The Carbon Dioxide-Equivalent Benefits of Reducing Black Carbon Emissions from U.S. Class 8 Trucks Using Diesel Particulate Filters:

A Preliminary Analysis

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ABSTRACT

Debates over climate change have shifted from scientific evidence of anthropogenic contribution to the greenhouse effect to the development of strategies to mitigate the impacts of global warming. One strategy that has yet to be fully explored is the reduction of black carbon particles. Diesel engines represent a significant, controllable source of black carbon. Targeting these emissions offers a supplemental and parallel strategy to pursue carbon dioxide (CO_2) reductions with the advantage of a much faster temperature response and the additional benefit of health risk reductions. As part of an integrated multi-prong strategy, reducing black carbon can provide net cooling benefits in the near term while carbon dioxide reduction strategies and technologies are developed and implemented.

This paper represents Clean Air Task Force's (CATF's) attempt to quantify the CO_{2-} equivalent climate benefits of removing black carbon from the diesel exhaust emissions of class 8 trucks using diesel particulate filters (DPFs). The DPF is a proven, off-the-shelf technology that can reduce black carbon emissions by 90 percent or more. Large U.S. Class 8 trucks (defined as exceeding 33,000 lbs.), for example, "combination" tractor-trailer trucks, waste haulers, large buses, constitute a significant contributor to U.S. diesel sector pollution from which black carbon emissions can be controlled fleet wide with this readily available technology. However, the methodology in this paper could be applied to smaller trucks and other diesel engines as well.

Climate scientists have proposed two metrics to calculate CO_2 equivalent (CO_2e) potencies of black carbon: global warming potential (GWP) and global temperature potential (GTP). In this paper, CATF summarizes GWP and GTP estimates from the published literature and uses them to calculate carbon dioxide equivalent benefits from DPFs installed on class 8 trucks. The weight of evidence described demonstrates that black carbon reductions from DPFs are climate beneficial and warrant support as a policy priority.

CATF examined four questions that have a bearing on whether installation of DPFs on class 8 trucks would provide significant climate benefits: I.) What is the CO_2e reduction from a diesel truck equipped with a DPF? II.) What is the break-even fuel penalty, i.e., assuming DPFs cause a measurable fuel penalty, the point below which use of a DPF to reduce black carbon-related warming is beneficial? III.) How many years would black carbon reduction- related climate benefits from the installation of a DPF (measured in CO_2e) exceed the increased CO_2e from an assumed fuel penalty of 2 percent? and IV.) Using the above methods, what would the benefits be of a U.S. Class 8 class 8 truck rebuild rule in the United States?

Based on a calculated range of CO_2e values in this paper, we find Bond and Sun's (2005) twenty-year global warming potential (GWP_{20}) of 2,200 provides a reasonable "best estimate" for use in calculating CO_2e benefits. In addition, we report the results based on their one hundred-year global warming potential (GWP_{100}) of 680, which IPCC recognizes as a standard for such comparisons. CATF believes that the use of the longer-term GWP_{100} may understate the near-term climate benefits of black carbon reductions and that these black carbon reduction benefits are better represented by the GWP_{20}.

A review of the literature finds that fuel penalties associated with retrofit DPF applications range from zero as a best estimate to a few percent. The most comprehensive, controlled field study of 20 retrofit tractor-trailer trucks that each ran 150,000 miles a year/vehicle suggests there may be no measurable fuel penalty associated with the DPF itself. This conclusion is also supported by an analysis of four years worth of fueling records, covering 1.28 million fleet miles, for 10 MTA New York City transit buses that were retrofit with a DPF. Nonetheless, given the uncertainty across studies and to be conservative in this analysis, CATF assumed a 2 percent fuel penalty.

The following is a summary of CATF's findings:

I. Installation of a DPF on a typical pre-2007 U.S. class 8 truck yields a GWP_{20} benefit of 2000 gCO_2e/gal assuming a fuel penalty of 2 percent. This would achieve the equivalent climate benefits as eliminating the pollution from six passenger cars. In addition, retrofitting six class 8 trucks would be the equivalent of eliminating the combined CO2 and black carbon pollution from one such pre-2007 truck. (Using GWP_{100} CATF finds a net benefit of about 500 gCO_2e/gal, one quarter of the GWP_{20} benefit.)

II. A CO_2e benefit will result as long as the increase in fuel use (fuel penalty) from the installation of the retrofit is less than 22 percent—much higher than the highest documented DPF fuel penalties. Two comprehensive in-use studies tracking fuel consumption suggest that there may, in fact, be no measurable fuel penalty from the application of DPFs to class 8 trucks. (Even using $GWP_{100,}$ the breakeven fuel penalty is 7 percent, significantly higher than fuel penalty estimates.)

III. Installation of a DPF on a class 8 truck will result in climate benefits for approximately half a century.

IV. Retrofitting nearly one-million class 8 trucks in the U.S. with DPFs between 2012 and 2030 would provide the total equivalent carbon dioxide reduction of 96 million metric tons (GWP_{20}) –equivalent to eliminating the annual emissions of 21 million cars or 1.8 million class 8 diesel trucks.

The weight of this evidence suggests that reductions in diesel black carbon emissions could play an important role in short-term global warming mitigation.

THE STAKES

Scientists increasingly warn that the pace of climate change may not be linear or gradual. The Arctic is warming at twice the rate of the Earth as a whole, with sea ice melting much faster than climate models have previously predicted. As a result of this rapid warming, the famed Northwest Passage was ice free and "navigable" in 2007 for the first time since satellite records began in 1978. The 2008 ice melt was comparable, with the added risk of a continuously declining multi-year ice pack. This sea ice retreat, combined with an accelerating pace of Greenland ice sheet discharge, poses another more serious risk: these ice sheets could well be on their way to a "tipping point" past which their disintegration will be nearly impossible to reverse. Melting of continental ice is predicted to significantly raise the sea level in some of the world's most densely populated coastal areas. Open waters from retreating Arctic sea ice will also reduce the southerly flow of cold Arctic air. Releases of carbon and methane stored in Arctic permafrost from accelerated melting could swamp current anthropogenic emissions.

Reducing CO_2 emissions is of paramount importance in mitigating long-term climate changes, however short-term benefits may result from reducing black carbon particles. Black carbon, one of the most important warming agents of the past century, warms the atmosphere in two ways. First, its dark color absorbs light and radiates heat back to the atmosphere thereby raising the temperature of the ambient air. Second, black carbon deposits darken snow and ice surfaces, absorbing heat and accelerating spring melt. In light of black carbon's major role in climate warming, reducing black carbon can also play an important role in providing near-term benefits by slowing the rate of the warming and the pace of sea ice and continental ice sheet melting. Diesel particulate filter technology, which is capable of eliminating nearly all black carbon particles currently emitted from diesel engines, may prove to be one of the most promising measures available to capture immediate climate benefits.

REDUCING BLACK CARBON WITH DIESEL RETROFITS

Particulate diesel exhaust is a complex combination of black carbon and organic carbon, and to a much lesser extent sulfate (ultra low sulfur fuel in use nationwide in the U.S. since 2006 has minimized emissions of diesel sulfates.) Black carbon is dark and therefore a light absorptive heat sink, whereas organic carbon particles are typically reflective and serve to cool, as do sulfate particles.

This analysis examines the climate impacts of reducing particulate emissions from diesel engines, where black carbon, a potent warming agent, typically represents the largest fraction of diesel particulate matter mass. U.S. EPA rules will ensure that all new highway diesels meet stringent emission standards that will reduce fine particle (and therefore black carbon) emissions by over 90 percent in engines built starting in 2007. Similar rules have been passed for many off-road engines that go into effect in 2010. These fine particle standards are set at a level that only engines equipped with DPFs can attain. In practice, DPFs can reduce particles, including black carbon, by up to 99 percent. Despite the EPA rules, over 11 million engines that lack these emission controls remain in use today and will for many years to come. Furthermore, black carbon is perhaps the most hazardous component of diesel exhaust to breathe, thus there are substantial health advantages to controlling the millions of older diesels.[1]

There are three general levels of particulate matter control devices recognized by CARB and EPA based on their effectiveness at removing particles:

1. LEVEL 1 RETROFIT DEVICES: The diesel oxidation catalyst (DOC) is a 'level 1" retrofit device achieving up to 25 percent reductions in particle mass. However, the DOC removes the wet or soluble organic fraction from the exhaust stream via oxidation while leaving the solid fraction –including black carbon—largely unmitigated. Level 1 devices incur no fuel penalty.

2. LEVEL 2 RETROFIT DEVICES: Level 2 devices, such as the high performance DOC (e.g., Donaldson Diesel Multistage Filter or DMF), verified by CARB and U.S. EPA for 50 percent reduction in particle mass, reduce the soluble organic fraction, but only remove a

fraction of the black carbon-dominated solid particles. Because level 2 devices are defined as greater than 50 percent but less than 85 percent performance, there can be a wide variation in Level 2 device performance. Moreover there is little data documenting the effectiveness of these devices in reducing black carbon. CATF engineering consultants suggest that Level 2 devices may provide black carbon reductions of as little as 10 percent or as much as 50 percent. Level 2 devices typically incur no fuel penalty.

