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Estimated Cost of Gasoline Particulate Filters

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The gasoline particulate filter (GPF) is a device that can be installed on the tailpipe of a gasoline vehicle to capture and reduce emissions of particulate matter, a common pollutant. The European Commission is considering proposals for early adoption of gasoline particle number limit values by late 2011 or early 2012 (Steininger, 2011a). Likewise in California in tandem with the US EPA, regulators are considering actions to lower the particle mass limit based on the cost and availability of control strategies for particulate matter emissions from gasoline direct injection engines (GDI). The cost of a GPF may therefore affect the stringency of new tailpipe standards.

Some GPF cost estimates have been given publicly. The European Commission's Klaus Steininger has suggested a GPF cost between \$57 and \$184 (Steininger, 2011b). The Manufacturers of Emissions Controls Association (MECA) currently estimates a cost between \$50 and \$100 (Kubsh, 2011). The European Joint Research Center (JRC) is now undertaking a cost benefit analysis intended to evaluate GPF costs.

Based on an assessment of production costs for two GPF designs, we estimate for a 2.0L gasoline engine a cost of \$106 for a stand-alone GPF and between \$114 and \$154 for a four-way catalyst, presented here as a three-way catalyst (TWC) with PM trapping capabilities. The true cost will depend on the choice of the system being installed, the production volume, and changes in the cost of raw materials, among other inputs. One potential difference between these estimates and those cited above is that they include labor costs, which are uncertain given the lack of recent data and potential variation between manufacturers. Nevertheless, we find that these GPF cost estimates are reasonably consistent with others offered to-date.

Approach 1: Stand-Alone GPF

The GPF can be installed as a separate addition to the three-way catalyst. We can make a preliminary cost estimate based on past experience with the diesel particulate filter. Both devices operate on a similar principle. All things being equal, an estimate can be based on the change in volume of the filter alone. However, we make one important distinction: we assume a regeneration system is not necessary since we expect gasoline exhaust to achieve sufficiently high average temperatures to continuously regenerate. Therefore, we do not include a regeneration system in this cost estimate.

A study of particle filters installed on GDI engines considered three filter sizes (Mikulic, Koelman, Majkowski, & Vosejpka, 2010). Based on an engine displacement of 2.0 L, the catalyst to engine ratio or Swept Volume Ratio (SVR) for each of these was 0.41, 0.55, and 0.7 for a 3", 4" and 5" length filter, respectively. This gives an average SVR of 0.55. For comparison, the average SVR of a conventional diesel particulate filter is 2.0.

Other assumptions for estimating GPF cost are taken from the ICCT diesel particulate filter cost model. These include assumptions about the cost of substrate (\$30 per catalyst volume in liters), washcoat (\$10 per CV), and filter can housing (\$5 per CV). Accessories (\$5) and a differential pressure sensor (\$28) are a fixed cost irrespective of CV. Precious metal loading is taken from an ICCT cost study of emission control technologies (ICCT, 2011). Precious metal costs are taken from the historical five-year average (Platinum Today, 2011).

To estimate labor costs, we use 1994 production figures from the California Air Resources Board (ARB, 1994). We assume per-unit cost is fixed regardless of the size of the catalyst unit. Assuming a production line of 20,000 units per year and a 40-hour work week, we estimate 10 units per hour per person. At a wage rate of $30 per hour with a 40 percent overhead, this equates to $4.2. We add costs of machinery, and we assume a $100,000 welding unit amortized over a 10-year period gives an additional $0.50 for a total $4.70 per unit in 1994 dollars. We convert this to 2010 dollars using a change in CPI of 1.4 for a final labor cost estimate of $6.60.

Near-term baseline costs are the sum of total manufacturing costs plus a 3 percent warranty claim rate. As production reaches economies of scale, costs are assumed to decline an additional twenty percent from baseline. This approach is based on US EPA cost volume effects and represents two cycles of doubling production. Table 1 gives the long-term production cost of a stand-alone GPF for various engine sizes. Appendix A provides more detail.

Table 1. Estimated GPF production cost for various engine sizes

Engine Displacement	Estimated Long-Term Production Cost (USD 2010)
1.5	$88
2.0	$106
2.5	$124
3.0	$143

Approach 2: Four-way catalyst

Rather than install a GPF as a separate addition to the three-way catalyst, a wholly integrated four-way catalyst can be designed to control NOx, hydrocarbons and carbon monoxide in addition to PM (Zhan and Eakle, 2010). This approach would position a wall-flow particulate filter underfloor, instead of the typical flow-through substrate used in three-way catalyst applications. A wall-flow substrate underfloor would not suffer the same space constraints as a closed-coupled GPF, which might be unable to achieve the proper flow characteristics. This filter would require some re-design to optimize for low back pressure. It would also require a small waschoat containing an amount of precious metals similar to what is already in use. Regeneration similarly would be unnecessary, since the gasoline engine would do this continuously. However, additional sensors may be needed to monitor temperature and pressure over the filter. To guard against filter clogging, some ability to increase temperature may be needed as well.[1] The volume of the GPF would also need to be in direct proportion to the three-way catalyst, so we assume a 1:1 ratio between GPF volume and engine displacement, which adds cost for precious metals, substrate, washcoat, and filter can housing.[2]

