DOE EERE Program Record	
Record #: 14001	**Date:** February 10, 2014
Title: Platinum Group Metals (PGM) for Light-Duty Vehicles	
Originator: Tien Nguyen, Dave Andress, Todd Toops, Sujit Das	
Approved by: Pat Davis Sunita Satyapal	**Date:** March 4, 2014

Item

Today's average gasoline light-duty vehicle (GLDV) in the U.S. requires approximately 5.6 g Platinum Group Metal (PGM) for its emissions control system, versus approximately 10 g PGM for an average diesel LDV (DLDV). This average LDV is slightly larger than the average U.S. midsize car because it is the weighted average of all new LDVs sold in the U.S. in 2011. By 2025, the GLDV and DLDV's PGM contents are estimated to be 5.3 g and 9.6 g, respectively. For 2025 LDVs outside of North America, their sizes were assumed to be the average European LDV (smaller engines relative to U.S. LDVs), resulting in approximately 1.3 g for a GLDV and 4.2 g PGM for a DLDV. The estimates for 2025 (5.3 g, 9.6 g, 1.3 g, 4.2 g), are median values, with approximately -20% to +20% uncertainty associated with future engine sizes (PGM requirements are roughly proportional to engine size; the derivation of the range of future engine sizes is discussed in the *Data and Assumptions* section).

Overview of Results

The average PGM loadings of emissions control systems in U.S. LDVs, assuming that the U.S. Tier 3 emissions standards (expected in 2017) will hold through 2025, are approximately (references and detailed assumptions are listed in the *Data and Assumptions* section on Page 3):

- United States (U.S.) Mid-Range Case: A literature search of the past 20 years revealed that the most significant decrease in PGM loading for GLDVs took place in the U.S. between 2000 and 2005. GM and Ford achieved a reduction of 40%-50% in PGM per car during this period (Wards Auto 2001, White 2002). While R&D could result in further reduction in PGM loading, this analysis assumed that the more significant source of reduction will be from engine downsizing, i.e., the reduction in PGM is proportional to engine displacement (typically measured in liters). In 2013 the U.S. is still under Tier 2 emissions standards. When the proposed Tier 3 standards become effective beginning in 2017, the sulfur content in U.S. gasoline will decrease to 10 ppm from the current 30 ppm level, based on Environmental Protection Agency regulation. Additionally, the fuel economy standards (negotiated between the Obama Administration and automobile industry) will result in an increasing number of LDVs with downsized, turbocharged engines using direct injection (this combination of technologies is abbreviated as GTDI for gasoline turbo direct injection, based on the automobile industry's convention) that are significantly more efficient than current LDVs. These advanced gasoline engines may require an increase in emissions catalyst size per liter of displacement (Johnson Matthey 2009a), a factor that could partially negate the effect of downsizing. The U.S. average LDV engine was approximately 3.1 L in 2011 for new sales, and could be as small as 2.2 L in 2025, assuming that the future LDV's power will be approximately 80 kW (107 hp) per liter of GTDI engine (details and references provided in the *Data and Assumptions* section).

Table 1. Emissions Control System's PGM for Average U.S. Gasoline LDV (slightly larger than midsize car) – Medium-Optimism (Mid-Range)

	2011	2020	2025
Grams PGM per Gasoline LDV - U.S.	**5.58**	**6.00**	**5.28**
Pt Fraction in Gasoline catalyst	0.06	0.06	0.06
Pd Fraction in Gasoline catalyst	0.89	0.89	0.89
Rh Fraction in Gasoline catalyst	0.06	0.06	0.06
Engine Power in kW/L	55	80	80
Engine Volume in Liters	3.10	2.50	2.20
Grams Pt per Gasoline LDV	0.31	0.33	0.29
Grams Pd per Gasoline LDV	4.96	5.33	4.69
Grams Rh per Gasoline LDV	0.31	0.33	0.29

Table 2. Emissions Control System's PGM for Average U.S. Diesel LDV (slightly larger than midsize car) - Medium-Optimism (Mid-Range)

	2011	2020	2025
Grams PGM per Dies. LDV - U.S.	**10.1**	**10.9**	**9.57**
Pt Fraction in Diesel LDV	0.74	0.74	0.74
Pd Fraction in Diesel LDV	0.22	0.22	0.22
Rh Fraction in Diesel LDV	0.04	0.04	0.04
Engine Power in kW/L	55	80	80
Engine Volume in Liters	3.10	2.50	2.20
Grams Pt per Diesel LDV	7.53	8.08	7.11
Grams Pd per Diesel LDV	2.22	2.38	2.10
Grams Rh per Diesel LDV	0.39	0.41	0.36

Results for U.S. LDVs under the mid-range scenario are shown in Tables 1 and 2.