3. LEVEL 3 RETROFIT DEVICES: Verified CARB and EPA level-3 devices, meeting reductions of 85 percent level or higher, consist of a wall-flow honeycomb filter (diesel particle filter or DPF) (see Figure 1) that traps particles in a dead-end chamber and allows gases to flow back out through the porous walls of the ceramic filter. Literature suggests that DPFs consistently achieve in excess of the 90 percent removal efficiency of fine particles and black carbon. DPFs are the only devices that can trap the majority of the solid black carbon fraction, and therefore represent the best available technology for diesel black carbon reductions. A 90 percent DPF effectiveness is assumed for the calculations embodied in this paper.[2] Some have suggested that a small fuel penalty may be incurred by level 3 filter devices as a result of backpressure from the ceramic honeycomb design. However, the only two in-use studies (described below) suggest that there may be no measurable fuel penalty.

FUEL AND CO_2 PENALTIES OF DIESEL PARTICULATE FILTERS

The net climate benefit of a diesel particle filter is limited to the extent that it overcomes incremental CO_2 and black carbon emissions resulting from any related increased fuel use ("fuel penalty.") To achieve a net climate benefit, a DPF must reduce black carbon particles beyond any incremental increases in black carbon and CO_2 associated with the increased fuel use. This paper uses a simple method to examine that tradeoff, and to determine whether there is likely to be a net climate benefit from the use of DPFs on trucks.

Figure 1: The honeycomb cross-section of a DPF. In theory, build-up of backpressure in the engine may result from the honeycomb design, resulting in loss of fuel efficiency and an increase in fuel use. Based upon the best available data, the calculations in this paper conservatively assume that a DPF retrofit on a large commercial truck may result in a 2 percent fuel penalty.

U.S. EPA, in reviewing these studies, finds a possible 1-3 percent fuel penalty for a ‘highly oxidizing” passive particle filter (e.g. a Johnston Matthey CCRT) with a reduction performance of about 90 percent. [3] M. J. Bradley & Associates, for CATF, conducted a literature survey to identify studies that tracked fuel use with DPF retrofits, most of which were dynamometer-based laboratory data (Tables 1 and 2, below). Documented investigations displayed a wide range of measured fuel penalties ranging from increased fuel use to decreased fuel use, and a similar range of changes in per-mile CO_2 emissions (see below.) However, dynamometer-based testing used for most of these studies has an inherent error margin of at least +/- 5 percent, making it difficult to detect small changes in fuel use with any degree of certainty. Also confounding the results is the substantial variability in the fuels utilized in the various studies, with, in some cases, different fuels used for the baseline and retrofit test cases. Differences in fuel density and volumetric energy content can also confound any assessment of fuel penalty and related CO_2 emissions. Finally, these studies were typically limited to a few vehicles, with tests typically including three repeats of a 20 – 30 minute drive cycle. All of these factors combine to make it challenging to identify a robust standard assumption for the fuel penalty associated with retrofit DPF applications based on the current literature.

The most methodologically sound fuel penalty study was undertaken by the National Renewable Energy Laboratory (NREL) using on-road data from *Ralph’s Grocery* of California.[4] The *Ralph’s* study was based on 20 DPF-retrofitted tractor-trailer trucks (Figure 2) following their regular routes over a one-year period, each accumulating approximately 150,000 miles during the study. The *Ralph’s* study found that trucks incurred a *“statistically insignificant*” 2-3 percent fuel penalty (decrease in MPG), *attributed to differences in the fuels* used for the baseline (conventional CARB fuel) and retrofit fleets (“ECD” ultralow sulfur diesel fuel with a 2.4-2.8% lower energy content), rather than the DPF itself. Given the significant number of trucks and the real-world mileage over which the results were calculated, the NREL study likely provides the best estimate of the actual near-zero fuel penalty.

Supporting the Ralph’s findings, M.J. Bradley & Associates also analyzed 48 months of fueling records for ten transit buses, which was provided by MTA New York City Transit (Table 3, Figure 3). All ten buses were retrofit with passive DPF in 2004. The records analyzed covered two years prior to retrofit (2002 – 2003) and two years after retrofit (2005 – 2006) for each bus. During the periods covered each bus accumulated over 125,000 miles in service (1.28 million fleet miles). As shown in the table below, six of the ten buses had marginally lower average fuel economy after retrofit (indicating a potential fuel penalty), but four of the buses had marginally higher average fuel economy. On average, *the ten-bus fleet had virtually the same average fuel economy after retrofit as before*. As shown in the graph below, average monthly fuel economy for these buses varied significantly from bus-to-bus and from month-to-month. This data provides further evidence that if retrofit with a passive DPF has an effect on vehicle fuel economy, the magnitude of the effect is small enough to be lost in the “noise” of normal variation based on other, more significant factors.

Balancing the broad range of study results and their inherent uncertainty with the theoretical probability of the existence of a fuel penalty based on an increase in engine back pressure resulting from the retrofit, CATF adopts a conservative 2 percent fuel penalty for retrofit DPF applications in the calculations below.

Figure 2. NREL testing of tractor-trailer trucks operated by Ralphs' Grocery of California concludes: ***"The fuel economy results do not indicate a fuel economy penalty for using DPFs in this application. The in-service fuel economy results are consistent with the lower energy content of the ECD^{TM} [7 ppm-S, low aromatic] fuel used."***

Table 1: Table of Fuel Penalties in Published Tests of DPFs (Source: M. J. Bradley & Associates).

Technology	Device	Source	Test Type	Calculation Method	Increased Fuel Use		Reference
					low	*high*	
Passive DPF	JMI CRT	ERMD	Chassis Dyno, CBD	Δ avg CO2 g/mi	-7.1%	9.8%	SAE 2001-01-0511
	Englehard DPX	WVU	Chassis Dyno, CSHVR	Δ avg CO2 g/mile	-6.0%		SAE 2000-01-1854 (Grocery truck on CSHVR route)
	JM CRT	WVU	Chassis Dyno, CSHVR	Δ avg CO2 g/mile	-6.0%		SAE 2000-01-1854 (Grocery truck on CSHVR route)
	Englehard DPX	WVU	Chassis Dyno, CSHVR	Δ avg CO2 g/mile	-5.7%		SAE 2000-01-1854 (School bus on CSHVR route)
	JM CRT	NYDEC & EC	Engine Dyno, FTP	Δ avg CO2 g/hp-hr	-3.2%		SAE 2004-01-1085
	JM CRT	WVU	Chassis Dyno, CSHVR	Δ avg CO2 g/mile	-2.3%		SAE 2000-01-1854 (Tanker truck on CSHVR route)
	Purem GreenTec	ETV	Engine Dyno, ETV	Δ avg BSFC, carbon balance	-1.9%	-0.6%	http://www.epa.gov/etv/pubs/600r07039.pdf
	Englehard DPX	WVU	Chassis Dyno, 5 Mile	Δ avg CO2 g/mile	-1.5%		SAE 2000-01-1854 (Grocery truck on 5 Mile route)
	Englehard DPX	WVU	Chassis Dyno, CSR	Δ avg CO2 g/mile	-1.4%		SAE 2000-01-2815 (CSR route)
	JM CRT	WVU	Chassis Dyno, CSR	Δ avg CO2 g/mile	-1.4%		SAE 2000-01-2815 (CSR route)
	Cleaire	CARB	Chassis Dyno, UDDS & NYB	Δ avg CO2 g/mi	0.1%	3.3%	http://www.arb.ca.gov/research/apr/past/icat04-2.pdf
	Various	EPA Summary	Unknown	Unknown	1.0%	4.0%	http://www.epa.gov/otaq/retrofit/tech-summary.htm
	JM CRT	WVU	Chassis Dyno, 5 Mile	Δ avg CO2 g/mile	3.3%		SAE 2000-01-1854 (Grocery truck on 5 Mile route)
	Englehard DPX	WVU	Chassis Dyno, 5 Mile	Δ avg CO2 g/mile	3.3%		SAE 2000-01-2815 (5 Mile route)
	JM CRT	WVU	Chassis Dyno, 5 Mile	Δ avg CO2 g/mile	8.2%		SAE 2000-01-2815 (5 Mile route)
	DPF + FBC	Octel/Meritor	Chassis Dyno, Euro Cert	Δ avg l/100km	-6.8%	4.5%	SAE 2002-01-2784 [Retrofit London taxis]
	JMI CRT Englehard DPX	WVU	Chassis Dyno, CSHVR, CBD, OCRTC, NYGTC	Δ avg CO2 g/mile	-19.5%	15.9%	SAE 2002-01-0433
	JMI CRT Englehard DPX	DOE/Ralph's Grocery	One year in-use test	Fueling & mileage records	2.0%	3.0%	Chandler, K., et al; *Ralph's Grocery Company EC-Diesel ™ Truck Fleet: Final Reslts*; Feb 2003
	JMI CRT Englehard DPX	MJB&A/NYCT	48 months of in-service data	Fueling & mileage records	-4.4%	4.1%	M.J. Bradley & Associates LLC
	Englehard DPX + low NOx cal	SWR	Chassis Dyno, CSHVC	Δ avg CO2 g/mi	6.3%		SAE 2003-01-1381
Active DPF	Peugot (w/FBC)	Puegot	Onroad, city driving	Unknown	3.5%	5.0%	SAE 2000-01-0473
	Cleaire Horizon	CARB	Executive Order	Unknown	0.0%		CARB EXECUTIVE ORDER DE-05-010-03

