Quantifying the Emission Benefits of Opacity Testing and Repair of Heavy-Duty Diesel Vehicles

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The objective of this study was to begin to quantify the benefits of a smoke opacity-based (SAE J1667 test) inspection and maintenance program. Twenty-six vehicles exhibiting visible smoke emissions were recruited: 14 pre-1991 vehicles and 12 1991 and later model year vehicles. Smoke opacity and regulated pollutant emissions via chassis dynamometer were measured, with testing conducted at 1609 m above sea level. Twenty of the vehicles were then repaired with the goal of lowering visible smoke emission, and the smoke opacity testing and pollutant emissions measurements were repeated. For the pre-1991 vehicles actually repaired, pre-repair smoke opacity averaged 39% and PM averaged 5.6 g/mi. NO_x emissions averaged 22.1 g/mi. After repair, the average smoke opacity had declined to 26% and PM declined to 3.3 g/mi, while NO_x emissions increased to 30.9 g/mi. For the 1991 and newer vehicles repaired, pre-repair smoke opacity averaged 59% and PM averaged 2.2 g/mi. NO_x emissions averaged 12.1 g/mi. After repair, the average opacity had declined to 30% and PM declined to 1.3 g/mi, while NO_x increased slightly to 14.4 g/mi. For vehicles failing the California opacity test at >55% for pre-1991 and >40% for 1991 and later model years, the changes in emissions exhibited a high degree of statistical significance. The average cost of repairs was $1088, and the average is very similar for both the pre-1991 and 1991+ model year groups. Smoke opacity was shown to be a relatively poor predictor of driving cycle PM emissions. Peak CO or peak CO and THC as measured during a snap-acceleration were much better predictors of driving cycle PM emissions.

Introduction

A number of states have been concerned about the contribution of heavy-duty diesel vehicle (HDDV) emissions to emission inventories. This is because HDDVs are important sources of fine particulate matter (PM) and nitrogen oxide (NO_x) air pollutants (*1*, *2*). Fine carbon or primary PM can lead to reduced visibility (*3*, *4*), and potentially mutagenic and carcinogenic polycyclic aromatic hydrocarbons (PAH) are associated (*1*, *5*) with these respirable particles (*6*−*9*). Gas-phase toxics such as formaldehyde are also emitted. The U.S. Environmental Protection Agency (U.S. EPA) has proposed new national ambient air quality standards for $PM_{2.5}$. Nitrogen oxides contribute to the formation of visibility-reducing and respirable secondary PM (*10*) as well as ground-level ozone (*11*). Furthermore, a broad spectrum of other organic compounds can also be found in the gaseous fraction of diesel exhaust (*1*, *12*).

To limit or reduce pollutant emissions from diesel vehicles, the U.S. EPA regulates both the quality of on-road diesel fuel and the pollutant emission levels from engines under the authority of the Clean Air Act. Additionally, smoke opacity tests are used by many states as part of inspection programs for control of PM emissions. Opacity is defined as the percentage of light transmitted from a source that is prevented from reaching a light detector. In smoke opacity measurements from a diesel vehicle, a beam of light is transmitted across the exhaust plume to a light detector. High opacity may indicate engine malfunction and increased emissions of air pollutants, primarily unburned fuel hydrocarbons (emitted as an aerosol) or soot particles (*13*). It is well-known that diesel engine malfunction or maladjustment can result in increased emissions of pollutants (*14*), and repair of high opacity emitters may therefore result in a decrease in the contribution of diesel vehicles to the pollutant inventory. The measured value of smoke opacity is highly dependent upon the test procedures, including ambient conditions, engine operating mode, measurement configuration, and instrumentation. In recent years, the SAE J1667 test procedure has been suggested as a standard test (*15*). This test was developed specifically to identify gross emitting heavy-duty trucks and buses.

To date, no study has quantified the actual emission benefits of smoke opacity testing. The objective of this study is to begin to quantify the benefits of a smoke opacity-based inspection and maintenance (I/M) program. To that end, a number of vehicles exhibiting visible smoke emissions were recruited. Smoke opacity and regulated pollutant emissions were measured. The vehicles were then repaired with the goal of lowering visible smoke emissions, and the smoke opacity testing and pollutant emissions measurements were repeated. Because of cost and time limitations and because relatively few vehicles exhibit high opacity, no effort was made to test a representative sample of the in-use heavy-duty vehicle fleet in Colorado. Instead, all vehicles emitting visible smoke that could be obtained during the time period of the study were tested.

The study was conducted in Denver, CO, at 1609 m above sea level. At this altitude, the barometric pressure is typically 82.6 kPa versus 98.9 kPa at sea level. This change in altitude has been estimated to increase engine transient test PM emissions by from 50 to more than 100% in several studies (*16*−*18*). During short duration accelerations, engine mechanisms that sense air pressure may not adequately compensate for the reduced air density at altitude, leading to a decrease in air/fuel ratio and increased emissions of PM. Maximum speed in the snap-acceleration test cycle is reached in 1−1.5 s, leading to similarly low air/fuel ratio and increased smoke opacity at altitude. The SAE has recommended that a correction factor be applied to smoke opacity measured on the J1667 test conducted at high altitude (*15*). The calculated correction is quite large for typical values of dry air density

