2017 Off-Road Diesel Emission Factor Update for NO_x and PM

Contents

1. Summary

Background

The California Air Resources Board (ARB) emissions inventory for off-road diesel engines quantify the amount of pollutants from thousands of engines in equipment used in industrial applications, agriculture, construction, mining, oil drilling, power generation, and many other industries. These off-road diesel engines are significant sources of air pollutants such as nitrogen oxides (NO_x) and particulate matter (PM). Since 1995, these engines have been subject to a series of emissions standards that progressively reduce the emissions of pollutants, with requirements for manufacturers to certify and report information annually. Previous emissions factors were developed (circa 1999) under the assumption that all off-road diesel engines would simply meet (or slightly exceed) the emissions standards in each applicable year.

This report updates the PM and NO_x emission factors for all off-road diesel engines (except for locomotives and marine engines). This update focuses on PM and NO_x as the currently available data (primarily the off-road engine certification values[1]) provide a large amount of data on PM and NO_x emission rates, but allow limited ability to determine average emission rates for other pollutants (such as hydrocarbons).

Summary of Methodology

In general, the methodology used to determine updated diesel NO_x and PM emissions factors is to average the engine certification values of a given horsepower range and model year. In most cases this average reflects a wide range of values, from engines that meet or exceed the

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[1] Manufacturers of off-road diesel are required to certify their engines and report the resulting emissions, further information is available on ARB's website; https://www.arb.ca.gov/msprog/offroad/cert/cert.php

standard in that year, to others that use a variety of flexibility provisions (emission credits) to meet previous year's standards. An example of this is shown in the figure below, for one horsepower group of diesel engines in 2016. Each circle on the chart represents a single engine family certification value reported to US EPA and ARB. Note that although many engine families meet the Tier 4 Final standard effective for model year 2014 and later engines, a large number are closer to the earlier Tier 4 Interim or even Tier 3 standards or higher. These engines were sold (and reported in ARB's emissions inventories) as Tier 4 Final engines, but used flexibility provisions to meet the Tier 4 Final standards for NO_x.

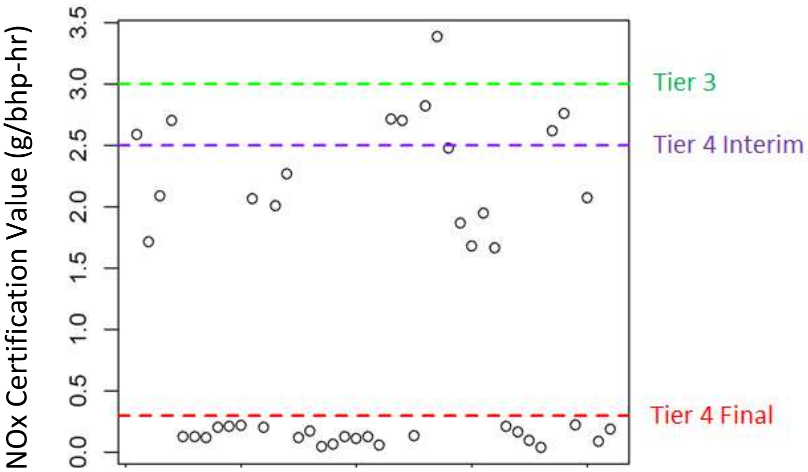


Figure 1: NO_x Values for Off-road Diesel Engines in 2016, 100 to 175 Hp Bin

The updated emission factors are a result of average groups of data, such as the one shown above, to determine average representative emission factors for each year.

Impact of Update

In general the impacts of this update can be characterized by the following trends:

1. The adoption of a Tier standard can be seen more as a gradual trend downwards in emissions, as opposed to the step function previously assumed.

2. The full adoption of Tier 4 Final engines did not occur in 2015 as previously assumed, and is now a slower transition from 2015 through the mid-2020s.