Table 2: Table of CO_2 Penalties from Different Truck Types in one Published Test of DPFs (Source: SAE 2002-01-0433)

Test Number	Vehicle Type	Vehicle ID Number	Test Cycle	Filter	CO2 g/mi CARB Fuel No Filter	CO2 g/mi ECD Fuel No Filter	CO2 g/mi ECD Fuel w/ Filter	% Diff Fuel	% Diff Filter
1	School Bus	8439	CSHVR(1&2)	DPX	2,056	2,034	1,875	-1.1%	-7.8%
1	School Bus	8435	CSHVR(1&2)	DPX	2,211	2,137	2,122	-3.3%	-0.7%
1	Tanker Truck	8181	CSHVR(1&2)	CRT	2,065	1,607	1,727	-22.2%	7.5%
1	Tanker Truck	8182	CSHVR(1&2)	CRT	1,601	1,986	1,930	24.0%	-2.8%
1	Grocery Truck	5905	CSHVR(1)	DPX	2,119	2,153	2,054	1.6%	-4.6%
1	Grocery Truck	5907	CSHVR(1)	DPX	2,148	2,000	2,002	-6.9%	0.1%
1	Grocery Truck	5903	CSHVR(1&2)	CRT	1,809	1,703	1,826	-5.9%	7.2%
1	Grocery Truck	5904	CSHVR(1&2)	CRT	1,840	1,751	1,775	-4.8%	1.4%
1	Refuse Hauler	37066	CBD(2)	CRT	3,679	3,122	3,570	-15.1%	14.3%
1	Refuse Hauler	37067	CBD(2)	CRT	3,676	3,834	3,811	4.3%	-0.6%
1	Refuse Hauler	37065	CBD(2)	DPX	3,120	2,976	3,117	-4.6%	4.7%
1	Refuse Hauler	37066	OCRTC(1)	CRT	4,085	3,677	3,702	-10.0%	0.7%
1	Refuse Hauler	37067	OCRTC(1)	CRT	4,465	4,681	3,770	4.8%	-19.5%
1	School Bus	8439	CSHVR(1&2)	DPX	1,690	1,670	1,705	-1.2%	2.1%
1	School Bus	8435	CSHVR(1&2)	DPX	1,960	1,951	1,943	-0.5%	-0.4%
2	Tanker Truck	8181	CSHVR(1&2)	CRT	1,866	1,857	1,862	-0.5%	0.3%
2	Tanker Truck	8182	CSHVR(1&2)	CRT	1,791	1,780	2,063	-0.6%	15.9%
2	Grocery Truck	5903	CSHVR(1&2)	CRT	2,015	1,860	1,939	-7.7%	4.2%
2	Grocery Truck	5904	CSHVR(1&2)	CRT	1,921	1,934	1,740	0.7%	-10.0%
2	Refuse Hauler	37066	CBD(2)	CRT	3,170	3,054	3,117	-3.7%	2.1%
2	Refuse Hauler	37067	CBD(2)	CRT	3,289	3,206	3,240	-2.5%	1.1%
2	Refuse Hauler	37066	NYGTC(2)	CRT	8,085	8,184	8,547	1.2%	4.4%
2	Refuse Hauler	37067	NYGTC(2)	CRT	8,868	8,727	8,957	-1.6%	2.6%
2	Refuse Hauler	37065	OCRTC(1)	DPX	3,154	3,139	3,350	-0.5%	6.7%
2	Transit Bus	3005	CBD(2)	CRT	3,019	2,704	2,613	-10.4%	-3.4%
							Average Difference	-2.7%	1.0%

Table 3: Table of Fuel Penalties of DPF Retrofit in NYC Transit Buses (Source: M.J. Bradley & Associates.)

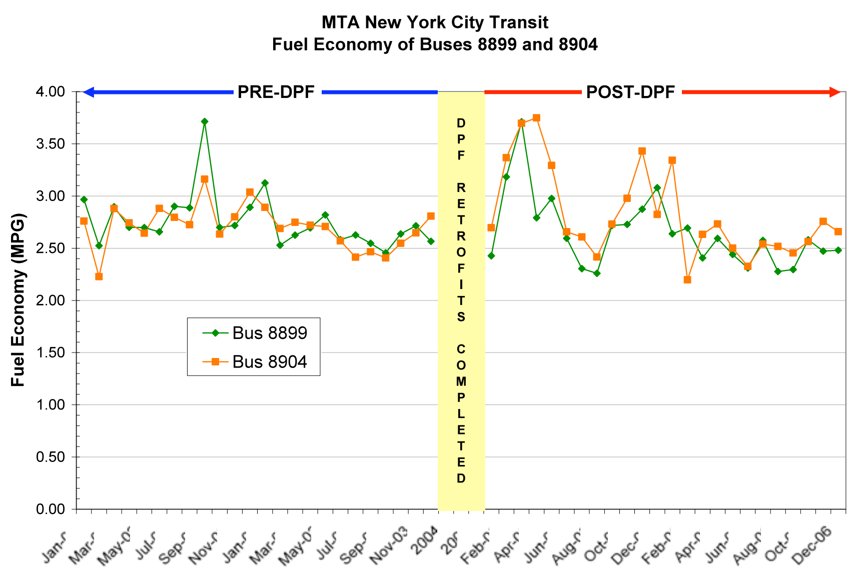
MTA New York City Transit Bus Fleet

Effect of DPF Retrofit on Fuel Economy

Bus Num	Average MPG [1]		
	Pre-DPF (2002 - 2003)	Post-DPF (2005 - 2006)	Difference
8899	2.76	2.64	-4.4%
8900	2.67	2.70	1.0%
8901	2.73	2.78	1.8%
8902	2.70	2.79	3.4%
8903	2.72	2.71	-0.2%
8904	2.70	2.82	4.1%
8905	2.81	2.76	-1.5%
8908	2.68	2.68	-0.1%
8909	2.75	2.74	-0.4%
8910	2.70	2.64	-2.1%
FLEET AVG	**2.72**	**2.73**	**0.2%**

[1] Based on monthly fueling records for 2002 - 2003 (pre-DPF) and 2005 -2006 (post-DPF).

Figure 3: Monthly Fuel Economies for Two NYC Transit Buses (Source: M. J. Bradley & Associates.)



ESTIMATING THE CARBON DIOXIDE EQUIVALENT BENEFITS

Carbon Dioxide Equivalency Metrics

The debate over the development and use of carbon dioxide equivalency metrics for short-term warming pollutants, particularly aerosols, has yet to be fully resolved. Two fundamental approaches to modeling carbon dioxide equivalency are represented in the literature: "global warming potential" (GWP), which is based on integrated radiative forcing and "global temperature change potential" (GTP), a metric based on temperature change. Both metrics are based on short term or "pulse" emissions of black carbon, the impacts of which have typically been modeled globally over 20, 50 or 100 year periods. GWP and GTP are less commonly estimated based on sustained emissions. In addition to the global estimates, several studies estimate GWP and GTP by region. Table 4 summarizes GTP and GWP CO_2e values from a variety of published sources; many are values derived from the original publications by Fuglestvedt et al (2009.)[5,6,7]

Global Warming Potential (GWP).