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TABLE 1. Properties of Vehicles Tested

vehicle no.	mileage (mi)	GVW (lb)	test weight	model year	engine model	engine family	engine hp	vehicle use
1999-1	86 671	25 000	20 000	1995	Navistar X4L	SNV466D6DARA	190	rental
1999-2[a]	33 649	34 000	28 000	1988	DDC 6V-92	JDD0552FZG8	350	bus
1999-3	112 436	50 000	35 000	1986	Caterpillar 3208	GCT0636DAA2	210	delivery
1999-4[a]	129 345	50 000	39 000	1987	Caterpillar 3208	E6HT-6007-FH	215	delivery
1999-5	160 817	80 000	39 000	1989	Cummins NTC315	G93E	315	class 8
1999-5[b]	160 817	80 000	39 000	1989	Cummins NTC315	G93E	315	class 8
1999-6	99 024	50 000	39 000	1986	Caterpillar 3208	GCT0636DAA2	210	delivery
1999-7	116 004	50 000	39 000	1986	Caterpillar 3208	GCT0636DAA2	210	delivery
1999-8	122 360	80 000	52 000	1990	Cummins NTC315	093E	315	class 8
1999-9	23 519	32 000	26 000	1989	International DT466	unknown	210	school bus
1999-10	191 525	80 000	52 000	1989	Cummins NTC315	093E	315	class 8
1999-10[c]	191 525	80 000	52 000	1989	Cummins NTC315	093E	315	class 8
1999-11	128 292	50 000	39 000	1987	Ford 8000	HFM07-8FPA3-01	210	delivery
1999-12	119 280	54 000	43 000	1987	International DT466	unknown	210	delivery
1999-13[a]	52 031	42 000	30 000	1994	International DT466	unknown	250	delivery
1999-14	83 000	54 000	39 000	1990	Cummins LTA10	unknown	240	delivery
1999-15[a]	47 511	50 000	39 000	1993	Cummins C8.3	413C	210	delivery
1999-16	131 349	50 000	39 000	1989	Ford	KEM708FPD1	210	delivery
1999-17	125 127	50 000	39 000	1989	Ford	KFM078FD1	210	delivery
2000-1	108 490	30 000	22 244	1995	Cummins B5.9	SCE359D6DAAA	210	box truck
2000-2	43 151	15 000	12 500	1994	GMC 6.2L	RGM6.5C6DAA	190	flat bed
2000-3	36 872	16 000	13 715	1998	Cummins B5.9	WCEXH0359	175	step van
2000-4	50 319	16 000	13715	1999	Cummins B5.9	unknown	175	step van
2000-5	84 039	16 000	13 715	1997	Cummins B5.9	TCE359D6DARW	160	step van
2000-6	189 155	11 050	11 625	1991	Isuzu 4BD2TC	NSZ0235FAAX	135	box truck
2000-7[d]	145 596	15 000	12 500	1995	GMC TSA6.5L	RGM6.5C6DAA	190	box truck
2000-8	162 005	62 000	52 000	1992	Cummins L10	unknown	250	garbage
2000-9[a]	106 567	60 000	37 310	1996	Cummins M11	TCE661EJDARB	280	class 8

[a] Vehicles rejected after initial tests because of low smoke opacity. [b] Vehicle 5 was repaired and tested twice. [c] Vehicle 10 was repaired and tested twice. [d] Vehicle not tested after repair because the owner could not make it available.

encountered at Denver. A vehicle whose measured smoke opacity at Denver exceeds 70% points would have an "adjusted" smoke opacity at reference conditions (0.0755 lb/ft^3 air density) of around 40%.

Recently the U.S. EPA has recommended that the states use smoke opacity failure points developed by the State of California (55% for pre-1991 and 40% for 1991 and newer engines) to ensure uniformity across state lines (*19*). In a 1997 analysis performed for the California Air Resources Board (CARB), EEA and CARB reviewed the diesel I/M programs currently in place in the United States (*20*). Many other states were using or planning to use the 55/40% points. In some states there are random roadside smoke inspections while others require the opacity test annually as a part of vehicle registration. Additionally, some states merely require vehicles that fail to be repaired while others issue a fine in addition to requiring repair.

Very little information is available on the performance of HDDV I/M programs other than failure rates. For the California program in place before 1997 (a snap-acceleration with smoke opacity measurement by SAE 1243 procedure), the failure rate was 34% from spring of 1989 through autumn of 1991 but declined to 18.5% in 1993 (*20*). This decline was presumably caused by vehicle owners repairing their vehicles to avoid being cited and fined. The current California opacity program experiences a failure rate of about 8% (for the HDVIP in March 2000; *21*). NESCAUM (Northeast States for Coordinated Air Use Management) performed a pilot study of SAE J1667 during 1996 (*22*). On the basis of a sample of 781 heavy-duty vehicles, the failure rates (at 40/55%) were 4% for 1991 and later model years and 25% for pre-1991 model years.

There appear to be no studies of the impact of I/M programs on actual pollutant emissions from HDDVs. However, in the 1980s Ragazzi and co-workers conducted a study of the impact of an I/M program on emissions from light-duty diesel vehicles (LDDVs; *23*). Repair of these vehicles produced, on average, a 37% decrease in PM, a 50% decrease in CO, a 34% decrease in HC, and a 21% increase in emissions of NO_x. Several of the vehicles actually exceeded the NO_x standard after repair. While the NO_x increase was not discussed in depth, this is apparently a manifestation of the well-known NO_x/PM tradeoff where factors (such as injection timing) that decrease PM cause an increase in combustion temperature and hence emissions of NO_x. At least two studies of light-duty IM240 programs have also shown NO_x increases following repair of high CO-emitting gasoline automobiles (*24*, *25*).

