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2007 Diesel Emissions Impact on Indoor Air Quality

FAMA Chassis Technical Committee
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Heavy Duty Diesel Engine Emissions Regulations

History

Since 1973, the Clean Air Act administered by the EPA has imposed regulations on diesel engines to reduce exhaust emissions. The following chart shows how significantly tailpipe emissions limits have been tightened over the past 17 years.

EPA Heavy-Duty Engine Emission Standards

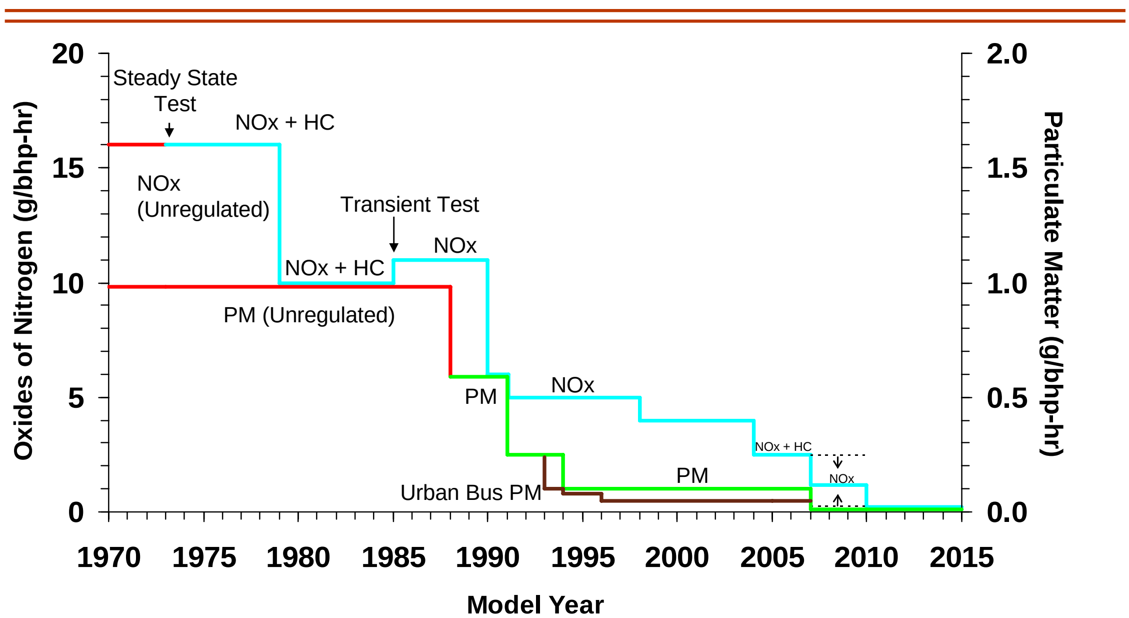

Figure 1

2007 Emissions Limits

The 2007/2010 EPA regulations place limits on four main pollutants for diesel engines:

Oxides of Nitrogen (NOx) (2010)	0.2	gm/bhp-hr
Non Methane Hydrocarbons (NMHC)	0.14	gm/bhp-hr
Carbon Monoxide (CO)	15.5	gm/bhp-hr
Particulates	0.01	gm/bhp-hr

These limits can be found in the Code of Federal Regulations 40CFR§86.007-11. This code can be searched on the web at www.gpoaccess.gov/cfr.

Alternative Methods of Emissions Compliance

EPA rules allow the engine manufactures a phase-in period between 2007 and 2010 to meet the NO_x portion of the regulations.

During the phase-in period engine OEMs can meet the regulations using one of two methods:

1) Producing half of their engines at the 2006 limit of 2.5 gm/bhp-hr NO_x plus Hydrocarbons and the other half at the 2007 limit of 0.2 gm/bhp-hr NO_x.

2) Producing all engines at an average NO_x emission level between the two regulations (1.2 gm/bhp-hr).

Note that these alternate methods only apply to the NO_x portion of the regulations. Particulate matter emissions are limited to the .01 gm/bhp-hr regardless of the NO_x compliance method selected.

Visual Progress

The virtual absence of smoke emitted from the tailpipe of a 2007 engine demonstrates the impact of the regulations. A new white handkerchief placed in front of the tailpipe of a 2006 engine for 45 seconds will show a distinct black smudge. A 2007 engine will leave no mark on the handkerchief. (see figure 2).