Adopted as a part of the Kyoto Protocol, "Global Warming Potential" or GWP, was established to create a common CO_2-equivalent scale for comparing the potential effects of different greenhouse gases in meeting each country's reduction commitments. GWP is the most widely accepted CO_2-equivalency metric presently. GWP is traditionally calculated from a pulse emission of a gas, the effects of which are integrated over a 20, 50 or 100 year period. More recently, GWP has been adapted by some researchers for application to some short-lived climate-forcing aerosol (particle) emissions, such as black carbon, organic carbon and sulfate. The advantage of GWP is that it provides a simple, transparent metric that is widely accepted in policy circles. However, critics of the GWP approach cite the following disadvantages: 1) radiative forcing is an abstract concept (as compared with temperature change), 2) two equally-weighted GWP emissions do not result in equivalent temperature changes along a 20, 50 or 100 year time path, and 3) Using integrated radiative forcing to calculate GWP may overestimate the impacts of short-lived pollutants in the context of policies to limit long term temperature change.[8]

Global Temperature Potential (GTP)

An alternative to GWP proposed by Shine et al (2007)[9], Global Temperature Potential (GTP), is a *temperature-change* based metric recently highlighted as potentially a more practical approach to CO_2-equivalency.[10] Boucher and Reddy (2008) use GTP to consider climate response from a diesel truck retrofit with a DPF, an approach we adopt in this paper.[11] GTP offers certain advantages: 1) temperature change is a metric of actual atmospheric warming and is an easily understandable concept (as compared with radiative forcing), and 2) two equally-weighted GTP emissions would result in the same temperature change at the end of a stipulated target date, making it easier to compare the response of control strategies. Currently, the standard GTP approach is to estimate a "pulse" GTP based on a short burst of emissions. However, for very short-lived species, the pulse GTP yields a conservative estimate of CO_2 equivalence, approximately 5-7 times smaller than the corresponding GWP.[12] The alternative, a "sustained" GTP, based on continuous stream of emissions (e.g. an applied DPF in operation for a decade) may represent the best alternative to the pulse GTP and GWP metrics and yet may be similar in magnitude to GWP. However, estimates of sustained GTPs are not readily available in the published literature at this time. One exception may be Hansen et al (2007), which presents results as "GWP" but is actually a temperature change based on sustained emissions (Table 4).[13] Thus, Hansen may represent a "sustained" GTP rather than a GWP (by the IPCC definition of GWP). Note that results based on Hansen et al's sustained GTP are similar in magnitude to our "best estimate" GWP that is based on Bond and Sun (2005).

Table 4. Published carbon dioxide equivalency metrics.
(* Derived values based on original publications (cited in table) by Fuglestvedt et al (2009 in press).[14,15]

Carbon Equivalent (CO2e) Metric	BC CO_2e metric	OC CO_2e metric
Global GWP100		
GWP 100 [sustained] (Hansen et al, 2007)	500	
GWP 100 (BC: Bond and Sun, 2005, OC: Bond et al, 2004)	680	-75
GWP 100 (Jacobson, 2007) (lower bound estimate)	1500	
GWP100 (Reddy and Boucher, 2007)	480	
GWP100 (Schulz et al, 2006)*	460	-69
Global GTP100		
GTP100 (Schulz et al, 2006)*	64	-10
Global GWP20		
GWP20 [sustained] (Hansen et al 2007)	2000	
GWP20 (BC: Bond and Sun, 2005, OC: Bond et al, 2004)	2200	-250
GWP20 (Jacobson, 2007)	4480	
GWP20 (Schulz et al, 2006)*	1600	-240
Global GTP20		
GTP20 (Schulz et al, 2006)*	470	-71
North America GWP100		
North America GWP100 (Reddy and Boucher, 2007)*	430	
North America GWP100 (Koch et al, 2007)*	550	-42
North America GWP100 (Naik et al, 2007)*	920	-88
North America GTP100		
North America GTP100 (Reddy and Boucher, 2007)*	62	
North America GTP100 (Koch et al, 2007)*	77	-6
North America GTP100 (Naik et al, 2007)*	130	-12
North America GWP20		
North America GWP20 (Reddy and Boucher, 2007)*	1500	
North America GWP20 (Koch et al, 2007)*	1900	-150
North America GWP20 (Naik et al, 2007)*	3200	-310
North America GTP20		
North America GTP20 (Reddy and Boucher, 2007)*	450	
North America GTP20 (Koch et al, 2007)*	560	-43
North America GTP20 (Naik et al, 2007)*	940	-90

DIESEL PARTICULATE FILTER CARBON DIOXIDE EQUIVALENT REDUCTION ESTIMATES

CATF identified and attempted to answer four questions relative to the carbon dioxide equivalent benefits of retrofit DPFs on class 8 trucks:

I. **What are the net carbon dioxide equivalent (CO_2e) reduction benefits of reducing diesel particulate matter with a diesel particulate filter?**

II. **What is the break-even fuel penalty, i.e., assuming DPFs cause a measurable fuel penalty, the point below which use of a DPF to reduce black carbon-related warming is beneficial?**

III. **How long does the climate benefit of the DPF last? (What is the number of years in which the black carbon reduction-related climate benefits would exceed increased CO_2e from an assumed 2 percent fuel penalty?[16])**

IV. **What are the climate benefits of a hypothetical rule requiring the installation of diesel particulate filters on U.S. class 8 trucks?**

I. Calculating the Global Warming Potential (GWP_{20}) benefits of reducing diesel particulate matter with a diesel particulate filter.

This approach estimates the reduction in global warming potential (GWP) resulting from the removal of diesel particulate matter using a DPF retrofit expressed in CO_2 GWP-equivalent grams per gallon of fuel (abbreviated below as CO_2e) based on assumptions summarized in Table 5. The estimate assumes an incremental 2 percent increase in fuel use attributable to the filter and any corresponding increases in CO_2 and black carbon emissions.

The following calculations spell out, step-by-step, the estimates of the effect of a retrofit DPF removing 90 percent[17] of the diesel particles. We assume the particle mass is made up of two principal components—organic carbon (OC) (an assumed constant 25 percent of the mass) and black carbon (an assumed constant 75 percent of the mass).[18] For simplicity, the sum of black carbon and organic carbon is assumed to be 100 percent, with negligible (<1%) sulfate make as a result of the use since 2006 of 15 ppm ultralow sulfur fuel due to the EPA mandate. The emission rates used in the calculation represent emissions typical of a Class 8 truck in the U.S.

The focus on the shorter-term metrics in this paper, the GWP_{20}, is predicated on CATF's approach to diesel control strategies that would address CO_2e impacts over the next two decades. At the same time, this paper provides CO_2e benefits estimates across a range of metrics including a variety of GWP_{100} values that may be more appropriate for the assessment of CO_2e benefits over a century-long time frame. Specifically, we adopt the black carbon GWP_{20} (2,200) from Bond and Sun (2005)[19] for use in this paper as a "best estimate" based on the available metrics and how they were derived.[20] This value compares to other estimates such as 2,000 by Hansen et al. (2007)[21,22], Schulz et al's (2006) 1,600 and Jacobson's (2007) much higher 4,480. [23,24] In addition, we report results based on GWP_{100} which the IPCC recognizes as a standard for such comparisons. See Table 7 for the full range of estimates using published magnitudes of GWP and GTP.

Step-by-step calculations.[25,26] Results for all estimates are found in Table 6.

Table 5: Table of assumptions and constants.

lbs per gallon of diesel fuel	7.1
grams per lb	453.59
% carbon in a gallon of fuel	85%
average emissions rate of HD truck (g/bhp-hr)	0.1
average emissions rate of HD truck (g/mi)	0.29
average output energy in a gallon of diesel fuel (bhp-hr)	16
GWP CO_2 (by definition)	1
BC fraction assumed in DPM	75%
GWP20 black carbon (Bond, and Sun 2005)	2,200
GWP20 organic carbon (Bond and Sun, 2005)	-250
OC fraction assumed in DPM	25%
DPF efficiency	90%
Fuel Penalty	2%

1. Calculate CO_2 content of diesel fuel.

7.1 lbs /gal * 453.59 g/lb = 3220.49g/gal

85% carbon * 3220.49 = 2737.42 g carbon/ gal

2737.42 g/gal carbon * 3.67 (3.67 = 44/12 molecular wt ratio CO_2/C) =10046g CO_2/gal

2.Calculate grams BC per gallon of fuel based on DPM emissions rate of 0.1 g/bhp-hr (equivalent to 0.29 g/mi) and 16 hp-hr of output energy in a gallon of diesel fuel, and 75% of the particulate emissions fraction BC.

16 bhp-hr * 0.1 g/bhp-hr * 0.75
= 1.2 g BC /gal diesel fuel

(Note: based on mass alone, the ratio of BC to CO_2 is 1.20g /10046 g = 0.00012 or 0.012%, but when leveled by GWP, it is much more significant as calculated below)

3. Calculate, using GWP_{20}, CO_2 equivalent (CO_2e) grams of emissions based on Bond and Sun (2005) estimate of GWP_{20} 2200 for BC:

1.20g * 2200
= 2640 g CO_2e *(g/gal diesel fuel)*

4. Calculate grams organic carbon particles per gallon of fuel based on DPM emissions rate of 0.1 g/bhp-hr (equivalent to 0.29 g/mi) and 16 hp-hr of output energy in a gallon of diesel fuel, and 25% of the particulate emissions fraction organic carbon.