Precious metals enable three-way catalyst functionality, but increasing costs have put pressure on manufacturers to reduce precious metal loading. We consider two scenarios for precious metal loading given these trends. First, we define high precious metal loading assuming that the total amount of PGMs is additive. According to ICCT estimates, Euro 5/6 TWC have PGM loadings around 0.9 g/L with a ratio of Platinum (Pt)/Palladium (Pd)/Rhodium (Rh) of 0.1/0.7/0.1. US Tier 2 loading are estimated as having almost twice as much Pd (ICCT,2011). ICCT data confirmed by expert consultants estimates that a DPF used in a diesel light-duty vehicle have PGM loadings around 1.0 g/l, with a Pt/Pd distribution of 0.75/0.25 (ICCT, 2011; Johnson, 2011). Thus, the high load PGM case estimated for a four-way catalyst is 1.9 g/l with a Pt/Pd/Rh distribution of 0.85/0.95/0.1. Second, given that the engine-out rate of PM generated from a GDI vehicle is lower than from a diesel vehicle, it is assumed that the PGM load might be reduced to 1.0 g/L, with an averaged composition of Pt and Pd, while keeping the same Rh load, resulting in Pt/Pd/Rh= 0.425/0.475/0.1. Given the absence of available literature describing PGM loading for GPF applications, the high and load cases are presented as educated guesses for cost purposes, rather than a projection of current or future technical solutions to GDI PM emissions control. All other assumptions remain consistent with the estimate for a stand-alone GPF.

One important advantage of this approach is that a cost savings is realized due to the integration of the three-way catalyst and GPF into a single unit. We use a separate ICCT cost model to estimate the cost of producing a separate three-way catalyst and subtract this from our long-term production cost estimate. Although we would not expect a closed-coupled catalyst given the design limitations described above, we take a conservative approach and assume this remains in place for cold start control. Therefore, the credit does not account for the potential removal of the closed-coupled catalyst.

Table 2 gives the final long-term production cost estimate using two levels of precious metal loading for various engine sizes. Appendix B provides more detail.

Table 2. Estimated four-way catalyst production cost for various engine sizes (USD 2010)

Engine Displacement	Estimated Long- Term Production Costs (including TWC credit)*	
	High PGM Load	Low PGM Load
1.5	$121	$91
2.0	$154	$114
2.5	$186	$136
3.0	$219	$158

* TWC Credit refers to costs avoided from production of separate three-way catalyst. See Appendix B for details

Conclusion

Most gasoline vehicles on the road today emit low levels of particulate matter. However, newly adopted fuel economy and greenhouse gas emission standards in the United States, Europe and Japan will demand more efficient gasoline engine technologies such as direct

1 A differential pressure sensor is included in Approach 1 to guard against filter clogging as well.

2 Tier 2 gasoline vehicles have a TWC with an SVR= 0.8-1.0 based on a review of the literature and independent confirmation from technical experts. A four-way catalyst with an SVR=1 is an educated guess based on a similar design explored by Toyota for the diesel European market. The DPNR, capable of reducing HC, CO NOx and PM (diesel), was designed for the Toyota Avensis (2.0L) and had a volume of 2.8 L (SVR=1.4) [SAE 2002-01-2877]. We assume the ratio for gasoline is smaller, and so we use 1:1.

injection engines. These can emit particulate matter at levels several times higher than current port fuel injection engines. The European Commission is preparing to review proposals to establish particle limits on gasoline engines under the Euro 6 standard, while in the United States regulators are also considering more stringent limits on gasoline engines under LEV III or Tier 3 regulations. The cost of meeting revised particulate matter standards may inform the stringency of new particulate matter limits.

The GPF may not be necessary to meet more stringent PM limits on direct injection gasoline engines, since other technological approaches are available. These include changes to the position and timing of fuel injection, among other strategies. Nonetheless, the wall-flow filter is a proven technology used widely on diesel engines and provides a backup option should unexpected engineering and cost challenges obstruct the adoption of the alternatives. Therefore this GPF cost estimate provides a rough upper bound estimate for the cost to the manufacturer to meet a PM tailpipe limit sufficiently stringent to require a GPF for GDI vehicles.

The GPF operates on the same basic principle as a diesel particulate filter (DPF). We find that a GPF can be much smaller than a DPF relative to the size of the engine. We also find that gasoline engines emit exhaust at higher average temperatures, eliminating the need for a regeneration system. These reduce the relative cost of the GPF. We treat all remaining assumptions as essentially equivalent to the production costs for a DPF.

