DOE EERE Program Record

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Title: Platinum Group Metals (PGM) for Light-Duty Vehicles

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Item

Today's average gasoline light-duty vehicle (GLDV) in the U.S. requires approximately 5 g of platinum group metals (PGM) for its emissions control system, versus approximately 10 g PGM for an average diesel LDV (DLDV). By 2025, the GLDV and DLDV's PGM contents are projected to be approximately 6 g and 8.5 g, respectively, under the medium R&D success scenario (the less optimistic and more optimistic scenarios are discussed later in this document).

Purpose of Analysis

This analysis of the baseline LDVs (conventional internal combustion engines using gasoline or diesel) is intended to inform future R&D targets for fuel cell electric vehicles (FCEVs) and serve as a baseline for future PGM scenario analyses involving vehicles, including FCEVs.

Overview of Results

The average PGM loadings of emissions control systems in future U.S. LDVs were estimated (references and detailed assumptions are listed in the Data and Assumptions section on Page 4), assuming U.S. Tier 3 emissions standards (expected to begin in 2017) and medium R&D success. A sensitivity scenario, high R&D success, assumed that innovative engine designs would keep PGM loadings from increasing, and future mid-size car engines will continue to decrease in size through reduced vehicle weights and other R&D successes. A second sensitivity scenario involves more moderate R&D success than the medium case, coupled with an additional degree of stringency for particulate emission control.[1]

U.S. Medium Case: When Tier 3 standards start to be phased in beginning in 2017, the sulfur content in gasoline will decrease to 10 ppm (current: 30 ppm). Additionally, the fuel economy standards will result in an increasing number of LDVs with downsized, turbocharged engines using direct injection (GTDI for *gasoline turbo direct injection*) that are more efficient than current LDVs. In spite of the lower sulfur content of gasoline under Tier 3, gasoline direct injection engines will likely require an increase in PGM per engine liter because they emit significantly more particles than conventional gasoline engines (from Gladstein et al. 2013's citation of Ford Motor Company's research, GTDI without emission control was shown to emit up to 11 mg of particulates per km compared to less than 0.5 mg per km for conventional engines). The U.S. average LDV engine was approximately 3.1 L in 2011 for new sales, and could be as small as 2.3 L in 2025, assuming that the future LDV's power will be approximately 80 kW (107 hp) per liter (L) of GTDI engine (details and references provided in the Data and Assumptions section). Tier 3 standards alone would also require significant particulate emission reduction compared to today, albeit less than Euro-6 standards.

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[1] This potential requirement was assumed to be the same as the Euro-6 standard for particulates.

Table 1 and Table 2 show GTDI and DTDI results for the Medium scenario. Results for the More Optimistic and Less Optimistic scenarios are shown after the Medium scenario's tables (Figure 1). The results were derived from emissions control studies by the International Council for Clean Transportation (ICCT), the Environmental Protection Agency's draft regulatory analysis of Tier 3 emissions standards, other public sources, and input from car manufacturers as described in the Data and Assumptions section of this analysis record.

Table 1. Emissions Control System's PGM for Average U.S. Gasoline LDV (Slightly Larger than Mid-Size Car) – Medium-Optimism (Mid-Range)

	2011	2020	2025
Grams PGM per Gasoline LDV - U.S.	**5.12**	**6.75**	**6.21**
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	2.30
Grams PGM per Engine kW	0.030	0.034	0.034
Grams Pt per Gasoline LDV	0.28	0.38	0.35
Grams Pd per Gasoline LDV	4.55	6.00	5.52
Grams Rh per Gasoline LDV	0.28	0.38	0.35

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

	2011	2020	2025
Grams PGM per Dies. LDV - U.S.	**10.1**	**9.25**	**8.51**
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	2.30
Grams PGM per Engine kW	0.059	0.046	0.046
Grams Pt per Diesel LDV	7.53	6.87	6.32
Grams Pd per Diesel LDV	2.22	2.03	1.86
Grams Rh per Diesel LDV	0.39	0.35	0.32