16 bhp-hr * 0.1 g/bhp-hr * 0.25 OC
= 0.4 g OC /gal diesel fuel

5. Calculate, using GWP_{20}, CO_2 equivalent OC emissions, based on Bond et al (2004)[27] estimate of -250 GWP_{20} factor for OC:

0.4 g * -250
= -100g CO_2e *(g/gal diesel fuel)*

6. Sum the DPM CO_2 equivalent grams per gallon from 75% and 25% OC:

2640g CO_2e + -100g CO_2e
= 2540g CO_2e emissions *(g/gal diesel fuel)*

7. Calculate total CO_2 equivalent warming from a gallon of diesel fuel

10046 + 2540
= 12586g CO_2e *(g/gal diesel fuel)*

8. Calculate the CO_2e fuel penalty resulting from a 2% increase in DPF-related fuel use:

10046 * .02 = 200.92 g CO_2 (CO_2 FP)
+
2540 * 0.02 * 0.1= 5.08 g CO_2e (DPM FP)

= 206 g CO_2e *(g/gal diesel fuel)*

9. Calculate DPM CO_2 equivalent grams/gal removed by a 90% DPF

2540 (total DPM CO_2e grams from step 6) * 90%
=2286 g CO_2e removed/ gal diesel fuel.

10. Calculate the net CO_2e benefit from the DPF per gallon of fuel.
(Subtract the 2% fuel penalty from the net reduction from the DPF)

2286 g CO_2e /gal (DPM reduction) -206 g/gal CO_2 (FP)
= 2,080g CO_2e/gal **net** benefit / gal diesel fuel
(total CO_2e retrofit emissions 10506 g/gal)

11 Calculate the percent reduction in carbon dioxide equivalent (CO_2e) from the application of a DPF on a class 8 truck, with the 2% fuel penalty:

2080 g CO_2e /12586 g CO_2 *100%

Net CO_2e benefit = 16.53%

12. In order to express the calculations above in a form that is easy to understand for policymakers, the calculation below (using Bond and Sun (2005) GWP) examines how many DPFs it would take to offset the combined CO_2 and black carbons emissions of one class 8 truck and how many DPFs it would take to offset the CO_2 emissions of one car.

Based on the CO_2e net benefit of one DPF, calculate the number of DPFs required to remove the equivalent emissions (combined CO_2 and black carbon) and related warming of one class 8 truck:

12,586g CO_2 / 2080g
= 6.05 DPFs to eliminate the equivalent emissions of one class 8 truck.

Thus, using GWP_{20}, approximately 6 DPF retrofits offset the CO_2e emissions of one class 8 truck**.**

13. Calculate the benefit of one DPF in terms of the elimination of an equivalent amount of pollution from passenger cars.

A. Calculate annual average CO2 emissions from one car: According to the U.S. Statistical Abstract, the average car is driven 12,500 miles per year and has a fuel efficiency of 22.44 miles per gallon for an annual usage of 557 gallons of gasoline per year. Each gallon of gasoline burned emits 8,788 g of CO_2.

557 gallons per year * 8788 g CO_2 per gallon / 1,000,000 g/ metric ton = 4.89 metric tons of CO_2 per year per car.

B. Calculate tons of CO_2e from a tractor trailer truck per year: According to the Bureau of Transportation Statistics[28], the average tractor trailer truck is driven 70351 miles per year and has a fuel efficiency of 5.3 miles per gallon, for an annual usage of 13274 gallons of diesel fuel per year. Each gallon of diesel fuel burned emits 12586 g of CO_2e per year including black carbon and organic carbon impacts. (See step 7 above.)

13274 gallons per year * 12586 g CO_2e per gallon / 1,000,000 g/metric ton
= 167.1 metric tons of CO_2 per year per class 8 truck without a DPF.

C. Calculate CO_2e of tractor trailer truck with a DPF. With a DPF the CO_2e emission rate drops to 10506 gCO_2e per gallon with the DPF. (From Step 10 the net emissions are 12586 – 2080 (DPF benefit) = 10506 net CO2e emissions)

13,274 gallons per year * 10506 gCO_2e per gallon / 1,000,000 g/metric ton
= 139.5 metric tons per year per tractor trailer truck with DPF.

27.6 metric tons per year per truck retrofit / 4.89 metric tons per year per car
= eliminating the pollution from 5.7 cars for every tractor trailer truck retrofitted with a DPF.

(e.g. if DPFs were installed on 1,000,000 tractor trailer trucks in the U.S. it would be equivalent to taking 5.7 million cars off the road.)

(Alternatively, using GWP_{100}: 13274 * 10832 = 143.8 metric tons but with retrofit 13274* 10328 = 137.1 metric tons. Delta = 6.7 metric tons/ 4.89 = eliminating the pollution from 1.37 cars for every DPF.)

RANGE OF BENEFIT ESTIMATES: DISCUSSION. In order to demonstrate how the assumptions affect the comparison, CATF also calculated the CO_2e for the installation of a DPF based on a range of recently published estimates of GWP and GTP and assuming the 2 percent fuel penalty (see Table 6, Figure 4 below). As discussed previously the GTP based calculations result in much lower net CO_2e benefits than GWP (with the exception of Hansen et al, 2007—see below.)

To summarize the ranges of global CO_2e benefits (in grams per gallon of diesel fuel): for GWP_{100}: 270 to 1391 (mean=554); GWP_{20}: 1437 to 4541 (mean = 2481); GTP_{100}:-136 and for GTP_{20}: 280. North American regional CO_2e benefits were of a similar but modestly lower magnitude: for GWP_{100}: 247 to 759 (Mean=461); GWP_{20}: 1,362 to 3136 (mean = 2097); GTP_{100}:-136 to -65 (mean=-107) and for GTP_{20}: 269 to 780 (mean = 479).

The use of Bond and Sun's (2005) GWP_{20} (2200) to calculate the net CO_2e benefits of a DPF, appears to be a reasonably justifiable "best estimate." The resultant 2080 g/gal lies within the range of the 5 estimates GWP_{20}: 1437 to 4541 and similar but lower in magnitude to the mean of the 5 estimates (mean = 2481) and much more conservative than the 4541 based on Jacobson (2007.) [29] In addition, if Hansen et al (2007) is considered by IPCC definition not to be a GWP but instead a "sustained GTP", the CO_2e of 1868 is close in magnitude (within 10 percent) to the 2080 value using Bond et al.

Part I Conclusions:

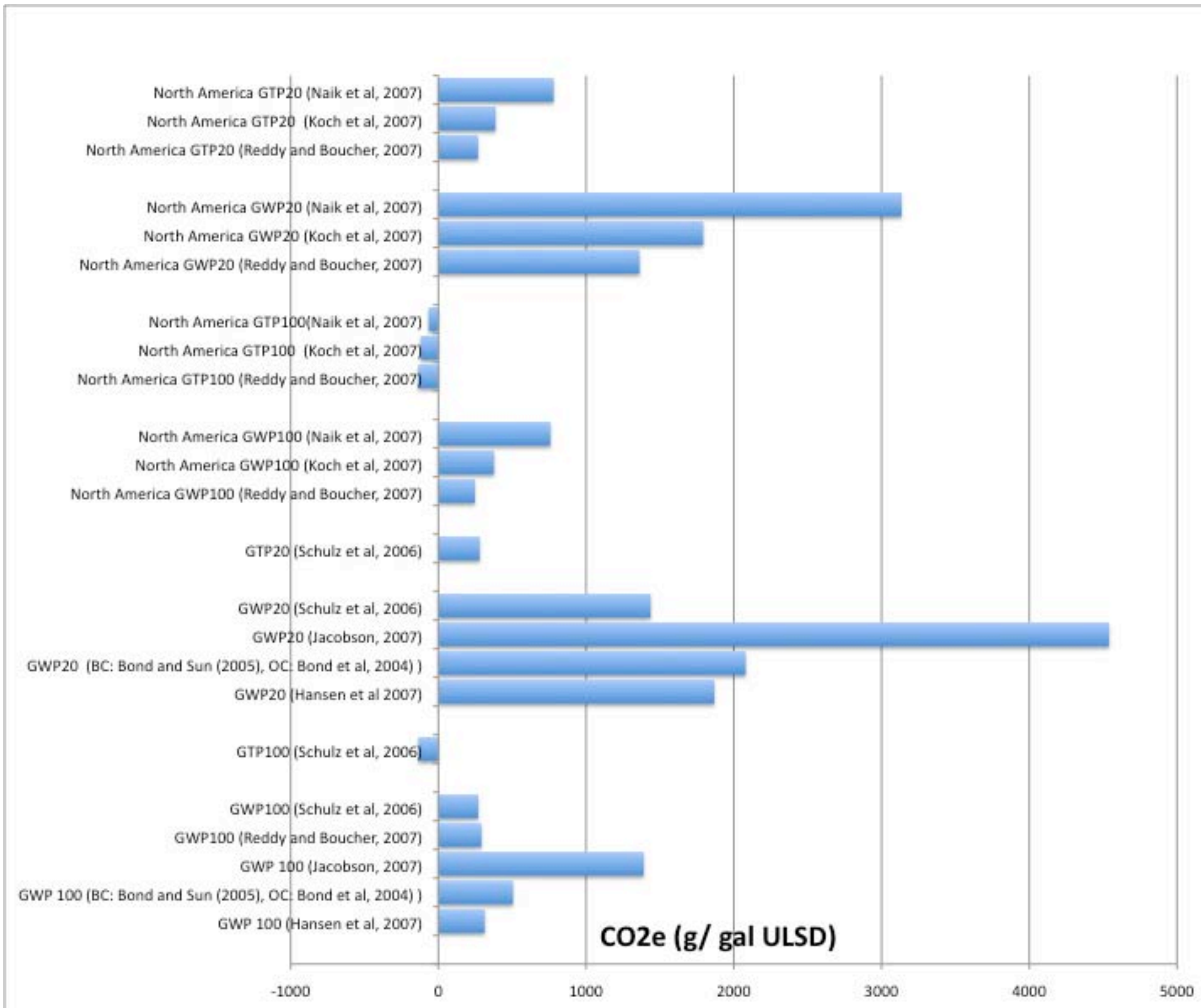
Based on a "best estimate" GWP_{20} of 2,200, the installation of a DPF on a class 8 truck, despite an assumed 2 percent fuel penalty, yields a net climate benefit of approximately 2000 g CO_2e per gallon of diesel fuel (2080g). The magnitude of the benefit can be related to the number of DPFs it would take to effectively eliminate the pollution from one truck. DPFs installed on 6 class 8 trucks would offset the total CO_2/BC warming from one equivalent truck, assuming same engine and duty cycle. This is also equivalent to eliminating the pollution from approximately 6 cars. The net climate benefit based on GWP_{100} is about 500 gCO_2e/gal (505g).

