserves

The third scenario is the platinum crisis; a situation where platinum mining is reduced due to a natural or man-made disaster. In an event similar to the power crisis in South Africa, the price of platinum would experience dramatic fluctuations in price over the course of the crisis and even a few years beyond the crisis (see Figure 24). However, in the long-run, prices returned to the control case where there was no disaster. Therefore, such a crisis would probably have little effect on FCV market, especially in the long run.

The fourth scenario, worldwide production was used to see how the market would respond to global FCV adoption. With 100% global adoption, the price of platinum reached $93,500 per kilogram within 30 years. It wasn’t until a market penetration of 15% was modeled that the scenario started to look feasible. At 15%, this price reached $50,000 within 30 years, proving much more feasible, but still a significant challenge.

4.5: Recommendations

After developing the system dynamics model and establishing several scenarios, it is clear that the development of fuel cell vehicles in the United States is largely dependent on other factors such as platinum loading, FCV life expectancy, recycling efficiency, and how rapid FCVs are introduced to the market. Under the worst conditions, the development of the FCV market seems infeasible as the price of platinum per FCV is more than twice that of a conventional internal combustion engine. However, the FCV market isn’t heavily limited by platinum in the middle ground scenario. It is still expensive, but it could be overcome by declining prices for other fuel cell components such as Nafion.

The middle ground scenario provides a basis for establishing goals with regard to fuel cell technology. If platinum loadings are 50 grams or lower, the average life is around 8 years, recycling efficiency is able to achieve 90% or better, and FCVs are not rapidly introduced into the market, then the platinum barrier can be surmounted as long as the price of other FCV components is reduced.

Worldwide production of FCVs is possible, but only on a small scale. FCV can only reach about 15% of global vehicle production before the price of platinum severely hinders production.

Appendices

Appendix A: Platinum Model Testing

STEP Function

During this test, step functions of various magnitudes were tested. The step function instantaneously increases a variable to a specified value, where it remains constant for the rest of the run. The function was used on FCV production. Platinum Price was used as a gauge to see how the step affected the model. All the step functions are initiated on the 15th year of the model. The result is shown in Figure 30.

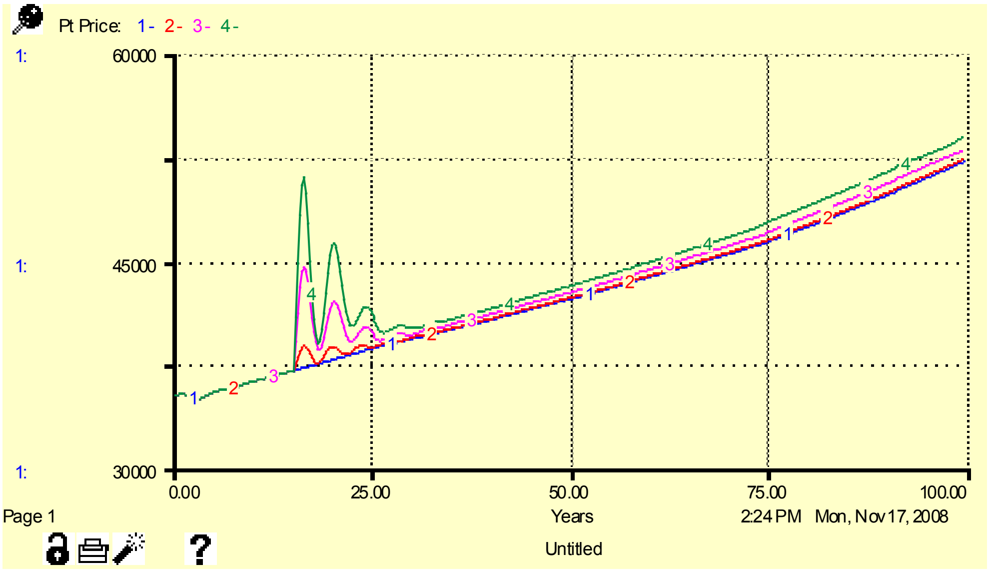


Figure 30: Step Function in FCV Production and its Effect on Platinum Price

Legend:	Line 1: No STEP (no FCV production)	Line 2: 10,000 kg/yr STEP
	Line 3: 50,000 kg/yr STEP	Line 4: 100,000 kg/yr STEP

When the step function first increases instantaneously, the price also jumps dramatically. Since the step function remains constant after that, recycling is able to kick in and the price decreases. There are oscillations due to delays that are amplified by the rapid increase in FCV production.

RAMP Function

The RAMP function allows a variable to take on linear growth. The initial time when the RAMP function should begin and the slope are the inputs. The RAMP function was applied to FCV production and began at year 0 (see Figure 31).