A number of different engine malfunctions can cause retarded or delayed injection timing, which would increase PM emissions while decreasing NO_x (*26*). These include fuel pump and injector wear as well as tampering with pump settings and smoke-limiting throttle controls. Other malfunctions and maladjustments can apparently have the same result, as was demonstrated by Ullman and co-workers (*14*). In their study, two 1979 model year engines were tested with various maladjustments including increased intake air restriction, intake air leak, improperly set injector lash, disabling of throttle delay, and injection timing retard. One engine was tested new and with a set of fuel injectors that had accumulated 50 000 mi of service in a city bus. All maladjustment configurations produced a doubling in PM emissions and a decrease in NO_x emissions of roughly 25–30%. In a second study, Ullman and Human examined maladjustment of a 1986 transit bus engine (*27*). Retarded fuel injection timing, increased intake air restriction, and reduced throttle delay all resulted in a decrease in NO_x emissions. All of these studies taken together indicate that diesel engines deteriorate with use to have higher PM emissions but generally lower NO_x emissions.

Methods

Vehicles Tested. Table 1 lists the properties of the 26 vehicles recruited: 14 pre-1991 and 12 of 1991 and later model year.

The only criterion for vehicle selection was the emission of visible levels of smoke during acceleration; no attempt was made to test a fleet representative of in-use smoking vehicles. Thus, the study results cannot be directly applied to inventory calculations of the impact of smoke opacity testing and repair.

Five vehicles were rejected for repair after initial testing as not being acceptable candidates (smoke opacity too low and reasonably low emissions), but emissions results are included for comparison. Two vehicles, nos. 1999-5 and 1999-10, were repaired twice with emissions testing after each repair. These vehicles both had high smoke opacity and PM emissions, and initial repairs were not successful at reducing emissions. Vehicle no. 2000-7 could not be made available for final testing in a timely manner and so was not tested following repair.

Decisions regarding what repairs to perform were largely left to shop technicians. However, repair shops were requested to use the following sequence of checks in order to determine the cause of smoke:

(i) Intake air restriction or malfunctioning turbocharger.

(ii) Malfunctioning or maladjusted throttle controls.

(iii) Fuel pump or fuel injector malfunction or maladjustment.

No fixed limit to repair costs was used. Reduction of the smoke opacity for many of the vehicles required replacement of all fuel injectors, which typically cost in excess of $1500.

Smoke Opacity Testing. Snap-idle tests were performed with the warmed-up vehicle in neutral using a Wager Digital Smoke Meter, model 6500. The accelerator is rapidly pushed to the floor held there for 5 s or until the engine reaches maximum (governed) speed, while smoke opacity is measured. The maximum opacity observed is reported. For the SAE J1667 test, three practice tests are first performed. This is followed by three real tests, which are averaged to obtain the reported value. The three tests must meet an allowable spread criterion, and the percentage of smoke opacity is corrected for stack diameter using an extinction coefficient specific to the instrument. The correction factor for ambient temperature, humidity, and barometric pressure specified in the J1667 procedure was applied.

Chassis Dynamometer Testing. The chassis dynamometer system employed in this work has been described in detail in previous publications (*28*, *29*). The system is suitable for operating at vehicle speeds up to 60 mph (97 km/h) at up to 52 000 lb (23 586 kg) vehicle inertial weight. Inertia is simulated mechanically using flywheels, while wind and road friction are simulated electrically. The vehicle is driven on twin 40-in. rolls. The driver manages the vehicle speed. The cycle is displayed for the driver using a driver's aid prompt that shows the driver his current speed and approximately 30 s into the future so he can anticipate shifting. For quality control purposes, $\pm$2 mph error bands are displayed for the heavy-duty driver. This study used the Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (*30*), except for vehicle 1999-2 (a transit bus), which was tested using the Central Business District Cycle (*31*).

All testing was performed using certification diesel fuel obtained from Phillips Chemical Company. While five different lots of certification diesel were used over the course of the study, every vehicle was tested before and after repair on fuel from the same lot. The fuel lots employed were W-642, D434, 9CP05201, 9HP5202, and 0KP05202.

Emissions Measurement. The system for emissions measurement includes supply of conditioned intake and dilution air, exhaust dilution system, and capability for sampling of particulate and analysis of gaseous emissions. All components of the emissions measurement system meet the requirements for heavy-duty engine emissions certification testing as specified in Code of Federal Regulations 40, Part 86, Subpart N.

Engine and Dilution Air. Engine intake and dilution air are supplied to the chassis test cell through a conditioning system at 77 $\pm$ 9 °F at 0 $\pm$ 0.5 in. of water column. The air is filtered to ASHRAE 80% minimum. Humidity is controlled to produce a NO_x humidity correction factor of 1 $\pm$ 0.03. Humidity is measured continuously in the conditioned air inlet by two independently calibrated methods: a dew point meter and a polymer membrane sensor. The relative humidity obtained is converted to absolute humidity using the intake air temperature.

The emissions measurement system includes an 18-in. dilution tunnel for exhaust conditioning. Engine exhaust and dilution air are mixed at the tunnel inlet with a typical dilution ratio of 20 (dilution ratio varies in a narrow range with the size of the engine being tested). Exhaust emission samples are removed through a secondary sampler to the emission bench 10 tunnel diameters downstream. The total flow is controlled with a critical flow venturi (CFV) system. A centrifugal blower provides suction.