Table 6: Range of calculated black carbon CO_2e benefits for a DPF-retrofit U.S. class 8 truck based on a range of published estimates of 100 and 20-year GWPs and GTPs. Highlighted in blue is CATF's preferred "best estimate."

Carbon Equivalent (CO2e) Metric	BC CO2e metric	OC CO2e metric	CO2e (g/gal)
Global GWP100			
GWP 100 (Hansen et al, 2007)	500	-69	313
GWP 100 (BC: Bond and Sun, 2005, OC: Bond et al, 2004)	680	-75	505
GWP 100 (Jacobson, 2007) (lower bound estimate)**	1500	-69	1391
GWP100 (Reddy and Boucher, 2007)**	480	-69	292
GWP100 (Schulz et al, 2006)	460	-69	270
Global GTP100			
GTP100 (Schulz et al, 2006)	64	-10	-136
Global GWP20			
GWP20 (Hansen et al 2007)**	2000	-240	1868
GWP20 (BC: Bond and Sun, 2005, OC: Bond et al, 2004)	2200	-250	2080
GWP20 (Jacobson, 2007)**	4480	-240	4541
GWP20 (Schulz et al, 2006)	1600	-240	1437
Global GTP20			
GTP20 (Schulz et al, 2006)	470	-71	280
North America GWP100			
North America GWP100 (Reddy and Boucher, 2007)**	430	-42	247
North America GWP100 (Koch et al, 2007)	550	-42	377
North America GWP100 (Naik et al, 2007)	920	-88	759
North America GTP100			
North America GTP100 (Reddy and Boucher, 2007)**	62	-6	-136
North America GTP100 (Koch et al, 2007)	77	-6	-120
North America GTP100 (Naik et al, 2007)	130	-12	-65
North America GWP20			
North America GWP20 (Reddy and Boucher, 2007)**	1500	-150	1362
North America GWP20 (Koch et al, 2007)	1900	-150	1793
North America GWP20 (Naik et al, 2007)	3200	-310	3136
North America GTP20			
North America GTP20 (Reddy and Boucher, 2007)**	450	-43	269
North America GTP20 (Koch et al, 2007)	560	-43	387
North America GTP20 (Naik et al, 2007)	940	-90	780

NOTE: **Where OC unavailable, Koch et al (2007) used for default GWP and GTP for North America and Shulz (2007) used for global GWP and GTP.

Figure 4: Ranges of black carbon CO2e benefits (g/gal) for the DPF retrofit of a U.S. class 8 truck, assuming a 2 percent fuel penalty.



<u>II. Calculating the Break-Even Fuel Penalty (FPbe),</u> i.e., the percent reduction in fuel economy, below which using a DPF to reduce black carbon-related warming is found to be beneficial.

To determine the point at which emissions from a fuel penalty overcome the benefits of a DPF, CATF calculated break-even fuel penalties for all recently published estimates of GWP and GTP (Table 7). Table 7 shows break-even fuel penalties (FPbe) are all positive ranging from 1 to 45 percent. Ranges of GWP_{100} FPbe range from 5 to 16 percent, while GWP_{20} values range from 16-45 percent. The 22 percent break-even fuel penalty using CATF's "best estimate" based on Bond and Sun (2005) falls in the middle of the range of North American GWP_{20}-based estimates. Furthermore, FPbe based on Bond and Sun's (2005) GWP_{100} is 7 percent, well beyond the range of fuel penalties seen in studies. Pulse GTP FPbe values are much lower than those calculated with GWPs, (with the exception of Hansen) and therefore represent the most conservative case. These estimates (Table 7) show that there is a net positive CO_2e benefit from a DPF if the fuel penalty is small. As noted earlier, sustained GTP values may be more appropriate for estimating the benefits of a DPF that has a long useful life and attendant sustained emissions reductions. As a point of comparison between sustained and pulse GTPs, Hansen's FPbe of 20 percent is close in magnitude (within 10 percent) to the 22% utilizing Bond and Sun (2004).[30]

The Calculation:
The general form of the equation to solve for break-even fuel penalty (the % increase in fuel use, below which would still allow for a climate benefit) is that the CO_2e, after the application of the filter, is equal to the CO_2e before the filter is applied. See below for the full range of estimates of FPbe using this method and other published magnitudes of GWP and GTP.

1. Calculate total initial CO_2e in a gallon of fuel

Total initial CO_2e per gallon of fuel
= grams CO_2 per gallon + GWP * grams carbon per gallon
= 10046 + 2640

2. Calculate total CO_2e in a gallon of fuel after the application of the filter.
   Since the addition of the DPF may affect the fuel efficiency of the truck, we cannot just compare the CO2 emissions per gallon, but instead must also adjust for the increased fuel usage. It takes more than one gallon of fuel to go as far as one gallon would take the truck absent the fuel penalty.

Total CO_2e after the filter is applied to cover the same distance as one gallon would take the truck absent the filter
= CO_2 per gallon * (1+FP) + [GWP * (grams carbon per gallon)] * (1+FP) * (1-filter efficiency)

Assuming 90% filter efficiency, total CO_2e per gallon of fuel after the filter is applied:

= CO_2 per gal * (1+FP) + [GWP * (grams carbon per gal)] * (1+FP) * (0.1)
= 10046 * (1+FP) + 2540 * (1+FP) * 0.1

3. Calculate the break-even fuel penalty (FPbe):

10046 + 2540
= 10046 * (1+FPbe) + 2540* (1+FPbe) * 0.1

4. Solving for FPbe

FPbe = (2,540 * 0.9) / (10046 + 2,540* 0.1)
=2286 /10,300 *100%
=22.18
Break-Even GWP_{20} Fuel Penalty = 22 Percent
(7 percent for GWP_{100})

Table 7: Table of Break-even Fuel Penalties for Typical U.S. Class 8 Truck Using a Range of Published GWP and GTP Magnitudes. CATF's "best estimate" result is highlighted in blue.

Carbon Equivalent (CO2e) Metric	BC CO2e metric	OC CO2e metric	Break-even fuel penalty
Global GWP100			
GWP 100 (Hansen et al, 2007)**	500	-69	5%
GWP 100 (BC: Bond and Sun, 2005, OC: Bond et al, 2004)	680	-75	7%
GWP 100 (Jacobson, 2007)**	1500	-69	16%
GWP100 (Reddy and Boucher, 2007)**	480	-69	5%
GWP100 (Schulz et al, 2006)	460	-69	5%
Global GTP100			
GTP100 (Schulz et al, 2006)	64	-10	1%
Global GWP20			
GWP20 (Hansen et al 2007)**	2000	-240	20%
GWP20 (BC: Bond and Sun, 2005, OC: Bond et al, 2004)	2200	-250	22%
GWP20 (Jacobson, 2007)**	4480	-240	45%
GWP20 (Schulz et al, 2006)	1600	-240	16%
Global GTP20			
GTP20 (Schulz et al, 2006)	470	-71	5%
North America GWP100			
North America GWP100 (Reddy and Boucher, 2007)**	430	-42	4%
North America GWP100 (Koch et al, 2007)	550	-42	6%
North America GWP100 (Naik et al, 2007)	920	-88	9%
North America GTP100			
North America GTP100 (Reddy and Boucher, 2007)**	62	-6	1%
North America GTP100 (Koch et al, 2007)	77	-6	1%
North America GTP100 (Naik et al, 2007)	130	-12	1%
North America GWP20			
North America GWP20 (Reddy and Boucher, 2007)**	1500	-150	15%
North America GWP20 (Koch et al, 2007)	1900	-150	19%
North America GWP20 (Naik et al, 2007)	3200	-310	32%
North America GTP20			
North America GTP20 (Reddy and Boucher, 2007)**	450	-43	5%
North America GTP20 (Koch et al, 2007)	560	-43	6%
North America GTP20 (Naik et al, 2007)	940	-90	10%

NOTE: **Where OC unavailable, Koch et al (2007) used for default GWP and GTP for North America and Shulz (2007) used for global GWP and GTP.