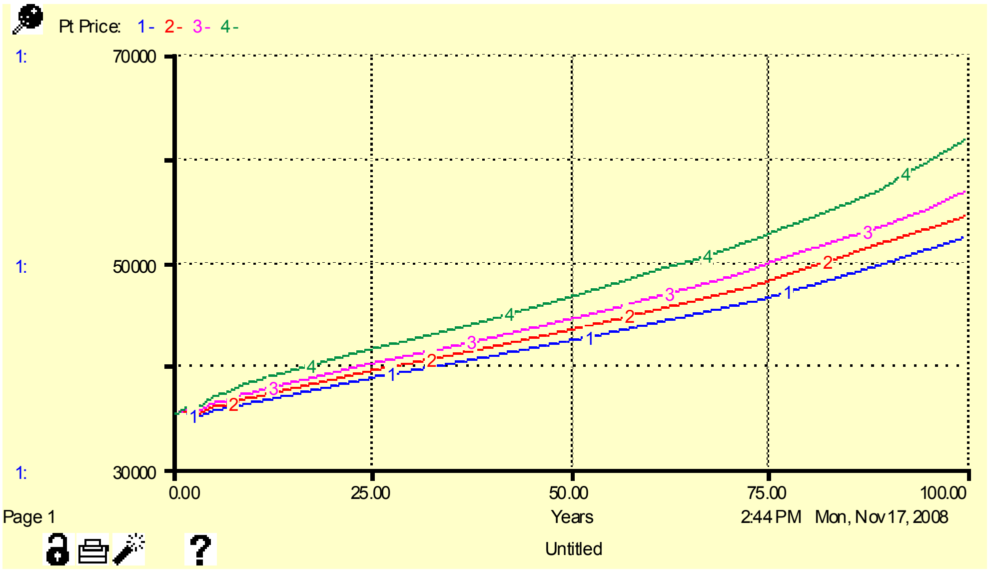


Figure 31: Ramp Function in FCV Production and its Effect on Platinum Price

Legend: Line 1: No RAMP (no FCV production) Line 2: RAMP with slope of 1,000
Line 3: RAMP with slope of 2,000 Line 4: RAMP with slope of 4,000

Unlike the STEP function, there is no "bump" in Pt Price. Since platinum production is always increasing by the same amount each year (as defined by the slope), recycling is never able keep up with platinum production. In both the STEP and RAMP functions, the price is generally increasing with time. This is due to depletions of the platinum reserve, making it harder to mine.

Gompertz Function

To get a closer estimation of how FCV market penetration might actually occur, the Gompertz function was used. This function is defined as:

$$y(t) = ae^{-be^{-ct}}$$

Three variations of the Gompertz function were used:

$$y(t) = 8{,}000{,}000\, e^{-e^{-0.11t+1.9}}$$

$$y(t) = 8{,}000{,}000\, e^{-e^{-0.15t+2}}$$

$$y(t) = 8{,}000{,}000\, e^{-e^{-0.2t+2.2}}$$

The functions are ordered from the slowest growth to the most rapid growth. The slowest growth takes about 70 years to reach saturation. The second slowest takes about 50 years while the fastest takes only 35 years. The functions can be seen in Figure 32.

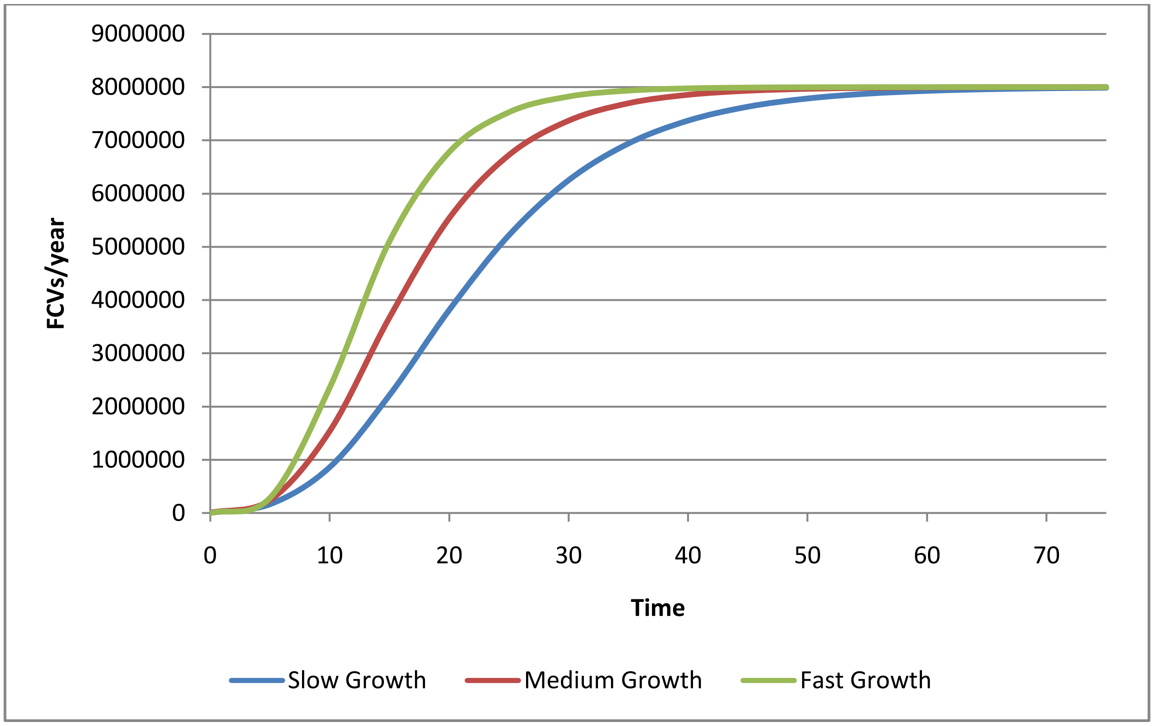


Figure 32: FCV Annual Growth Estimated with the Gompertz Function for Testing Purposes

The results of the testing can be seen in Figure 33. Each test was performed with a loading of 50 grams per FCV.