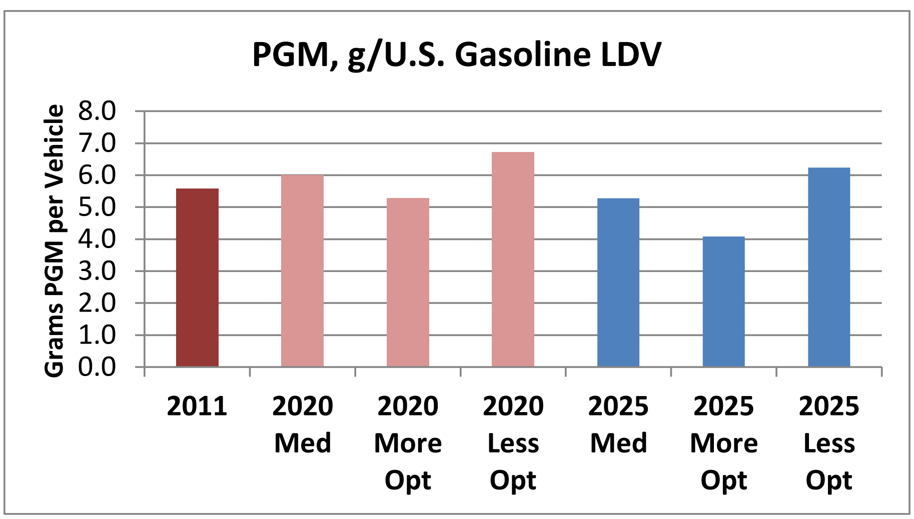

Figure 1. PGM for U.S. Gasoline LDVs under 3 Scenarios

Note: In 2025, the estimated reduction in engine size and the increase in PGM loadings required by Tier 3 emissions standards nearly balance each other out when compared with 2011 loadings

On a per average GLDV basis, the loadings are approximately 5.6 g in 2011, 6.0 g in 2020, and 5.3 g PGM in 2025. Tier 3 will begin to apply in 2017, resulting in higher loadings per liter; however, the engine volumes will likely decrease by ~30% as shown in the column for Year 2025. For DLDVs, the loadings are approximately 10 g in 2011, 11 g in 2020, and 9.6 g PGM in 2025, assuming the same engine size as GLDVs. Figure 1 shows the results under three scenarios (medium, less, and more optimistic).

- **U.S. Less Optimistic Case**: The average (sales-weighted) engine size would be 2.6 L in 2025 (from 3.1 L in 2011), the loading could be 6.2 g PGM per GLDV in 2025. For DLDVs with 2.6-L engines, the PGM loading would be approximately 11.3 g in 2025.
- **U.S. More Optimistic Case**: In theory, if R&D on LDV efficiency and lightweight materials was highly successful, significantly less powerful (smaller) engines would be able to deliver nearly the same performance as today's LDVs. For example, Table 2.9 of National Research Council 2013 shows that today's gasoline engine with 118 kW power may be replaced by a GTDI engine in the 84-90 kW range (14% to 19% decrease in power) in 2030. Based on this reasoning, in 2025, the average engine size of new U.S. LDVs was assumed to be reduced to the average size of new European engines of 2011, namely 1.7 L. This corresponds to approximately 4.1 g PGM for an average GLDV in 2025 and 7.4 g PGM for an average DLDV in 2025. Today's EU LDV fleet has not yet achieved the 2025 fuel economy envisioned for U.S. LDVs under the latest fuel economy standards that the U.S. government and automobile industry had signed up to (MARTEC, 2012). Therefore, while the reduction from 3.1 L for 2011 LDV sales to 1.7 L for 2025 LDV sales is major, it is consistent with the United States' ambitious fuel economy target.

Figure 2 and Table 3 summarize the medium-optimism results for U.S. GLDVs based on the results cited. Past loadings shown are based on literature information (*Data and Assumptions* section).

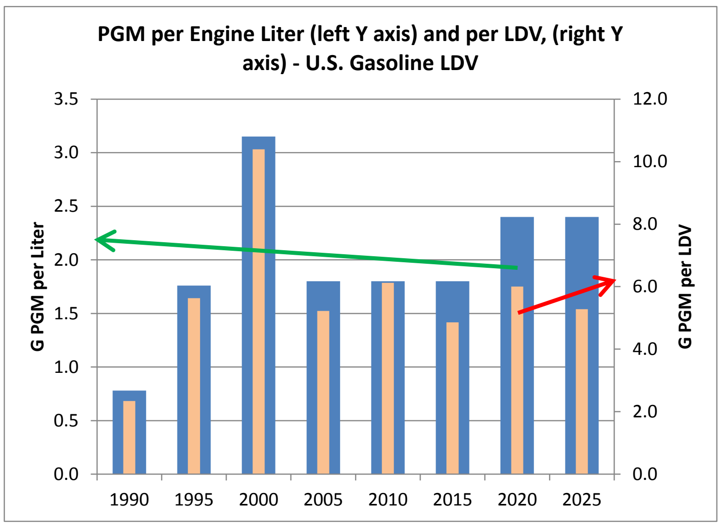

Figure 2. Platinum Group Metals for U.S. Gasoline LDV (Medium Optimism)
Note: After 2017, the more stringent Tier 3 emissions standards will increase PGM loadings per liter (Environmental Protection Agency 2013)

Table 3. PGM Loadings of U.S. GLDV Emissions Control Systems (Medium Optimism)

	1990	1995	2000	2005	2010	2015	2020	2025
g PGM/L	0.78	1.8	3.2	1.8	1.8	1.8	2.4	2.4
Engine L	3.0	3.2	3.3	2.9	3.4	2.7	2.5	2.2
g PGM/LDV	2.3	5.6	10	5.2	6.1	4.9	6.0	5.3

Data and Assumptions

Based on the current state of the art and extrapolating into the future, the following assumptions were made for future emissions control systems on LDVs, using the following references:

- Current loadings for internal combustion engine vehicles (ICEVs) are from a 2012 International Council for Clean Transportation (ICTT) study (Sanchez 2012).
- Future ICEV loadings are based on ICEV engine downsizing resulting from widespread adoption of turbocharging or supercharging in conjunction with direct fuel injection (this set of combined technologies will be abbreviated as "GTDI" for gasoline turbo direct injection and "DTDI" for diesel turbo direct injection) as a result of more stringent fuel economy standards. This assumption is based on the rapid rate of adoption in the U.S. (Department of Energy, Fact #720) and expert opinion that the U.S. is likely to follow Europe where 75% of LDVs already have turbocharged or supercharged engines with direct injection (Forbes 2013).

