An Exploration of Automotive Platinum Demand and its Impacts on the Platinum Market

by

Christopher George Whitfield

Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

May 2009
[June 2009]

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Abstract

The platinum market is a material market of increasing interest, as platinum demand has grown faster than supply in recent years. As a result, the price of platinum has increased, causing end-user firms to experience material scarcity through the presence of these high prices. A significant driver of this demand growth for the last several decades is demand automotive sector, which is responsible for almost 60% of total primary platinum demand, due to the use of platinum in three way catalysts. Platinum is one of the materials utilized to catalyze reactions that prevent vehicle emissions from entering the atmosphere, which can have a severe impact on air quality. Two factors will likely contribute to the future growth of automotive platinum demand: the trend in increased use of platinum per vehicle, and expected growth in the number of automobiles produced and sold around the world. While the automotive market is relatively saturated in developed economies, automotive sales growth potential is particularly high in developing areas, such as BRIC countries. It follows that future growth in automotive platinum demand is likely to be significant. As such, the study aims to characterize the drivers of automotive platinum demand and to establish how this demand sector impacts the platinum market as a whole. This characterization is achieved through regression analysis and by utilizing a platinum market simulation model. The regression results indicate that the automotive platinum demand has historically been an inelastic one. Global automotive sales have indeed been a driver of platinum demand behavior. Regression on automotive sales in India, a BRIC country has high correlation with wealth as measured by GDP per capita. In the US and Japan, automotive sales show high autocorrelation and additional correlative relationships were not confirmed. Model results show that the automotive industry drives platinum price increases when there is a combination of low elasticity of platinum demand and large growth rates in the global automotive industry. Recent news about new technologies suggests that demand elasticity may increase, and the model suggests that higher elasticity would reduce the impact of automotive industry growth on the total demand for platinum.

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Acknowledgements

First off, I am thankful for the opportunity to perform my undergraduate thesis research under Professor Randy Kirchain, as it allowed me to pursue a thesis topic that was engaging and in line with my interests. The entire research project would not have been possible, however, without the help of Elisa Alonso. Her patience, perspective, and guidance helped direct my research for the last six months, and I cannot express how appreciative I am of her support along the way. I am perhaps most thankful for the unwavering support that my family has shown me throughout the years, including my wonderful parents; my brothers Richard and David; my sister Kathleen; my sister-in-law Lindsay; and of course my beautiful goddaughter Chloe Violet. I also cannot be thankful enough for the constant support and encouragement provided by Jenny over the course of the year. Finally, I would like to thank my friends, especially my fraternity Brothers, and all of those whom I have had the honor of meeting during my time at MIT, for making this the experience of a lifetime.

I. Introduction

A. Motivation & Background

Economics informs the idea that high material prices are a result of increased scarcity of that material. While the threat of consuming all the material available on the planet is mitigated by market mechanisms and technological development, increases in extraction costs can cause firms to experience scarcity through the presence of high prices [1]. In the view of for-profit end-users who purchase materials, scarcity is thus a motivating factor for examining strategies that may dampen the effect of high prices in both the short and long term. Examination of these strategies must first be informed by an understanding of market dynamics as a whole. Only with the foundation of this understanding can appropriate strategies be recognized. The goal of this study is to characterize the drivers of automotive platinum demand and establish how this demand sector impacts the platinum market as a whole.

Previous research has discussed the platinum market as a material market of increasing interest [1,2]. From 1999 to 2007, platinum demand grew faster than supply, and price has steadily grown. Additionally, early 2008 brought a significant shortage of platinum and thus a price spike, due in large part to power shortages in South Africa, the world's largest supplier of primary platinum [2]. Several factors suggest that the platinum market will be more risk-prone in the future to such price excursions. One factor is the high concentration of platinum supply within one primary country and five primary corporations. Another important factor is that, relative to other materials, platinum is typically extracted from lower grade ores and more energy is typically required for extraction, thus causing platinum to be much more susceptible to energy price increases [2].

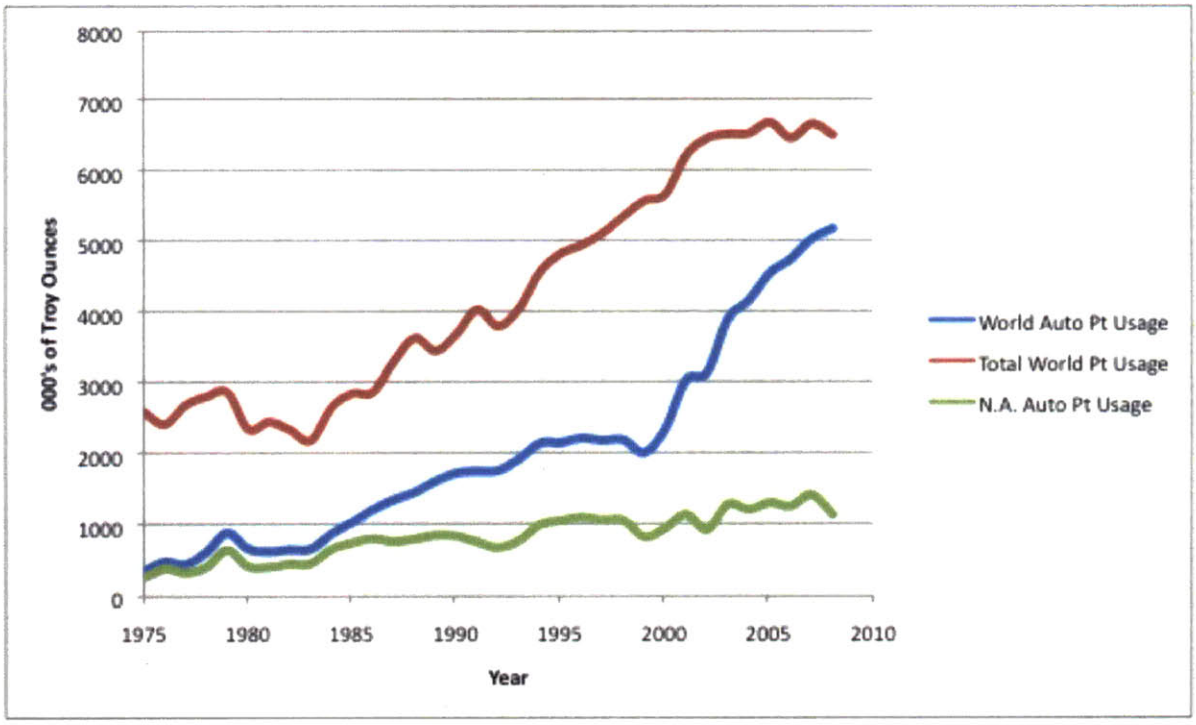


Figure 1 Platinum demand aggregated by: total global usage, total global automotive usage, and total North American automotive usage [12].

An additional factor to be considered with regard to platinum demand is the significant amount of platinum used in automobile catalysts, which accounted for almost 60% of total global platinum primary demand in 2007 [3]. The significant growth rate of automotive platinum usage can be seen in Figure 1. The origination of catalyst use in the United States and thus the origin of significant demand for platinum from this sector is an interesting history and one that is important to understand, given that other countries have or may in the future follow a similar trend in policy and technology choices.

Air pollution became a central topic of interest in the U.S. in the mid 20th century as air quality in urban areas worsened, mainly due to the increased numbers of vehicles on the road. Emissions standards developed as a reaction to this air deterioration, established first at the State level and eventually, in 1967, established by the Federal Government through the Air Quality Act [4]. The main function of this act was to exert federal control over emissions standards, as this

control had previously been a point of debate. This set the stage for the defining legislation in this area with the 1970 Clean Air Act.

The requirements of the legislation were aggressive: car companies were required to make 90 percent reductions in unburned hydrocarbons (HC) and carbon monoxide (CO) for model year 1975 vehicles, and 90 percent reductions in nitrogen oxides (NOx) for model year 1976. To meet these standards, which would in reality evolve over the next several years given technological limitations, the auto companies adopted the catalytic converter in 1975. This first generation technology did little to help reduce NOx emissions, and was thus replaced in 1981 by the three-way catalyst (TWC), the catalyst installed in many vehicles today.

Understanding the technology behind TWCs helps to explain why the utilization of these elements led to a significant increase in platinum demand. The basic reaction occurring in a typical internal combustion engine is the combustion of gasoline. However, this combustion is not complete, thus there are byproducts of the reaction emitted through the exhaust, including benign elements as well as three major pollutants: CO, HC, and NOx. TWCs are intended to prevent large portions of these pollutants from entering the atmosphere [5].

TWC's eliminate the pollutants in the exhaust through a combination of oxidation/reduction reactions. For CO and HC, these are oxidation reactions, and for NOx, it is a reduction reaction. Heck & Farrauto have captured these basic chemical reactions:

$$C_yH_n + \left(1 + \frac{n}{4}\right) O_2 \rightarrow yCO_2 + \frac{n}{2}H_2O$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$NO\ (\text{or } NO_2) + CO \rightarrow \tfrac{1}{2}N_2 + CO_2$$

$$NO\ (\text{or } NO_2) + H_2 \rightarrow \tfrac{1}{2}N_2 + H_2O$$

$$\left(2 + \frac{n}{2}\right) NO\ (\text{or } NO_2) + C_yH_n \rightarrow \left(1 + \frac{n}{4}\right) N_2 + yCO_2 + \frac{n}{2}H_2O$$

Figure 2 Basic oxidation and reduction reactions desired in three-way catalysts [5].

These reactions occur in a more thermally efficient manner in the presence of a catalyst. Even with a catalyst, the reactions require some heat and therefore the TWC uses heat from the gasoline combustion reaction that is transferred to the catalyst through the exhaust system. Once the required level of heat for any given reaction is reached on the surface of the catalyst, the reaction will proceed and eliminate much of the pollutant from the exhaust [5].

Understanding why precious metals are selected to catalyze these reactions is important, and Shelef and McCabe provide justification for this choice [6]. First, the catalytic activity of precious metals is significantly higher than most other options, which is particularly important considering the high speed at which the reactions must occur—since the flow rate of exhaust determines how quickly pollutants must be eliminated—as well as the required size of the catalyst, in terms of practical application to vehicles. Secondly, sulfur oxides in the exhaust have the potential to poison many possible catalytic materials, with precious metals being an exception. Finally, precious metals are, for the most part, immune to deactivation caused by interactions with "the insulator oxides of Al, Ce, Zr, etc., which constitute the so-called high surface area "washcoat" on which the active catalytic components are dispersed" [6].

Since the development of the TWC, platinum group metals (PGMs) have been utilized as catalysts. Originally, platinum and palladium were used in catalysts, with the adoption of rhodium coming only after regulations surrounding NOx emissions were tightened, as rhodium is a particularly effective reducing agent for nitrogen oxides [6]. Platinum and rhodium were, at the advent of the increased demand for PGMs, significantly more expensive than palladium; however, palladium was not utilized more widely because of its sensitivity to lead poisoning. Only as the lead content of gasoline dropped throughout the 70s and 80s did palladium not only became a viable substitute for platinum and rhodium, but one that was heavily utilized beginning in 1989. It is

important to recognize that palladium use in catalysts hinges on the availability of unleaded gasoline for the vehicles utilizing the technology, and thus is not a perfect substitute in all countries or regions. Evidently, adoption of TWCs has led to an increased demand for all PGMs for use as catalysts, with platinum being no exception.

Examining the link between these policy and technology choices and the price of platinum highlights their impact on the overall platinum market. The impact of this new demand is most evidently illustrated by the trend in the price of platinum, which spiked significantly in the years following the establishment of this new automotive platinum demand sector. While this price increase was partially offset soon thereafter, the real price did not return to its pre-1980 levels until recently, suggesting a permanent impact on the price of platinum and thus on the platinum market, the details of which will be expanded upon [Figure 3].

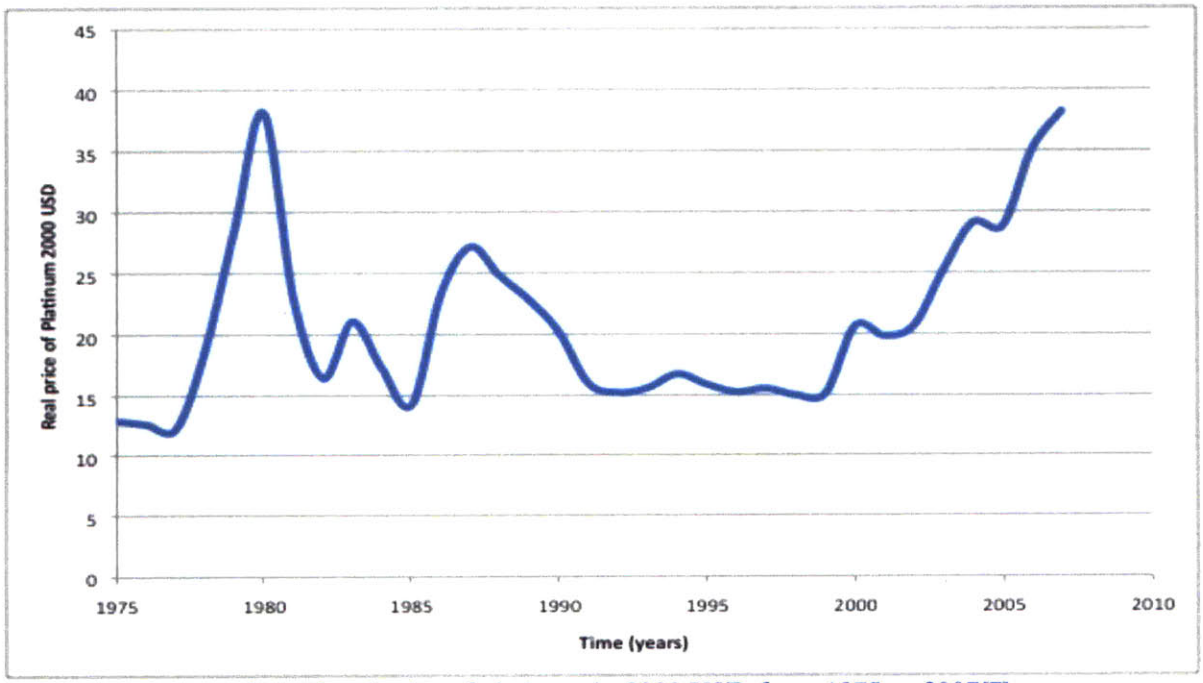


Figure 3 Inflation-adjusted teal price of platinum in 2000 USD from 1975 to 2007[7].

A simplified view of the world, broken down into developed and developing economies, allows assumptions about future vehicle demand to be made concerning each. While developed

economies, such as the U.S. and Japan, are more saturated with regard to the vehicle market, developing economies are far behind by this metric. This dichotomy is captured in Figure 4. Clearly, if the rate at which the U.S. has ascended in terms of vehicles per capita is any indication, expectations for future automobile sales in developing economies should be significant. Indeed, to capture the true magnitude of this potential ascension to the current U.S. ratio of over 800 vehicles per 1000 people, consider that both Asia, which includes India, and China currently possess around 50 vehicles per 1000 people. If India and China attained a level of even 250 vehicles per 1000 people – a level attained by the U.S. in the1940s – this would require almost 500 million vehicles to be sold in these countries, and only if population were constant. Considering that the number of vehicles in the world currently stands at around 900 million, this would be an increase of well over 50% solely from the growth of two countries [8].