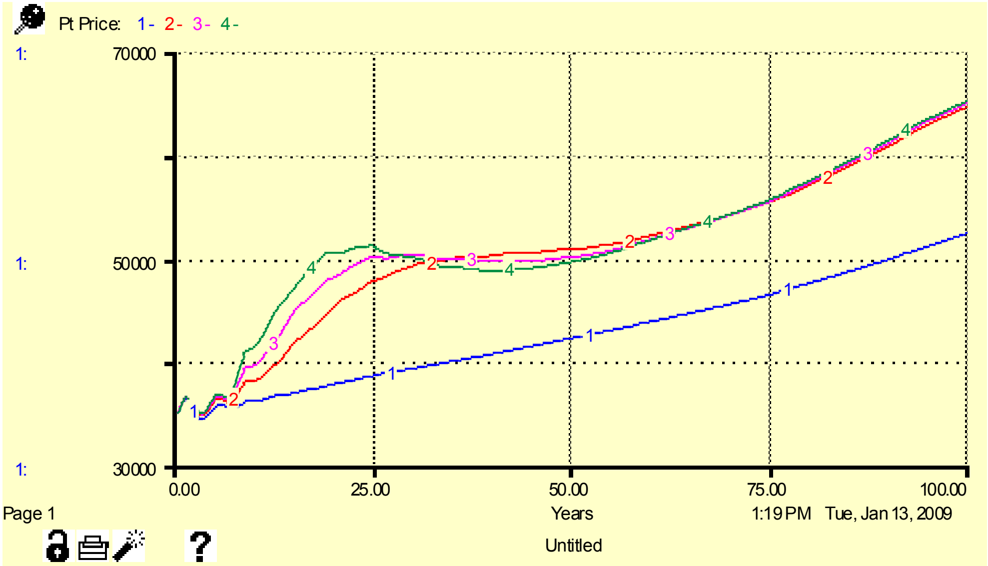


Figure 33: Platinum Price based on FCV Growth Estimated by the Gompertz Function

Legend: Line 1: No FCV production Line 2: Slow Growth Line 3: Medium Growth
Line 4: Fast Growth

As expected, the fast growth results in the most dramatic price increase followed by the medium and then the slow growth. What's not very intuitive is the sharp decrease in price. After hitting the peak price, the fast growth price actually falls lower than the slow and medium growth prices. This is due to recycling. Since FCVs are produced in a shorter period of time with the fast growth, recycling is able to catch up to production in a shorter period of time. The resulting quick burst of production followed by a quick burst of recycling results in a sharp increase in price followed by a sharp decrease in price.

Establishing FCV Production

Current sources regarding FCV Production are limited in their predictions. The research that currently has been done usually only considers FCV production in the next 20-30 years. Unfortunately, this time frame is not large enough to reach market saturation. As a result, current estimates had to be extrapolated to saturation. Using results from the HyTrans model (see Table 3); known data was extrapolated using the Gompertz function.

Table 3: HyTrans Model Predictions

Scenario 1	Scenario 2	Scenario 3
500,000 FCVs/year by 2025	1,000,000 FCVs/year by 2025	2,500,000 FCVs/year by 2025

Using this data, a Gompertz function was used to fit the points for each scenario. The resulting equations can be seen below (also see Figure 34).