Estimating future technical success is subject to significant uncertainties. Therefore three scenarios were considered - average, less optimistic, and more optimistic, with respect to reducing future engine sizes.

The U.S. sales-weighted LDV engine was approximately 3.1 L from new LDV sales information for 2011 (Transportation Energy Data Book). The mid-size car's average engine size was 2.6 L (for new cars sold in 2011). From this, a rough approximation can be made for the factor that relates the size of all LDVs sold to the size of all mid-size cars sold: 3.1/2.6 = 1.2 in 2011. In 2025, the U.S. ambitious fuel economy targets could result in a decreasing fraction of larger LDVs in the annual number of cars sold, and 1.1 times the engine size of the midsize car could be assumed to represent the engine size of the weighted average LDV sold in the U.S.

Table 4. Sales & Engine Data of LDVs Sold in U.S. in 2011

LDVs		2011 U.S. Engine Sizes (Liters)			
Small	Midsize	Large	Small	Midsize	Large
	Cars			Truck SUV's	
2.37	2.51	3.12	3.8	2.99	4.11
	Station Wagons			Non-Truck SUV's	
2.01	3.35	Not sold	Not sold	2.78	3.25
	Pick-Ups			Vans	
Not sold	2.49	4.84	Not sold	3.47	5.1

LDVs		2011 U.S. Sales Percent			
Small	Midsize	Large	Small	Midsize	Large
	Cars			Truck SUV's	
17.7%	21.4%	9.9%	0.8%	8.7%	9.6%
	Station Wagons			Non-Truck SUV's	
3.9%	0.0%	0.0%	0.0%	6.3%	3.1%
	Pick-Ups			Vans	
0.0%	0.6%	13.5%	0.0%	4.3%	0.1%

Source: Transportation Energy Data Book 2012

In 2012, the six most popular mid-size cars in the U.S. were the Toyota Camry, Honda Accord, Nissan Altima, Ford Fusion, Hyundai Sonata, and Chevrolet Malibu, with engines sized at 2.0 L, 2.4 L, 2.5 L and

3.5 L (Cain 2012, Edmunds.com). The 2.0-L engines are found on 4-cylinder models with turbocharging, with power between 230 and 274 hp (171-204 kW, or 85-102 kW per liter). These smaller engines are only slightly less powerful than 270-280 hp engines in current 6-cylinder cars with aspirated engines displacing 3.3 to 3.5 liters. By 2025, a large fraction of new cars will likely be GTDI because this technology can deliver high power while keeping fuel consumption low thanks to smaller engines (Forbes, 2013). The average power per L in 2025 was assumed to be 80 kW for a GTDI mid-size car because if one assumed that future midsize cars have 2.0-L engines on average, each GTDI engine would deliver 160 kW, an acceptable power level compared today (the 2013 Camry's power is 133 kW with a 2.5-L engine and 200 kW with a 3.5-L engine; in addition, the increased use of lightweight materials will likely reduce the weight of LDVs, further justifying this assumption). Using the 1.1 factor for estimating the fleet-averaged engine size from the mid-size car's engine size, one gets 2.2 L for the average sales-weighted US LDV for the mid-range optimism scenario.

For the more optimistic scenario, 1.7 L was assumed to be the sales-weighted average engine size in 2025. This estimate appears reasonable because 1.7 L is the average engine size of EU LDVs sold in 2011 (ACEA 2013).

The least optimistic scenarios (larger engines and attendant higher PGM needs) involved assuming a less aggressive reduction in future LDV engine size, i.e., more moderate PGM loading change for the U.S. (2.6 L in 2025 versus 3.1 L in 2011). The power of the average new gasoline LDV would be 2.6 x 80 kW, i.e. approximately 208 kW in 2025 (comparable to 2013 midsize SUVs). This is indeed a conservative assumption.

Major assumptions are listed in the following tables, with PGM loadings per engine liter adapted from Sanchez 2012 for current LDVs and increased further to reflect Tier 3 standards, based on Environmental Protection Agency 2013 (assumed loading per liter of engine volume was reviewed in July 2013 by an emissions catalyst expert of a major automaker, identity withheld by request). A discussion of the approach used for the results shown is presented after the last table.

Table 5. Major Assumptions: Platinum Group Metals (PGM) for U.S. Gasoline LDVs Under 3 Scenarios.

	2011	2020 Med Opt	2020 Low Opt	2020 High Opt	2025 Med Opt	2025 Low Opt	2025 High Opt
Grams PGM per Gasoline LDV - U.S.	**5.58**	**6.00**	**6.72**	**5.28**	**5.28**	**6.24**	**4.08**
Pt Fraction in Gasoline catalyst	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Pd Fraction in Gasoline catalyst	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rh Fraction in Gasoline catalyst	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Engine Volume in Liters	3.10	2.50	2.80	2.20	2.20	2.60	1.70
Grams Pt per Gasoline LDV	0.31	0.33	0.37	0.29	0.29	0.35	0.23
Grams Pd per Gasoline LDV	4.96	5.33	5.97	4.69	4.69	5.55	3.63
Grams Rh per Gasoline LDV	0.31	0.33	0.37	0.29	0.29	0.35	0.23

Note: 2011 grams per liter and fractions are from Sanchez 2012. Sanchez et al provided their synopsis of the Society of Automotive Engineers (SAE) literature and input that relevant experts provided to their study of the costs of LDV emissions control technologies. 2011 LDV sales data (engine sizes) are from the Transportation Energy Data Book. Future engine sizes were derived from this record's analysis of LDV technology trends based on recent public information. Tier 3 PGM requirements were derived from the Environmental Protection Agency 2013's estimate of incremental emissions control costs under Tier 3.