Part II. Conclusion:

Black carbon reductions from a DPF retrofit on a class 8 truck will have a cooling benefit as long as the increase in fuel use resulting from the installation of the DPF is less than 22 percent. Thus, for GWP_{20}, the break-even fuel penalty is much higher than fuel penalties found in studies of DPF fuel consumption as reviewed above. The GWP_{100} breakeven fuel penalty is 7 percent, still exceeding the range of most published potential fuel penalties.

III. How long does the black carbon benefit from a DPF last?

Boucher and Reddy (2008) have proposed a method to determine the length of time that climate benefits of reducing black carbon with a DPF exceed any incremental fuel penalty-related carbon dioxide.[31] Using their method, a parameter X is calculated based on the magnitude of the BC reduction, BC radiative effects (GWP), as well as additional CO_2 emissions from the filter. X is then manually applied to Figure 5. Using their method, we estimate the number of years over which the black carbon reduction-related climate (CO_2e) benefits from the installation of a DPF on a U.S. class 8 truck would exceed any incremental CO_2e from an assumed 2 percent fuel penalty with Bond and Sun's (2005) GWP_{100} input for radiative forcing.[32] Note that because the benefits of a class 8 truck program would extend about 20 years, we interpolate between the 10 and 30-year trajectories on the graph.

Results (Table 9) suggest that the climate benefit from retrofitting a typical U.S. class 8 truck would last on the order of about a half century assuming a 2 percent fuel penalty. In addition, Olivier Boucher has, on behalf of CATF, run a GTP-based scenario based on a proposed program to retrofit the U.S. class 8 truck fleet with diesel particulate filters. Those results are presented in Part IV of this discussion.

Table 8: Constants used in application of Boucher and Reddy (2008) method below.

ASSUMPTIONS/ CONSTANTS		
BC GWP_{100}	680	Bond and Sun (2005) GWP [33]
OC GWP_{100}	-75	Bond et al (2005)
CO_2 g/mi	1700	(Per MJBA, Based on class 8 fleet average fuel econ)
EC fraction	75.00%	Assumes 75-25 EC -OC split (MJB Associates)
OC fraction	25.00%	Assumes 75-25 EC -OC split (MJB Associates)
Mean truck emissions g/mi	0.29	
DPF Efficacy	90.00%	

Note: the calculation requires interpolation of Boucher and Reddy's (2008) Figure 6 (see figure below).

1. Calculate the change in black carbon due to the filter (ΔX_{BC}) (@ 75 % BC) expressed as CO_2e -- the CO_2 equivalent global warming potential (GWP) ***in grams per mile***.

$$\Delta X_{BC} = 0.29 \text{ g/mi (emissions rate} * 680\ GWP_{100} * 0.75 \text{ (BC fraction)} * 90\% \text{ reduction}$$
$$= 133.11\ CO_2e \text{ (g/mi)}$$

2. Calculate the change in organic carbon (ΔX_{OC}) (@ 25% OC) from the application of the DPF expressed in CO_2e (CO_2 equivalent grams per mile)

$$\Delta X_{OC} = 0.29 \text{ g/mi} * -75 \text{ OC } GWP_{100} \text{ X } 0.25 \text{ (BC fraction)} * 90\% \text{ reduction}$$
$$= -4.89\ CO_2e \text{ (g/mi)}$$

3. Calculate net change in GWP equivalent for diesel particulate matter removed (ΔX_{BC+OC}) in CO_2e g/mi)

$$(\Delta X_{BC+OC}) = 133.11 + -4.89$$
$$= 128.22\ CO_2e\ (g/mi)$$

4. Calculate ratio X based on 2% fuel penalty where X is defined as:

$$\boldsymbol{X} = \Delta X_{BC+OC} / \Delta X_{CO_2}$$

$$\boldsymbol{X} = 128.22 / (1700\ g/mi\ CO_2\ X\ 0.02\%\ \text{fuel penalty})$$

$$= \mathbf{3.77}$$

5. Apply, by inspection, factor X to Boucher and Reddy's graph (Figure 5) interpolating between 10 and 30 years years line for the BC time horizon. For the 2% fuel penalty, where x= 3.77 the approximate time horizon for BC before warming from the excess fuel overtakes BC cooling from the DPF is about 50 years (assuming an interpolated 20 year trajectory).

Table 9: Duration of black carbon benefit for a range of fuel penalties:

Fuel Penalty	X	Duration of BC benefit (Years)
0.1%	75.42	100+
1.0%	7.54	75+
2.0%	3.77	50
3.0%	2.51	40
4.0%	1.89	35
5.0%	1.51	30

Figure 5: Boucher and Reddy (2008) Figure 6 used to estimate how long the black carbon lasts from the calculated X value using a 20-year trajectory (halfway between 10 and 30 year trajectories below).

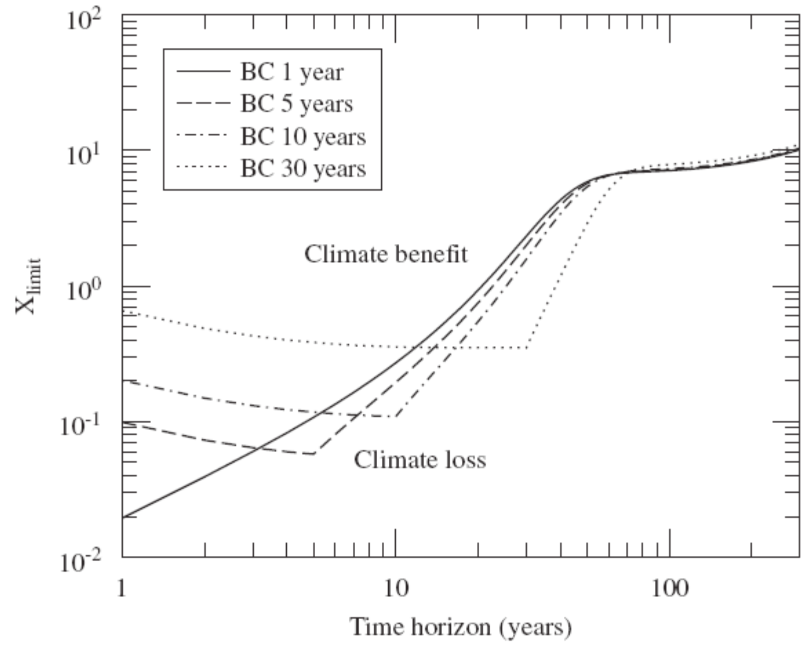


Fig. 6. Critical X_{limit} parameter as a function of the time horizon. If X is larger than X_{limit}, there is a climate benefit for this time horizon to reduce BC emissions despite the associated CO_2 penalty.

Part III. Conclusion: *Installation of a DPF will produce net climate benefits that last approximately 50 years assuming a 2 percent fuel penalty*

IV. APPLICATION TO A HYPOTHETICAL U.S. CLASS 8 TRUCKn REBUILD RULE

CATF, with the technical assistance of M. J. Bradley and Associates LLC, developed a proposal to the U.S. Environmental Protection Agency for a mandatory class 8 truck rebuild program. Modeling of the CATF-proposed program beginning in 2012 and ending in 2030 (see Tables 10 and 11 below) would result in approximately 70,761 metric tons of diesel particulate matter reduced.[34] The climate benefits of this program would be equivalent to 96 million metric tons of carbon dioxide (CO_2e) reduced (GWP_{20}), the equivalent of eliminating the annual emissions of 21 million cars or 1.8 million class 8 diesel trucks (GWP_{20}).[35]

A supplemental analysis of the black carbon reduction program benefits, courtesy of Olivier Boucher, U.K. Met Office, Hadley Centre, suggests that the benefits of the black carbon reduction would last approximately 50 years based on the method of Boucher and Reddy (2008).[36] After 50 years, the assumed fuel penalty-related CO_2 and black carbon-related warming overtakes the black carbon benefits but with only a minimal residual net warming as a result of increased DPF-related fuel use (See Figure 6).