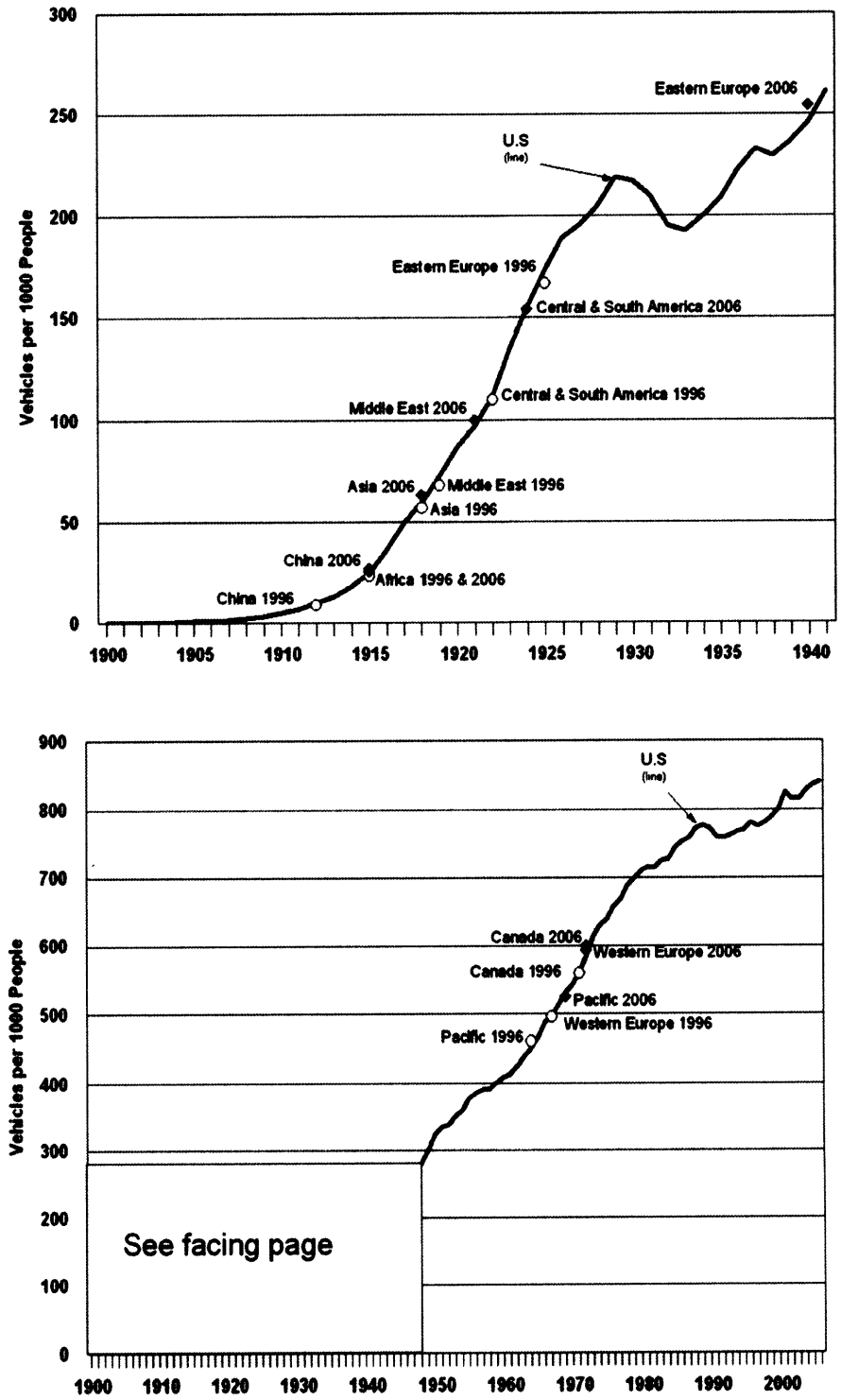


Figure 4 Vehicles per Thousand People: U.S. (Over Time) Compared to Other Countries (in 1996 and 2006) [9]

A potential trend, which is of importance due to the significant portion of platinum demand accounted for by the automotive sector, is the increased demand for automobiles in these developing countries. This trend will likely be realized, as evident market potential and recent news developments suggest [10]. Additionally, platinum demand has historically been driven by automotive sales due to the use of platinum in TWCs. The remaining factor is defining the strength of the link between these trends in developing economies; that is, what the current state of TWC utilization in these economies is, and thus how much platinum is used. With regard to official policies, China, India, and Brazil, in addition to many other developing countries, have passed emission standards requiring the reduction of HC, CO, and NOx emissions from vehicles, presumably through the utilization of TWCs. The adherence to these policies may be another question altogether in these countries, and thus the assumption that a TWC is included with every vehicle may be erroneous, though for now this assumption will be accepted.

B. Problem Statement

The goal of this study is to characterize the drivers behind automotive platinum demand and establish how this demand sector impacts the platinum market as a whole.

II. Methodology

A. Regression Analysis Methodology

To define the impact of the automotive demand sector on the platinum market, statistical analysis on several variables was performed. Analysis of these relationships was initially examined utilizing trend-line fitting in Microsoft Excel, which in the case of linear relationships defined the slope of the line relating the two variables, and also provided an estimate of the determination

coefficient between the variables. Utilizing the program STATA, more rigorous regression analysis was used to determine the strength of these correlative relationships. Three statistical results were utilized to determine the strength of the relationships examined: the determination coefficient (R^2), the t-statistic, and the Durbin-Watson statistic.

R^2 values approaching the value of 1 represent a strong linear relationship between two variables being examined. T-statistics are used to define whether a given variable is independent of another variable. At any value less than 2, the T-statistic indicates that there is a greater than 95% probability that two variables are independent. Finally, the Durbin-Watson statistic indicates how well a set of time-series data fits a first-order autocorrelation model. A value of 2 indicates that there appears to be no autocorrelation.

The time-series nature of the data analyzed necessitated use of the Durbin-Watson test, which tests for autocorrelation. The Durbin-Watson statistic informs the level to which this autocorrelation exists. An additional test, Prais-Winsten regression, was also performed; this corrects for first-order autoregressive errors [11]. Consideration of these statistical results was combined with theoretical approaches to the dynamics of the automotive and platinum markets to suggest whether a causal relationship may be present in each case.

The choice of variables to examine stemmed mainly from the theoretical expectations for their role in driving automotive platinum demand. For example, GDP-driven factors are one metric to capture affluence, which should impact peoples' ability to purchase vehicles. Data to inform the analysis was collected from a variety of sources. The main source for platinum and palladium data used in statistical analysis was the CPM Platinum Yearbook 2008, although data from a few other sources were also considered for use[3, 7, 12, 13]. Data for real GDP per capita, which is adjusted for inflation and presented in 2000 U.S. dollars, and population data, come from the Penn World Table [14]. Price Parity Index used to normalize the price of platinum was obtained from the

Bureau of Labor Statistics [15]. All vehicle data was taken from Ward's Motor Vehicle Data 2007 [8].

B. Platinum Market Simulation Model Methodology

Examination of the impact of automotive demand for platinum on the overall platinum market was achieved through the use of a platinum market simulation model created by Elisa Alonso, a PhD student in the Material Systems Laboratory at the Massachusetts Institute of Technology. Sensitivity analyses were conducted utilizing this model. These allowed for an increased understanding of the effects that variations in the macroeconomic characteristics of the automotive market for platinum could have on the overall platinum market. Specific characterizing variables, including *demand elasticity,* and *demand growth* were the inputs to these sensitivity analyses. The main outputs explored were *platinum price* and *gross demand* for the automotive sector, as well as *total gross demand* for the overall platinum market. For each sensitivity analysis, 200 runs were conducted over a time period of 60 years. The output data was exported to Microsoft Excel, where analyses on the average values and standard deviations of each output against variations in the input as well as against time were conducted.

III. Understanding Automotive Platinum Demand

A. Automotive Demand Factors

In developing a picture of automotive platinum demand, several elements had to be considered. They fit into a rather simple but inclusive equation:

Vehicle Production per Capita x Platinum per Vehicle x Population =

Total Automotive Platinum Demand

The first of these elements is the element of automotive production, specifically the number of *vehicles produced per year per capita* in a given country or region. As presented before, expected sales growth rates in developing countries are significant, though relatively unpredictable, especially given the current global economic environment; this has an impact on production insofar as vehicles that are produced will eventually be sold. The best model for sales growth in these countries may then simply be the historical activity of more developed sectors such as the U.S. and Japan. Examining these historical trends as well as considering forecasts from various sources informs the first element of the equation for future years.

The second element, *platinum per vehicle*, is an essential multiplier that translates automotive production per capita to platinum demand per capita. Since this is the main use for platinum in vehicles, this translates to the amount of platinum used in each TWC; however, most of this information is proprietary to the automotive companies, and thus platinum per vehicle was estimated from North American platinum and palladium demand and U.S. automobile production data. As seen in Figure 5, platinum group metal use has been on the rise in the U.S. since 1980. Evidently, multiple factors complicate the precise quantification of the value of platinum use, including the interchangeability of palladium and platinum, such that the percentage of each used in TWCs has varied significantly over time in the U.S. This fluctuation has typically been attributed to changes in the relative prices of each metal.

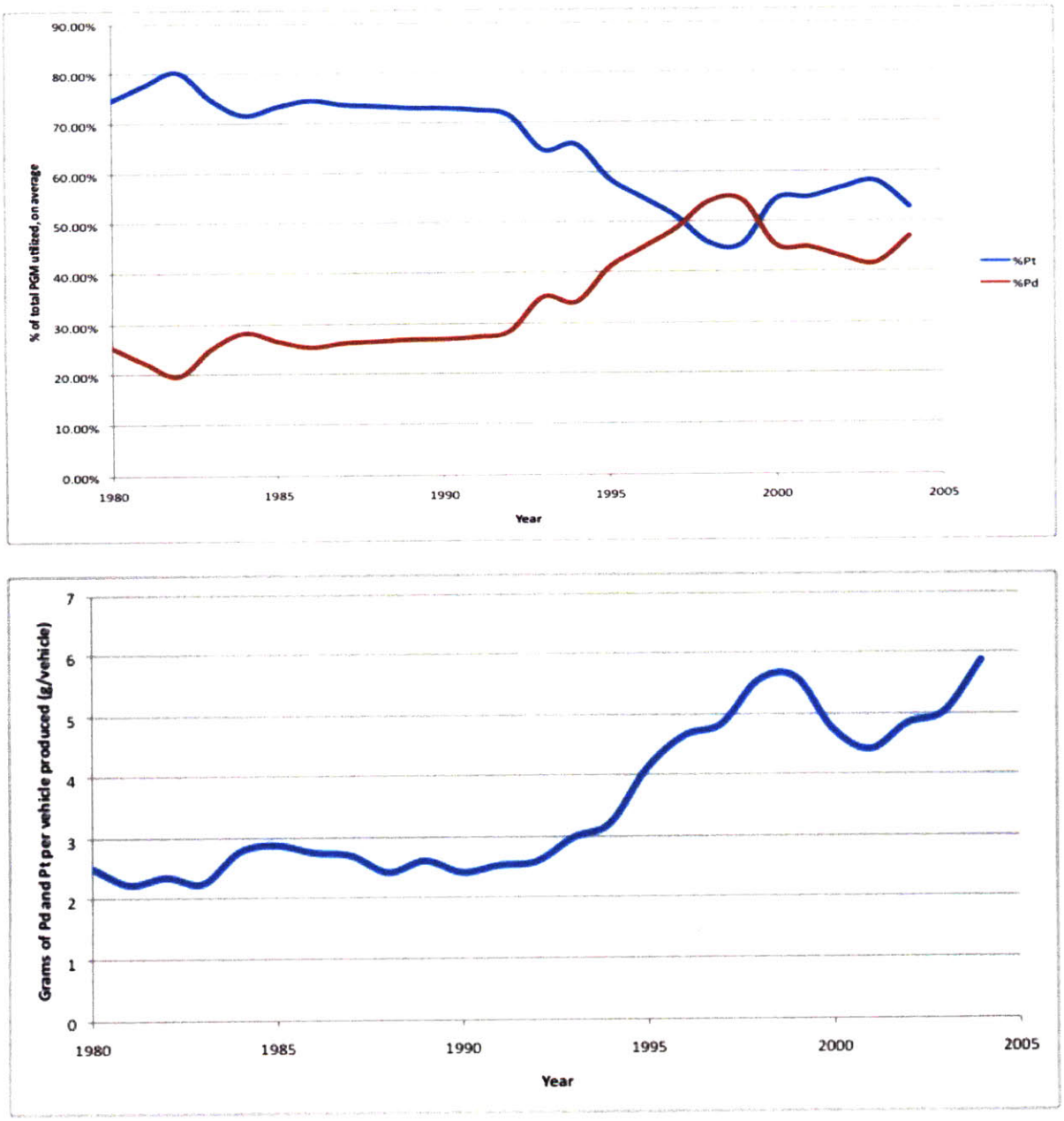


Figure 5: Percentage of platinum and palladium per vehicle from 1980 to 2004 and total platinum and palladium per vehicle (in grams) from 1980 to 2004 [3].

The forecasts for *automotive sales and production*, *platinum per vehicle values*, or *population* numbers from developing economies will inform the forecast for total automotive platinum demand, a value

which will act as an input to the entire platinum market. These are examined through regression analysis.

IV. Regression Results

A. Why Regression?

Regression analysis is performed with demographic and automotive market data to determine correlative relationships between the factors examined. The motivation is a general one: to explore the dynamics of the market, especially the huge future growth potential in developing countries, from a statistical point of view to determine which factors drive the variables of interest, including automotive sales and automotive platinum demand. While some theoretical basis exists for explaining the dynamics of this market, the strength of the statistical relationships between the factors analyzed will strengthen the analysis. Statistics also provides a basis for comparison, which in this case is utilized first to compare the aggregate global trends in automotive sales/production and automotive platinum demand to trends within individual countries, and second, to compare these country specific results for developed countries to the developing world.

B. Global Automotive Sales Relationships

The first relationships examined are those at the global level that inform global automotive sales, as part of the framework presented previously. The result of initial analysis via trend-line fitting in Excel is captured in Table 1 which suggests significant linear relationships between global automotive sales and both GDP per capita and population. This analysis is not sufficient, however, especially considering the expected presence of significant autocorrelation. Thus, STATA was utilized to run a more rigorous analysis and determine the level of autocorrelation in the relationships.

	vs. GDP/capita coefficient	*vs. GDP/Capita R2*	*vs. Population coefficient*	*vs. Population R2*
US Sales(1000s) (1950-2004)	1.878	0.861	0.086	0.844
US Production(1000s) (1950-2004)	2.586	0.542	not examined	not examined
Japan Car Sales (1000s) (1950 - 2004)	4.417	0.867	not examined	not examined
Japan Total Production (1000s) (1950 - 1991)	1.238	0.974	not examined	not examined
Japan Total Production (1000s) (1950 - 2004)	1.491	0.861	not examined	not examined
India Car Sales (1000s) (1980 - 2003)	2.315	0.963	not examined	not examined
India Total Sales (1000s) (1950 -2003)	2.057	0.944	exponential relationship	0.958
Brazil Car Sales (1000s) (1990 - 2003)	0.42	0.543	0.009	0.52
Global Auto Production (1000s) (1960-2005)	0.067	0.968	0.011	0.928

Table 1 Results from Excel trend line fitting for various automotive data.