Table 6. Major Assumptions: PGM for U.S. Diesel LDVs Under 3 Scenarios.

	2011	2020 Med Opt	2020 Low Opt	2020 High Opt	2025 Med Opt	2025 Low Opt	2025 High Opt
Grams PGM per Diesel LDV - U.S. Avg (80% SCR, 20% LNT)	**10.1**	**10.9**	**12.2**	**9.57**	**9.57**	**11.3**	**7.40**
Pt Fraction in Diesel LDV	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Pd Fraction in Diesel LDV	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Rh Fraction in Diesel LDV	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Engine Volume in Liters	3.10	2.50	2.80	2.20	2.20	2.60	1.70
Grams Pt per Diesel LDV	7.53	8.08	9.05	7.11	7.11	8.40	5.49
Grams Pd per Diesel LDV	2.22	2.38	2.67	2.10	2.10	2.48	1.62
Grams Rh per Diesel LDV	0.39	0.41	0.46	0.36	0.36	0.43	0.28

Same notes as seen for Table 5

Automotive Catalysts for U.S. Gasoline LDVs

Modern gasoline vehicles are equipped with three-way catalytic converters (TWCs). This refers to the three regulated emissions that catalytic converters help to control: NOx, CO and hydrocarbons (HCs). The TWC relies on Pt, Pd and/or Rh to catalyze both the reduction of NOx and the oxidation of CO and HCs. These competing oxidation and reduction reactions can only both be effective when the air to fuel mixture is very close to stoichiometry; therefore, an additional control system monitors the oxygen concentration in the exhaust stream and uses this information to control the fuel injection system. Emissions control systems are designed to work with expected fuel quality, including expected limits on sulfur content (30 ppm average per oil company and 80 ppm for any given batch of fuel). Higher sulfur levels in gasoline could reduce the effectiveness of emissions catalysts.

With the advent of the technological feasibility of a one-to-one ratio for substituting Pt with Pd in gasoline catalysts (White 2002), the choice of which metal to use is primarily influenced by their relative costs. Historically, Pd has had significant price advantage, resulting in a significant reduction in Pt use in recent years. In a 2012 report, the International Council for Clean Transportation (Sanchez 2012) estimated current PGM loadings as shown in Table 7 for U.S. LDVs that must meet Tier 2, Bin 5 requirements (among the most stringent to date). Sanchez 2012 assumed that the PGM requirement is proportional to engine size (displacement liters). This analysis adopted that assumption and used the same value per engine liter (5.4 g/3 = 1.8 g PGM per L for Tier 2) in the low/medium/high scenarios. Sanchez 2012 did not look at Tier 3 emissions standards. This analysis used Environmental Protection Agency 2013's results for increased gasoline catalyst costs under Tier 3 to derive increased PGM loadings under Tier 3. From the EPA report's estimate of $60 increase in catalyst cost for a 4-cylinder gasoline car, and assuming that PGM loading accounts for 2/3 of the cost increase, with the other 1/3 going to the substrate, washcoat, canning process, and labor (based on Table 4-4 in Sanchez 2012), the PGM increase for GLDVs was derived to be 0.6 g (primarily Pd) per engine liter, assuming a 2.5-L engine and approximately $25 per g ($786/Troy oz.) of PGM (weighted average of market prices in August 2013, with Pt at $1,452, Pd at $732, Rh at $995 per Troy oz.).

Beginning in 2009, car manufacturers started to market more efficient models that pack high power in smaller engines, partly a result of the current U.S. fuel economy standards. While there are still older cars on the road with larger engines, it appears that the average engine size is on a downward trend for the foreseeable future. Advanced, downsized gasoline engines such as turbocharged and supercharged engines, when combined with fuel direct injection (DI), result in a smaller catalyst volume, but possibly higher PGM loading per liter of catalyst (Johnson Matthey 2009a).

Table 7. PGM for Current Gasoline Catalysts in U.S. – 1.8 gram per engine liter

Gasol 3-Way Catalyst (Tier 2 Bin 5)		
Engine Liters	1.5	3.0
PGM Mass		
Pt, g	0.15	0.30
Pd, g	2.40	4.80
Rh, g	0.15	0.30
Total PGM	**2.70**	**5.40**

Source: Sanchez 2012

Automotive Catalysts for U.S. Diesel LDVs

Over the last decade, emissions regulations have become progressively more stringent. Required reductions for CO, hydrocarbons (HC), NOx, and soot emissions have occurred in phases, with the most recent phase completed in 2010. Ultra-low sulfur diesel (ULSD) with 15 ppm sulfur is used throughout the U.S. instead of the 500-ppm version used prior to 2010. Emissions control systems are designed to work with expected fuel quality, including expected limits on sulfur content. Higher sulfur levels could reduce the effectiveness of diesel emissions catalysts.