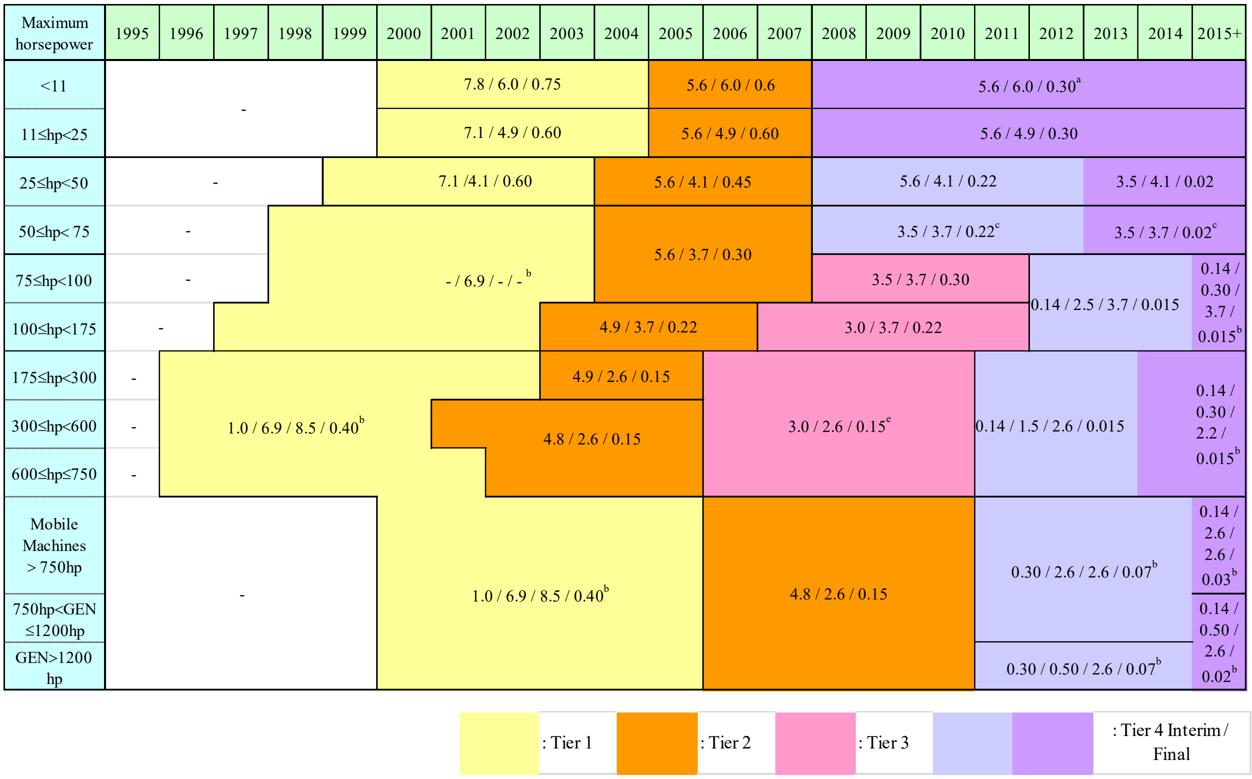
2. Technical Appendix

A. Background on Emission Standards and Credits

The emission standards for off-road diesel engines in California are presented in Table 1 below. The emissions standards represent the maximum allowable level of pollution the engine may produce per unit of time and energy. Engine manufacturers may meet the emissions standards by controlling pollution below the allowable limit laid out in the standard, or use a variety of emission credits that provide flexibility in meeting the standards. The California Code of Regulation (CCR) gives a detailed explanation of the emission credits and how they can be used by manufacturers.

“Emission credits represent the amount of emission reduction or exceedance, by an off-road engine family, below or above the emission standard, respectively. Emission reductions below the standard are considered as “positive credits,” while emission exceedances above the standard are considered as “negative credits”. Engine manufactures can average, bank, or trade the emission credits. Averaging for off-road engines means the exchange of emission credits among engine families within a given manufacturer's product line. Banking means the retention of off-road engine emission credits by the manufacturer generating the emission credits for use in future model year averaging or trading as permitted by these regulations. Trading means the exchange of off-road engine emission credits between manufacturers.” (CCR Title 13) [1] The emission factors of off-road engines are determined by the combined effects of emission standards and emission credits.