Gaseous Emissions Measurement. A Pierburg emissions bench provides total hydrocarbon from a heated FID, NO_x from a chemiluminescence analyzer (CLA), and CO and CO_2 from infrared detectors. All instruments meet or exceed CFR (Title 40, Part 86, Subpart N) requirements for response and accuracy. The gas analysis bench is calibrated against U.S. EPA protocol gases. NO_x and hydrocarbon analyses are performed on wet gas while the CO and CO_2 analysis is for a dried gas sample.

Gas samples are also collected in an automated bag sampler through a small sampling CFV rated at about 5 L/min and maintained at the same temperature and pressure as the main exhaust CFV to ensure proportionality. The sample line is equipped with a Balston filter to remove particulate matter and most of the water in the sampled gas. The bag sampler gives an integral average emission directly. Dilution air is also collected in the bag sampler system. Correction for background emissions is performed using the dilution air analysis.

Particulate Matter Sampling. Particulate matter is sampled in a Pierburg secondary dilution tunnel with sampling temperature maintained below 52 °C. Particulate is proportionally collected in filtering units equipped with two filter coupons in series. The particulate weighing is conducted in a temperature and humidity controlled room meeting CFR specifications. The weighing room is kept at a temperature of 71 $\pm$ 1 °F, a nominal relative humidity of 50%, and a dew point of 48 $\pm$ 3 °F. Weighing is accomplished on a Sartorius R200D semimicro-balance meeting CFR specifications. The loading of particulate on the filter coupons ranged from 1 to 8 mg, depending upon vehicle and test cycle.

Results and Discussion

Smoke Opacity. The study was performed in two phases during 1999 (phase 1) and 2000 (phase 2). Smoke opacity (via SAE J1667) test results are reported in Tables 2 and 3, respectively, for each phase. Also noted are visual observations regarding smoke (i.e., if the vehicle was a white smoker) and a very brief description of repairs made to the engine. Nine of the 26 vehicles emitted white smoke. Of the pre-1991 vehicles, four would have failed the California I/M test level of 55%. Other pre-1991 vehicles that were repaired exhibited visible smoke at lower opacity levels. Of the 1991+ model year vehicles, five failed the opacity cutpoint of 40% used in California.

In most cases repair resulted in an apparent reduction in opacity, although not always to a passing level. For several of the vehicles, additional repairs were probably needed in order to pass the opacity test, but this could not be done because of cost and demands of the vehicle owners for return of their vehicles.

TABLE 2. Average Emissions and Fuel Economy for Phase 1 Vehicles before and after Repair (g/mi)

vehicle no.	pre/post repair	smoke opacity (%)	THC (g/mi)	NO_x (g/mi)	CO (g/mi)	PM (g/mi)	mpg	comments
1999-1	pre	72	43.6	15.3	28.9	5.29	5.32	black and white smoke
1999-1	post	11	2.4	15.4	12.3	1.18	6.11	replace one injector
1999-2	nr	6	1.0	44.3	24.4	1.59	3.61	
1999-3	pre	21	2.2	41.7	26.8	3.61	5.56	black smoke
1999-3	post	8	2.8	35.1	54.5	4.58	5.37	broken throttle pedal, reset pump timing
1999-4	nr	8	1.5	29.8	14.8	2.33	5.09	
1999-5	pre	82	2.7	20.4	58.8	6.99	4.39	black and white smoke
1999-5	post	77	2.2	21.5	44.5	5.84	4.54	6 new injectors, black smoke
1999-5	2nd post	29	2.2	26.1	22.4	3.25	4.49	new fuel pump
1999-6	pre	13	1.3	25.3	42.3	5.14	5.40	low level of black smoke
1999-6	post	7	1.2	32.9	54.6	4.43	5.36	major tune up, pump timing
1999-7	pre	13	0.8	15.8	37.5	6.82	4.84	low level of black smoke
1999-7	post	13	1.2	29.8	55.6	5.00	5.09	major tune up
1999-8	pre	76	2.4	19.1	73.7	9.98	4.19	black and white smoke
1999-8	post	34	2.8	24.3	15.3	2.64	4.00	reset tampered fuel pump
1999-9	pre	19	1.6	16.6	17.0	2.32	6.70	low levels of black smoke
1999-9	post	23	2.1	36.8	21.3	2.01	5.57	new injectors, rebuild fuel pump
1999-10	pre	59	60.2	28.2	79.4	16.4	3.95	black and white smoke
1999-10	post	36	58.9	26.2	79.2	15.5	3.97	replace fuel pump
1999-10	2nd post	33	2.8	25.4	20.2	5.39	4.04	replace one fuel injector
1999-11	pre	31	1.1	25.7	17.6	2.56	5.18	low level of black smoke
1999-11	post	35	1.6	54.1	26.2	1.86	5.21	fuel pump, overhead, governor control
1999-12	pre	31	1.8	26.6	41.2	4.69	4.48	black and white smoke
1999-12	post	30	1.3	29.7	38.9	3.98	5.05	replace injectors
1999-13	nr	11	0.36	13.6	8.1	1.08	5.77	
1999-14	pre	76	7.5	14.3	18.6	3.62	5.11	black and white smoke
1999-14	post	49	4.4	21.4	17.2	2.32	5.05	new injectors and camshaft
1999-15	nr	4	0.96	14.5	3.2	0.89	5.58	
1999-16	pre	30	1.4	16.6	15.3	2.68	4.90	black smoke
1999-16	post	25	1.4	26.3	14.7	1.75	5.48	rebuilt throttle linkage
1999-17	pre	21	1.4	15.2	13.1	2.00	5.10	black smoke
1999-17	post	24	1.1	29.2	18.3	2.03	4.88	set pump timing, repair throttle linkage

[a] nr,=not repaired.