The current system consists of an oxidation component, a particulate (soot) filter, and a NOx reduction component. Diesel oxidation catalysts (DOC) are typically used to remove CO and HC in the exhaust and are primarily of the PGM group. The DOC component is similar to the catalytic converter on a gasoline LDV, but reducing NOx emissions from diesel engines is more challenging than gasoline engines and one needs a NOx control capability in addition to the catalytic converter for diesel engines. Diesel particulate filters (DPF) feature channels through which exhaust gases are funneled and particulates are trapped. DPFs typically have some PGM content (Umicore 2011). As stated earlier, diesel NOx emissions must be reduced with special equipment: (a) selective catalytic reduction devices (SCR) that do not contain PGM, or (b) NOx adsorbing devices (lean NOx traps, abbreviated as LNTs) that rely on PGM[1].

Diesel engines operate at lower temperatures than gasoline engines, making it more challenging for catalysts to function properly. Although the catalyst loading and catalyst size vary greatly, metal formulations varied little in the past, being mainly based on Pt which is generally considered the most efficient metal for oxidizing emissions from the oxygen-rich exhaust gas of the diesel engine (Jollie 2007). Until a few years ago, catalysts for diesel engines were nearly exclusively Pt. However, more recent research (Kim et al, 2011; Lambert 2012) shows that combining Pt and Pd while optimizing the Pt/Pd ratio can improve oxidation for CO and HCs and more readily oxidize NO to NO_2 (excess NO_2 in the exhaust facilitates the oxidation of the carbon in the soot). In recent years manufacturers started increasing the ratio of Pd to Pt to approximately 30% Pd/70% Pt (Stillwater 2012).

Table 8 (Sanchez 2012) shows current PGM loadings for the combined system consisting of the DOC, DPF and LNT. LNT, a more recent component of emissions control systems on diesel vehicles, is required as a result of more stringent regulations. Both LNT and SCR have shown good NOx reduction performance and durability. For heavy-duty vehicles, SCR appears to be the preferred technology (Schnitzler 2006, Facts About SCR 2008). In 2013, automakers began to introduce diesel models in the U.S. SCR is so far the technology of choice (announcements by VW, BMW, Chevrolet, Mercedes Benz,

[1] From Sanchez 2012: LNT is based on materials that can adsorb NOx during periods of low temperature, or lean periods, and then release them during minimal periods (5% of operational time) of rich operation during which they are reduced in a TWC function. The catalyst wash coat (used to disperse catalytic materials over a high surface area) combines three active components, very similar to those found in the TWC: an oxidation catalyst (platinum), a NOx adsorbent (barium oxide, BaO), and a reduction catalyst (rhodium).

Jeep, etc.) In this analysis, the average DLDV is assumed to be weighted at 80% SCR/20% LNT to reflect current offerings.

Industry can be expected to continue to find ways to reduce PGM loading in order to lower costs. For example, in 2010 Panasonic began shipping a new catalyst for DPFs that can result in "significantly" less PGM requirement in the diesel oxidation catalyst (Panasonic 2010). On the other hand, more stringent emissions standards under Tier 3 will cause PGM loading to increase. In this analysis, the PGM loading per liter of diesel engine in 2017 and beyond is assumed to increase from current numbers (current technology in U.S. is shown in Table 8). The percent increase was assumed to be similar to that estimated for gasoline catalysts.

Table 8. PGMs for Diesel Emissions Control (Current Technology)

	Diesel Oxidation Catalyst			Diesel Particulate Filter			Lean NOx Trap		
	0.66 g Pt/Catalyst Liter 0.33 g Pd/Catalyst Liter			0.75 g Pt/Catalyst Liter 0.25 g Pd/Catalyst Liter			2.0 g Pt/Catalyst Liter 0.5 g Rh/Catalyst Liter		
Engine Liters	DOC Liters	Pt grams	Pd grams	DPF Liters	Pt grams	Pd grams	LNT Liters	Pt grams	Rh grams
1.5	0.98	0.64	0.32	3.00	2.25	0.75	1.88	3.75	0.94
3.0	1.95	1.29	0.64	6.00	4.50	1.50	3.75	7.50	1.88

Source: Sanchez 2012

Table 9 shows the PGM content as a function of diesel emissions control technology, LNT or SCR. For this study, 80% SCR and 20% LNT were assumed as the selected case, considering the more numerous SCR offerings in the current U.S. market.

Table 9. PGMs for Diesel Emissions Control System for LNT, SCR and Average of Both (Current Technology)

	With LNT				With SCR (no need of LNT)			Avg. (80% SCR, 20% LNT)		
Engine Liters	**Catal Vol**	**g Pt**	**g Pd**	**g Rh**	**g Pt**	**g Pd**	**g Rh**	**g Pt**	**g Pd**	**g Rh**
1.5	5.9	6.64	1.07	0.94	2.89	1.07	0.0	3.64	1.07	0.19
		PGM Total, grams		**8.65**	**PGM Total, grams**		**3.97**	**PGM Total, grams**		**4.90**
3.0	11.7	13.3	2.14	1.88	5.79	2.14	0.0	7.29	2.14	0.38
		PGM Total, grams		**17.3**	**PGM Total, grams**		**7.93**	**PGM Total, grams**		**9.81**

Source: Sanchez 2012

As a result, it was assumed in Table 9 that a 3.0 L diesel engine needs 9.81g (7.3g Pt, 2.1 g Pd and 0.38 g Rh) as shown in the column labeled "Average (80% SCR, 20% LNT)" (for current technology). Therefore, from Table 6 (medium optimism column), a future 2.2-L diesel car's emissions control system would consist of approximately 7.1 g Pt, 2.1 g Pd, and 0.36 g Rh in 2025, with Tier 3 standards raising the PGM content relative to today's LDV and negating the effect of decreased engine size.