Table 1: ARB and US EPA Off-Road Compression-Ignition (Diesel) Engine Standards



Maximum horsepower	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015+
<11	-					7.8 / 6.0 / 0.75					5.6 / 6.0 / 0.6			5.6 / 6.0 / 0.30[a]							
11≤hp<25						7.1 / 4.9 / 0.60					5.6 / 4.9 / 0.60			5.6 / 4.9 / 0.30							
25≤hp<50	-				7.1 /4.1 / 0.60					5.6 / 4.1 / 0.45				5.6 / 4.1 / 0.22					3.5 / 4.1 / 0.02		
50≤hp< 75	-			- / 6.9 / - / -[b]						5.6 / 3.7 / 0.30				3.5 / 3.7 / 0.22[c]					3.5 / 3.7 / 0.02[c]		
75≤hp<100	-													3.5 / 3.7 / 0.30				0.14 / 2.5 / 3.7 / 0.015			0.14 / 0.30 / 3.7 / 0.015[b]
100≤hp<175	-		- / 6.9 / - / -[b]						4.9 / 3.7 / 0.22				3.0 / 3.7 / 0.22								
175≤hp<300	-	1.0 / 6.9 / 8.5 / 0.40[b]							4.9 / 2.6 / 0.15			3.0 / 2.6 / 0.15[e]					0.14 / 1.5 / 2.6 / 0.015			0.14 / 0.30 / 2.2 / 0.015[b]	
300≤hp<600	-						4.8 / 2.6 / 0.15														
600≤hp≤750	-																				
Mobile Machines > 750hp	-					1.0 / 6.9 / 8.5 / 0.40[b]						4.8 / 2.6 / 0.15					0.30 / 2.6 / 2.6 / 0.07[b]				0.14 / 2.6 / 2.6 / 0.03[b]
750hp<GEN ≤1200hp																					0.14 / 0.50 / 2.6 / 0.02[b]
GEN>1200 hp																	0.30 / 0.50 / 2.6 / 0.07[b]				

🟨 : Tier 1 🟧 : Tier 2 🟥 : Tier 3 🟦 🟪 : Tier 4 Interim / Final

a) The PM standard for hand-start, air cooled, direct injection engines below 11 hp may be delayed until 2010 and be set at 0.45 g/bhp-hr.

b) Standards given are NMHC/NO_x/CO/PM in g/bhp-hr.

c) Engine families in this power category may alternately meet Tier 3 PM standards (0.30 g/bhp-hr) from 2008-2011 in exchange for introducing final PM standards in 2012.

d) The implementation schedule shown is the three-year alternate NO_x approach. Other schedules are available.

e) Certain manufacturers have agreed to comply with these standards by 2005.

B. Methodology for Calculating Emission Factors

The emission factor for an off-road diesel engine with a given horsepower in a given model year is determined using the following equation:

$$EF = EF_0 + (DR * CHrs) \qquad \textbf{Equation 1}$$

where:

EF = emission factor, in grams per horsepower-hour (g/hp-hr)

EF_0 = zero-hour emission factor (g/hp-hr)

DR = deterioration rate, or the increase in emissions as the equipment ages (g/hp-hr^2)

CHrs = cumulative hours

This analysis groups the emission factors and deterioration rates of off-road engines by model year and horsepower. The grouping of horsepower is consistent with that in the emission standards: 0-25, 25-50, 50-75, 75-100, 100-175, 175-300, 300-600, 600-750, and >750.

Uncontrolled engines were grouped into two categories: pre-1988 uncontrolled engines and 1988 to Tier 1 engines or “Tier 0” engines. The distinction was made based on the difference in emission factor data before and after 1988 – one source was available for pre-1988 engines, while different data source and testing method was available for 1988 and later uncontrolled engines.