$$Scenario\ 1: y(t) = 8{,}000{,}000\ e^{-e^{-0.087t+2.5}}$$

$$Scenario\ 2: y(t) = 8{,}000{,}000\ e^{-e^{-0.105t+2.5}}$$

$$Scenario\ 3: y(t) = 8{,}000{,}000\ e^{-e^{-0.140t+2.5}}$$

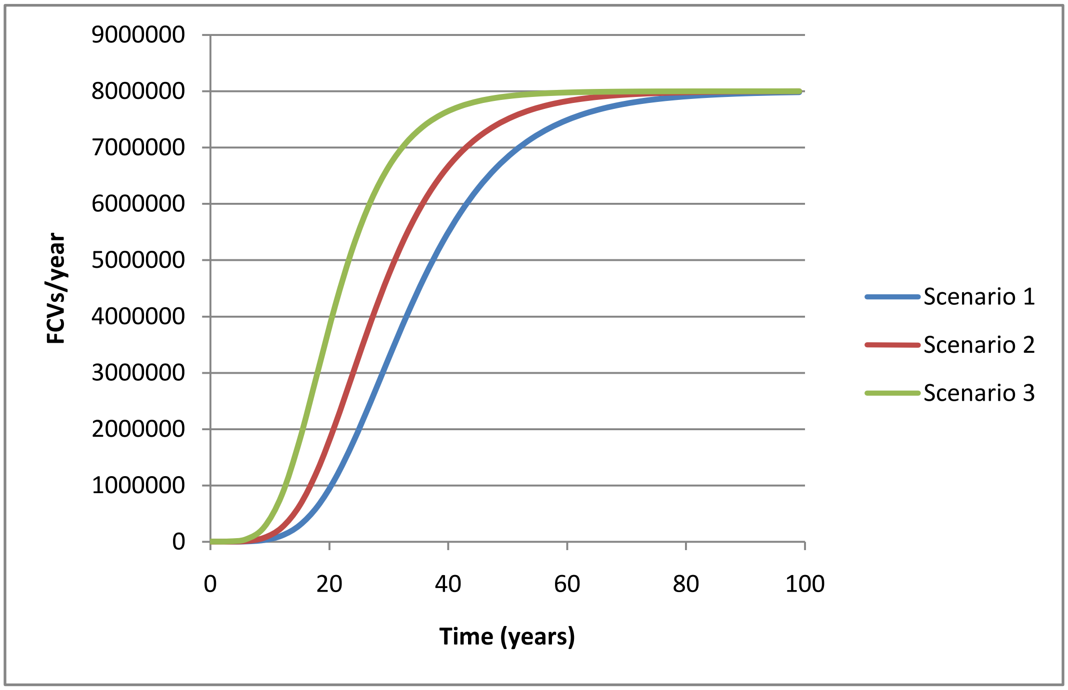


Figure 34: Predicted Annual FCV Growth Based on the HyTrans Model Fit to the Gompertz Function