Supplemental Analysis: Derivation of PGM Loadings for Non-U.S. LDVs in 2025

Using the assumption that PGM loadings are proportional to engine volumes and assuming that emissions standards in other countries would be eventually identical to those in the U.S., the PGM loadings for LDVs in the "rest of the world" could be as shown in the following tables (Year 2020 results included for information).

Table 10. PGM Loadings for Non-U.S. GLDVs if U.S. Emissions Standards Were Adopted

	2011	2020 Med Opt	2020 Low Opt	2020 High Opt	2025 Med Opt	2025 Low Opt	2025 High Opt
Grams PGM per Gasoline LDV - Europe	**3.06**	**3.36**	**3.84**	**3.12**	**3.12**	**3.60**	**2.88**
Pt Fraction in Gasoline catalyst	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Pd Fraction in Gasoline catalyst	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rh Fraction in Gasoline catalyst	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Engine Volume in Liters	1.70	1.40	1.60	1.30	1.30	1.50	1.20
Grams Pt per Gasoline LDV	0.17	0.19	0.21	0.17	0.17	0.20	0.16
Grams Pd per Gasoline LDV	2.72	2.99	3.41	2.77	2.77	3.20	2.56
Grams Rh per Gasoline LDV	0.17	0.19	0.21	0.17	0.17	0.20	0.16

Note: From ACEA 2013,2011 sales-weighted engine size was 1.7 L in the EU (assumed to be representative of the rest of the world). Rate of reduction in future average engine volume in EU and rest of the world assumed to be proportional to U.S. rate of reduction shown in preceding tables.

However, if one assumed that the upcoming Euro 6 standards will apply to the rest of the world, less PGM would be required for the GLDV as shown in the following table (NOx standards in the EU are less strict than U.S. standards).

Table 11. PGM Loadings for Non-U.S. Gasoline LDVs if Euro-6 Emissions Standards Were Adopted

	2011	2020 Med Opt	2020 Low Opt	2020 High Opt	2025 Med Opt	2025 Low Opt	2025 High Opt
Grams PGM per Gasoline LDV - Europe	**1.45**	**1.40**	**1.60**	**1.30**	**1.30**	**1.50**	**1.20**
Pt Fraction in Gasoline catalyst	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Pd Fraction in Gasoline catalyst	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Rh Fraction in Gasoline catalyst	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Engine Volume in Liters	1.70	1.40	1.60	1.30	1.30	1.50	1.20
Grams Pt per Gasoline LDV	0.08	0.08	0.09	0.07	0.07	0.08	0.07
Grams Pd per Gasoline LDV	1.28	1.24	1.42	1.16	1.16	1.33	1.07
Grams Rh per Gasoline LDV	0.08	0.08	0.09	0.07	0.07	0.08	0.07

Note: Fractions of Pt, Pd and Rh, and PGM loadings for Euro-6 standards derived from Sanchez 2012. 2011 sales-weighted engine size was 1.7 L in the EU (ACEA 2013). Rate of reduction in future average engine volume in EU and rest of world assumed to be proportional to U.S. rate of reduction.

Table 12. PGM Loadings for Non-U.S. Diesel LDVs if U.S. Emissions Standards Were Adopted

	2011	2020 Med Opt	2020 Low Opt	2020 High Opt	2025 Med Opt	2025 Low Opt	2025 High Opt
Grams PGM per Diesel LDV - Euro Avg (80% SCR, 20% LNT)	**5.56**	**6.09**	**6.96**	**5.65**	**5.66**	**6.53**	**5.22**
Pt Fraction in Diesel LDV in EU	0.73	0.74	0.74	0.74	0.74	0.74	0.74
Pd Fraction in Diesel LDV in EU	0.27	0.22	0.22	0.22	0.22	0.22	0.22
Rh Fraction in Diesel LDV in EU	0.00	0.04	0.04	0.04	0.04	0.04	0.04
Engine Volume in Liters	1.70	1.40	1.60	1.30	1.30	1.50	1.20
Grams Pt per Diesel LDV	4.06	4.52	5.17	4.20	4.20	4.85	3.88
Grams Pd per Diesel LDV	1.50	1.33	1.52	1.24	1.24	1.43	1.14
Grams Rh per Diesel LDV	0.00	0.23	0.26	0.21	0.21	0.25	0.20

Note: Rate of reduction in future average engine volume in EU and rest of world assumed to be proportional to U.S. rate of reduction.

Table 13. PGM Loadings for Non-U.S. Diesel LDVs if Euro-6 Emissions Standards Were Adopted

	2011	2020 Med Opt	2020 Low Opt	2020 High Opt	2025 Med Opt	2025 Low Opt	2025 High Opt
Grams PGM per Diesel LDV - Euro Avg (80% SCR, 20% LNT)	**4.42**	**4.58**	**5.23**	**4.25**	**4.25**	**4.91**	**3.92**
Pt Fraction in Diesel LDV in EU	0.73	0.74	0.74	0.74	0.74	0.74	0.74
Pd Fraction in Diesel LDV in EU	0.27	0.22	0.22	0.22	0.22	0.22	0.22
Rh Fraction in Diesel LDV in EU	0.00	0.04	0.04	0.04	0.04	0.04	0.04
Engine Volume in Liters	1.70	1.40	1.60	1.30	1.30	1.50	1.20
Grams Pt per Diesel LDV	3.23	3.40	3.89	3.16	3.16	3.64	2.92
Grams Pd per Diesel LDV	1.19	1.00	1.15	0.93	0.93	1.07	0.86
Grams Rh per Diesel LDV	0.00	0.17	0.20	0.16	0.16	0.19	0.15

Note: Fractions of Pt, Pd and Rh, and PGM loadings for Euro-6 standards derived from Sanchez 2012. Rate of reduction in future average engine volume in EU and rest of world assumed to be proportional to U.S. rate of reduction

Figure 3 shows that the U.S. has the most stringent NOx emission standards among the three major LDV markets (EU, U.S., and Japan). As the U.S. transitions from Tier 2 to Tier 3 (Tier 3 standards are harmonized with California LEV III standards), PGM loadings will rise and could offset any reduction through R&D success.