We evaluate two different approaches to the production of a GPF: a stand-alone design and a four-way catalyst. We find the long-term production cost range for a stand-alone GPF is between $88 and $143 for a range of gasoline engine sizes between 1.5 and 3.0 L. For a four-way catalyst we estimate a cost range between $91 and $219. This wider range is affected by some uncertainty regarding the amount of precious metals the catalyst would require. We conclude that these cost estimates are generally in line with other public estimates.

Appendix A: Production cost estimate for a stand-alone GPF

		Engine Displacement (Vd) in liters			
		1.5	**2.0**	**2.5**	**3.0**
Catalyst volume, CV , liters (SVR=0.55)		0.8	1.1	1.4	1.7
Platinum 0.75g/liter x CV x $44/g		$27	$36	$45	$54
Palladium 0.25g/liter x CV x $12/g		$2	$3	$4	$5
	Precious Metal Costs	*$29*	*$39*	*$49*	*$59*
Substrate ($30.0*CV)		$25	$33	$41	$50
Washcoat ($10.0*CV)		$8	$11	$14	$17
Filter can Housing ($5*CV)		$4	$6	$7	$8
Accessories		$5	$5	$5	$5
Differential Pressure Sensor		$28	$28	$28	$28
	Additional Component Costs	*$70*	*$83*	*$95*	*$108*
Labor costs per unit		$7	$7	$7	$7
	Total Manufacturing Costs	*$106*	*$129*	*$151*	*$174*
Warranty costs (3% claim rate)		$3	$4	$5	$5
Cost - Near term		$109	$133	$156	$179
Cost - Production volume effects		$88	$106	$124	$143
	Final Long-Term Cost	**$88**	**$106**	**$124**	**$143**

Appendix B1: Production cost estimate for four-way catalyst assuming high PGM load

		Engine Displacement (Vd) in liters			
		1.5	**2.0**	**2.5**	**3.0**
Catalyst volume, CV , liters (SVR=1.0)		1.5	2.0	2.5	3.0
Platinum 0.85g/liter x CV x $44/g		$56	$75	$94	$112
Palladium 0.95g/liter x CV x $12/g		$17	$23	$29	$34
Rhodium 0.10 g/liter x CV x $137/g		$21	$27	$34	$41
	Precious Metal Costs	*$94*	*$125*	*$157*	*$187*
Substrate ($30.0*CV)		$45	$60	$75	$90
Washcoat ($10.0*CV)		$15	$20	$25	$30
Filter can Housing ($5*CV)		$8	$10	$13	$15
Accessories		$5	$5	$5	$5
Differential Pressure Sensor		$28	$28	$28	$28
	Additional Component Costs	*$101*	*$123*	*$146*	*$168*
Labor costs per unit		$7	$7	$7	$7
	Total Manufacturing Costs	*$202*	*$255*	*$310*	*$362*
Warranty costs (3% claim rate)		$6	$8	$9	$11
Cost - Near term		$208	$263	$319	$373
Cost - Production volume effects		$166	$210	$254	$299
Three-Way Catalyst Credit		-$45	-$56	-$68	-$80
	Final Long-Term Cost	**$121**	**$154**	**$186**	**$219**

Appendix B2: Production cost estimate for four-way catalyst assuming low PGM load

		Engine Displacement (Vd) in liters			
		1.5	**2.0**	**2.5**	**3.0**
Catalyst volume, CV , liters (SVR=1.0)		1.5	2.0	2.5	3.0
Platinum 0.425g/liter x CV x $44/g		$28	$37	$47	$56
Palladium 0.475 g/liter x CV x $12/g		$9	$11	$14	$17
Rhodium 0.10 g/liter x CV x $137/g		$21	$27	$34	$41
	Precious Metal Costs	*$58*	*$75*	*$95*	*$114*
Substrate ($30.0*CV)		$45	$60	$75	$90
Washcoat ($10.0*CV)		$15	$20	$25	$30
Filter can Housing ($5*CV)		$8	$10	$13	$15
Accessories		$5	$5	$5	$5
Differential Pressure Sensor		$28	$28	$28	$28
	Additional Component Costs	*$101*	*$123*	*$146*	*$168*
Labor costs per unit		$7	$7	$7	$7
	Total Manufacturing Costs	*$166*	*$205*	*$248*	*$289*
Warranty costs (3% claim rate)		$5	$6	$7	$9
Cost - Near term		$170	$212	$255	$298
Cost - Production volume effects		$136	$170	$204	$238
Three-Way Catalyst Credit		-$45	-$56	-$68	-$80
	Final Long-Term Cost	**$91**	**$114**	**$136**	**$158**

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