Appendix B: The Other Scenarios Model

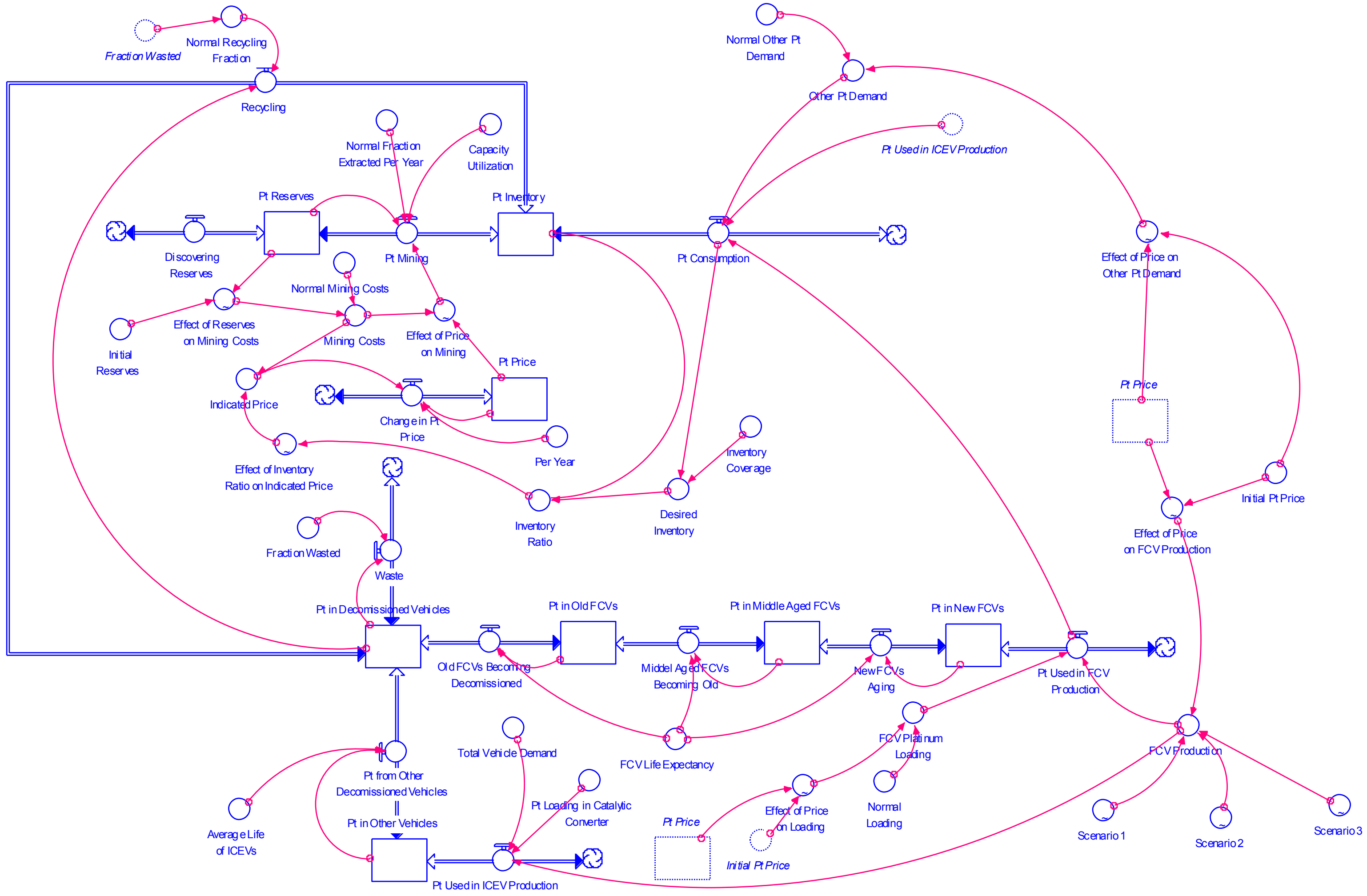


Figure 35: The Other Scenarios Model

Appendix C: Model Equations & Graphical Functions

Based on the system dynamics model programmed with iThink we reproduced the diagram as seen in Figure 36, for a better understanding of the model.

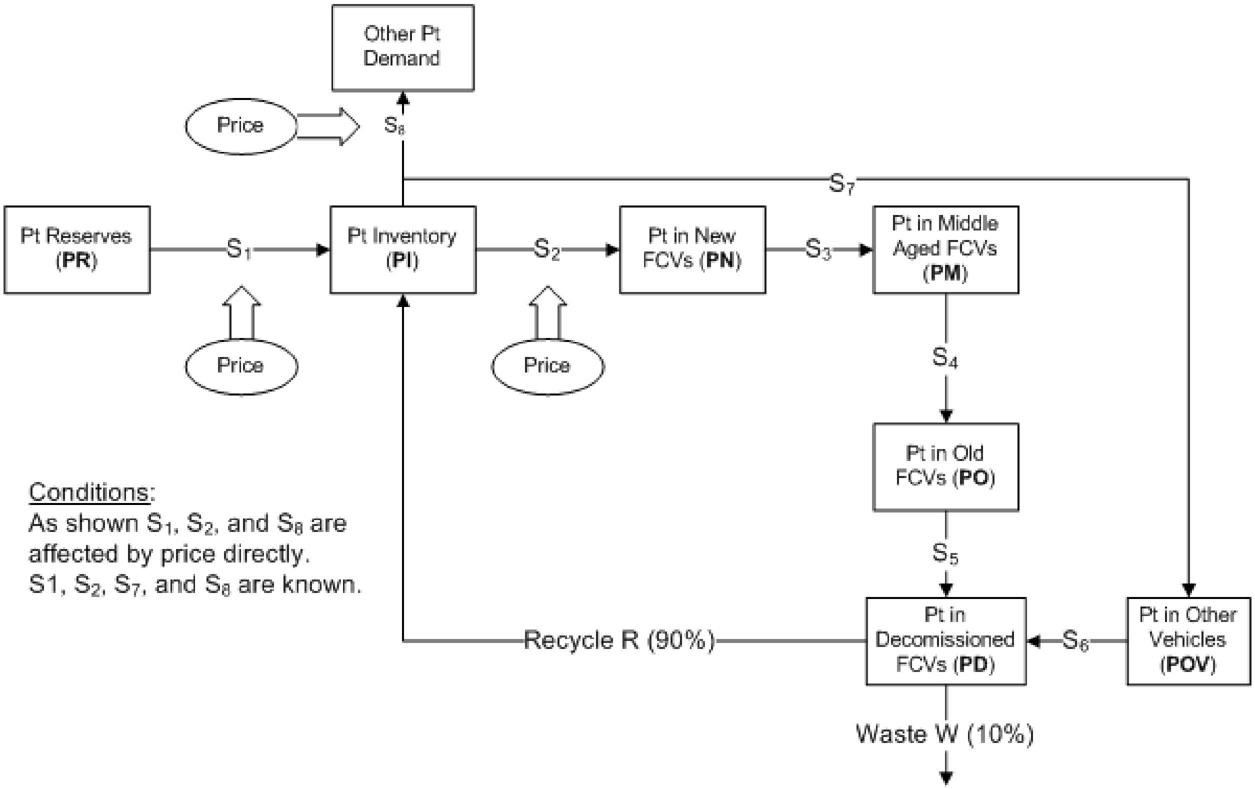


Figure 36: Block Diagram of System

The amount of platinum flowing through each stream, represented with arrows that connect two blocks, is represented by the following equations. Each equation is based on the theory followed for the design of the system dynamics model. The units for each stream are [kg Pt/year].

$S_1 = PR * 0.00417 * f(Price)$ where $f(Price)$ represents the effect of price on mining.