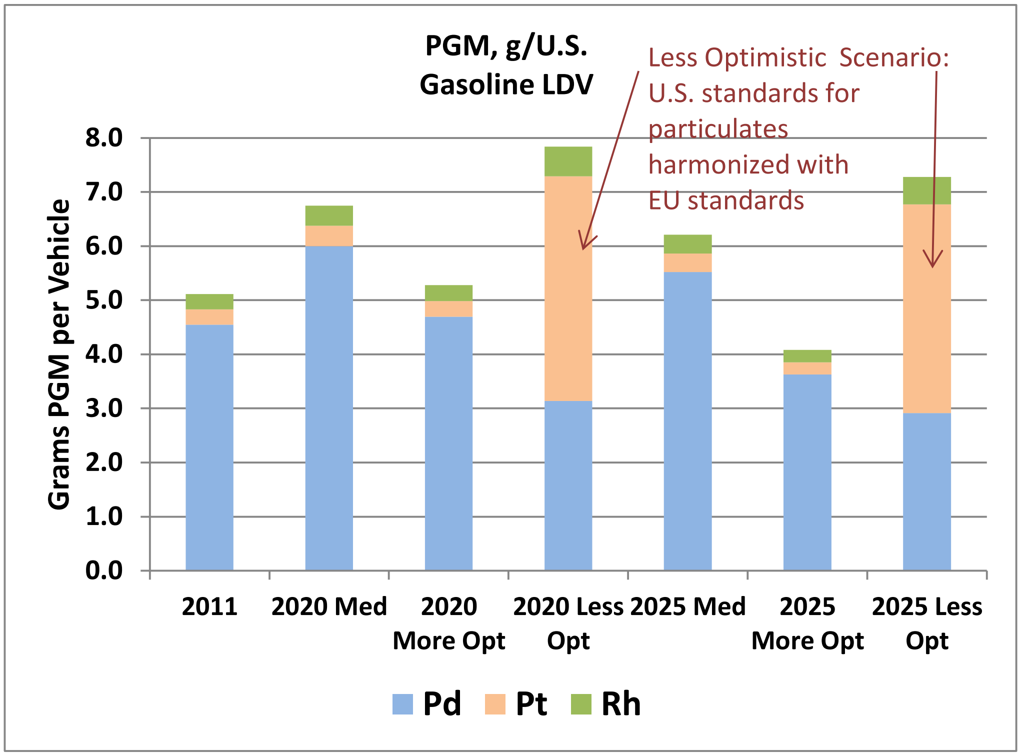

Figure 1. **PGM for U.S. Gasoline LDVs under 3 Scenarios**

Per average GLDV, the loadings are approximately 5.1 g in 2011, 6.7 g in 2020, and 6.2 g PGM in 2025 (medium case). Tier 3 will begin to apply in 2017, resulting in higher loadings per liter (L). 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, 9.3 in 2020, and 8.5 g PGM in 2025, assuming the same engine size as GLDVs. Figure 1 shows the results under three scenarios (medium as previously described, less optimistic, and more optimistic).

- **U.S. Less Optimistic Case**: The average (sales-weighted) engine size for GLDVs is 2.6 L in 2025 (from 3.1 L in 2011); the loading is 7.3 g PGM per GLDV in 2025. For DLDVs with 2.6-L engines, the PGM loading is approximately 9.6 g in 2025. For this sensitivity scenario, platinum (Pt) loadings will increase from 2011 with the assumption of convergence with the Euro-6 particulate emission standards.
- **U.S. More Optimistic Case**: If R&D on LDVs was highly successful, smaller engines would be able to deliver nearly the same performance as today's LDVs. Based on this reasoning, in 2025, R&D success was assumed to result in a major reduction in the average engine size of new U.S. LDVs to that of new European LDVs sold in 2011, namely 1.7 L. This corresponds to approximately 4 g PGM for an average GLDV in 2025 and 6.3 g PGM for an average DLDV in 2025.

Figure 2 and Table 3 summarize the medium-optimism results for U.S. GLDVs (see Data and Assumptions section for basis), with the LDV being a GTDI beginning in 2015.