	World Total Sales			
Price	***Coefficient***	***R2***	***T-Stat***	***DW Stat***
Price of Platinum	-0.00014	0.005	1.07	0.706
Price of Platinum (Prais)	-0.00025	-0.0275	1.22	1.495

Table 2 STATA regression results for platinum price and world total automotive sales.

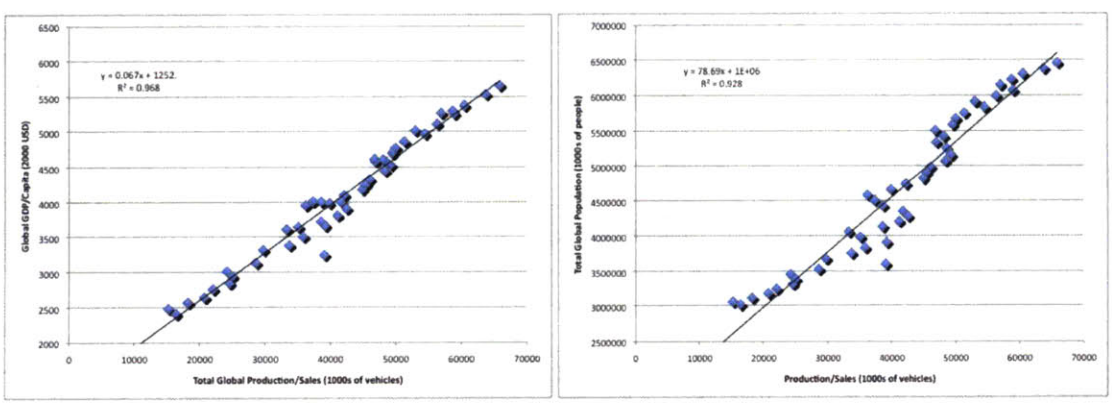


Figure 6 Example trend-line fitting performed in Excel. On the left, total global automotive production versus global GDP per capita; on the right, versus total global population.

Table 3 STATA regression results for automotive demand and automotive platinum demand.

	GDP/Capita				Population				GDP/capita & Population				Total GDP			
	Coeff.	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coefficient*	*R2*	*T-Stat*	*DW Stat*
Auto Sales																
World	14.10	0.95	24.06	0.63	0.01	0.90	16.67	0.51	26.9/-.01	0.96	7.12/-3.42	0.73	1.25E-06	0.94	21.37	0.78
World - Prais	15.08	0.83	13.76	1.61	0.01	0.65	8.49	1.53	28/-.01	0.89	6.09/-2.93	1.55	1.34E-06	0.79	12.47	1.59
U.S.	0.34	0.58	6.40	0.46	0.07	0.49	5.39	0.47	1.75/-.31	0.74	5.35/-4.36	0.84	8.50E-07	0.55	6.03	0.73
U.S. - Prais	0.46	0.56	4.55	0.88	0.08	n/a	3.58	1.26	1.74/-.30	0.42	4.7/-3.73	1.39	1.03E-02	0.04	4.11	1.27
Japan	0.20	0.86	13.32	0.58	0.15	0.77	9.61	0.49	.32/-1.05	0.88	5.05/-2.01	0.57	1.29E-06	0.82	11.47	0.58
Japan - Prais	0.22	0.55	7.16	1.17	0.15	0.31	4.79	1.02	.40/-.158	0.59	4.52/-2.18	1.32	1.31E-06	0.41	5.96	1.19
India	0.42	0.96	23.92	0.93	0.45	0.90	14.88	0.56	.45/-.0001	0.96	5.49/-0.42	0.92	3.06E-07	0.96	23.97	1.00
India - Prais	0.41	0.90	15.18	1.89	0.46	0.60	7.16	1.51	.46/-.0002	0.89	4.11/-0.51	1.88	3.01E-07	0.90	15.61	1.85
Brazil	0.30	0.15	2.41	0.30	0.01	0.50	5.42	0.45	-1.83/.01	0.47	-0.29/none	0.56	1.00E-06	0.42	4.53	0.40
Brazil - Prais	0.13	0.08	1.13	1.80	0.01	0.20	2.40	1.84	.078/.006	0.13	0.65/1.36	1.78	7.69E-07	0.16	1.87	1.78
Auto Sales Growth																
World	2.94	0.47	5.29	1.59	-2.20	-0.03	-0.49	1.82	2.95/.375	0.46	5.16/0.11	1.59		0.42	4.69	1.33
World - Prais	3.19	0.51	5.70	1.94	-2.45	0.03	-0.51	1.94	3.21/.575	0.49	5.54/0.14	1.94		0.44	4.76	1.79
U.S.	3.70	0.44	4.91	1.65	-10.70	-0.03	-0.23	1.63	3.71/-17.4	0.43	4.86/-0.50	1.67		0.42	4.57	1.08
U.S. - Prais	3.69	0.44	4.91	1.93	-5.83	none	-0.11	1.94	3.70/-14.26	0.42	4.85/-0.50	1.93				
Japan	2.32	0.46	4.91	1.49	3.99	-0.02	0.75	1.11	2.53/-4.19	0.46	4.9/-0.99	1.57		0.43	4.66	1.41
Japan - Prais	2.25	0.39	4.31	1.74	2.08	-0.04	0.26	1.52	3.41/-4.07	0.39	4.36/-0.81	1.77				
India	2.37	0.12	2.16	1.48	-2.99	-0.03	-0.24	1.66	2.48/6.69	0.09	2.19/0.53	1.49		0.19	2.70	1.45
Brazil	0.70	-0.02	0.66	2.34	-4.28	-0.03	-0.50	2.44	.74/-3.89	-0.06	0.68/-0.43	2.36		-0.02	0.66	2.33

	GDP/Capita				Population				GDP/capita & Population				Total GDP							
	Coeff.	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*
Automotive Platinum Demand																				
World	1.77	0.95	23.81	0.25	0.00	0.90	15.7	0.13	2.67/-.0007	0.96	6.29/-2.16	0.45	1.59E-07	0.96	24.12	0.19	0.11	0.92	17.28	0.61
World - Prais	1.63	0.50	8.66	0.99	-0.01	0.47	-4.87	0.95	1.01/.0007	0.41	2.64/1.76	0.86	1.65E-07	0.63	10.39	0.97	0.05		3.54	1.09
U.S.	0.06	0.87	12.88	0.53	0.01	0.85	11.49	0.55	.08/-.05	0.87	2.33/-0.71	0.54	1.46E-07	0.87	12.95	0.56	0.13	0.73	8.52	0.33
U.S. - Prais	0.06	0.60	7.09	1.43	0.01	0.50	6.07	1.32	.07/-.003	0.59	2.4/-0.52	1.45	1.50E-07	0.60	7.15	1.37	0.05	0.35	3.83	1.80
Japan		0.30	3.3	0.34																
Japan - Prais		0.12	2.2	1.01																

	Total Production (1 Year Delay)				Price				Production				Total Production (year plus 1)			
	Coeff.	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*	*Coeff.*	*R2*	*T-Stat*	*DW Stat*
Automotive Platinum Demand																
World	0.12	0.92	16.89	0.64	66.67	0.16	2.51	0.10		0.92	17.28	0.61		0.92	17.22	0.61
World - Prais	0.02	0.04	1.44	0.73	4.08	0.03	1.3	1.25			3.54	1.09		none	4.01	0.97
U.S.	0.06	0.85	11.95	0.51	15.32	0.07	1.74	0.11	0.15	0.71	7.8	0.51		0.58	5.75	0.66
U.S. - Prais	0.06	0.49	6.11	1.24	1.95	n/a	0.52	1.03	0.01	0.35	3.69	2.01		none	1.19	1.26
Japan						0.41	4.41	0.29	0.00	-0.04	0.2	0.19		-0.03	0.53	0.24
Japan - Prais						0.03	2.41	1.15	0.04	0.34	3.61	1.76		0.12	1.99	1.51

Using STATA, regressions were performed to examine how well GDP per capita, population, GDP per capita & population, and total GDP explain global automotive sales. The findings, summarized in Table 3, suggest that each of these four relationships shows a strong correlation. In each case, the initial regression analysis suggests that there is a strong presence of autocorrelation, as no Durbin-Watson (D-W) statistic exceeds 0.78. However, Prais-Winsten (P-W) analyses adjust these D-W statistics to a minimum of 1.53, while maintaining significant determination coefficient (R^2) values as well as t-statistics (t-stats), suggesting that even when single-period autocorrelation is adjusted for, these relationships are significant. Of the three variables examined, the results of population both in individual regression as well as part of GDP per capita & population suggest that it is the least statistically significant variable, with the lowest R^2 value and t-stat in individual analysis and a noticeably smaller t-stat than GDP per capita in the combined analysis. More importantly, the coefficient for the population in the multiple regressions switches to negative, which is counter-intuitive. It is expected that as population increases, for a given GDP per capita, the sales of cars would also increase. Thus, population is the weakest of the three variables examined.

In determining whether this correlation implies causation, we consider the theoretical implications, and determine that this significance does not come as a surprise. Theoretically, increases in GDP per capita should increase the ability of people to buy additional vehicles, while population increases should drive increased demand especially in the presence of increasing GDP per capita as well. Total GDP increases, which effectively capture the total affluence of the world, should also drive sales. Of course, for each of these variables, decreases should also have the opposite effect on automotive sales. These theoretical ideas also apply to the year-on-year growth rates for each of these variables, which have the strength of isolating the changes in each variable in relation to one another and thus removing much of the time-series issues with the data. This

analysis was done purely in STATA with both standard regression as well as P-W analysis and the results are presented in Table 3. Due to the relatively insignificant presence of autocorrelation in the growth rates data, however, P-W results were very similar to the standard regression results. The findings suggest that growth rates for GDP per capita growth as well as total GDP growth have strong correlations with automotive sales growth, with relatively low R^2 values of just over .40, but significant t-stats of 4.69 and 5.29 respectively. Population growth, however, does not show any relationship with global automotive sales growth. This reinforces the finding that autocorrelation is a significant consideration for population.

In all, the relations of GDP per capita and Total GDP to global automotive sales suggest both empirically and theoretically that they share causal relationships, while population's position as a correlation factor is in question due to its insignificant year-on-year growth relationship with global automotive sales.

C. Global Automotive Platinum Demand Relationships

The factors we have examined thus far would be utilized to inform ***vehicle production per capita***, which is only one piece in the determination of the ***total automotive platinum demand*** variable. In this vein, two analyses follow: first, relating these demographic factors directly to the platinum demand is an interesting exercise to determine whether automotive production might be circumvented in attempting to define automotive platinum demand dynamics; second, defining the strength of the relationship between automotive production and platinum demand can suggest the extent to which these factors are directly related. Additionally, the relation of platinum demand to price is an analysis of great interest. The findings of these analyses are captured in Table 3.

A point of clarification for this analysis: regression analysis with regional platinum demand data as the dependent variable will use regional automotive production data, as opposed to sales data

as the independent variable. Since many countries import and export vehicles, production and sales can be drastically different, thus we cannot assume that sales in a given country drive platinum demand, as many of those cars could have been imported.

The regression analyses between global automotive platinum demand and fundamental demographics such as GDP per capita, population, and total GDP show statistical significance by the metrics of R^2 values and t-stats, but also suggest a strong presence of autocorrelation. None of the four relationships examined had D-W statistics larger than 1 even after a P-W test, thus suggesting that much of the relationship's strength is derived from the time-series element of the data. Moreover, P-W regression only corrects for single-period autocorrelation and another tool should be used to correct for the longer periods correlation. Thus at a global level we cannot determine with confidence based on the analyses that we have run that there is a significant correlation between these demographics and automotive platinum demand.

Examination of the relationship between global automotive platinum demand and global automotive production also shows similarly strong dependence on time. Significant autocorrelation is suggested by a maximum D-W statistic of 1.09, though the t-stat suggests significance. Two other iterations of global automotive production are analyzed: production minus 1 year and production plus 1 year, to capture either a lag in market information or by assuming that platinum is purchased in the year previous to the year of production, which is presumably the year of sale. The relationships support neither of these theories, as the results are basically the same as those seen for the "year 0" analysis. In summary, the time-series data do not show that correlative relationships exist although we would expect a causal relationship between automotive production and automotive platinum demand. Theoretically, however, we may consider the lack of correlation as a result of the observed increase in platinum used per vehicle.

Another way to examine this relationship is with data of the year-on-year growth of automotive platinum demand and global automotive production data. This relationship again suggests very little correlative strength. Additionally, no significant relationship was found with respect to global automotive sales plus 1 year. A relatively strong relationship, however, is shown for global automotive sales minus 1 year: despite low R^2 values (<.20), significant t-stats are measured. This is suggestive of a relationship between the two variables but likely additional variables need to be included in the regression.

Finally, the relationship between global automotive platinum demand and the real price of platinum is analyzed, and the results are shown in Table 2. The findings show that there is no statistically significant relationship between these two factors once autocorrelation is accounted for by P-W testing. This is suggestive of an inelastic market, since the demand for automotive platinum is not affected by changes in the price. Theoretically, this inelasticity fits into the context of automotive use. The cost of an automobile is often well into the tens of thousands of dollars, while six grams of platinum, which we have estimated to be approximately the amount included in the average catalyst today in the U.S., is approximately US$225, merely a fraction of the overall cost of the material. Additionally, while substitutes do exist, mainly in palladium, it is limited when applied to diesel engines or leaded gasoline [3]. This finding also is in line with what platinum literature suggests, in light of the consistent level of platinum demand seen historically despite rising platinum prices [3].

D. Country Specific Automotive Sales Relationships

Relationships are also examined at a country-specific level, and variations from the global correlations as well as between countries are noted; they are captured in Table 3. Two countries represent developed countries, and their findings are extremely similar. The United States is the first

of these countries, specifically of interest because of its status as a "first-mover" with regard to the utilization of catalytic converters for emissions regulation, and thus a significant source of platinum demand. Japan was on the heels of the U.S. in defining emissions standards, not least because they knew the requirements established by the U.S. would be enforced on vehicles exported from Japan to the U.S. [4]. There exist significant similarities in the findings from the two countries. Both U.S. and Japan findings show that the correlations between automotive sales and any of the demographics—GDP per capita, population, and total GDP—are not particularly different from global data results, though both R^2 values as well as t-stats are somewhat weaker than those realized for global data. The only notable difference between the two countries' results comes in the analysis of total GDP, where Japan shows a significantly higher R^2 value than the U.S. along with a slightly higher t-stat; this difference is, however, relatively small, especially relative to the global findings. As seen globally, autocorrelation is clearly present but is accounted for by P-W tests, while the relationships remain statistically significant. Comparison of growth rates for automotive sales and demographics again show very similar results to the global relationships for each of these developed nations. As seen before, a strong relation is found between automotive sales growth and GDP per capita as well as with total GDP; both results are markedly similar to the global data.

The second pair of countries examined are of interest due to their status as developing countries, specifically as members of BRIC (Brazil, Russia, India, China). From 2005 to 2006, the last year for which auto sales data was obtained for each country, Brazil car sales grew by over 14% while India's grew at a staggering 21.6%. These patterns of significant growth, along with a *combined* GDP per capita which was less than half that of Japan and less than a third that of the United States in 2003, suggest that the future market demand will be significant. Understanding how these markets compare to both global trends as well as trends seen in developing countries is significant motivation.