TABLE 3. Average Emissions and Fuel Economy for Phase 2 Vehicles before and after Repair (g/mi)

vehicle no.	pre/post repair	smoke opacity (%)	THC (g/mi)	NO_x (g/mi)	CO (g/mi)	PM (g/mi)	mpg	comments
2000-1	pre	31	0.33	13.81	8.94	1.59	7.04	very large volume of white smoke
2000-1	post	31	0.22	14.27	6.10	1.06	7.04	replace fuel injectors and thermostat
2000-2	pre	82	0.98	6.62	24.44	2.78	9.99	very heavy black smoker
2000-2	post	40	0.08	5.88	3.66	0.77	10.76	replace fuel injectors
2000-3	pre	37	0.27	13.34	6.46	0.52	9.50	black and white smoke
2000-3	post	8	0.23	13.36	5.46	0.44	9.58	replace cracked intercooler
2000-4	pre	41	0.32	11.72	5.64	0.70	9.54	moderate black smoke
2000-4	post	12	0.35	11.65	4.79	0.44	9.54	moderate adjustment to fuel pump
2000-5	pre	33	0.31	11.39	5.41	0.35	10.25	black and white smoke
2000-5	post	10	0.27	11.05	6.27	0.50	10.32	replace fuel injectors, pressure release valve
2000-6	pre	70	0.23	4.94	10.15	1.46	11.42	very heavy black smoke
2000-6	post	57	0.13	4.84	6.21	0.96	11.62	replace fuel injectors, recalibrate fuel pump
2000-7	pre	38	0.19	5.35	6.50	0.95	10.65	moderate black smoke
2000-8	pre	80	3.52	26.45	61.93	6.17	3.38	heavy black smoke
2000-8	post	69	2.24	38.56	73.72	4.76	3.32	replaced fuel injectors
2000-9	nr[a]	11	0.28	14.13	27.26	2.71	5.08	low smoke, vehicle rejected

[a] nr,=not repaired.

Regulated Emissions. Table 2 reports average regulated emissions and fuel economy for each phase 1 vehicle before and after repair, and the same results are reported in Table 3 for phase 2 vehicles. Raw data can be obtained from the study final report (*32*). Table 4 reports average emission values for all of the vehicles in this study by the two opacity cutpoint model year ranges, both before and after repair. For comparison, average emission values from the Northern Front Range Air Quality Study (NFRAQS; *28*) and average emission values from a recent review of all heavy-duty vehicle emissions data (*33*) are included. This later study included data for on the order of 100 trucks. Both of the studies are believed to include almost entirely data for properly functioning vehicles, although this cannot be proven.

The vehicles in both model year groups have PM, THC, and CO emissions well above the averages from the earlier studies. The pre-1991 vehicles examined in this study are on average likely to be high PM emitters with an average of more than 5 g/mi as compared to 2.8 g/mi for NFRAQS and 2.0 g/mi for vehicles covered in the review. Average PM emissions from the 1991 and later vehicles are also more than two times higher than the average values from the

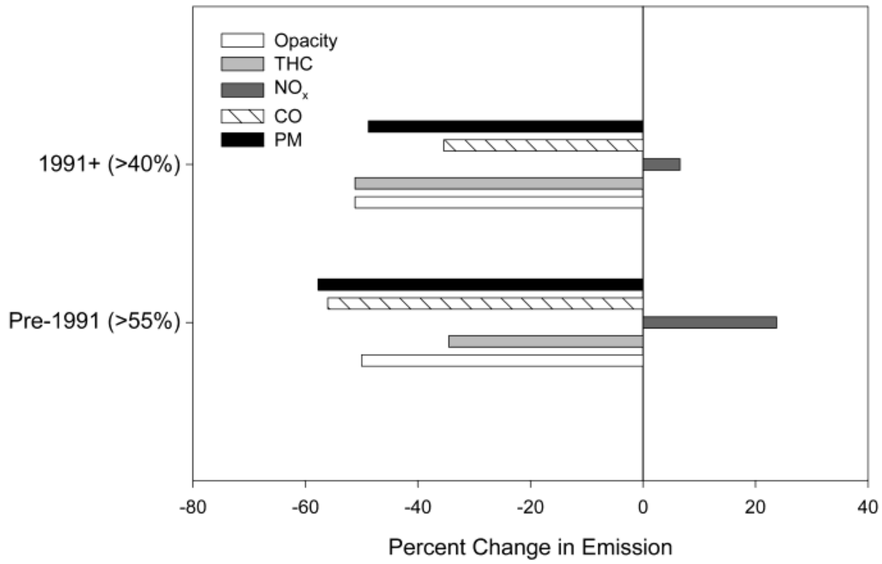

FIGURE 1. Average percent change in opacity and g/mi emissions after repair for failure points of 55% (pre-1991) and 40% (1991 and later). Failing vehicles only.