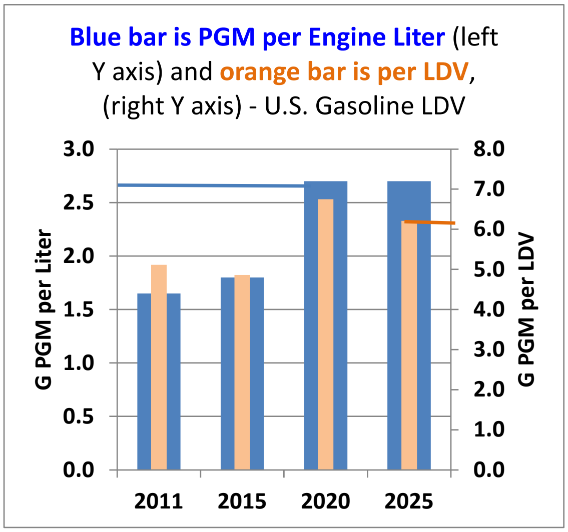

Figure 2. Platinum Group Metals for U.S. Gasoline LDV (Medium Optimism)
Note: After 2017, the more stringent Tier 3 emissions standards will increase PGM loadings per liter (derived from results in Environmental Protection Agency 2013).

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

	2011	2015	2020	2025
g PGM/L	1.7	1.8	2.7	2.7
Engine L	3.1	2.7	2.5	2.3
g PGM/LDV	5.1	4.9	6.8	6.2

Data and Assumptions

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

- Current loadings for internal combustion engine vehicles (ICEVs) were slightly scaled down from a 2012 International Council for Clean Transportation (ICTT) study (Sanchez et al. 2012).[2]
- Future ICEV loadings are based on ICEV engine downsizing associated with the adoption of turbocharging or supercharging in conjunction with direct fuel injection as a result of more stringent fuel economy standards. This set of combined technologies will be abbreviated as "GTDI" for gasoline turbo direct injection and "DTDI" for diesel turbo direct injection. The dominance of this technology is an assumption based on its rapidly rising 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.

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[2] This small reduction was suggested by catalysts experts from the auto industry with access to confidential data.

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. This factor is also assumed to hold in 2025, i.e., 1.2 times the engine size of the mid-size car is assumed to represent the engine size of the weighted average LDV sold in the U.S. in 2025.

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 2013-2014, 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 (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 L). 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 L. By 2025, a large fraction of new cars will likely be GTDI because this technology can deliver high power while keeping fuel consumption low due 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 mid-size 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 1.2 factor for estimating the fleet-averaged engine size from the mid-size car's engine size, one gets 2.3 L for the average sales-weighted U.S. 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., 2.8 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 mid-size SUVs).

Major assumptions are listed in the following tables, with PGM loadings per engine liter adapted from Sanchez et al. 2012 for current LDVs (after a slight reduction for current cars per industry reviewers' input) and increased further to reflect downsizing, turbocharging and Tier 3 standards, based on Environmental Protection Agency (EPA) 2013. Assumptions for the Less Optimistic sensitivity scenario reflect more recent industry input specific to particulates from GTDI vehicles in the context of **potential** (not current policy) regulation of ultrafine particle emission. 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.	**5.12**	**6.75**	**7.84**	**5.28**	**6.21**	**7.28**	**4.08**
Pt Fraction in Gasoline Catalyst	0.06	0.06	0.53	0.06	0.06	0.53	0.06
Pd Fraction in Gasoline Catalyst	0.89	0.89	0.40	0.89	0.89	0.40	0.89
Rh Fraction in Gasoline Catalyst	0.06	0.06	0.07	0.06	0.06	0.07	0.06
Engine Volume in Liters	3.10	2.50	2.80	2.20	2.30	2.60	1.70
Grams Pt per Gasoline LDV	0.28	0.38	4.16	0.29	0.35	3.86	0.23
Grams Pd per Gasoline LDV	4.55	6.00	3.14	4.69	5.52	2.91	3.63
Grams Rh per Gasoline LDV	0.28	0.38	0.55	0.29	0.35	0.51	0.23

In Table 5, 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 EPA estimate of incremental emissions control costs under Tier 3. Table 6 shows diesel LDV assumptions.

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)	**10.14**	**9.25**	**10.4**	**8.14**	**8.51**	**9.62**	**6.29**
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	2.30	2.60	1.70
Grams Pt per Diesel LDV	7.53	6.87	7.70	6.05	6.32	7.15	4.67
Grams Pd per Diesel LDV	2.22	2.03	2.27	1.78	1.86	2.11	1.38
Grams Rh per Diesel LDV	0.39	0.35	0.39	0.31	0.32	0.37	0.24

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 be effective when the air to fuel mixture is very close to stoichiometry. As a result, 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.