The findings for India and Brazil regarding the relation of automotive sales with demographics present a significant dichotomy: India's data shows extremely strong relationships between automotive sales and each of the demographics considered, especially in the case of GDP per capita and Total GDP, whereas Brazil's data shows very weak correlations in the data, with a maximum R^2 value of .20 and a maximum t-stat of only 2.4 after a P-W test. Similarities between Brazil and India are seen, however, in comparison of the automotive sales growth rate with demographic growth rates. These results both show relatively insignificant correlations, especially compared to the global data and developing countries data, albeit India's relationships still tend to be stronger than Brazil's. Nonetheless, growth of GDP per capita and total GDP, factors for which statistical significance holds generally constant at the global and developed country level, are suggested to be only weakly correlated with automotive sales growth, if at all.

E. Country Specific Platinum Demand Relationships

Automotive platinum demand was also examined for both the United States and Japan. Since platinum demand is a production-driven process (car manufacturers order the platinum for use in the cars they are producing), developing countries were excluded from this analysis, in part because the data was not available. Also, these two countries accounted for almost one-third of total world vehicle production in 2006 [8].

Relationships exhibiting similar strength to that of global data were found for automotive platinum demand and automotive production. The strengths of these relationships are almost precisely the same, in terms of statistical significance as measured by R^2 values and t-stat values. Probably due to the countries huge production numbers, this is also similar to the relationship at the global level.

Price is the last factor considered in defining automotive platinum demand, and the results for each country are almost as weak as at the global level. These results can be seen in Table 2. This finding simply reiterates the reasoning stated before regarding the understanding that the automotive platinum market has historically been considered an inelastic one.

F. Comparison to Palladium Dynamics

Palladium is one of the few substitutes for platinum in its role as a catalyst, albeit in a limited fashion. As such, examination and comparison of palladium with platinum is of interest, and the results are captured in Table 4. The findings show that global automotive palladium demand is related statistically significantly to the demographics GDP per capita, population, and Total GDP, though these relationships are certainly weaker than in the case of platinum. Again, we might expect the strongest link to exist between palladium demand and vehicle production, as was seen in the case of automotive platinum demand. Interestingly, palladium demand does not show a statistically significant relationship with global automotive production or with U.S. automotive production. This could be explained by several theories. One is the consideration that palladium was not used significantly in vehicles until the early 1990s, and thus 15 years of automotive demand captured in this analysis would be responsible for the use of a relatively small amount of palladium. Additionally, palladium's role as a substitute with weaknesses in specific areas may imply that price is a significant factor in a switch away from platinum to palladium. In this vein, palladium prices spiked in the late 1990s as a response to rapid adoption, and the literature suggests that this would have made palladium a less attractive substitute for automotive manufacturers [3].

	GDP/Capita				Population				Total GDP			
Auto Pd Demand	*Coeff.*	*R2*	*T-Stat*	*DW*	*Coeff.*	*R2*	*T-Stat*	*DW*	*Coeff.*	*R2*	*T-Stat*	*DW*
World	0.09	0.69	7.85	0.3	7.85E-05	0.7	8.07	0.3	8.13E-09	0.7	8.07	0.31
World - Prais	0.074	0.17	3.17	1.19	6.79E-05	0.17	3.19	1.1	7.01E-09	0.18	3.28	1.14
	Price				Production				Pd Price			
Auto Pd Demand	*Coeff.*	*R2*	*T-Stat*	*DW*	*Coeff.*	*R2*	*T-Stat*	*DW*	*Coeff.*	*R2*	*T-Stat*	*DW*
World	1.254	-0.01	0.72	0.108	0.00614	0.61	6.38	0.4		0.49	5.21	0.43
World - Prais	0.102	n/a	0.12	1.048	0.00219	n/a	1.28	1.3		0.1	2.59	1.4
U.S.	14.189	0.004	1.05	0.101	0.149	0.28	3.5	0.37	36.32	0.12	2.25	0.2
U.S. - Prais					0.0111	—	0.49	1.09		n/a	-0.9	1.2

Table 4 STATA regression results for automotive palladium demand.

The regression of the demand for automotive palladium with the price of palladium as well as with the price of platinum differs from the results seen with platinum. The price of palladium proves to be a statistically significant determinant of global automotive palladium demand, a relationship that was unquestionably weak in the case of platinum and the price of platinum. Examination of U.S. – specific demand shows an absence of statistical significance after a P-W test. The finding can be taken to show that some elasticity exists in the palladium market, which is backed up by the literature [3]. As discussed before, this can also explain some of the weakness in the relationship between palladium demand and automotive production. Palladium is a less essential commodity for automotive manufacturers so there is a certain amount of price elasticity in automotive palladium demand.

G. Regression Analysis Discussion and Conclusions

Several significant conclusions arise from regression analysis of automotive sales data and automotive platinum demand data with various drivers. First, the findings suggest that automotive sales are driven by GDP factors, including GDP per capita and total GDP, at least at the global level and for most of the countries explored. This is a reasonable finding, and it is no significant theoretical jump to suggest that these GDP factors drive automotive sales. Only in the case of

Brazil does this relationship lack significant correlation, the reasons for which we are unlikely to define without a more in depth examination of Brazil's economic factors.

Additionally, we find that automotive platinum demand is correlated significantly with automotive production at both global and country-specific levels. This relationship is theoretically the most direct, though there is some expectation that the relationship should be stronger than the results show. Recognizing that platinum per car is a metric that is also growing over this time may explain the lack of correlation between platinum demand and automotive production. The findings also suggest that the market for automotive platinum demand is inelastic, as there is no significant relationship between automotive platinum demand and price.

Finally, a comparison to palladium shows that platinum has stronger correlations with demographic factors such as GDP as well as automotive production data. Also, unlike with the automotive platinum market, the automotive palladium market is price elastic.

These findings serve to characterize the drivers of the automotive platinum market. They support much of our theoretical understanding of the platinum market while raising additional questions about the dynamics of this market. Finally, while they do not directly inform the subsequent platinum market simulation model analysis for the most part, they do allow us to further inform and understand additional attempts to characterize the automotive platinum market and its impacts on the overall platinum market.

V. Platinum Market Simulation Model Results

A. Model Structure and Base Case Behavior

Examination of the impact of automotive demand for platinum on the overall platinum market was achieved through the use of a platinum market simulation model. The platinum market simulation model's structure is basically captured in Figure 7. Price fluctuations occur in the market

as a response to shifts in supply and demand, which in turn can lead to changes in supply and demand. Price increases on the supply side can increase the incentive for either mining more material or exploring to define new supplies of that material. Increases in supply can drive the price down as more material is available to fulfill demand. On the demand side, price increases can cause those demanding of the material to switch to lower price substitutes or to simply demand less of the material, decreasing the overall demand. Decreased demand can also drive prices back down as suppliers attempt to capture more of the market with lower prices. Such are the basic drivers of the market that must be captured in the model for it to accurately capture the platinum market dynamic.

The automotive sector is no small piece of this puzzle. Automotive platinum demand accounted for approximately 59% of total primary and estimated secondary platinum demand in 2007 [3]. Additionally, as the results of STATA analysis have shown, the relation between automotive platinum demand and platinum price has historically been an inelastic one. More recent news reports on the availability of alternatives for the traditional three-way catalysts and traditional wash coats indicate that this trend of inelasticity may be breaking. Nanotechnology has been used to develop new designs for catalytic converters that obtain the same activity with less platinum. Thus there exists a dichotomy between historical patterns and future expectations [16]. These potentially shifting market dynamics coupled with significant growth in automotive demand in developing nations inspire an exploration of the way in which automotive platinum demand impacts the platinum market as a whole.

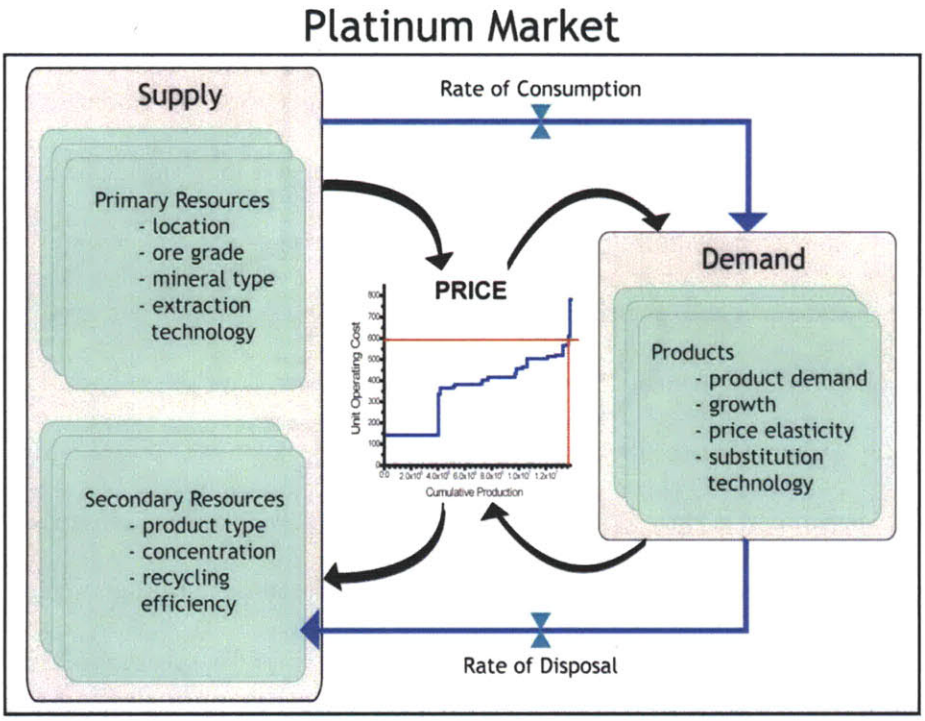


Figure 7: Schematic of the platinum market simulation model [17].

The sheer number of factors that influence even one sector of the platinum market recommend the use of systems dynamics simulation modeling to capture the complex feedbacks. The utilization of systems dynamics modeling with applications to the platinum market has been described previously [1,2]. Both endogenous and exogenous variables are used to capture the market dynamics. Endogenous variables are those explained by the model and include supply, demand, and price; exogenous variables are the inputs to the model that inform the endogenous variables.

An important context to provide is the level of calibration of the model. The model is built with platinum market data collected from literature. Variables that were not available were estimated through partial calibration with historical data for primary supply, demand and price normalized by the producer price index for commodities. The partially calibrated model cannot be used to predict future trends in endogenous variables. The trends produced by the model that inform analyses are

thus relative trends, not absolute. We do not attempt to predict absolute levels of price, demand, or otherwise, but simply focus on examining how delays and feedbacks impact market behavior. The model is intended to characterize the automotive market, so that more informed descriptions of the dynamics of the market can be made given various assumptions or predictions.

The base case behavior of the model is important to understand because it provides a baseline from which to vary certain exogenous variables and to recognize the impact of those variations. This behavior is based upon the calibrations of the variables chosen to capture the most realistic view of the future of the platinum market. Year 0 of the model represents the year 1975, and thus year 34 of the model is approximately calibrated to represent the current market. The baseline conditions for the model are:

- 60 year time horizon, with time steps of 1/32nd year
- Year 0 represents the year 1975
- 8 primary supply groups (mining regions)
- 7 demand groups (jewelry, vehicle catalyst, electronics, chemical catalyst, petroleum, glass, other)
- 7 recycling supply groups (same categories as for demand groups)
- product demand growth follows historical (1975 to 2008) trends and also depend on modeled price
- initial base case recycling rate:
    - *dynamic recycling rate* = secondary use/platinum in products reaching end-of-life = 67% ,
    - *static recycling rate* = secondary use/total use of platinum = 42%

Considering this baseline, we look first at the base case outputs of the model for several endogenous variables: gross demand, price, purchase of primary Pt, and sales recycling. We examine their behavior over a 60-year time horizon, broken down by industry where appropriate.

Gross demand for each industry is captured in Figure 8, and is an aggregate of primary and secondary platinum demand. Total gross demand is projected to grow significantly over the 60-year horizon, increasing by over ten times the year 0 total global platinum demand. Auto demand is also projected to grow significantly in an exponential fashion, though this is not obvious below. An

interesting observation is that jewelry demand grows typically in response to price drops, and clearly decreases over the last 20 years of the model, which corresponds with the price outputs seen in Figure 12.

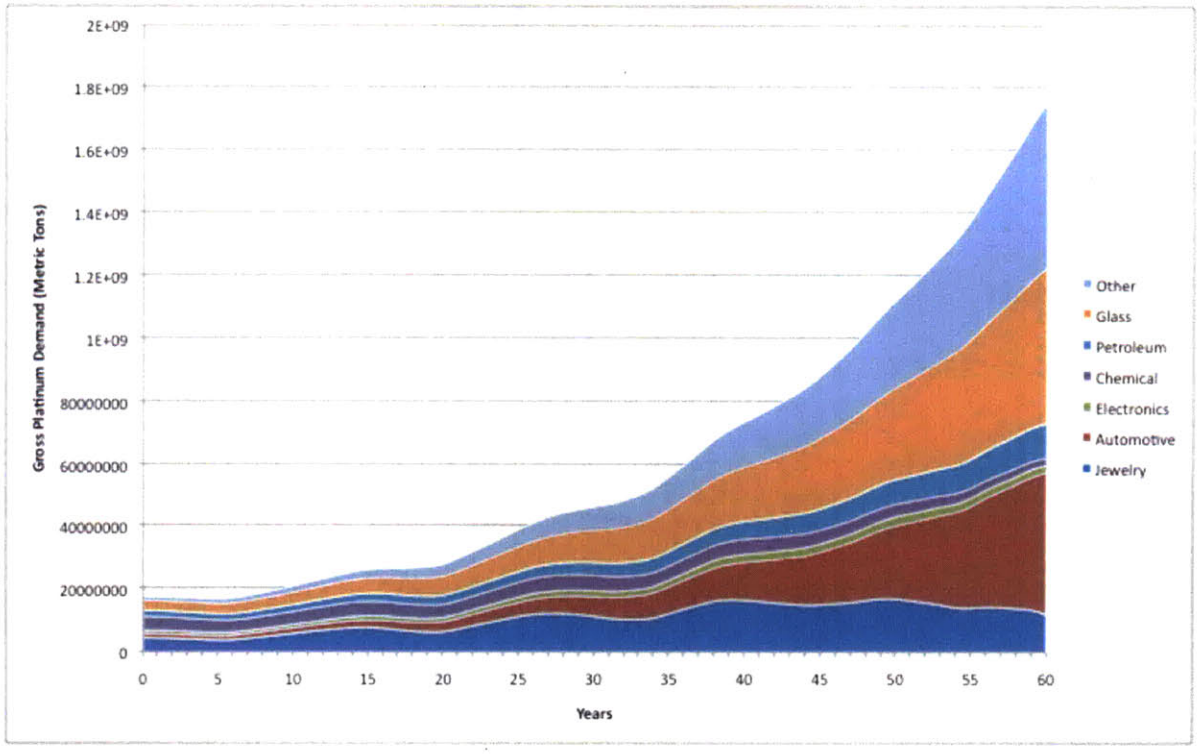


Figure 8 Gross platinum demand, stacked by industry, over 60-year time horizon

Trends in recycled platinum versus primary platinum are also of interest. These two outputs are captured in aggregate in Figure 9 and Figure 10, respectively. With specific regard to automotive primary and secondary platinum demand, Figure 11 shows that the percentage of primary and recycled platinum utilized is projected in the base case to remain relatively constant throughout the 60-year time frame. This consistency provides an interesting baseline, as we examine whether variations in exogenous variables may affect this trend.