TABLE 4. Average Emissions Levels from This Study Compared with Other Studies

	smoke opacity (%)	THC (g/mi)	NO$_x$ (g/mi)	CO (g/mi)	PM (g/mi)
Pre-1991					
repaired vehicles (pre)	39	7.0	22.1	36.8	5.6
repaired vehicles (post)	26	2.1	30.9	29.9	3.3
1991 and Later					
repaired vehicles (pre)	59	5.5	12.1	17.6	2.2
repaired vehicles (post)	30	0.74	14.4	14.8	1.3
NFRAQS Study (*28*)					
pre-1991	36	2.3	23.2	30.1	2.8
1991 and later	22	0.77	18.4	9.4	1.0
Review Study (*33*)					
pre-1991		2.6	28.1	15.1	2.0
1991 and later		1.2	25.9	9.0	1.0

previous studies. Emissions from the 1991 and later model year vehicles are on average much lower than for the older vehicles. In part this is because the vehicles are newer. However, these vehicles are on average much lower gross vehicle weight and hence lower horsepower, which also leads to lower grams per mile emissions.

Four of the pre-1991 vehicles failed the 55% failure point used in California and recommended by the U.S. EPA. The average change in emissions for this group of opacity test failing vehicles is shown in Figure 1. Apparent benefits in terms of reduced smoke opacity, PM, CO, and hydrocarbon emissions are observed. NO_x emissions appear to have increased by more than 20%. Additionally, five of the 1991+ model year vehicles exhibited greater than 40% opacity before repair, the failure point used in California and recommended by the U.S. EPA. The average change in emissions is shown in Figure 1, and this group also shows apparent benefits in reduced opacity, PM, CO, and hydrocarbon emissions. NO_x appeared to increase by about 6% for this group.

A statistical analysis of the data was performed to allow a determination as to whether observed differences in emissions after repair were significant. This analysis employed a two-sample *t*-test comparing mean emission before and after repair. The *t*-test tool in Microsoft Excel was used under the assumptions of equal variance, two tailed *t*-distribution, and hypothesized mean difference of zero.

TABLE 5. Significance of Emissions Changes after Repair Reported as *p* Value

vehicle no.	HC	NO$_x$	CO	PM	failing vehicles (%)
1999-1	0.0003	0.926	<0.0001	0.0001	>40
1999-3	0.015	0.0002	0.018	0.065	
1999-5	0.0200	0.0002	0.0420	0.0065	>55
1999-6	0.757	<0.0001	0.003	0.932	
1999-7	<0.0001	<0.0001	0.00063	0.075	
1999-8	0.018	0.267	0.051	0.076	>55
1999-9	0.085	0.0007	0.027	0.06	
1999-10	<0.0001	0.012	<0.0001	0.0067	>55
1999-11	0.012	<0.0001	0.0026	0.0087	
1999-12	0.06	0.0003	0.21	0.202	
1999-14	<0.0001	<0.0001	0.042	0.032	>55
1999-16	0.854	0.0006	0.482	0.0022	
1999-17	0.0069	<0.0001	0.024	0.845	
2000-1	0.089	0.051	0.138	0.316	
2000-2	0.018	0.044	0.0039	0.0045	>40
2000-3	0.119	0.683	0.274	0.545	
2000-4	0.121	0.775	0.28	0.134	>40
2000-5	0.013	0.41	0.202	0.022	
2000-6	0.0194	0.342	0.027	0.032	>40
2000-8	0.0057	<0.0001	0.178	0.094	>40
no. <1	16/20[a]	14/20	13/20	14/20	
no. <1, >55	4/4	3/4	4/4	4/4	
no. <1, >40	4/5	2/5	3/5	4/5	
avg	0.11	0.18	0.10	0.17	
avg failing >55	0.0095	0.070	0.034	0.030	
avg failing >40	0.0323	0.42	0.098	0.053	

[a] Numbers of vehicles for which $p < 0.1$ are noted as a fraction of the total number of vehicles in each group.

Results of this analysis are reported in terms of *p* value in Table 5. A low *p* value indicates a higher probability that the change in emissions was significant. For example, a *p* value of 0.01 corresponds to a significant change with 99% confidence. If we arbitrarily select 90% confidence as the significance level, about 75% of the repaired vehicles showed a significant change in emissions of all four criteria pollutants. All of the pre-1991 vehicles failing the opacity test exhibited significant reductions in emissions of HC, CO, and PM following repair. Two out of four of these vehicles exhibited a significant increase in emissions of NO_x while one exhibited a significant decrease. For the 1991+ vehicles, 4 out of 5 exhibited significant reductions in HC and PM, and 3 out of 5 exhibited a significant reduction in CO. NO_x emissions increased significantly for one and decreased significantly for a second one out of these 5 vehicles. Examination of the average *p* values for all 20 repaired vehicles indicates that, on average, changes in emissions after repair are significant with 80−90% confidence. However, this increases to greater than 90% confidence when the average is taken only for pre-1991 vehicles with greater than 55% opacity before repair, including a significant increase in NO_x emissions. For those vehicles failing the 1991 and later model year opacity cutpoint of 40%, changes in HC, CO, and PM were on average significant with greater than 90% confidence while the change in NO_x is not on average significant for this group as a whole.

It would be desirable to estimate the magnitude of the changes associated with a diesel I/M program. However, since a distribution function for J-1667 smoke opacity based on a large sample does not exist for the Colorado fleet, it is not possible to estimate how many vehicles an I/M program would impact.