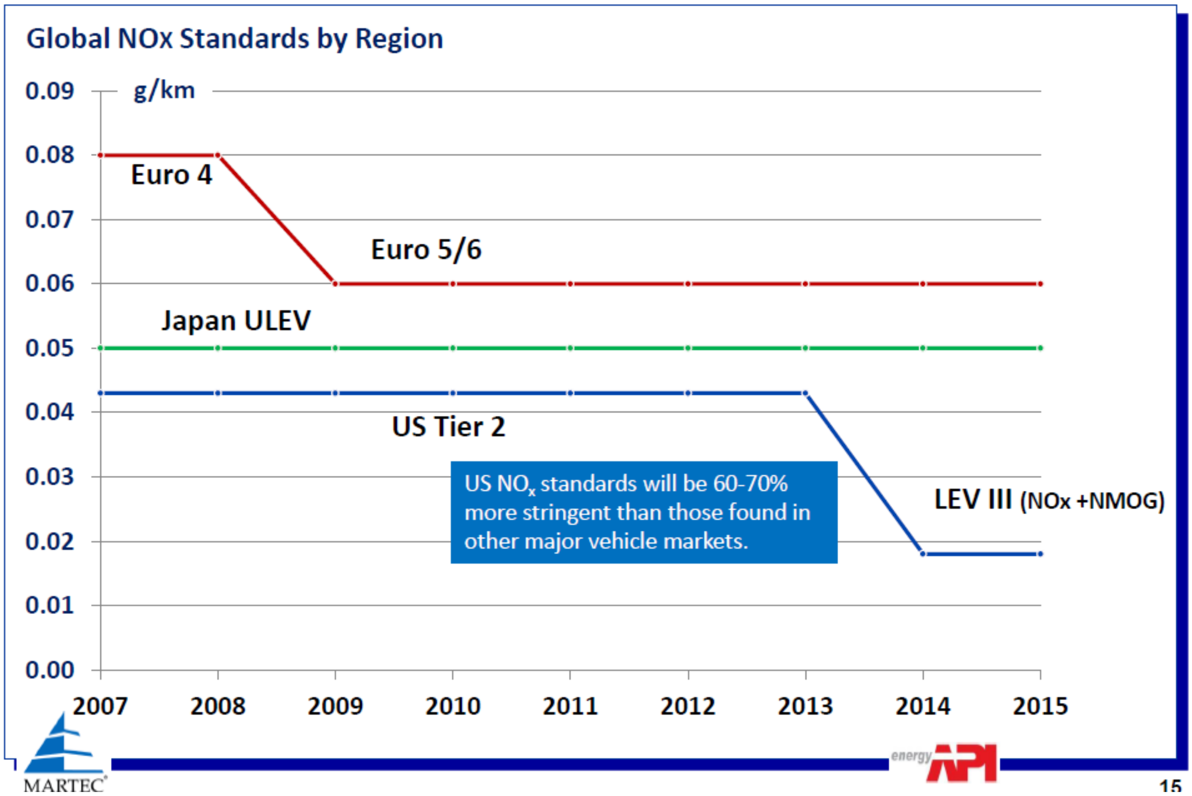

Figure 3. NOx Emission Standards in Major World Markets
Source: MARTEC 2010

Past PGM Loadings in U.S.

Figure 2 shows a rough reconstruction past PGM loadings per U.S. gasoline car and estimates of future loadings under the three R&D success scenarios. 1990-1995 estimates were derived from Johnson Matthey's market data tables (Market Data Tables) and Sanchez 2012. Beginning in 2001, U.S. automakers started to use new catalysts requiring much less Pd, after seeing Pd prices skyrocket in the late 1990's (Wards Auto 2001, White 2002). This is the reason for the decrease shown for 2001-2005 in Figure 2. Prior to 2001, the increase in PGM loadings in the U.S. was driven by the transition from Tier 1 to NLEV and from NLEV to Tier 2 emissions standards (mid to late 1990's).

Industry Input and Peer Review

The study used information from Sanchez 2012, a peer-reviewed study, and benefited from review by, and input from two experts working for a major U.S. and major Japanese automobile company, respectively (they requested anonymity). Both confirmed the Johnson Matthey paper's statement that GTDI engines could require increased PGM per liter of displacement compared to current aspirated engines. The results for the smaller gasoline engines that are likely to be found in future European and world LDVs reflect one of the reviewers' suggestion for a 25% increase in PGM loading per vehicle relative to the assumption in Sanchez 2012 (to 1.3 g) because the relationship between engine sizes and PGM requirements is not linear at such small engine sizes. A program manager from the U.S. Department of Energy's Vehicle Technologies Office also reviewed and approved the assumptions used in this analysis.