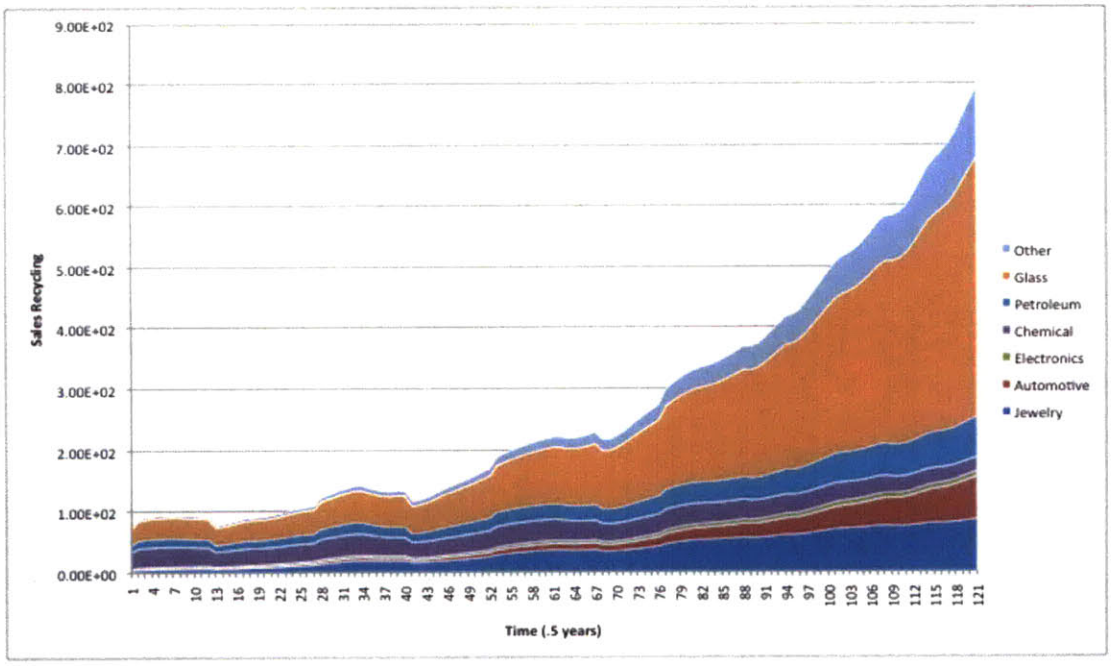


Figure 9 Sales recycling by industry, base case, 60 year horizon.

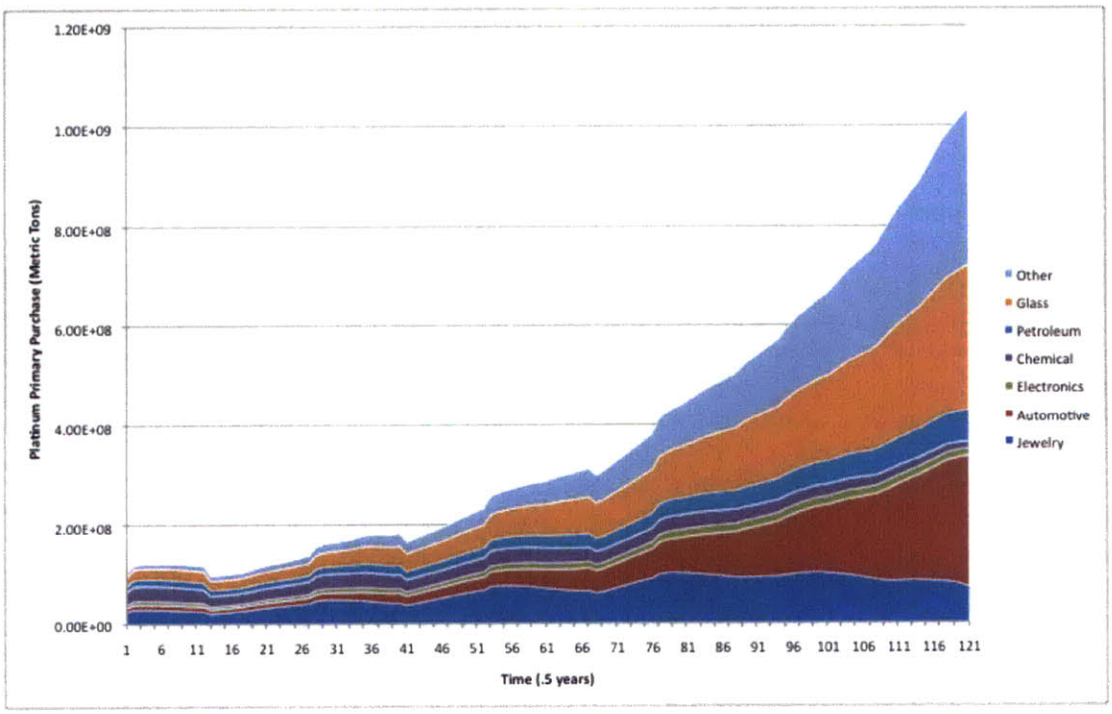


Figure 10 Primary purchase of platinum by industry, base case, 60 year horizon.

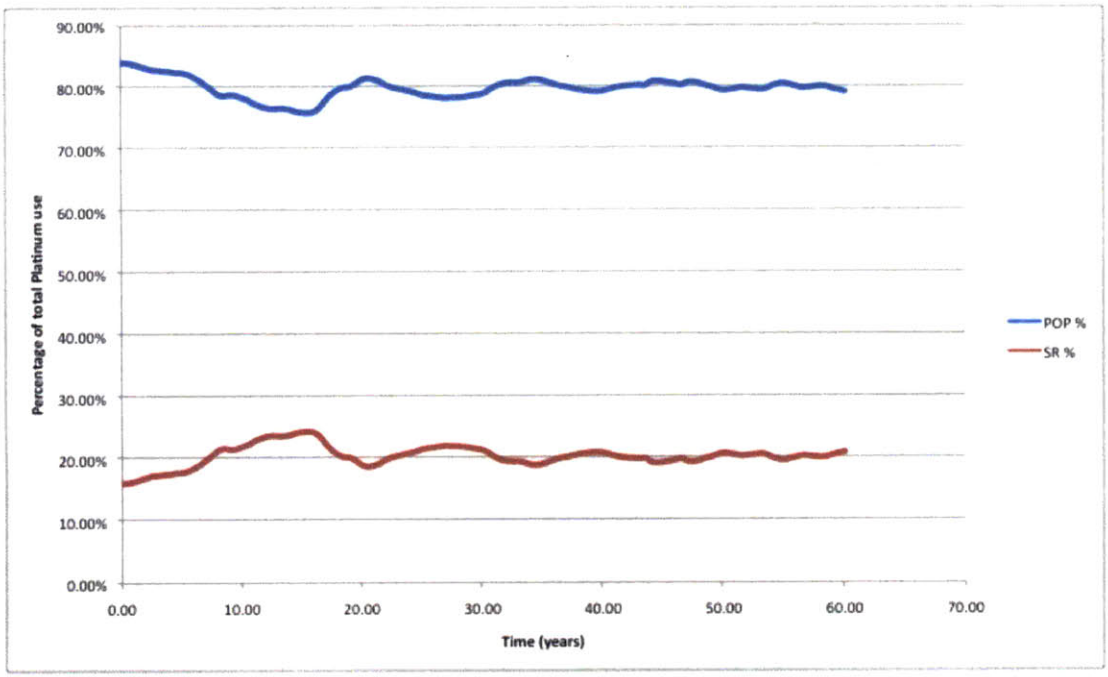


Figure 11 Automotive industry primary versus recycled platinum use by percentage, base case, 60 year horizon.

Another output examined in the base case is price. Price variations captured in Figure 12 suggest that price will more than double, in real terms over the 60-year time horizon. This price trend is likely explained by the fact that the quality of ore over time will likely degrade, thus increasing the cost of extraction and thus the overall price. The increase is certainly not a linear one, as price looks to increase rapidly for a period of time, then drop relatively sharply and return slowly to levels near those that were seen before an increase. This may be accounted for by the lag in bringing supplies online in response to increases in demand. These demand increases may push price upwards as less cost-effective supplies are utilized to meet this demand, followed by a significant drop and tapering-off of the price once these supplies are able to meet demand once again. The price tapers downward in the period following this peak, thus reducing the incentive for suppliers to increase or even maintain supplies, especially less cost-effective ones. Eventually, demand increases again, or supply falls to an insufficient level, and the price peak occurs once again.

This is a pattern of interest because price variations create an inherently more volatile environment for price-taking end users.

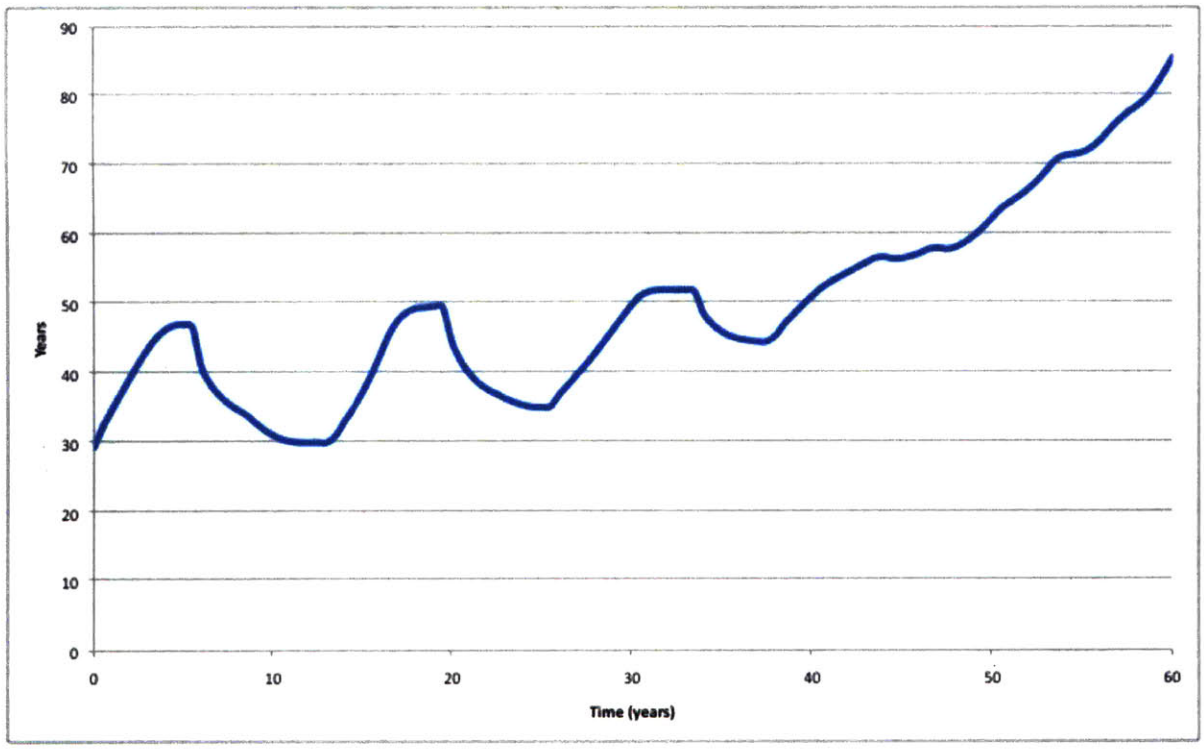


Figure 12 Price of platinum over 60-year time horizon.

B. Exogenous Variable Sensitivity Analysis

We utilize sensitivity analysis to answer the question of how various scenarios in the automotive market may affect the platinum market as a whole over our time horizon. Numerous scenarios and possibilities exist for the future of the market, but our focus on the potential for growth in developing economies informs some of these analyses, as does the potential for increased substitution options for platinum use that may lead to increased elasticity.

A high level review of the theoretical impact of high automotive platinum demand growth rates will help inform our results. High automotive platinum demand growth rates will clearly increase demand dramatically and thus can drive up the price of platinum if new supply does not

come on line immediately. This new supply would likely come on line relatively slowly, as there is a significant monetary and time investment to set up new mines; new mines are also likely to be of a lower ore quality than those utilized currently, further exasperating the delay on the supply side, since a greater quantity of ore must be extracted to achieve the same yield of platinum realized with higher quality ores. These delays will thus drive an increase in price, or at least prevent price from falling until supply is increased. In response to this increased price, substitute materials become more viable, especially if they are of lower cost. This substitution in turn decreases demand and thus feeds back to lower prices. As explored, however, this is not the trend seen historically in the market for automotive platinum demand, which is shown to be inelastic. As such, this mechanism for "relieving" a particularly high level of price via substitution has not been seen in the automotive platinum demand market, leading to significant price increases over time.

With this theory and behavior in mind, the impact of both various levels of growth in demand as well as various levels of elasticity are inquiries of interest. Again, these are informed by more than simply high level market dynamics, but by real-time considerations of factors that may influence the market: the evident automotive market potential in developing countries which is inextricably tied to platinum demand potential, and the increased availability of potential substitutes for platinum in TWCs. These analyses are described in Table 5. In summary, to examine the simultaneous effects of various exogenous automotive platinum demand growth rates and various levels of automotive platinum demand elasticity, growth rates were varied at three distinct levels of elasticity, labeled as low, medium, and high and corresponding to values of .05, .30, and 1.0, respectively. The endogenous outputs considered in each scenario were total platinum gross demand, automotive platinum gross demand, and price of platinum.

Scenario	Exogenous Variable #1	Assigned Value	Exogenous Variable #2	Sensitivity Range
Base case elasticity, vary growth	Demand Elasticity	0.05	Demand Growth	-0.01 to 0.10
Medium elasticity, vary growth	Demand Elasticity	0.30	Demand Growth	-0.01 to 0.10
High elasticity, vary growth	Demand Elasticity	1.0	Demand Growth	-0.01 to 0.10

Table 5 Analysis scenarios examining demand elasticity and demand growth.

1. Low Elasticity

The first scenario to consider is that which utilizes the base case demand elasticity, which, at a value of only 0.05, is also the scenario considering low elasticity. As shown through STATA analysis, this level of elasticity (close to 0) is representative of historical market relationships. The first endogenous variable whose output we will examine within the base case scenario is automotive platinum gross demand. The first finding, the average platinum gross demand, is shown in Figure 13. The average platinum gross demand scales with growth rate exponentially. The escalation of gross demand caused by increases in the growth rate is much more significant than the increases in total platinum gross demand, shown later in Figure 14. Theoretically this is reasonable, as it is the automotive demand growth rate we are varying, so the impact on the automotive sector should be relatively greater than the impact on the total platinum demand market. Indeed, the average automotive gross demand at a growth rate of 10% is over 17 times that of the gross demand given a growth rate of -.1%, whereas the difference in the total gross demand from the previous output was less than a multiple of 2. The exponential relationship is important to note as well. If we consider the significant recent growth rates for developing countries, such as 14% for Brazil and 21% for India, even considering that these rates are only a portion of the overall automotive platinum demand markets, any consistency in these rates year after year could lead to momentous, non-linear

increases in overall gross demand. A more interesting aspect of the difference between the total platinum gross demand and automotive platinum gross demand is that the automotive industry is one that has historically had very low elasticity, but some of the other industries have higher elasticity, such as the jewelry industry. While demand for platinum in TWC's can drive up platinum price during periods of growth of the automotive industry, jewelry demand will drop, partially offsetting the increased platinum demand in automotive.