For engines that reported engine certification testing data, ARB created an average of the emissions factors reported in each year based on the EPA certification data [2]. For future (2017+) engines, we predicted yearly emission factors based on the past trends in emission factors. This report mainly focuses on updating the zero-hour emission factors. Deterioration rates are adopted from the previous ARB study [3].

C. Zero-hour Emission Factors

I. Pre-1988 Uncontrolled Engines

As no new testing data are available for the pre-1988 uncontrolled engines, zero-hour emission factors are adopted from the previous ARB study [3,4]. The emission factors are summarized in Table 2 (These emission factors are based on pre-1993 diesel fuel with a sulfur content of 0.3% by weight or greater.)

Table 2. Zero-hour emission rates for pre-1988 uncontrolled engines

Power	**Model year**	**Emission factors (g/hp-hr)**			
		HC	**CO**	**NO_x**	**PM**
25<hp<50		1.84	5.0	7	0.76
50≤hp<100		1.44	4.8	13	0.84
	1969	1.32	4.4	14	0.77
	1971	1.10	4.4	13	0.66
	1979	1.00	4.4	12	0.55
	1984	0.94	4.3	11	0.55
	1988	0.88	4.2	11	0.55
	1969	1.26	4.2	14	0.74
	1971	1.05	4.2	13	0.63
	1979	0.95	4.2	12	0.53
	1984	0.90	4.2	11	0.53
	1988	0.84	4.1	11	0.53

II. 1988 and Later Uncontrolled Engines

For 1988-and-later uncontrolled (or Tier 0 engines), the emission factors are based on US EPA's emission testing data [5]. Due to the small size of the data, this analysis averages the emission rates by three horsepower groups: 50-100 hp, 100-175 hp, and >175 hp. No testing data are available for engines below 50 hp, therefore the emission rates from uncontrolled engines prior to 1988 are used until the introduction of Tier 1 engines in 1999 to 2000.

Table 3 Summary of EPA's emission testing data for Tier 0 Engines

Engine	**Model Year**	**Age (Hrs)**	**Sulfur (wt%)**	**Power (hp)**	**BSFC (lb/hp-hr)**	**Emission factor (g/hp-hr)**				
						HC	**CO**	**NO_x**	**PM**	**PMbase**
Ford New Holland	1991	0	0.26	127	0.358	1.02	7.7	7.48	1.1	1.12
John Deere 7068T	1990	0	0.26	139	0.349	0.45	2.98	11.74	0.41	0.43
Volvo TD 71G	1984	0	0.046	144	0.373	0.47	1.64	12.68	0.149	0.22
Volvo TD73 KBE	1992	0	0.046	139	0.386	0.64	0.85	4.52	0.12	0.20
Weterbeke 32BEDA	1995	0	0.033	95	0.484	1.95	7.43	7.99	1.5	1.60
Caterpillar 3176B	1995	0	0.033	451	0.358	0.09	2.94	6.37	0.213	0.29
Cummins KTA19-M3	1995	0	0.033	599	0.359	0.68	3.26	8.78	0.257	0.33
Caterpillar 3306	1990	0	0.26	285	0.354	1.1	1.4	6.5	0.18	0.20
Cummins 4BT	1990	0	0.26	100	0.365	0.8	2.1	11	0.39	0.41
John Deere 4039D	1991	0	0.25	72	0.385	0.6	3.5	7.2	0.59	0.61
Caterpillar 3116	1991	2,511	0.28	201	0.352	0.07	2.51	9.38	0.406	0.42
Caterpillar 3054	1991	1,964	0.28	85	0.393	0.66	1	7.53	0.387	0.40
John Deere 4039	1994	2,265	0.28	86	0.389	0.41	2.17	11.22	0.384	0.40
John Deere	1993	3,300	0.28	174	0.385	0.53	2.05	10.22	0.25	0.26
Consolidated Diesel 6TA-830	1990	4,370	0.28	226	0.365	0.86	1.5	6.53	0.397	0.41
John Deere 6619	1993	4,970	0.28	275	0.397	0.82	4.69	7.29	0.662	0.68
Consolidated Diesel 4039	1988	3,570	0.28	71	0.389	1.32	3.37	7.57	0.581	0.59
Caterpillar 3306	1990	6,700	0.28	278	0.373	1.27	1.46	6.52	0.248	0.26
Average (50≤hp<100)			**0.33**			**0.99**	**3.49**	**8.30**	**0.69**	**0.72**
Average (100≤hp<175)			**0.33**			**0.65**	**2.89**	**9.61**	**0.40**	**0.44**