Types of Repairs and Repair Costs. Excessive smoke is caused by operation at a fuel/air ratio above the smoke limit, and thus repairs typically involve components that affect fuel/air ratio. Virtually all repairs were to the injectors, fuel pumps, fuel pump calibration, and injection timing. Injection pump work was performed on 10 out of 20 engines. Eleven out of 20 engines had injectors replaced, of which 9 required replacement of all injectors. Injection timing and governor adjustment was the most common repair for pre-1991 vehicles, and injector replacement was the most common repair for 1991 and later vehicles. Three vehicles exhibited a maladjusted throttle linkage. There was also one replacement of a cracked intercooler. Repair costs ranged from $85 to $2053 with an average of $1088, including both repairs as a single cost for the vehicles that were repaired twice. Average repair cost for the pre-1991 opacity test failing group was $1202 and for the 1991+ opacity test failing group was $991.

Comparison to NO_x Emission Standards. NO_x emissions were observed to increase for 12 of the 20 repaired vehicles. To understand the cause of this increase, it is useful to compare the observed NO_x emissions to the NO_x standard in effect for each model year. Engine certification testing is performed on an engine dynamometer, and emissions are reported in units of grams of pollutant emitted per unit work (g/bhp-h). To compare vehicle emissions with the emissions standards, which are likewise in g/bhp-h, a method for converting the g/mi emissions to g/bhp-h is needed. The conversion of vehicle emissions in grams per mile to engine emissions in units of grams per bhp-h can be performed on a fuel consumption basis using eq 1:

$$\text{g/mi} = \frac{\text{g}}{\text{bhp-h}} \times \frac{\text{bhp-h}}{\text{g-fuel}} \times \frac{\text{g-fuel}}{\text{mi}} \tag{1}$$

The term g-fuel/bhp-h is the engine brake-specific fuel consumption (BSFC). The BSFC for new engines over the engine transient cycle is available from the manufacturers, as measured from the certification test. In general, the presence or absence of malperformances alters the BSFC by less than ±5% unless the malperformance is very severe.

A comparison of measured NO_x emissions, converted to g/bhp-h using eq 1, with the emissions standards is shown in Figure 2. For the pre-1991 vehicles, all but one was below the NO_x standard before repair, and all but one vehicle (a different one) was below after repair. Vehicle 1999-3 had high NO_x emissions (above the standard) before repair, and the injection timing may have been set incorrectly for the vehicle as received. Adjustment of timing resulted in decreased NO_x and increased PM emissions. Vehicle 1999-11's repairs also involved changing or resetting injection timing and it is possible that timing was set inaccurately resulting in the high g/bhp-h NO_x emissions. NO_x emissions were 54 g/mi (281 g/gal) after repair for this vehicle. These values are very high in comparison to other heavy-duty vehicles of this vintage (*33*). For the 1991 and later model year vehicles on average, pre and post repair NO_x emissions are near the standard, although the 1998 and 1999 model year vehicles fall slightly farther above the line. The increase in NO_x emissions for these newer vehicles is smaller and not evident in every case. Since BSFC is a function of speed and load, using an average value to estimate emissions is only an approximation. Additionally, it is not known if the emissions certification for any of these engines included any allowance for emissions banking or trading. Even with these considerations, the results suggest that in many cases repair results in an increase in NO_x, but to levels that are still near or below the standards for the engine's model year.

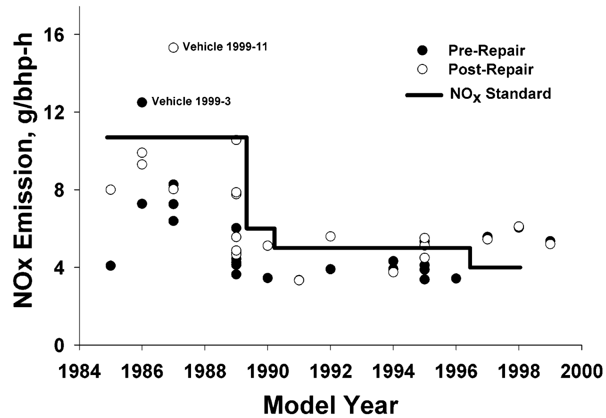

FIGURE 2. Brake-specific NO_x emissions before and after repair as compared to the NO_x emission standards.

The policy and regulatory implications of the observed NO_x increase are not clear at this time. The U.S. EPA pollutant inventory models do not consider emissions deterioration for heavy-duty diesels, so these models are already counting the increased NO_x emissions that would result from a widespread opacity based I/M program. However, in some urban areas the increase in actual NO_x, as opposed to model-predicted NO_x, could have a significant impact on air quality and lead to violation of the National Ambient Air Quality Standards for ozone and fine particles. Both the U.S. EPA's guidance document and all current diesel I/M programs are based on the belief that repair of high opacity vehicles will have only air quality benefits. Given data that this is not the case, it is recommended that deterioration be incorporated into inventory models and that these models be used to determine the overall air quality impact of diesel I/M. A great deal of additional data will clearly be required to model deterioration accurately.

Prediction of High PM Emitters. Early work on smoke opacity found some correlation between smoke and PM emissions. McGuckin and Rykowski (*34*) observed good correlation when comparing smoke opacity with steady-state emissions of PM. Alkidas (*35*) found that Bosch smoke number correlated reasonably well with total PM but that the correlation was better with the nonvolatile (soot) fraction of PM. A comparison of smoke opacity and PM emissions is presented in Figure 3. The data from this study has been combined with results from two previous studies (*28*, *36*) of properly functioning vehicles in order to examine the correlation between smoke opacity and PM emissions and to examine the potential for using other measurements to predict what vehicles are high PM emitters. Note that these previous studies used uncorrected opacity (not corrected for ambient temperature, humidity, or barometric pressure), and thus Figure 3 includes uncorrected opacity results from this study as well.