$S_2 = 0.06 * g(time) * h(Price)$ where $g(time)$ represents the trend in FCV population over the years in which case we will be considering three scenarios, and $h(Price)$ which represents the effects of price on FCV production.

$$S_3 = \frac{PN}{7/3}$$

$$S_4 = \frac{PM}{7/3}$$

$$S_5 = \frac{PO}{7/3}$$

This splitting of the Pt used in FCVs was done for the simple reason that we could have a smoother trend of the amount of platinum used as a function of time.

$$S_6 = \frac{POV}{12}$$

$$S_7 = 8{,}000{,}000 * 0.002 - \frac{0.6 * PO}{7/3}$$

$S_8 = 190{,}000 * k(Price)$ where $k(Price)$ represents the effect of price on other Pt demands.

$$R = PD * 0.9$$

$$W = PD * 0.1$$

One of the predefined functions mentioned above (function g) has time as an input. iThink uses time values from 0 to the value put by the user at increments of 0.25 years. However, the rest of the functions use Price as a variable. The relation that governs price is:

$$\frac{dP}{dt} = 35{,}000 * l(Pt) * m(\frac{PI}{S_2})$$

where P represents the platinum price, $l(Pt)$ is the function representing the effect of Pt reserves on mining costs, and $m(\frac{PI}{S_2})$ the effect of inventory ratio on price. The inventory ratio corresponds to the ratio between the Pt Inventory (PI) and the output stream from Pt Inventory, S_2. The price input of these functions was then normalized for each specific case based on data found in the literature.

The mass balances for each of the blocks are as follows:

$$\frac{dPR}{dt} = -\,PR * 0.00417 * f(Price)$$

$$\frac{dPI}{dt} = PR * 0.00417 * f(Price) + PD * 0.9 - 0.06 * g(time) * h(Price) - \left[8{,}000{,}000 * 0.002 - \frac{0.6 * PO}{\frac{7}{3}}\right] - 190{,}000 * k(Price)$$

$$\frac{dPN}{dt} = 0.06 * g(time) * h(Price) - \frac{PN}{7/3}$$

$$\frac{dPM}{dt} = \frac{PN}{7/3} - \frac{PM}{7/3}$$

$$\frac{dPO}{dt} = \frac{PM}{\frac{7}{3}} - \frac{PO}{\frac{7}{3}}$$

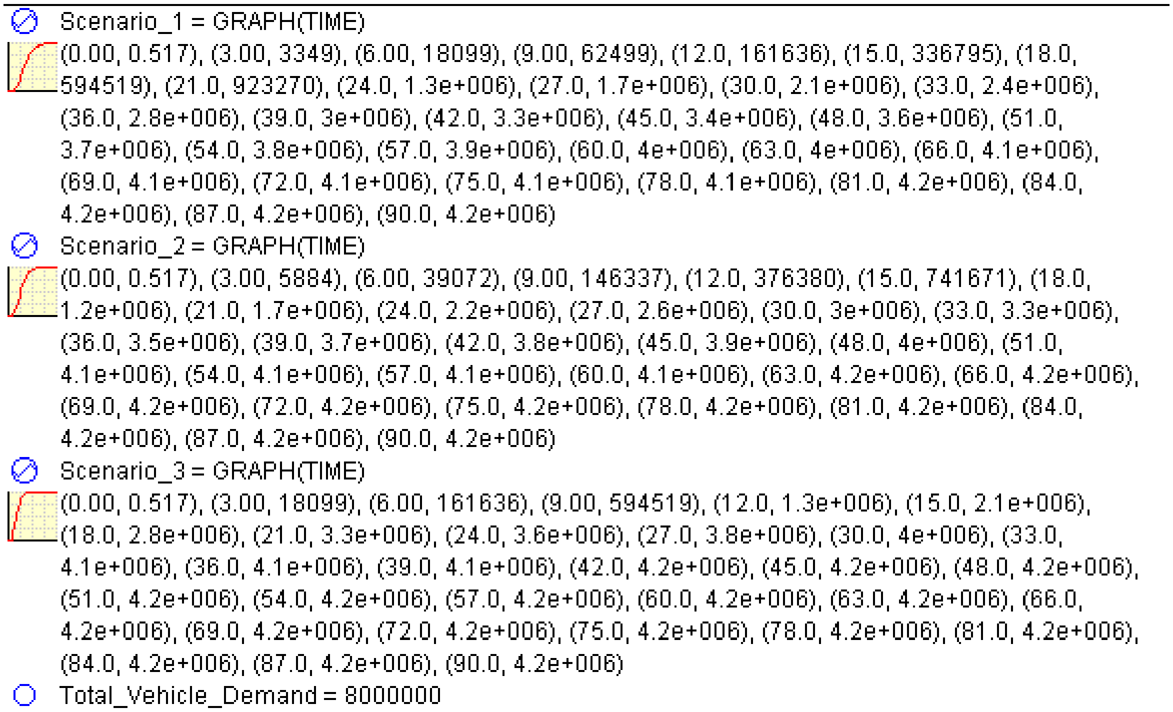
$$\frac{dPD}{dt} = \frac{PO}{7/3} + \frac{POV}{12} - \; PD * 0.9 - PD * 0.1$$

By solving these 7 ordinary differential equations we are able to determine the trend of each of the blocks with time.