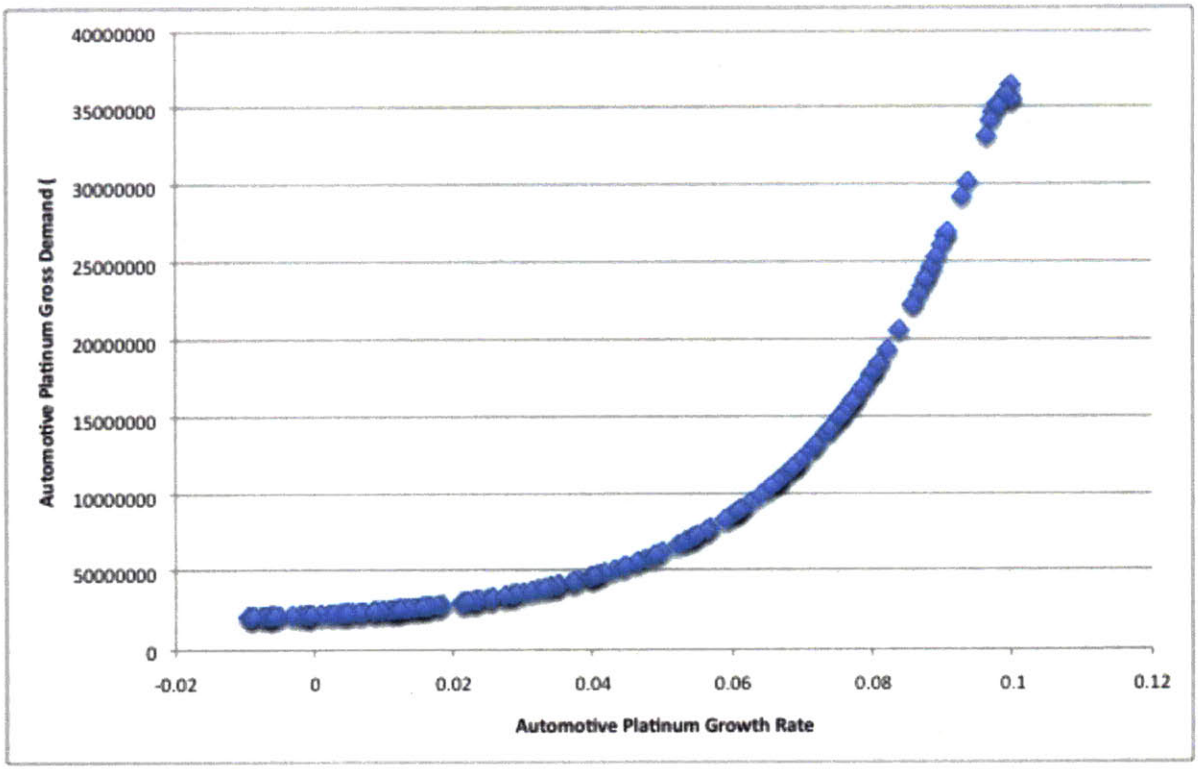
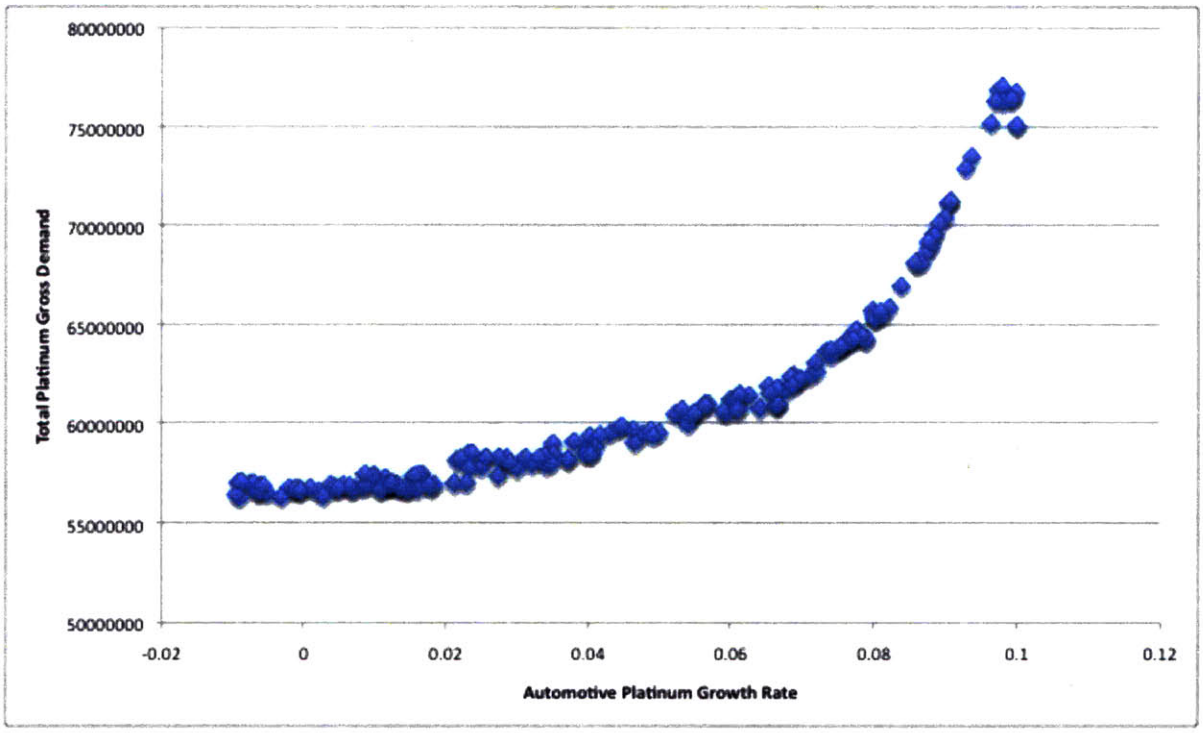


Figure 13 Automotive sector gross platinum demand, base case elasticity, varying growth.

Figure 14 captures the pattern of the average total platinum gross demand. The results show that increases in the automotive growth rate causes an increase in total gross demand, which is a reasonable relationship. Interestingly, the slope of this relationship increases as demand growth approaches 10%. This is important because it shows that increases in growth rate impact the total gross demand for platinum in a significant, non-linear fashion.



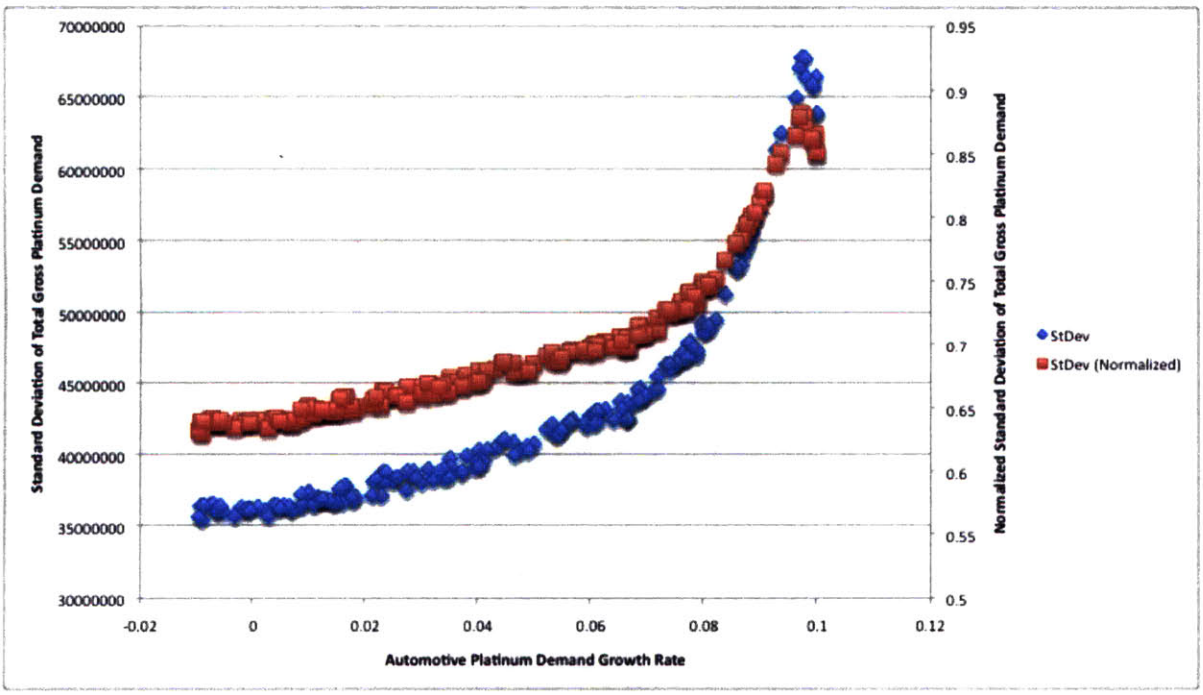


Figure 14 Total platinum gross demand average and standard deviations (regular and normalized), base case elasticity, varying growth.

As demand growth increases, so too do both the regular and normalized standard deviations. The implications of these findings are distinct, however, from those realized from the averages. The increase in standard deviation suggests that increases in demand growth cause the volatility of total gross demand to increase. Theoretically, this is explained first by the fact that higher growth rates can lead to higher prices, and second because higher prices in elastic markets can lead to substitution and thus decreases in demand, while lower prices (which may come as a result of this decrease) can push demand higher once again. By the mechanism described here, higher growth rates will, over the 60-year horizon, cause these fluctuations to occur more frequently and be of higher magnitude than the case of low growth rates. Finally, one aspect of the results is important with regard to both average total gross demand as well as the standard deviation: that changes in an automotive-specific variable have a noticeable impact on the platinum market as a whole.

The final endogenous variable examined is platinum price, and the results are captured in Figure 15. The general trend is that price increases as automotive platinum demand growth increases, which suggests two impacts. The first is that the mechanism described at the beginning of this section, which suggests that, in a relatively inelastic market, increased growth causes a disparity between supply and demand which leads to increased prices, is essentially reasonable. The second is that changes in automotive-specific growth rates indeed have a noticeable impact on the overall market, as seen with total gross demand. The general trend is an increasing slope between price and demand growth as growth increases, suggesting that this relationship is non-linear, similar to the behavior seen in previous outputs. The magnitude of the impact is also significant: the price at 10% growth is approximately double that seen at rates around 0%. A shift of this magnitude certainly implies that a general trend of increased demand growth may have a significant impact on price, suggesting that substitution or increase elasticity in the market could arise as a result.

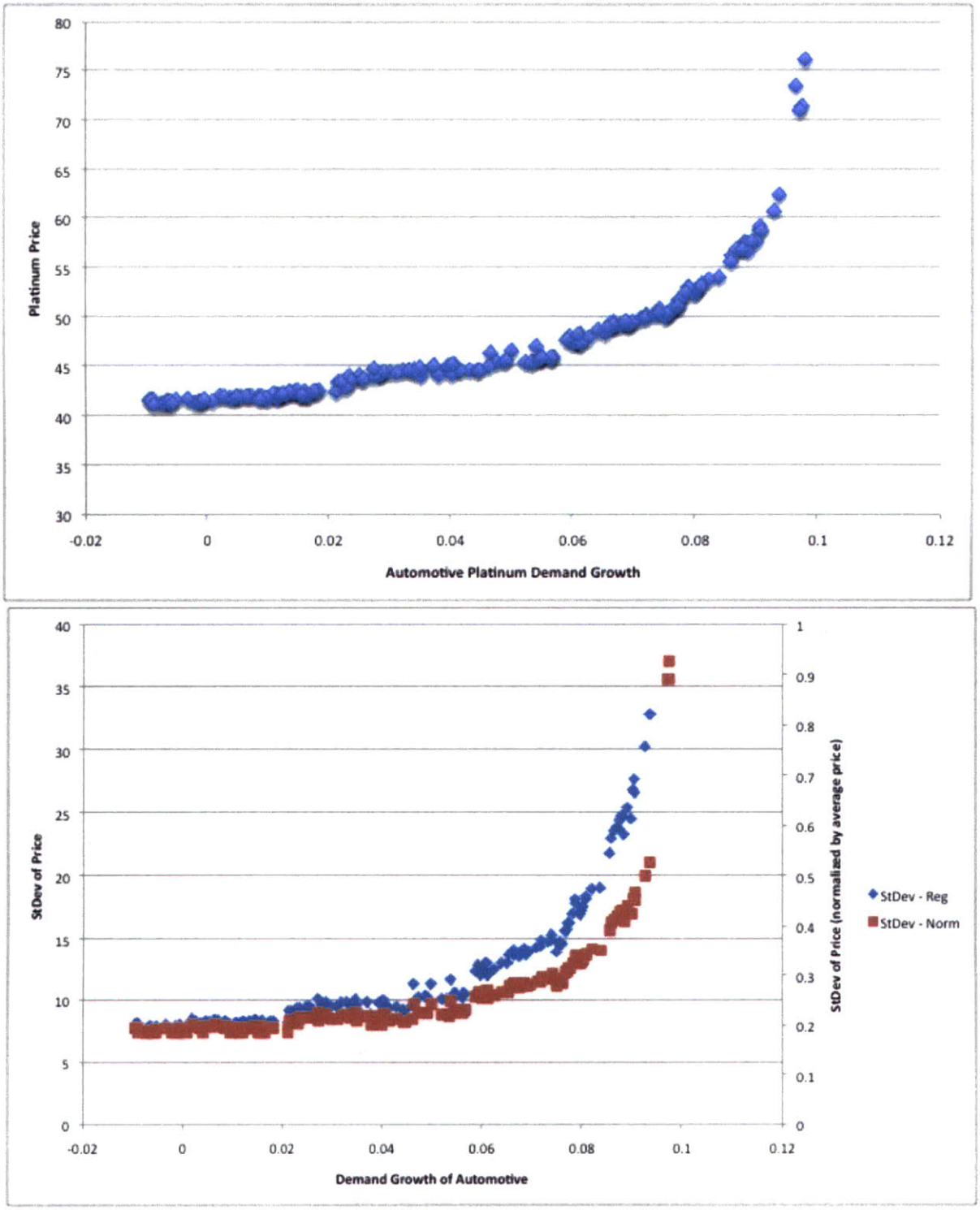


Figure 15 Platinum price, average and standard deviation (regular and normalized), base case elasticity, varying growth.

The behavior of the regular and normalized standard deviations are very similar in the case of platinum price. Both suggest an overall increase in the standard deviation as automotive demand growth increases, in an exponential fashion; however, the average price trend suggests asymptotic behavior, which is not seen in the standard deviation trend. Since the dynamics of price are such that it will initially increase as a response to growth in demand due to the shortcomings of supply in meeting demand, and then will subsequently fall as more supply comes online to meet this demand increase, the greater the growth that drives this mechanism, the more volatility experienced in the market. The onset of the increased volatility occurs at lower growth rates than the onset of the onset of the sudden increase in the average price. Additionally, the fact that the growth driver of this relationship, as has been seen in relationships with other endogenous variables, is exponential suggests that even slight increases in growth can have a significant impact on price. Understanding the base case for price is perhaps the most important of any of the endogenous variables assessed, as it arguably acts as the market's output, integrating the shifts in all the other aspects of the market. Also, it is the most directly applicable to the end user of platinum, and perhaps the simplest way to show or explain the impacts that a change such as significant increases in automotive industry demand growth rates could have on the bottom line.