With the advent of the technological feasibility of substituting Pt with Pd—gram for gram—in gasoline catalysts, 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 et al. 2012) estimated current PGM loading at 1.8 g per L under Tier 2. Sanchez et al. did not include the impact of Tier 3 emissions standards. Table 7 summarizes Sanchez et al. results, after a small adjustment based on the industry's input to this analysis.[3]

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, the average engine size appears to be on a downward trend. Advanced, downsized gasoline engines such as turbocharged and supercharged engines, will likely require more PGM (Gladstein & Neandross 2013) as mentioned previously due to the increase in particulate emissions with GTDI technology.

Table 7. PGM for Current Gasoline Catalysts in U.S. – Nearly 1.7 Grams per Engine Liter

Gasol 3-Way Catalyst (Tier 2 Bin 5)		
Engine Liters	1.5	3.0
PGM Mass		
Pt, g	0.14	0.28
Pd, g	2.20	4.40
Rh, g	0.14	0.28
Total PGM	**2.48**	**4.95**

Source: Adjusted results from Sanchez et al. 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 (vs. 30 ppm for gasoline) is being used throughout the U.S. instead of the 500-ppm version used prior to 2007. USLD was developed to allow the use of improved emissions control devices that reduce diesel emissions more effectively but can be damaged by sulfur.

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

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[3] Automakers provided qualitative input (e.g., "slightly too low", "somewhat high") in lieu of specific numbers because of the proprietary nature of their R&D data.

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.[4]

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, primarily Pt was used in catalysts for diesel engines. However, more recent research (Kim et al, 2011; Lambert 2012) has identified optimal combinations of Pt and Pd that 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 et al. 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 (on the order of 90%) and durability.[5] 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, Jeep, etc.). In this analysis, the average DLDV is assumed to be weighted at 80% SCR/20% LNT to reflect current offerings.

Although industry is expected to pursue ways to reduce PGM loading in order to lower costs, more stringent emissions standards under Tier 3 and potential future ultrafine particulate[6] regulation for GTDI may result in higher PGM loading (Minjarez et al. 2011; Gladstein & Neandross 2013). In this updated analysis, the basis is the likelihood of future convergence of particulate regulations from the EU and other world regions, such as the U.S. Euro-6 regulation that is directed at limiting the number of ultrafine particles from internal combustion engines in addition to limiting the per-km mass of emitted particles, whereas the corresponding U.S. regulation is a mass-based standard in maximum grams per mile.[7]

In this analysis, the PGM loading per L for diesel engine in 2017 and beyond is assumed to increase from current numbers (current technology in U.S. is shown in Table 8), albeit the percent increase would be less than that for gasoline car catalysts because most current diesel cars are already turbocharged and equipped with particulate filters.

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[4] From Sanchez et al. 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).

[5] Manufacturers of Emissions Controls Association 2011; Poojary et al. 2010.

[6] Gladstein & Neandross 2013 contains a discussion of the technology for controlling ultrafine particulate emission and related health concerns. Compliance with Euro-6 resulted in some OEMs deploying gasoline particulate filters (http://na.faurecia.com/en/faurecia-naias/emissions-control-technologies).

[7] Since ultrafine particles have very low mass, a mass-based standard may still allow the emission of a large number of such particles.

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

	Diesel Oxidation Catalyst			Diesel Particulate Filter			Lean NOx Trap		
	0.66	g Pt/Catalyst Liter		0.75	g Pt/Catalyst Liter		2.0	g Pt/Catalyst Liter	
	0.33	g Pd/Catalyst Liter		0.25	g Pd/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 et al. 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 et al. 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 2.3-L diesel car’s emissions control system would consist of approximately 6.3 g Pt, 1.9 g Pd, and 0.32 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. For the 80% SCR technology mix, Tier 3 was assumed to require 3.7 g PGM per L versus the current estimate of 3.27 g per L derived from Table 9 (9.81 g for 3.0 L).

Industry Input and Peer Review

The study used information from Sanchez et al. 2012 and input from emissions control experts working for four major U.S. and Japanese automobile companies. In addition, experts from the Advanced Combustion Engines group in the DOE Vehicle Technologies Office, an emissions control catalysts producer, and the Pacific Northwest National Laboratory emissions control team provided information and reviewed this analysis.

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