Table 10: Table of diesel census data and tons of diesel particulate matter for proposed class 8 truck fleet rebuild rule. (M.J. Bradley & Associates LLC for CATF)

	Model Years 1998 - 2007 Class 8			
YEAR	Trucks in Service	New Rebuilds	Rebuilds in Service	Short Tons PM reduced
2010	1,754,940			
2011	1,698,740			
2012	1,638,140	143,567	143,567	2,323
2013	1,572,590	186,722	325,982	4,991
2014	1,503,900	212,956	528,914	7,452
2015	1,433,240	127,147	638,520	8,091
2016	1,360,010	50,156	665,943	7,501
2017	1,284,400	27,408	668,421	6,717
2018	1,208,290	25,984	669,230	6,025
2019	1,134,730	27,624	672,249	5,443
2020	1,059,710	36,432	682,809	4,989
2021	985,280	45,612	701,730	4,656
2022	912,750	39,080	681,463	4,121
2023	842,400	12,000	631,142	3,439
2024	773,410	-	583,681	2,853
2025	706,490	-	546,341	2,403
2026	643,580	-	510,238	2,018
2027	585,780	-	477,073	1,697
2028	530,640	-	444,816	1,421
2029	483,070	-	415,292	1,194
2030	443,200	-	387,621	1,008
	TOTAL	934,688		78,342

Table 11: Net Annual and Total CO2e Reductions (million metric tons) from a U.S. class 8 truck rebuild rule. (M. J. Bradley & Associates LLC for CATF)

Net CO2e Benefits of Proposed Class 8 Truck Rebuild Rule				
Year	Rebuilt Fleet Mileage (bill mi)	Rebuilt Fleet Fuel (bill gal)	Net CO2e Reduction [1] (million tonnes)	
			GWP100	GWP20
2012	8.1	1.4	0.69	2.85
2013	17.3	2.9	1.48	6.12
2014	25.9	4.4	2.22	9.13
2015	28.1	4.8	2.41	9.91
2016	26.1	4.4	2.23	9.19
2017	23.3	4.0	2.00	8.23
2018	20.9	3.5	1.79	7.38
2019	18.9	3.2	1.62	6.67
2020	17.3	2.9	1.48	6.11
2021	16.2	2.7	1.39	5.71
2022	14.3	2.4	1.23	5.05
2023	12.0	2.0	1.02	4.21
2024	9.9	1.7	0.85	3.50
2025	8.4	1.4	0.71	2.94
2026	7.0	1.2	0.60	2.47
2027	5.9	1.0	0.50	2.08
2028	4.9	0.8	0.42	1.74
2029	4.1	0.7	0.36	1.46
2030	3.5	0.6	0.30	1.23
TOTAL	**272.3**	**46.2**	**23.3**	**96.0**
[1] Net BC benefit (gCO2e/gal):			**GWP100**	**GWP20**
			505	2080

Figure 6. Modeled GTP-based benefits a CATF-proposed class 8 truck rebuild rule in the U.S., assuming a 2 percent fuel penalty, courtesy, Olivier Boucher, Hadley Centre, UK (2009). The net CO_2e reduction benefit lasts about half a century followed by a very small CO_2 warming as a result of the fuel penalty.

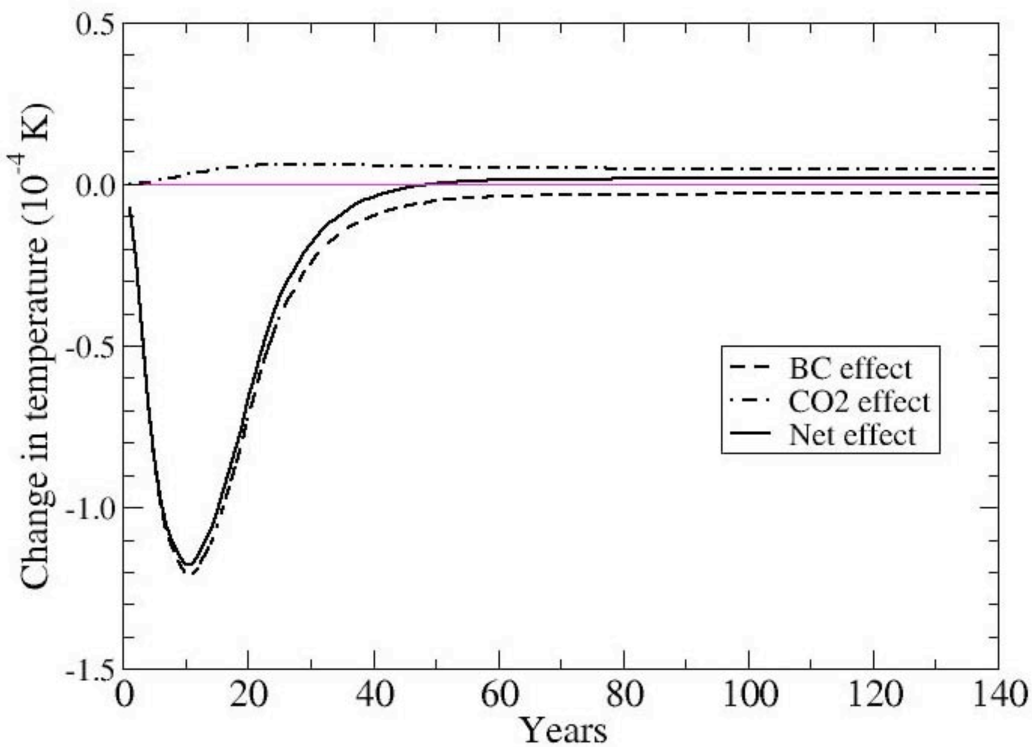


Table 12: The estimated benefits (GWP20) of installing DPFs on class 8 trucks, showing that retrofitting the nearly one million U.S. class 8 trucks with DPFs, would yield the equivalent of eliminating the annual emissions* of 21 million cars or 1.8 million class 8 diesel trucks.[37]

	DPF Retrofits	MTCO2e (Program T)	Equiv Trucks Retired (Program T)	Cars Retired (Program T)
GWP 100	934,688	23.3 MMT	434,542	5,029,339
GWP 20	934,688	96 MMT	1,789,797	20,714,899

*emissions for one year

Part IV Conclusions.

Between 2012 and 2030 there would be a 96 million metric ton CO_2e reduction (GWP_{20}) from retrofitting nearly one-million class 8 trucks in the U.S. with DPFs, the equivalent of eliminating the annual emissions of 21 million cars or 1.8 million class 8 diesel trucks (GWP_{20}).[38]

The retrofit benefit would persist for approximately a half century (Boucher).

CONCLUSIONS

The weight of evidence suggests that reductions in diesel black carbon emissions could play an important role in short-term climate mitigation:

- A review of the literature finds that fuel penalties associated with retrofit DPF applications range from zero as a best estimate to a few percent. The most comprehensive, controlled field study of 20 retrofit class 8 trucks that each ran 150,000 miles a year/vehicle suggests there may be no measurable fuel penalty associated with the DPF itself. This conclusion is also supported by an analysis of four years worth of fueling records, covering 1.28 million fleet miles, for 10 MTA New York City Transit buses that were retrofit with a DPF. If there is no fuel penalty then *all* the black carbon removed by the DPF benefits climate. Nonetheless, given the uncertainty across studies and to be conservative in this analysis, CATF assumed a 2 percent fuel penalty.
- CATF calculated a range of CO_2e values per gallon of fuel for a typical U.S. class 8 truck retrofit with a DPF based on a range of GWP and GTP values found in the scientific literature. Based on this analysis, and a review of the various metrics and how they were derived, we conclude Bond and Sun's (2005) black carbon GWP_{20} of 2,200 is defensible as a reasonable "best estimate" for use in calculating CO_2e benefits. However we report a range of results based on GWP_{20} and GWP_{100} values.
- Using the above assumptions, we found a GWP_{20} CO_2e benefit of about 2000 gCO_2e/gal for installation of a DPF on a typical U.S. class 8 truck assuming a fuel penalty of 2 percent. Alternately, based on GWP_{100} there is an approximate 500g CO_2e/gal benefit.
- A DPF retrofit is equivalent to eliminating the pollution from 6 passenger cars.
- Retrofitting six class 8 trucks with DPFs would be the equivalent of eliminating the pollution from one such pre-2007 truck (both CO_2 and black carbon emissions.) (21 retrofits based on GWP_{100})
- The installation of a DPF on a class 8 truck is likely to produce net climate benefits for approximately half a century assuming a 2 percent fuel penalty.
- Carbon dioxide reductions from a DPF retrofit on a class 8 truck will provide a CO_2e benefit as long as the increase in fuel use (fuel penalty) from the installation of the retrofit is less than 22 percent (based on GWP_{20}) or 7 percent (based on GWP_{100}).
- Retrofitting nearly one-million class 8 trucks in the U.S. with DPFs between 2012 and 2030 would provide the total equivalent carbon dioxide reduction of 96 million metric ton CO_2e (GWP_{20}) (23 million metric ton CO_2e reduction based on GWP_{100}) –equivalent to eliminating the annual emissions of 21 million cars or 1.8 million class 8 diesel trucks (for one year).
- An analysis by Olivier Boucher of the U.K. Hadley Centre on behalf of CATF suggests that the benefits of a proposed class 8 truck retrofit program would last a half-century with only a minimal residual net warming as a result of increased DPF-related fuel use.

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