Figure 2

Emissions Compliance Certification Data

It is important to recognize the distinction between the regulatory emission limits, and what the engines actually produce. In certain cases, engines might produce much lower emissions for a certain pollutant than the regulations require. Each engine manufacturer must perform emissions measurements using the prescribed methods, and submit the results to the EPA.

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Official test results are posted on the EPA website at www.epa.gov/otaq/certdata. The download lists the results submitted by the engine manufacturers that were used by the EPA to verify compliance to the 2007 standards.

Table 1 lists data for typical engines used in custom fire apparatus. Those engines with data in the NO_x + HC column use the 2006 NO_x compliance method. Those with data in the NO_x column use the NO_x averaging method.

Manufacturer	Test Model	Displacement	Rated HP	@ Rated RPM	@ Torque	@ RPM	Units	NOx + HC	NOx	PM	CO	NMHC/ OMNMHCE
Caterpillar Inc	C13	763 CID	525	1800	1750	1200	g/bHp-hr		1.000	0.000	1.600	0.000
Caterpillar Inc	C7	442 CID	350	2400	860	1600	g/bHp-hr		0.800	0.000	0.800	0.100
Caterpillar Inc	C9	567 CID	425	2100	1350	1400	g/bHp-hr		1.000	0.000	0.400	0.000
Caterpillar Inc	C9	567 CID	425	2100	1350	1400	g/bHp-hr		1.000	0.000	0.400	0.000
Caterpillar Inc	C9	567 CID	425	2100	1350	1400	g/bHp-hr		1.000	0.000	0.700	0.000
Caterpillar Inc	C9	567 CID	425	2100	1350	1400	g/bHp-hr		1.000	0.000	0.400	0.000
Cummins Inc.	ISC 330	505 CID	320	2200	1000	1400	g/bHp-hr		1.140	0.000	0.100	0.000
Cummins Inc.	ISC 360	505 CID	350	2200	1050	1400	g/bHp-hr		1.000	0.000	0.300	0.000
Cummins Inc.	ISL 330	540 CID	310	2100	1100	1300	g/bHp-hr		1.000	0.000	0.100	0.000
Cummins Inc.	ISL 365	540 CID	350	2100	1250	1400	g/bHp-hr		1.100	0.000	0.100	0.020
Cummins Inc.	ISL 425	540 CID	425	2200	1200	1300	g/bHp-hr	1.600		0.000	0.200	0.000
Cummins Inc.	ISM 330	661 CID	330	1800	1150	1200	g/bHp-hr	2.200		0.000	0.000	0.000
Cummins Inc.	ISM 370	661 CID	385	1800	1450	1200	g/bHp-hr	2.300		0.000	0.000	0.000
Cummins Inc.	ISM 450	661 CID	450	2000	1550	1200	g/bHp-hr	2.300		0.000	0.100	0.000
Cummins Inc.	ISM 500	661 CID	500	2000	1550	1200	g/bHp-hr	2.400		0.100	1.000	0.100
Detroit Diesel Corporation	Series 60, 14L	14.0 L	515	1800	1650	1100	g/bHp-hr		1.095	0.006	0.230	0.010
Detroit Diesel Corporation	Series 60, 14L	14.0 L	515	1800	1650	1100	g/bHp-hr		1.140	0.000	0.200	0.010
Detroit Diesel Corporation	Series 60, 14L	14.0 L	515	1800	1650	1100	g/bHp-hr		1.004	0.004	0.100	0.017

Table 1-Select Values from EPA Engine Certification Results

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Air Quality in the Workplace

OSHA Indoor Air Quality Regulations

Although no smoke is emitted from the tailpipe, potentially harmful substances are still present. Consult the Occupational Safety and Health Administration (OSHA) for interior air quality regulations.