2. Medium and High Elasticity

Having established a foundation for further analysis, we can now examine the effects of various values of automotive platinum demand elasticity on the endogenous variables. As before, the first endogenous variable of interest is automotive platinum gross demand, and the outputs are viewed by their averages and standard deviations (in this case only normalized standard deviations

are presented). For automotive platinum gross demand, results are captured in Figure 16 and Figure 17.

The trends for average automotive platinum demand are fundamentally similar in that they are non-linear, exponential relationships. Variation occurs in how steep the slope escalates over the given range of automotive platinum demand growth rates. This escalation clearly occurs most quickly relative to the increase in growth rates at low elasticity, and suggests it may even have asymptotic behavior, which could be seen given only a few more percentage points of growth. As elasticity rises from low to medium, and from medium to high, the escalation of the slope diminishes; the exponential relationship between growth rate and gross platinum demand for low elasticity at 10% growth is an extremely shallow slope that looks to be surpassed by the slope of the low elasticity case at a growth rate of .4% or less. Theoretically, higher platinum demand growth rates will drive increased gross demand, which will also increase price. At low elasticity, however, there is very low sensitivity to price, and thus demand will grow without the consequences of increased price discouraging that growth. As the elasticity increases, the increase in price resulting from increased demand will discourage further growth from occurring.

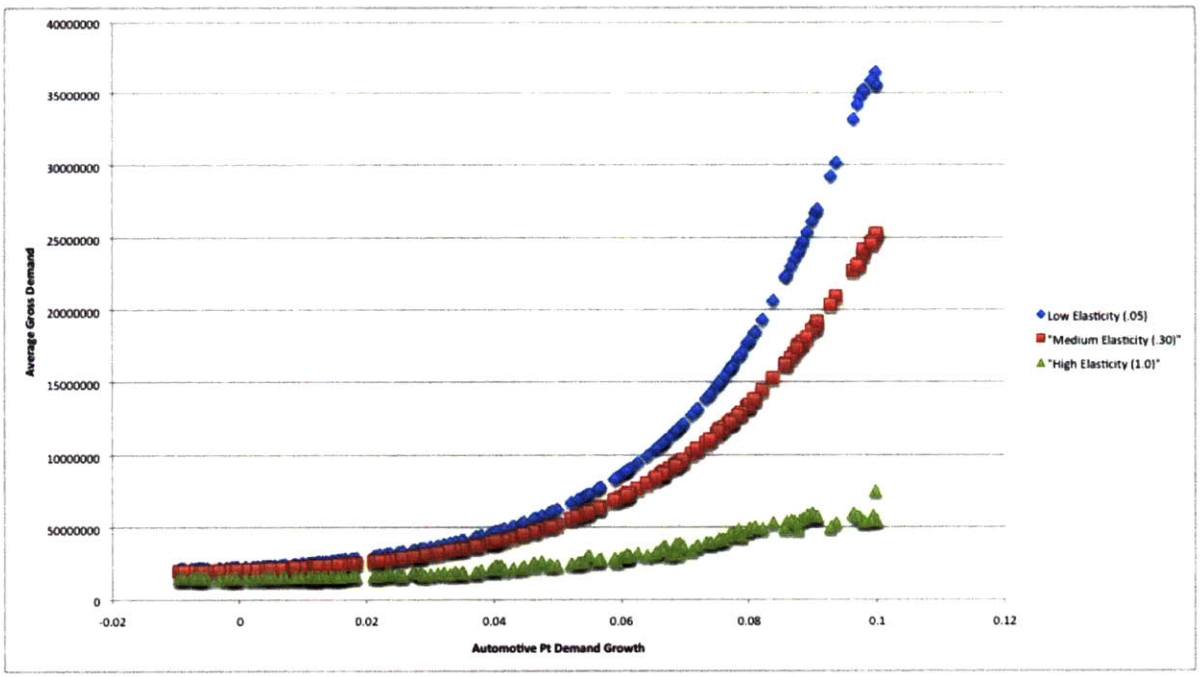


Figure 16 Average automotive platinum gross demand at three levels of elasticity, varying automotive platinum demand growth rates.

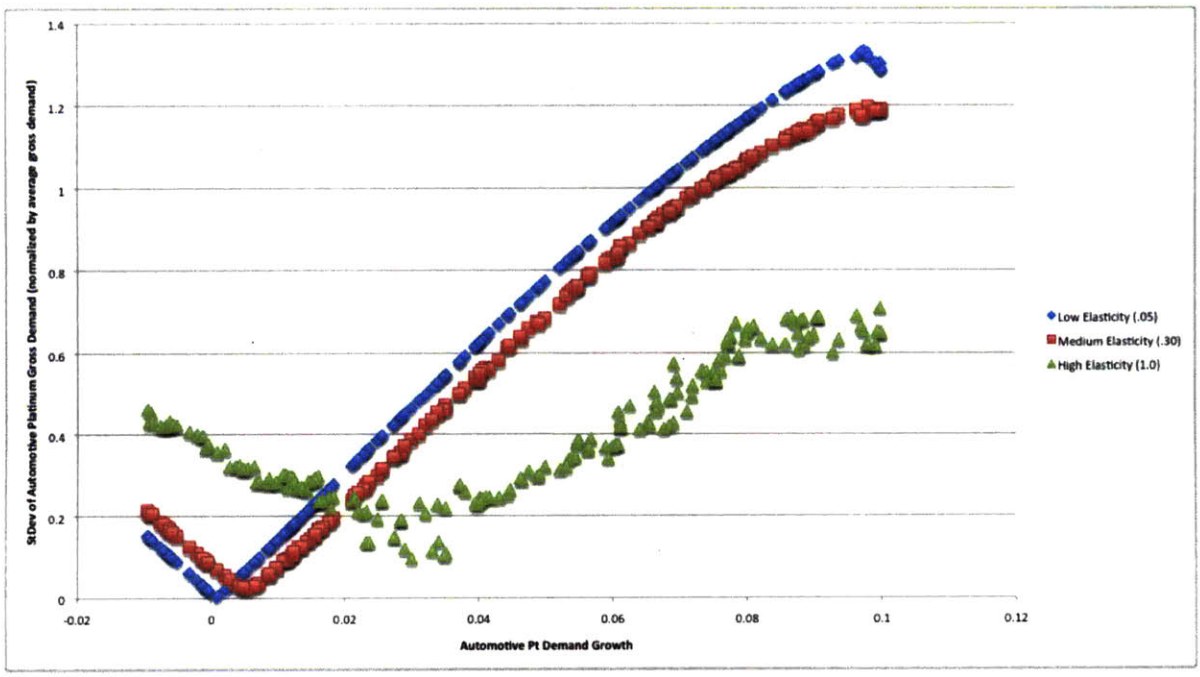


Figure 17 Normalized standard deviation of automotive platinum gross demand at three levels of elasticity, varying automotive platinum demand growth rates.

The normalized standard deviation results present close similarities between the volatility of low and medium automotive platinum gross demand. These relationships are essentially the same, except that the medium elasticity is shifted up approximately 0.05%, suggesting that it takes a marginally higher growth rate to capture the same trend between growth rate and standard deviation of gross demand for low and medium elasticities. The results for high elasticity are not as drastically different as initial observation may suggest, as they loosely follow the same general trend as the others. In each case, the pattern suggests that there is some minimum standard deviation at a given growth rate, which is very close to 0% in the high elasticity case and increases for the other results. Lack of volatility in a market may suggest a balance between supply and demand, and thus this minimum represents the growth rate for which the market is relatively stable. Considering the case of low elasticity, demand will be affected only minimally by shifts in price, and thus any growth rate at all will increase demand and disrupt market equilibrium. In the cases of the higher elasticities, the results suggest a "buffer," provided by the higher rates of elasticity; this buffer allows the market to absorb growth rates of a particular level due to this increased price sensitivity, which will ultimately offset some of the demand growth.

For growth rates greater than this minimum, the relationship between growth rates and standard deviation of gross demand is close to linear, although the slope does become shallower in each case as growth rates near 10% are seen. This supports the basic theory that has been presented for increases in volatility caused by increasing growth rates, whereby these growth rates drive up demand, which drives up prices, which can drive demand downward yet again, creating significant fluctuations in demand.

Total platinum gross demand is the next endogenous variable of interest and results for this are captured in Figure 18 and Figure 19. The general trends for the average total platinum gross demand are similar to those of automotive platinum gross demand. The exponential relationships

for each show less slope escalation in the given growth rate range as elasticity increases. Again, this is due to the offset of demand increases that comes of higher elasticity and thus price sensitivity, causing demand only to grow marginally relative to growth rate in the case of high elasticity. Interestingly, the data for low and medium elasticities diverge at a growth rate of approximately 8%, suggesting that the impact of automotive platinum demand growth rates is much more noticeable after this level of growth is achieved, a finding reinforced by the standard deviation data.

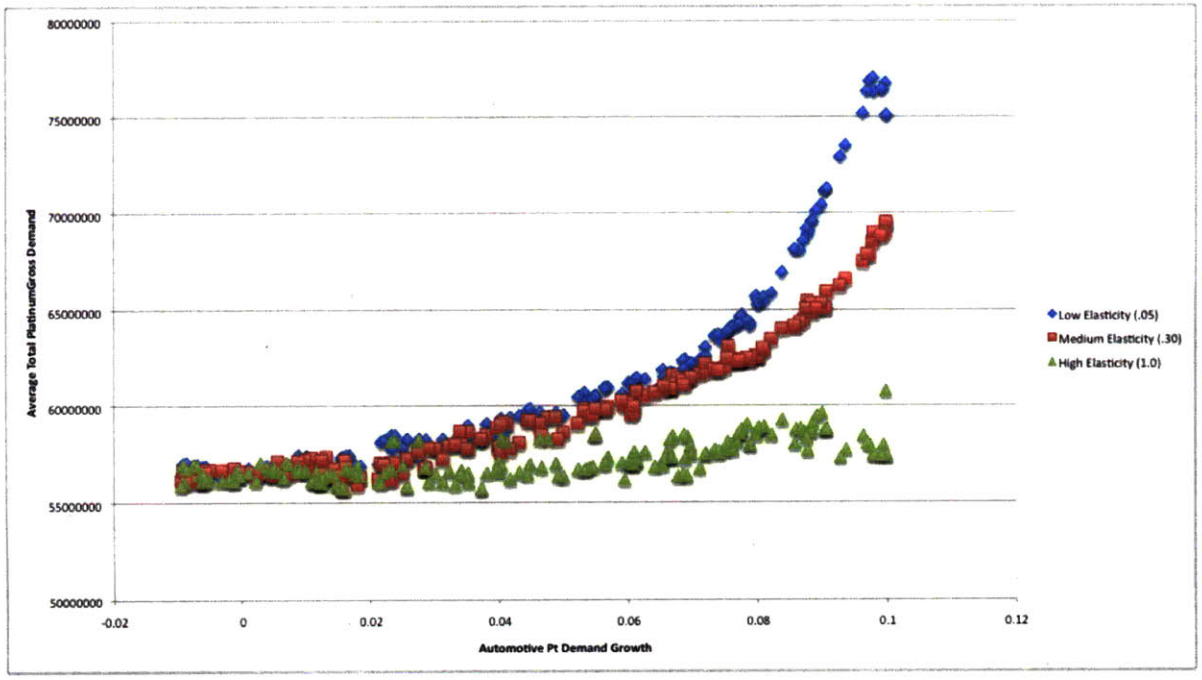


Figure 18 Average total platinum demand at three levels of elasticity, varying automotive platinum demand growth rates.

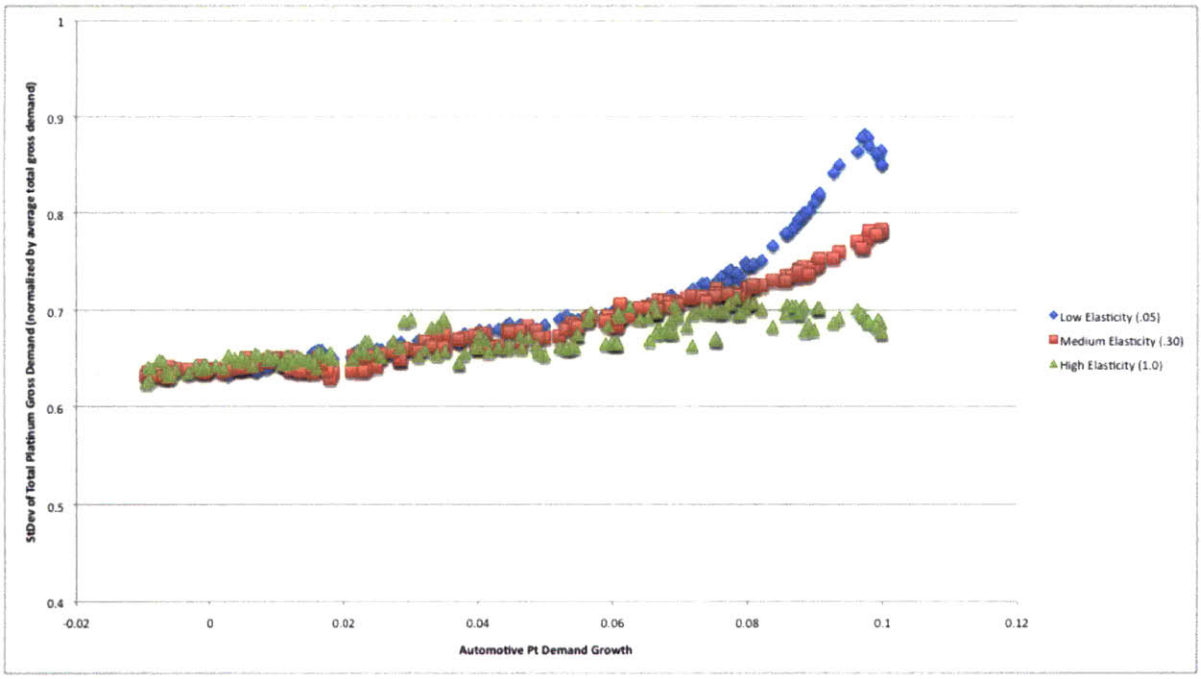


Figure 19 Normalized standard deviation of total platinum demand at three levels of elasticity, varying automotive platinum demand growth rates.

Normalized standard deviation results suggest that until an automotive platinum demand growth rate of approximately 8% is reached, the volatility at each elasticity level is similar. This suggests that a growth rate of 8% or higher must be attained for the automotive platinum sector's growth rate to impact the volatility of the platinum market as a whole. Indeed, after 8%, volatility in relation to growth rate increases significantly for low elasticity, noticeably for medium elasticity, and relatively insignificantly for high elasticity. Again, the price sensitivity that comes with an assumption of low elasticity is relatively low, causing demand to be pushed up in response to high growth rates. In this case, it takes a growth rate of over 8% to achieve this.

The last endogenous variable of interest is platinum price. The results are presented in Figure 20, Figure 21, and Figure 22. The average platinum price results show increasing price over time with increasing automotive platinum demand growth rates. The theory discussed at several points applies here as well, as higher growth rates drive up demand, which in turn cause price to rise

since additional supply cannot come online as quickly as demand grows. The elasticities play a role and clearly show distinguishing patterns for average price; this stems from the fact that low elasticity markets will not realize a decrease in demand given a price increase, thus demand will continue to grow despite this increase in price. The results also suggest a divergence point at an automotive platinum demand growth rate of approximately 6%, after which the average platinum price follows noticeably different increases as growth rates increase for each elasticity scenario. Low elasticity prices grow very rapidly after 6% growth, increasing approximately 30% to the price at 10% growth (extreme outliers put this price increase in the range of 500% or more, but we consider the visible graph as a reasonable bound to avoid outliers). High elasticity prices grow very little after the 6% mark, with growth of only about 5%. Medium elasticity prices grow at a level between these two extremes, of approximately 20%.