Average (hp >175)			**0.33**			**0.70**	**2.54**	**7.34**	**0.34**	**0.37**

In these tests, fuel sulfur was adjusted to the default sulfur level (0.33 wt.%) according to the following equation from EPA:

PMbase = PM + BSFC * A * (0.0033 - Fuel Sulfur) **Equation 2**

where:

PMbase = PM emissions with fuel sulfur fraction of 0.33%, in g/hp-hr

PM = PM emissions with test fuel, in g/hp-hr

BSFC = Brake Specific Fuel Consumption in g/hp-hr

A = 0.157 g PM/hp-hr/Weight Fraction sulfur/BSFC

Fuel Sulfur = Weight Fraction of sulfur in test fuel

Tier 1 to 2016 Engines

Emission factors for engines under Tier 1 and the following emission standards are based on the US EPA certification data for nonroad compression-ignition (NRCI) engines [2]. The certification dataset contains about 7000 testing reports for 1996-2016 model year engines. These tests include three different test modes, those being 8-mode, 4-mode tests and a cycle specific to transport refrigeration units. These testing cycles are intended to reasonably represent the range of activity for off-road engines[2].

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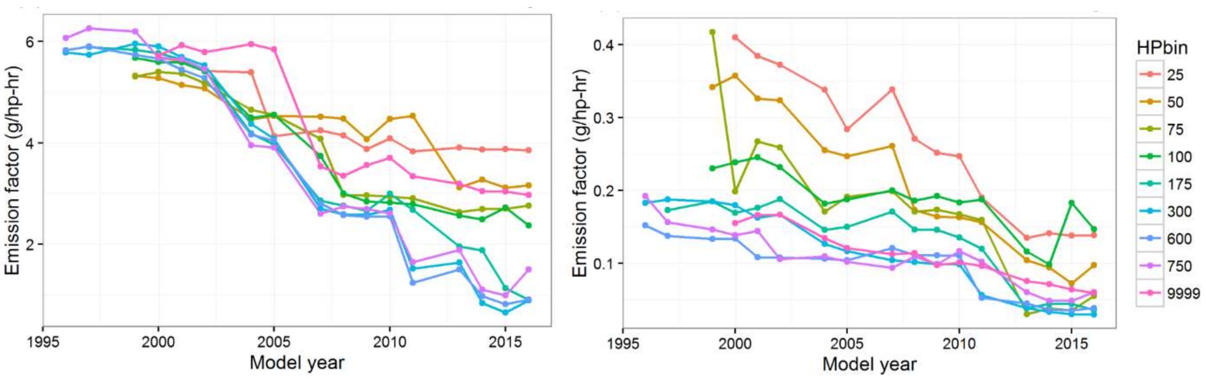
[2] More information on the test cycles is available here: https://www.epa.gov/vehicle-and-fuel-emissions-testing/engine-testing-regulations



(a) Zero-hour emission rates of NOx

(b) Zero-hour emission rates of PM

Figure 2 Zero-hour emission rates for controlled engines (Tier 1 to current year)

2017 and Future Engines

For all future years, all horsepower groups are subject to Tier 4 Final standards. However, manufacturers are still producing and selling many engines that meet Tier 4 Interim or even Tier 3 emissions standards. To determine how long this trend will continue, this analysis focused on the adoption rate of the previous engine Tiers after their introduction.

Figure 3 shows two examples of how NO$_x$ emission standards are adopted over time for engines in the 75-100 and 100-175 horsepower group. It is clear from Figure 3 that some new engines (engines built under more stringent standards than the current one) exist years ahead of the new standard, while some old engines (engines built under previous standards) are still produced after the new standards are in effect.