References

ACEA (European Automobile Manufacturers Association) – New Passenger Car Registrations – Breakdown by Specification Average Cubic Capacity. http://www.acea.be/images/uploads/files/2013Q1PC_Reg_by_Segment_Characteristics_CC.pdf

Best Selling Cars Blog. *Europe Full Year 2012*. February 10, 2013. http://bestsellingcarsblog.com/2013/02/10/europe-full-year-2012-top-350-all-models-ranking-now-available/

Department of Energy. *Fact #720: March 26, 2012. Eleven Percent of New Light Trucks Sold Have Gasoline Direct Injection*. http://www1.eere.energy.gov/vehiclesandfuels/facts/2012_fotw720.html

Cain, T. *December 2012 & 2012 Year End Small, Midsize, and Large Car Sales in America.* http://www.goodcarbadcar.net/2013/01/usa-december-2012-car-sales-figures.html

Environmental Protection Agency. *Draft Regulatory Analysis. Tier 3 Motor Vehicle Emission and Fuel Standards*. March 2013. http://www.epa.gov/otaq/documents/tier3/420d13002.pdf

Energy Information Administration. *Annual Energy Outlook 2012*. U.S. Department of Energy. http://www.eia.doe.gov/forecasts/aeo/

Edmunds. Find Your Next Car. http://www.edmunds.com/

Forbes. *Why Your Next Car Will Probably Have a Turbocharger*. April 20, 2013.

http://www.forbes.com/sites/jimhenry/2013/04/30/most-engines-could-be-turbocharged-some-day-taking-diesels-and-gasoline-into-account/

Johnson Matthey 2009a. *The Impacts of CO2 legislation on PGM Demand in Autocatalysts*. http://www.platinummetalsreview.com/article/53/3/179-180/

Johnson Matthey. Market Data Tables. http://www.platinum.matthey.com/publications/market-data-tables/

Khalek, I. A. *The Particulars of Diesel Particle Emissions.* http://www.swri.org/3pubs/ttoday/spring06/Particulars.htm

Kim, C., Schmid, M., Schmieg, S., Tan, J., Wei, L. *The Effect of Pt/Pd Ratio on Oxidation Catalysts Under Simulated Diesel Exhaust*. April 2011. SAE-2011-01-1134. http://papers.sae.org/2011-01-1134/

Lambert, C. *Future Directions in Diesel SCR Systems*. May 1, 2012. Cross-cut Lean Exhaust Emissions Reduction Simulations (CLEERS) Workshop. http://cleers.org/workshops/workshop2012/presentations/Lambert_CLEERS2012.pdf

MARTEC. Technology Cost and Adoption Analysis: Impact of Ultra-Low Sulfur Gasoline Standards. April 2010. http://www.api.org/~/media/Files/Oil-and-Natural-Gas/Gasoline/Martec_Tech_Cost_Adoption_Analysis_Impact_ULSG_Std_MainlReport.pdf

MARTEC. *The Case for a Rational Automotive Industry*. May 2012. http://www.martecgroup.com/news-detail.php?id=21

National Research Council of the National Academies. *Transition to Alternative Vehicles and Fuels*. April 2013

Panasonic 2010. *Panasonic Begins Shipping Samples of New Catalyst for Diesel Exhaust Gas Purification.*

http://www.panasonic.co.uk/html/en_GB/News/Latest+news/Panasonic+Begins+Shipping+Samples+of+New+Catalyst+for+Diesel+Exhaust+Gas+Purification/5091298/index.html

Sanchez, F., Bandivadekar, A., German, J., *Estimated Cost of Emission Reduction Technologies for Light-Duty Vehicles*. March 2012. http://www.theicct.org/sites/default/files/publications/ICCT_LDVcostsreport_2012.pdf

Schnitzler, J. *Particulate Matter and NOx Exhaust Aftertreatment Systems*. 2006. http://www.fev.com/fileadmin/fev-resources/Publications/Diesel_Systems/ParticulateMatterAndNOxExhaustAftertreatmentSystems.pdf

Stillwater Mining Company. *Palladium Fundamentals*. September 2012. http://www.corporatereport.com/stillwater/Palladium_Fundamentals_9-26-2012.pdf

Transportation Energy Data Book, Edition 31. Table 4.12. *Sales-Weighted Engine Size of New Domestic and Import Cars by Size Class, Model Year 1975-2011*. Oak Ridge National Laboratory. July 2012. http://cta.ornl.gov/data/download30.shtml

Transportation Energy Data Book, Edition 31. Table 3.12. *Car Scrappage and Survival Rates*. Oak Ridge National Laboratory. July 2012. http://cta.ornl.gov/data/download30.shtml

Umicore Precious Metals Refining, *Catalytic Converter*, http://www.autocatalyst-recycling.umicore.com/catalyticConverter/

U.S. Department of Transportation (National Highway Traffic Safety Administration). Vehicle Survivability and Travel Mileage Schedule. January 2006. http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf

Wards Auto. *GM to Halve Its Palladium Use by 2005*. April 2001. http://wardsauto.com/news-amp-analysis/gm-halve-its-palladium-use-2005

White, G.L. *A Mismanaged Palladium Stockpile Was Catalyst for Ford's Write-Off*. February 2002. https://msb040.msb.edu/faculty/bodurthj/unrestricted/teaching/articles/Derivatives/A%20Mismanaged%20Palladium%20Stockpile%20Was%20Catalyst%20for%20Ford's%20Write-Off.htm

Williamson, W., Nunan, J., Frownfelter, D., McClaughry, R., Tripp, G., Huynh, J. Palladium/Rhodium Dual-Catalyst LDV 2 and Bin 4 Closed-Coupled Emission Solutions. SAE-2007-01-1263. http://delphi.com/pdf/techpapers/2007-01-1263.pdf