Appendix D: iThink Code

```
Pt_Inventory(t) = Pt_Inventory(t - dt) + (Recycling + Pt_Mining - Pt_Consumption) * dt
INIT Pt_Inventory = 200000
 INFLOWS:
    Recycling = Pt_in_Decomissioned_Vehicles*Normal_Recycling_Fraction
    Pt_Mining = Pt_Reserves*Normal_Fraction_Extracted_Per_Year*Effect_of_Price_on_Mining
 OUTFLOWS:
    Pt_Consumption =
    Pt_Used_in_FCV__Production+Other_Pt_Demand+Pt_Used_in_ICEV_Production
Pt_in_Decomissioned_Vehicles(t) = Pt_in_Decomissioned_Vehicles(t - dt) +
(Old_FCVs_Becoming_Decomissioned + Pt_from_Decomissioned_ICEVs - Recycling - Waste) * dt
INIT Pt_in_Decomissioned_Vehicles = 0
 INFLOWS:
    Old_FCVs_Becoming_Decomissioned = Pt_in_Old_FCVs/(FCV_Life_Expectancy/3)
    Pt_from_Decomissioned_ICEVs = Pt_in_ICEVs/Average_Life_of_ICEVs
 OUTFLOWS:
    Recycling = Pt_in_Decomissioned_Vehicles*Normal_Recycling_Fraction
    Waste = Pt_in_Decomissioned_Vehicles*Fraction_Wasted
Pt_in_ICEVs(t) = Pt_in_ICEVs(t - dt) + (Pt_Used_in_ICEV_Production -
Pt_from_Decomissioned_ICEVs) * dt
INIT Pt_in_ICEVs = Pt_Used_in_ICEV_Production*Average_Life_of_ICEVs
 INFLOWS:
    Pt_Used_in_ICEV_Production =
    (Total_Vehicle_Demand-FCV_Production)*Pt_Loading_in_Catalytic_Converter
 OUTFLOWS:
    Pt_from_Decomissioned_ICEVs = Pt_in_ICEVs/Average_Life_of_ICEVs
Pt_in_Middle_Aged_FCVs(t) = Pt_in_Middle_Aged_FCVs(t - dt) + (New_FCVs_Aging -
Middel_Aged_FCVs_Becoming_Old) * dt
INIT Pt_in_Middle_Aged_FCVs = 0
 INFLOWS:
    New_FCVs_Aging = Pt_in_New_FCVs/(FCV_Life_Expectancy/3)
 OUTFLOWS:
    Middel_Aged_FCVs_Becoming_Old = Pt_in_Middle_Aged_FCVs/(FCV_Life_Expectancy/3)
Pt_in_New_FCVs(t) = Pt_in_New_FCVs(t - dt) + (Pt_Used_in_FCV__Production -
New_FCVs_Aging) * dt
INIT Pt_in_New_FCVs = 0
 INFLOWS:
    Pt_Used_in_FCV__Production = FCV_Platinum_Loading*FCV_Production
 OUTFLOWS:
    New_FCVs_Aging = Pt_in_New_FCVs/(FCV_Life_Expectancy/3)
Pt_in_Old_FCVs(t) = Pt_in_Old_FCVs(t - dt) + (Middel_Aged_FCVs_Becoming_Old -
Old_FCVs_Becoming_Decomissioned) * dt
INIT Pt_in_Old_FCVs = 0
 INFLOWS:
    Middel_Aged_FCVs_Becoming_Old = Pt_in_Middle_Aged_FCVs/(FCV_Life_Expectancy/3)
 OUTFLOWS:
    Old_FCVs_Becoming_Decomissioned = Pt_in_Old_FCVs/(FCV_Life_Expectancy/3)
```

```
Pt_Price(t) = Pt_Price(t - dt) + (Change_in_Pt_Price) * dt
    INIT Pt_Price = Initial_Pt_Price
    INFLOWS:
        Change_in_Pt_Price = Indicated_Price-(Pt_Price*Per_Year)
Pt_Reserves(t) = Pt_Reserves(t - dt) + (- Pt_Mining) * dt
    INIT Pt_Reserves = Initial_Reserves
    OUTFLOWS:
        Pt_Mining = Pt_Reserves*Normal_Fraction_Extracted_Per_Year*Effect_of_Price_on_Mining
Average_Life_of_ICEVs = 12
Desired_Inventory = Pt_Consumption*Inventory_Coverage
Effect_of_Inventory_Ratio_on_Indicated_Price = GRAPH(Inventory_Ratio)
(0.00, 3.00), (0.2, 2.37), (0.4, 1.93), (0.6, 1.56), (0.8, 1.24), (1.00, 1.00), (1.20, 0.84), (1.40, 0.735),
(1.60, 0.63), (1.80, 0.57), (2.00, 0.5)
Effect_of_Price_on_FCV_Production = GRAPH(Pt_Price/Initial_Pt_Price)
(0.00, 1.00), (0.3, 0.99), (0.6, 0.985), (0.9, 0.97), (1.20, 0.955), (1.50, 0.94), (1.80, 0.905), (2.10, 0.82),
(2.40, 0.685), (2.70, 0.42), (3.00, 0.00)
Effect_of_Price_on_Mining = GRAPH(Pt_Price/Mining_Costs)