OSHA regulations are found in 29CFR§1900.1000 and which can be accessed on the web at www.gpoaccess.gov/cfr. Some substances are given an 8-hour average exposure limit, while others are given a maximum ceiling that should never be exceeded (averaged over a 15 minute period in cases where instantaneous measurement is impractical). Among the compounds regulated by OSHA for an indoor business environment are:

Substance	Exposure Limit	
Nitrogen Monoxide (NO)	30 mg/m^3	(8 hour average)
Nitrogen Dioxide (NO_2)	9 mg/m^3	(ceiling)
Carbon Monoxide (CO)	55 mg/m^3	(8 hour average)
Particulates Not Otherwise Regulated (PNOR)		
Total Dust	15 mg/m^3	(8 hour average)
Respirable Fraction	5 mg/m^3	(8 hour average)

Oxides of Nitrogen (NO_x)

Nitrogen in its pure form (N_2) is stable at room temperature. It is the main ingredient in the air we breath, and is perfectly safe. At combustion chamber temperatures above 1350° F, however, the two nitrogen atoms disassociate and are free to combine with oxygen atoms to form nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Together these substances are known as oxides of nitrogen (NO_x) . Given time and in the presence of sunlight nitrogen monoxide combines with volatile organic compounds (VOCs) to form ozone (O_3). This is the reason the EPA imposes stringent limits on NO_x emissions.

Non Methane Hydrocarbons (NMHC)

Hydrocarbons mostly come from evaporation of fuel and oil in the crankcase, or as unburned constituents of the combustion process. Non Methane Hydrocarbons (NMHC) is a general term covering a range of hydrocarbon emissions. Approximately 2000 hydrocarbon compounds make up this mix. Beginning in 2007, diesel engines must control the NMHC emissions from both the crankcase and the combustion process.

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Cummins and Detroit Diesel accomplish the tailpipe component by adding a Diesel Oxidation Catalyst (DOC) in front of the Diesel Particulate Filter (DPF). This device oxidizes (burns) any hydrocarbons remaining in the exhaust stream before they reach the DPF. In some designs the engine actually adds hydrocarbons (diesel fuel) upstream of the DOC to raise the temperature of the gas before it reaches the DPF. Caterpillar controls tailpipe NMHC emissions using in-cylinder techniques.

Most large diesel engine manufacturers use some means of filtration to control the NMHC emissions from the crankcase. Some use mechanical filters, while others employ cyclone type devices.

For the purposes of this study, we reach no conclusion on the impact of NMHC emissions on indoor air quality because there is no direct correlation between the EPA regulations and a specific OSHA limit. The only general comment we can make is that emissions from on older engines are much higher than their 2007 counterparts.

Carbon Monoxide (CO)

Carbon Monoxide is a colorless, odorless gas that is toxic to humans. It is produced by the combustion process of both gasoline and diesel engines, but to a much lesser degree in diesels. The OSHA limit for 8 hour exposure is 55 mg/m^3. The EPA tailpipe limit for CO is 15.5 mg/bhp-hr, but actual diesel engines produce far less than this limit. This is why there has been much attention concerning the struggle to meet the NO_x and particulate regulations, but very little mention of carbon monoxide.

From Table 1, we can see that the highest CO level reported by the EPA during testing was 1.6 gm/bhp-hr on a 525 hp Caterpillar C13. If we use this worse-case value, our estimates will be conservative for all other engine makes and models.

Particulate Matter (PM)

Particulate Matter (PM) is composed of two general constituents: soot and volatile particulates. Soot is the carbon left over from the combustion process. It makes up 85% of the PM. In ideal complete combustion, there would be no soot. The remaining 15% of PM is the volatile fraction and is made up of sulfides and other components that condense (or solidify) as they are cooled while leaving the combustion chamber.

The EPA limit on 2007 and later diesel engines is 0.01 gm/bhp-hr. All 2007 diesel engines use a Diesel Particulate Filter (DPF) to trap particulate matter before it exits the tailpipe. DPF devices are so effective that the particulate matter emission levels in most EPA tests are not measurable (see Table 1).

OSHA does not set limits specifically on diesel particulate matter, but it does regulate two sizes of air-born particulates (dust and respirable fraction). To be conservative, we can use the EPA limit for PM, and compare it with the most stringent OSHA limit (that for respirable particles).

Estimating the Impact on Indoor Air Quality

Hypothetical Fire Apparatus Model

Although it is not a good practice to run internal combustion engines of any size inside any building, it is obviously necessary to run a vehicle's engine while pulling in and out of a garage. The extent to which a running vehicle will pollute the indoor environment depends on many factors, including the size of the garage and the degree of ventilation. Therefore to estimate the impact on indoor air quality of an idling engine we employ a number of generalized assumptions.