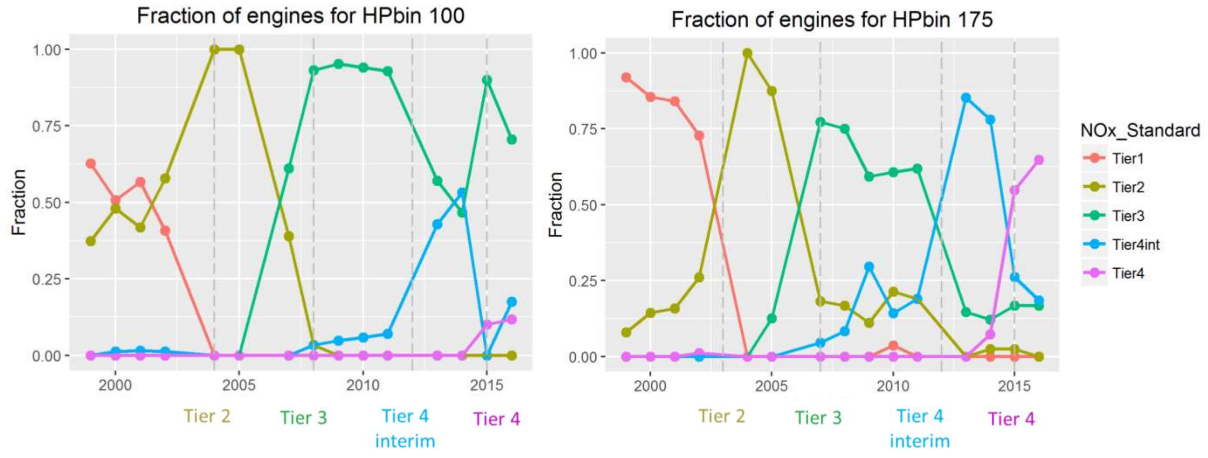


Figure 3. Fractions of Engines That Meet or Exceed Tier Standards by Model Year

No data about how companies use the emission credits are available, however, to predict the share of new and old engines in the future. Therefore, a linear regression was used to predict emission factors in future years.

This analysis uses a linear relationship between the average emission factor and model year to predict future emission factors. The regression equation largely depends on the range of model years included in the regression analysis. As changes in past emission factors are mainly driven by emission standards, each regression starts with the enforcement of an emission standard. Note that if the average emission factor of all engines in one horsepower group in 2016 is already below the Tier 4 Final standard, we do not use regression and assume that the emission factor stabilizes after 2016.

Once all engines meet the last Tier standard, Tier 4 Final, a constant factor is used for all future years. This Tier 4 Final emission factor is an average of the emission factors of all engines that meet or exceed the Tier 4 Final standard currently.

Figure 4 shows the linear regression and projections of future NO$_x$ and PM emission factors for engines in 75-100 hp group. Projections of NO$_x$ and PM emission factors for all horsepower groups are presented in Appendix A.