(0.00, 0.00), (0.2, 0.03), (0.4, 0.11), (0.6, 0.29), (0.8, 0.53), (1.00, 1.00), (1.20, 1.51), (1.40, 2.25),
(1.60, 2.61), (1.80, 2.85), (2.00, 2.94)
Effect_of_Price_on_Other_Pt_Demand = GRAPH(Pt_Price/Initial_Pt_Price)
(0.00, 1.20), (0.5, 1.10), (1.00, 1.01), (1.50, 0.96), (2.00, 0.912), (2.50, 0.894), (3.00, 0.882), (3.50,
0.828), (4.00, 0.726), (4.50, 0.504), (5.00, 0.00)
Effect_of_Reserves_on_Mining_Costs = GRAPH(Pt_Reserves/Initial_Reserves)
(0.00, 5.00), (0.1, 3.33), (0.2, 2.38), (0.3, 1.80), (0.4, 1.50), (0.5, 1.38), (0.6, 1.25), (0.7, 1.18), (0.8,
1.13), (0.9, 1.08), (1, 1.00)
FCV_Life_Expectancy = 8
FCV_Platinum_Loading = 0.05
FCV_Production =
(Scenario_1*0+Scenario_2*1+Scenario_3*0)*Effect_of_Price_on_FCV_Production*(8/4.2)
FCV_Pt_Consuming_from_Primary = Pt_Consumption-Recycling-Other_Pt_Demand
Fraction_Wasted = 0.1
Indicated_Price = Mining_Costs*Effect_of_Inventory_Ratio_on_Indicated_Price
Initial_Reserves = 48000000
Initial_Pt_Price = 35000
Inventory_Coverage = 1
Inventory_Ratio = Pt_Inventory/Desired_Inventory
Mining_Costs = Normal_Mining_Costs*Effect_of_Reserves_on_Mining_Costs
Normal_Fraction_Extracted_Per_Year = 0.00417
Normal_Mining_Costs = 35000
Normal_Other_Pt_Demand = 190000
Normal_Recycling_Fraction = 1-Fraction_Wasted
Other_Pt_Demand = Effect_of_Price_on_Other_Pt_Demand*Normal_Other_Pt_Demand
Per_Year = 1
Pt_Loading_in_Catalytic_Converter = 0.002
```



```
⊘ Scenario_1 = GRAPH(TIME)
(0.00, 0.517), (3.00, 3349), (6.00, 18099), (9.00, 62499), (12.0, 161636), (15.0, 336795), (18.0,
594519), (21.0, 923270), (24.0, 1.3e+006), (27.0, 1.7e+006), (30.0, 2.1e+006), (33.0, 2.4e+006),
(36.0, 2.8e+006), (39.0, 3e+006), (42.0, 3.3e+006), (45.0, 3.4e+006), (48.0, 3.6e+006), (51.0,
3.7e+006), (54.0, 3.8e+006), (57.0, 3.9e+006), (60.0, 4e+006), (63.0, 4e+006), (66.0, 4.1e+006),
(69.0, 4.1e+006), (72.0, 4.1e+006), (75.0, 4.1e+006), (78.0, 4.1e+006), (81.0, 4.2e+006), (84.0,
4.2e+006), (87.0, 4.2e+006), (90.0, 4.2e+006)
⊘ Scenario_2 = GRAPH(TIME)
(0.00, 0.517), (3.00, 5884), (6.00, 39072), (9.00, 146337), (12.0, 376380), (15.0, 741671), (18.0,
1.2e+006), (21.0, 1.7e+006), (24.0, 2.2e+006), (27.0, 2.6e+006), (30.0, 3e+006), (33.0, 3.3e+006),
(36.0, 3.5e+006), (39.0, 3.7e+006), (42.0, 3.8e+006), (45.0, 3.9e+006), (48.0, 4e+006), (51.0,
4.1e+006), (54.0, 4.1e+006), (57.0, 4.1e+006), (60.0, 4.1e+006), (63.0, 4.2e+006), (66.0, 4.2e+006),
(69.0, 4.2e+006), (72.0, 4.2e+006), (75.0, 4.2e+006), (78.0, 4.2e+006), (81.0, 4.2e+006), (84.0,
4.2e+006), (87.0, 4.2e+006), (90.0, 4.2e+006)
⊘ Scenario_3 = GRAPH(TIME)
(0.00, 0.517), (3.00, 18099), (6.00, 161636), (9.00, 594519), (12.0, 1.3e+006), (15.0, 2.1e+006),
(18.0, 2.8e+006), (21.0, 3.3e+006), (24.0, 3.6e+006), (27.0, 3.8e+006), (30.0, 4e+006), (33.0,
4.1e+006), (36.0, 4.1e+006), (39.0, 4.1e+006), (42.0, 4.2e+006), (45.0, 4.2e+006), (48.0, 4.2e+006),
(51.0, 4.2e+006), (54.0, 4.2e+006), (57.0, 4.2e+006), (60.0, 4.2e+006), (63.0, 4.2e+006), (66.0,
4.2e+006), (69.0, 4.2e+006), (72.0, 4.2e+006), (75.0, 4.2e+006), (78.0, 4.2e+006), (81.0, 4.2e+006),
(84.0, 4.2e+006), (87.0, 4.2e+006), (90.0, 4.2e+006)
○ Total_Vehicle_Demand = 8000000
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