For the purpose of this study we will consider a hypothetical fire truck that occupies a rectangular volume 8 feet wide, 9 feet tall, and 40 feet long. The subject truck will be parked in a sealed garage that is 14 feet wide, 14 feet tall, and 50 feet long. The truck pulls into the station, the engine drops to idle, and the door is closed. The engine continues to idle at an average power consumption of 25 hp (to account for parasitic loads from engine friction and accessories).

Considering this hypothetical model, we can calculate the time required to reach the OSHA indoor air quality limits for some of the key substances regulated by the EPA. We will consider NO_2 emissions using the NO_x averaging method of compliance as an example calculation.

Begin by calculating the air volume in the garage, and subtracting the volume of the truck. This gives us the air remaining in the garage that will be contaminated as it is drawn through the engine and expelled back out the tail pipe. This is a conservative approach since the truck is not actually a solid rectangular volume, so our model under-estimates the total air volume.

Example: $(50\ ft)(14\ ft)(14\ ft) - (40\ ft)(8\ ft)(9\ ft) = 6920\ ft^3$
Equivalence in Meters: $196\ m^3$

Next we can calculate the mass of each substance that the engine must emit before there is enough in the garage air to reach the OSHA allowable limits. We do this by multiplying the OSHA limit in weight per volume of air by the volume of air in the garage.

Example: $(9\ mg/m^3)(196\ m^3) = 1764\ mg$
Equivalence in grams: 1.764 gm

The EPA limits are given as the rate of substance emitted per hour for each unit of power the engine produces. The specific rate of emission at our idle power can be determined by multiplying the EPA limit by the power that the engine is producing.

For oxides of nitrogen the test data only provides the sum total for both NO and NO_2. Engine manufacturers suggest that a good estimate at idle would be 80 percent NO and 20 percent NO_2. We can multiply these percentages by the EPA limits to obtain individual values for each.

Example: *(1.2 gm/bhp hr)(20%)(25 bhp) =6 gm/hr*
Equivalence in gm/min: 0.1 gm/min

The time the engine will take to fill the garage with enough substance to reach the OSHA limit can now be determined by dividing the mass of the substance by the rate of emission.

Example: *(1.764 gm)/(0.1 gm/min) =17.64 min*

2007 Engine Results

Table 2 shows the results of these calculations for each of the four substances being considered using the values for a 2007 engine using the NO_x averaging method of compliance:

	NO	NO2	CO	Particulates
Garage Length (ft)	50	50	50	50
Garage Width (ft)	14	14	14	14
Garage Height (ft)	14	14	14	14
Garage Volume (ft^3)	9800	9800	9800	9800
Truck Size (ft)	40	40	40	40
Truck Width (ft)	8	8	8	8
Truck Height (ft)	9	9	9	9
Truck Volume (ft^3)	2880	2880	2880	2880
Air Volume (ft^3)	6920	6920	6920	6920
Air Volume (m^3)	196	196	196	196
OSHA Indoor Air Limit (mg/m^3)	30	9	55	5
Engine Emission Production (gm/hp-hr)	1.20	1.20	1.60	0.01
Percent of Total	80.0%	20.0%	100.0%	100.0%
Emissions Produced (gm/hp-hr)	0.96	0.24	1.6	0.01
Engine Idle Power (hp)	25	25	25	25
Time to reach OSHA Limit (min)	15	18	16	235

Table 2 – 2007 Engine Indoor Air Quality Time-to-Reach Estimates
Engine Using NO_x Averaging Method of Compliance

Table 3 shows the results of these calculations for 2007 engines using the 2006 NO_x method of compliance:

	NO	NO2	CO	Particulates
Garage Length (ft)	50	50	50	50
Garage Width (ft)	14	14	14	14
Garage Height (ft)	14	14	14	14
Garage Volume (ft^3)	9800	9800	9800	9800
Truck Size (ft)	40	40	40	40
Truck Width (ft)	8	8	8	8
Truck Height (ft)	9	9	9	9
Truck Volume (ft^3)	2880	2880	2880	2880
Air Volume (ft^3)	6920	6920	6920	6920
Air Volume (m^3)	196	196	196	196
OSHA Indoor Air Limit (mg/m^3)	30	9	55	5
Engine Emission Production (gm/hp-hr)	2.50	2.50	1.60	0.01
Percent of Total	80.0%	20.0%	100.0%	100.0%
Emissions Produced (gm/hp-hr)	2	0.5	1.6	0.01
Engine Idle Power (hp)	25	25	25	25
Time to reach OSHA Limit (min)	7	8	16	235

Table 3 – 2007 Engine Indoor Air Quality Time-to-Reach Estimates
Engines Using 2006 NO_x Method of Compliance

2007 Engine Conclusions

Using our hypothetical garage and typical fire truck model, we can conclude that the worst-case typical fire apparatus diesel engine will cause the air in the garage to exceed the OSHA indoor air quality limits if left to idle with no ventilation in the following time periods.