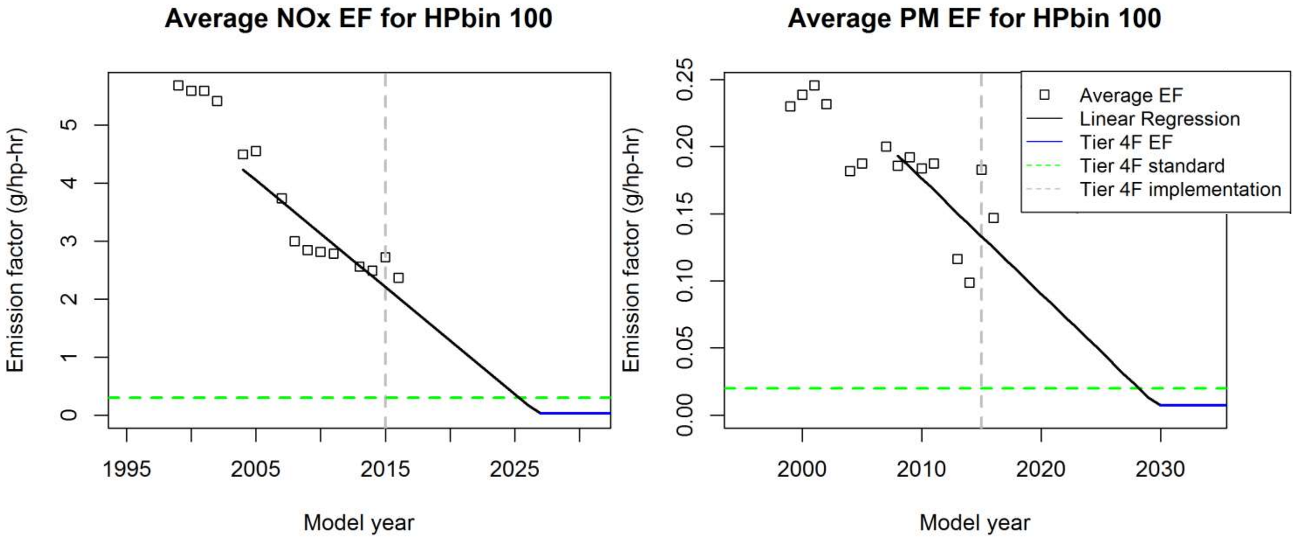


Figure 4: Example Projections of Emission Factors Using Linear Regression

D. Comparison between Previous and Current Emission Factors

Figure 5 shows the comparison of previous and current NO$_x$ and PM emission factors for engines in the 75-100 hp group. In general, current emission factors show a more gradual decreasing trend compared with previous analysis or predictions. Comparisons of NO$_x$ and PM emission factors for all horsepower groups are presented in Appendix B.

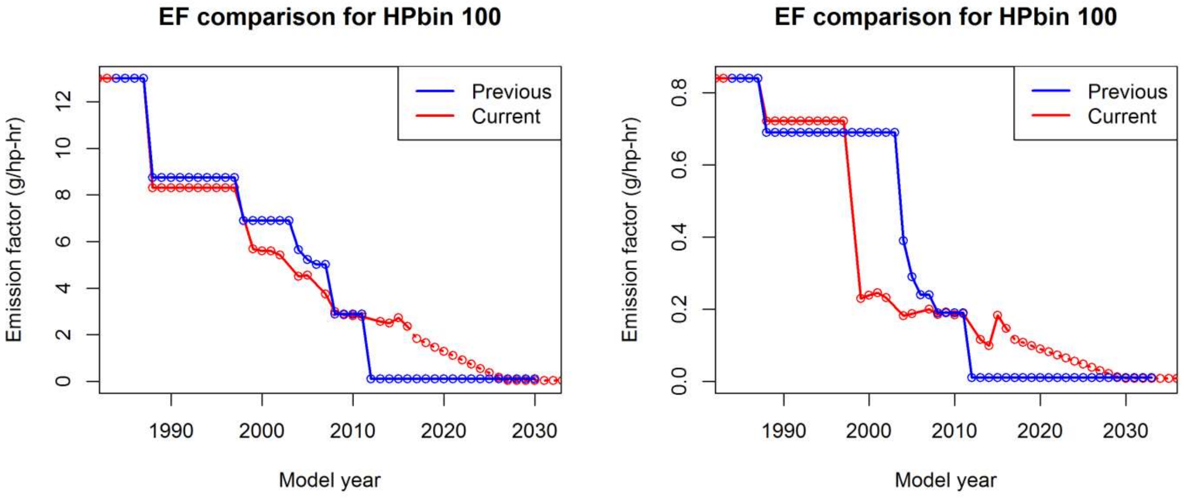


Figure 5: Comparison of Previous and Current NO_x and PM Emission Factors

E. Fuel Correction Factors

California off-road diesel fuel standards set by ARB has been ahead of federal standards by EPA since 1993. ARB set the sulfur content limit to be 500 ppm (low-sulfur diesel) in 1993 and 15 ppm (ultra-low-sulfur diesel) in 2006, while EPA followed the 500 and 15 ppm standard in 2007 and 2010, respectively, as shown in Figure 6. ARB has also regulated the aromatic hydrocarbon content (10 percent by volume) of diesel fuel since 1993, while EPA has not set any regulations on the aromatic content yet. Because the emission factors developed here are based on EPA testing data, these values need to be adjusted to account for the differences in sulfur and aromatic content between the federal and California fuel.