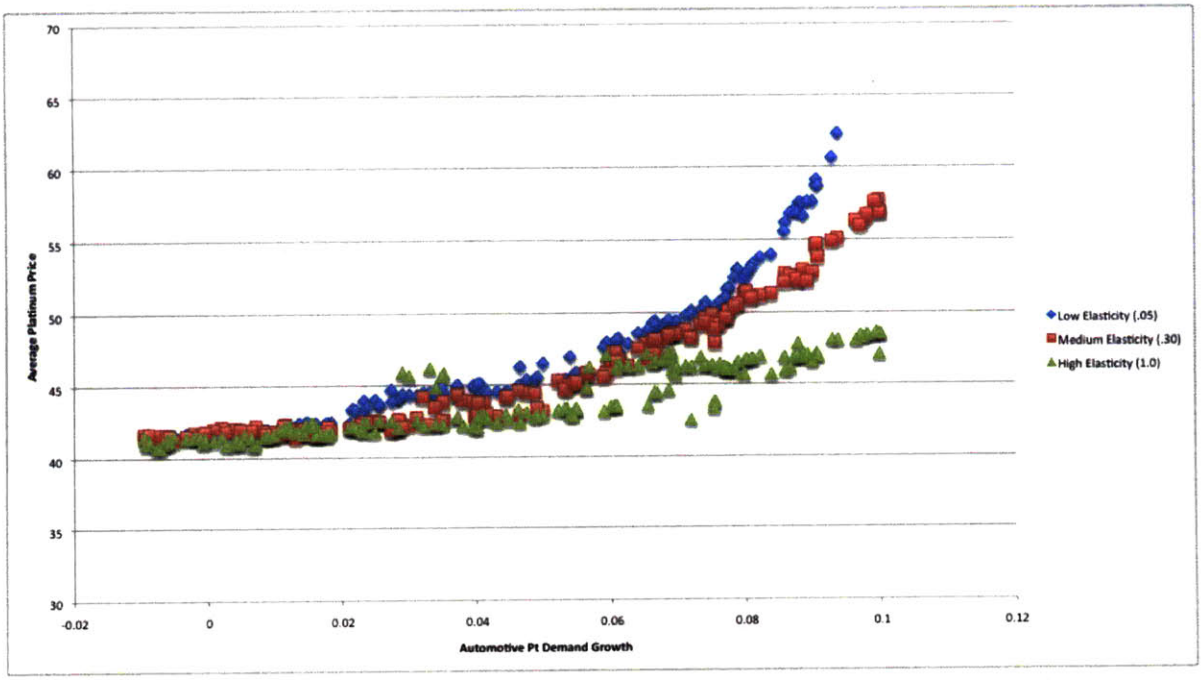


Figure 20 Average platinum price at three levels of elasticity, varying automotive platinum demand growth rates. Outliers excluded from analysis include a peak price of 334.9 for the low elasticity scenario.

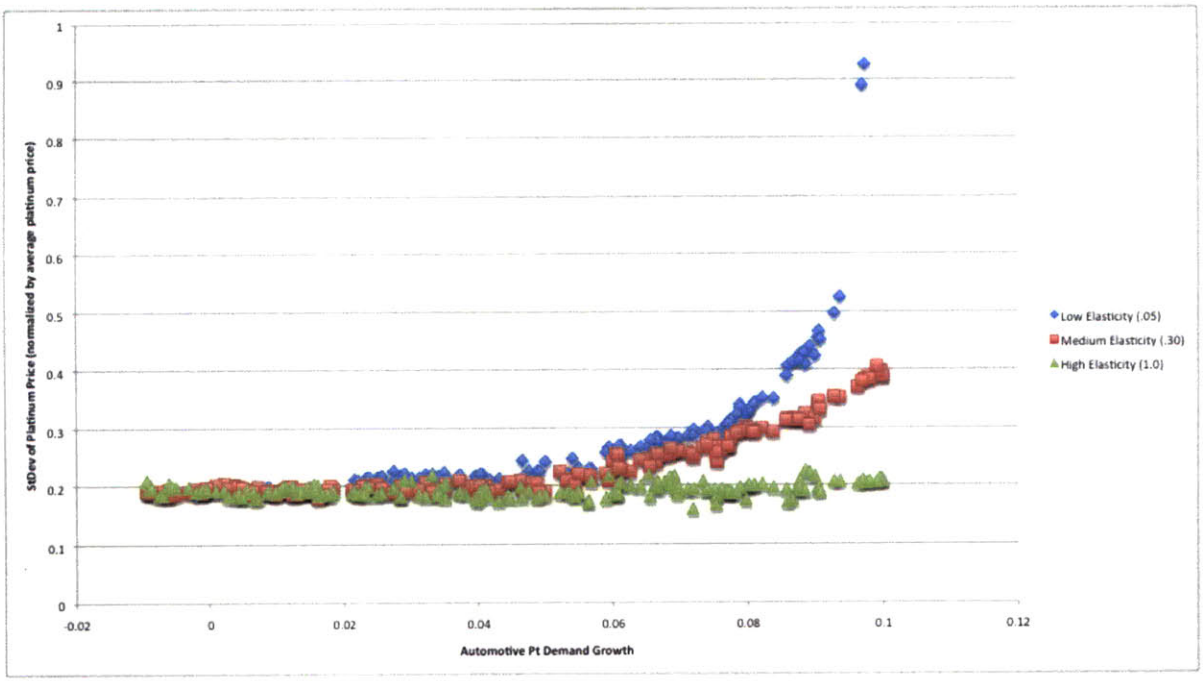


Figure 21 Normalized standard deviation of platinum price at three levels of elasticity, varying automotive platinum demand growth rates.

The standard deviation results show the same pattern of divergence at an automotive platinum demand growth rate of around 6%. In this case, the impact of the various elasticities is even more extreme: for low elasticity, the price grows by approximately 100%, even neglecting outliers; for medium elasticity, this growth is also substantial, around 75%; and for low elasticity, the growth is minimal, at 10% or less. The impact of various levels of automotive platinum demand elasticity on the standard deviation of price, and thus the volatility of price, occurs because increased demand growth of course drives demand to increase. Since supply cannot meet this new level of demand immediately, price increases and represents relative scarcity of the material. In a high elasticity market, the price will drive purchasers to use substitutes or generally demand less of the material, causing price to shift back down before reaching a significant level. Thus, since the price does not need to reach the same level to drive this drop in demand as it would need to reach for the same substitutions to occur in a lower elasticity market, the overall volatility of the market is low

relative to the lower elasticity market. In the low elasticity market, demand is less prone to drop given equivalent price increases and thus price will rise much higher, causing a higher standard deviation overall.

The trend of platinum price over time for each of these scenarios is also of interest and is captured in Figure 22. High elasticity, as seen previously with the average platinum price, is consistently the lowest price scenario. After the first peak and trough of the fluctuations in price, the price clearly varies much less than in the case of low or medium elasticity. Ultimately, the highest price reached is significantly lower than in either of the other two scenarios.

The platinum price trends for medium and low elasticity are very similar. The most noticeable difference is that low elasticity tends to be slightly delayed relative to medium elasticity. This is reasonable, since low elasticity markets should have a slightly lower propensity to substitute as a reaction to high prices, an action that drives the demand down and thus the price as well. Even though the prices drop significantly after the peak for each scenario, the drop for the low elasticity case should occur slightly later than for medium elasticity, and that is suggested by the results. Extrapolating this reasoning may suggest that high elasticity should thus have an even smaller delay relative to medium elasticity, which does not look to be the case. The reasoning here could be that the market is as a whole more stable when there is high elasticity, since demand increases which cause price to rise significantly are eased by the markets propensity to look for substitutes. Thus price increases are less abrupt, causing price to peak later relative to the lower elasticity scenarios. This would offset the relatively smaller expected delay on the downside of the price peak by increasing the delay seen on the upside.

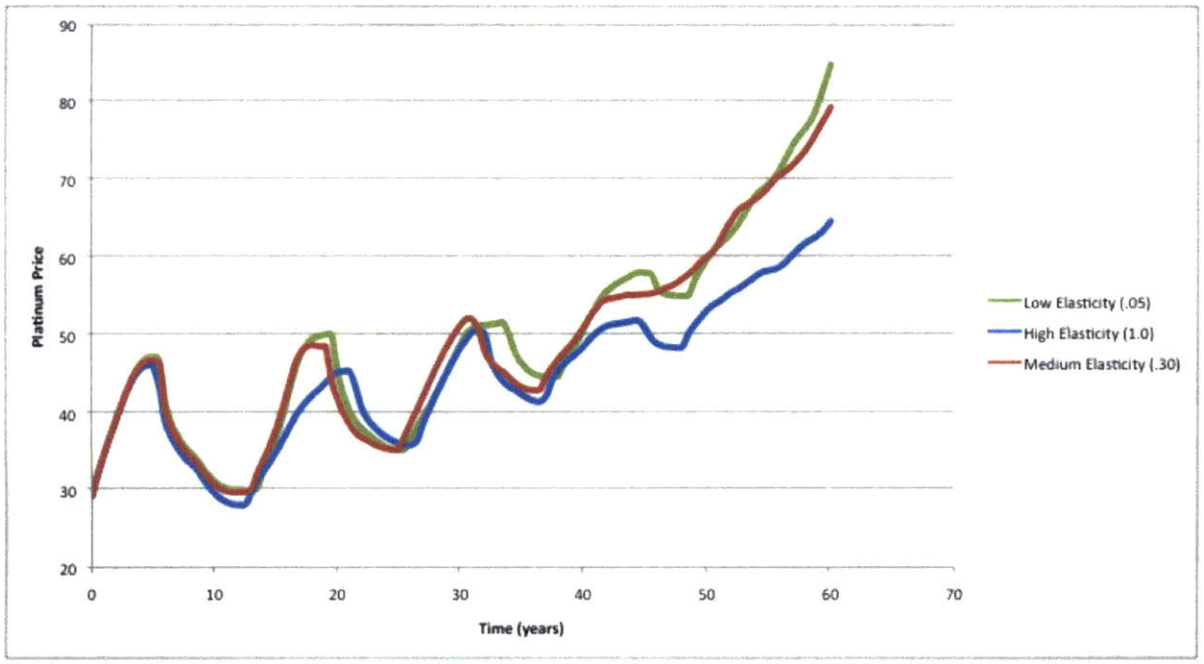


Figure 22 Platinum price over time at three levels of elasticity, 60 year time horizon.

C. Platinum Market Simulation Model Conclusions

Exploration of the base case results for various endogenous variables of the platinum market simulation model, as well as the effects of various sensitivity analyses, has allowed the automotive platinum market to be further characterized both as an isolated entity and with regard to its impact on the overall platinum market. The base case relationships provide important insight into the overall trends seen by the model. Over a 60-year time horizon, significant growth in both total platinum gross demand and automotive platinum gross demand is expected, and these trends are expected to be exponential. Price is expected to rise over the time horizon as lower grades of ore are utilized to fulfill primary platinum demand. Additionally, price is expected to fluctuate over this time period, due to the lag of bringing supply on line to meet rising platinum demand requirements, suggesting a volatile environment for price-taking end users. Such price fluctuations are not new for the platinum market.

Sensitivity analyses of the base case conditions allow us to isolate the effect of automotive platinum demand growth on various endogenous variables. The effects on automotive platinum

gross demand show that average gross demand over the time horizon grows exponentially with automotive industry growth rates as a result of low price elasticity. Additionally, the standard deviation of automotive platinum gross demand increases with increasing growth rates, as supply has a difficult time meeting the jumps in demand associated with these growth rate increases, causing price fluctuations which in turn create demand fluctuations. The findings for total platinum gross demand suggest that it follows similar overall trends as automotive platinum gross demand, though smaller relative impacts are seen because as prices increase industries with high price elasticity, such as the jewelry industry, will decrease their use of platinum and offset the automotive industry platinum demand growth. One key takeaway of this analysis is that variations in automotive platinum sector-specific growth rates can noticeably impact the overall platinum market.

The relationship between automotive platinum demand growth rates and price is also established. The modeling results indicate that very high growth rates in the automotive industry could push prices high if automotive manufacturers continue to behave as if platinum prices do not matter (i.e. exhibit low price elasticity). This is an important indicator of automotive platinum demand growth impacts, as price is the clearest signal to the end-user of platinum.

The findings clearly show that automotive demand growth has a significant effect on a variety of important variables in both the automotive platinum market as well as the platinum market as a whole, noticeably affecting factors such as total gross platinum demand and platinum price. These results are significant due to the potential for momentous growth in automotive sales in developing countries. Regression analysis has shown that automotive sales, which inherently drive automotive production, are a driver for automotive platinum demand at a global level as well as for specific countries.

Comparison of these sensitivity relationships at various levels of elasticity allows us to isolate the effect of automotive platinum demand elasticity on various market variables. Lower demand

elasticity causes gross platinum demand to increase more significantly at a given level of automotive demand growth. This is driven by the lower propensity for substitution in a lower elasticity market. Lower elasticity values, which represent a lower degree of substitution, also increase the volatility of gross demand, since this causes price to increase significantly more than in the case of high elasticity. Additionally, at and below a set growth rate, the market's elasticity and propensity to substitute for the lower price material allow growth in automotive demand without significant increases in price volatility. The automotive industry growth rate at which there is a significant onset of price volatility occurs is higher for higher levels of elasticity in the automotive industry.

Elasticity also impacts the trend of price over time. Low elasticity markets are delayed relative to higher elasticity markets due in part to their lower propensity to seek substitutes. This causes a delay in reaction to high prices, leading to higher average prices than in the case of higher elasticity. Notably, this delay occurs on both the upside and downside of price peaks, which works to create less abrupt price increases and decreases for high elasticity markets.

Two chief findings define the impact of growth on automotive platinum demand: first, minimums in volatility associated with specific growth rates are shown to exist, and suggest that there is a "buffer" in the market given higher levels of elasticity which can account for some level of demand growth; second, the impacts of automotive platinum demand growth on the overall platinum market look to occur only beyond a minimum level of demand growth, somewhere in the range of 6-8%. These two findings are likely linked, as both address the ability of the market to accommodate demand growth to some level but not beyond that.

The implications of these findings are important since the level of elasticity governs market behavior beyond these milestone growth rates. Although the automotive platinum market has historically been an inelastic market, we have discussed several events that may suggest an increase in elasticity. If this is the case, the behavior of both the automotive platinum demand market as well as

the overall platinum market will undoubtedly be influenced significantly. Understanding this potential is important for any player in the market, as this shift in market dynamics could make historical market patterns obsolete.

VI. Future Work

Both regression analysis and use of the platinum market simulation model have allowed us to characterize the automotive platinum market, including its impacts on the overall platinum market. Future work in this area has a variety of potential starting points. One of these is an analysis of the dynamic between primary and secondary platinum demand in the automotive market. Obtaining platinum from discarded vehicles is form of recycling that may ease the impact of potential automotive platinum demand growth on primary platinum suppliers. Further study of recently developed technologies that aim to reduce the required amount of platinum in catalysts is also in order, an understanding that could be used to develop a more current view of the automotive platinum market.

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