Substance	Time to exceed OSHA exposure limits
Nitrogen Monoxide (NO)	7 minutes
Nitrogen Dioxide (NO_2)	8 minutes
Carbon Monoxide (CO)	16 minutes
Particulate Matter (PM)	235 minutes
Non Methane Hydrocarbons (NMHC)	Unknown

1998 Engine Conclusions

This same approach can be used to estimate the impact on indoor air quality of engines produced to earlier emissions regulations. Table 4 provides the same hypothetical case, but using values from the 1998 regulations. (Note: The value for CO emissions is based on the reported values for a DDC Series 60 14.0 liter engine which was the highest reported value among Cummins, DDC, and Caterpillar heavy duty diesel engines for the 1999 model year).

	NO	NO2	CO	Particulates
Garage Length (ft)	50	50	50	50
Garage Width (ft)	14	14	14	14
Garage Height (ft)	14	14	14	14
Garage Volume (ft^3)	9800	9800	9800	9800
Truck Size (ft)	40	40	40	40
Truck Width (ft)	8	8	8	8
Truck Height (ft)	9	9	9	9
Truck Volume (ft^3)	2880	2880	2880	2880
Air Volume (ft^3)	6920	6920	6920	6920
Air Volume (m^3)	196	196	196	196
OSHA Indoor Air Limit (mg/m^3)	30	9	55	5
Engine Emission Production (gm/hp-hr)	4.00	4.00	1.52	0.10
Percent of Total	80.0%	20.0%	100.0%	100.0%
Emissions Produced (gm/hp-hr)	3.2	0.8	1.52	0.1
Engine Idle Power (hp)	25	25	25	25
Time to reach OSHA Limit (min)	4	5	17	24

Table 4 – 1998 Engine Indoor Air Quality Time-to-Reach Estimates

Assumptions

This hypothetical study ignores certain complexities and employs some simplifying assumptions:

- The sealed garage could not be used in real life. During the combustion process, the diesel fuel changes state from a liquid to a gas. These gases occupy more volume than they do as a liquid. The volume of exhaust gas coming out of the engine is greater than the volume of air that is drawn into the engine. The pressure in our hypothetical sealed garage would increase the longer the engine is run and either some of the air volume would have to be allowed to escape, or the garage windows would blow out.
- As the engine runs in our sealed garage, it will begin to use up the oxygen in the room. As the oxygen is depleted, the emissions output will change. The extent to which they change, either for better or worse, is not addressed by this study. We assume that the oxygen content of the air in the garage remains constant.

- The EPA certification tests are conducted using a prescribed engine profile that simulates a typical truck duty cycle. The emissions values are an average over the total duration of the test. Our model assumes that the average emissions rate per hp is the same as what it will produce at idle.
- The model truck is representative of the largest of fire apparatus. A typical pumper will be closer to 30 feet in length, providing more air volume and increasing the time to reach the allowable limits.
- The model assumes a single-stall garage of a specific size. The allowable limits will be reached sooner in a smaller garage and will take longer to reach in a larger garage.
- The assumption that the garage is sealed is rather extreme, and therefore produces conservative results. Most FD station garages are ventilated to some extent.

Disclaimer

This paper is written to provide some guidance in response to fire industry personnel questions on this subject and is intended to provide general information only.

The content of this paper is the work of the author, and does not represent any guarantee of performance by any engine or apparatus manufacturer.

The calculations use data available in the public domain, but the approach employs several broad assumptions and simplifications. The conclusions have not been validated by real-world testing or air quality measurement.

Fire chiefs and safety officers should

- Educate their drivers to limit to a minimum the engine idle time inside a building to make sure that healthy indoor air quality is maintained.
- Provide a means to vent the exhaust to the outside if it is necessary to run the engine longer than the time necessary to enter or exit the building.