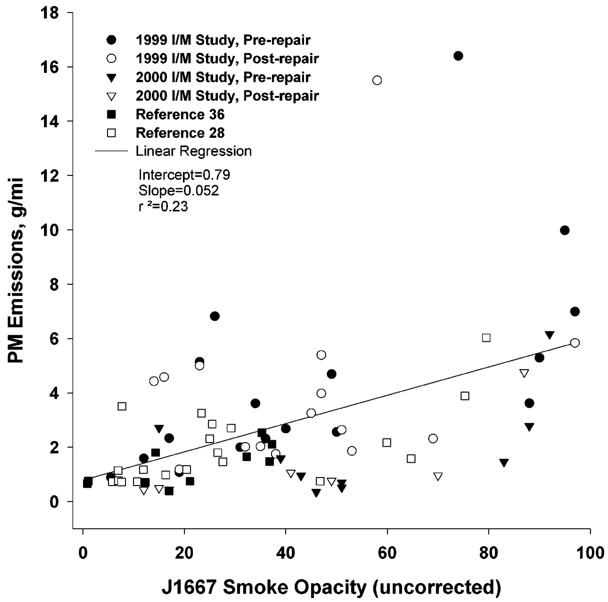

FIGURE 3. PM emissions as a function of smoke opacity for this study and two previous studies.

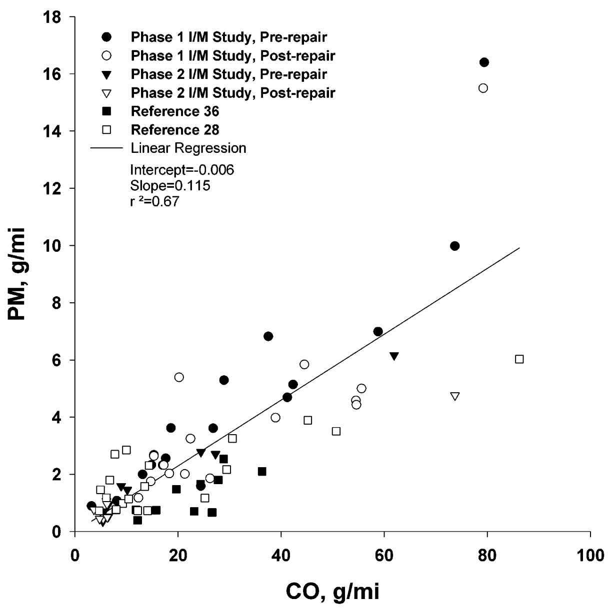

FIGURE 4. Correlation of PM and CO emissions.

Clearly there is a relationship between PM and smoke opacity, although smoke opacity is not a particularly good predictor of PM emissions ($r^2 = 0.23$, note that removal of the two >14 g/mi PM points increases r^2 to 0.40). For the results of this study only, r^2 values are about 0.1 for both uncorrected and corrected opacity. Examining pre-repair data from this study only, smoke opacity is still a poor predictor of PM emissions with an r^2 of 0.21. The fact that several vehicles with relatively high PM emissions exhibit low smoke opacity indicates that smoke opacity measurements may fail to identify all high emitters. One reason for this is probably emission of white smoke, which is primarily unburned fuel. White smoke is typically caused by fuel pump or fuel injector malfunctions but can also be caused by disabled or malfunctioning throttle controls.

Figure 4 compares CO and PM results from this study along with results from the previous studies. For all of the data taken together (pre- and post-repair), there is a reasonably good correlation ($r^2 = 0.67$, p value on slope much less than 0.01). However, considering only the pre-repair data from this study, r^2 improves to 0.85 and the coefficient for CO is significant at well above the 99% confidence level (p value much less than 0.01). Hydrocarbon emissions are a slightly better predictor of PM emissions than smoke opacity ($r^2 = 0.48$, $p < 0.01$); however, correlation of PM emissions with both CO and hydrocarbon produces an r^2 of 0.94 with highly significant coefficients for both independent variables. Thus, CO and hydrocarbon emissions for driving under load can be an excellent predictor of PM emissions.

For diesel inspection and maintenance purposes, CO and hydrocarbon emissions while driving a cycle under load may not be obtainable because of high testing equipment capital and operating costs. Measurement of CO and hydrocarbon during the snap-acceleration (as performed for smoke opacity measurement) would be a much easier measurement to make in the field. During the phase 2 study, concentrations of gaseous pollutants were monitored during snap-accelerations. To accomplish this, the snap-accelerations were performed repeatedly while the vehicle exhaust was connected to the dilution tunnel. Results for regression of UDDS cycle PM emissions as a function of snap-acceleration peak THC and CO emissions indicate that peak CO is a reasonable predictor of PM emissions ($r^2 = 0.74$, p value < 0.01) and multiple regression of both snap-CO and -THC is even better ($r^2 = 0.86$, p value < 0.01). Use of either CO or CO and THC from a snap-acceleration test has significantly better predictive capability for high PM emitters than does smoke opacity for the vehicles examined in this study.

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