The 1993 ARB regulation on diesel sulfur and aromatic content reduces PM and NO_x emissions by 25% and 7% from the pre-regulated level, respectively [6]. Further reduction of sulfur from 500 ppm to 15 ppm reduces PM emissions by 4% [6]. Engine testing data using ultra-low-sulfur diesel (15 ppm) show that California diesel emits 10% less PM, 5% less NO_x , and 10% less HC than federal diesel[7], mainly because of the difference in aromatic hydrocarbon content. We assumed that the difference in emissions between federal and California diesel caused by the aromatic content also apply to the low-sulfur diesel (500 ppm). **Table 4** summarizes the fuel adjustment applied to engines given a specific model year and calendar year.

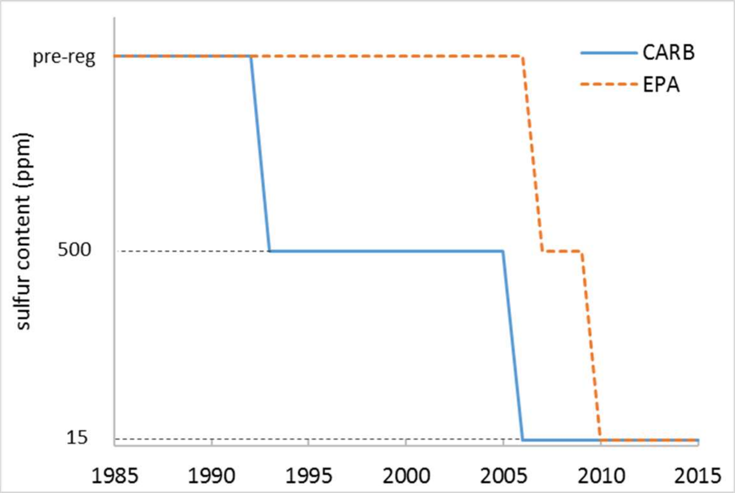


Figure 6 Comparison of off-road diesel sulfur content levels regulated by CARB and EPA

Table 4 Fuel correction factors for specific model year and calendar year group

Model year	Calendar year	Fuel correction factors		
		PM	NO_x	HC
pre-1993	pre-1993	1	1	1
pre-1993	[1993,2005]	0.75	0.93	0.9
pre-1993	2006+	0.71[a]	0.93	0.9
[1993, 2006]	[1993,2005]	0.75	0.93	0.9
[1993, 2006]	2006+	0.71[a]	0.93	0.9
[2007, 2009]	all	0.86[b]	0.95	0.9
2010+	all	0.9	0.95	0.9

[a] PM emission difference between pre-reg and California ultra-low-sulfur diesel is calculated as the combined difference between pre-reg and California low-sulfur diesel (25%), and that between California low-sulfur and ultra-low-sulfur diesel (4%).

[b] PM emission difference between federal low-sulfur diesel and California ultra-low-sulfur diesel is calculated as the combined effects of difference in sulfur content (4%) and aromatic content (10%).

References

1. California Code of Regulations (CCR), https://govt.westlaw.com/calregs/Index?transitionType=Default&contextData=%28sc.Default%29. (Last access: Nov 2016)
2. EPA. Engine Certification Data for nonroad compression-ignition. https://www.epa.gov/compliance-and-fuel-economy-data/engine-certification-data. (Last access: Nov 2016)
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5. EPA. 1998. Exhaust Emission Factors for Non-road Engine Modeling-Compression-Ignition. Report No. NR-009A
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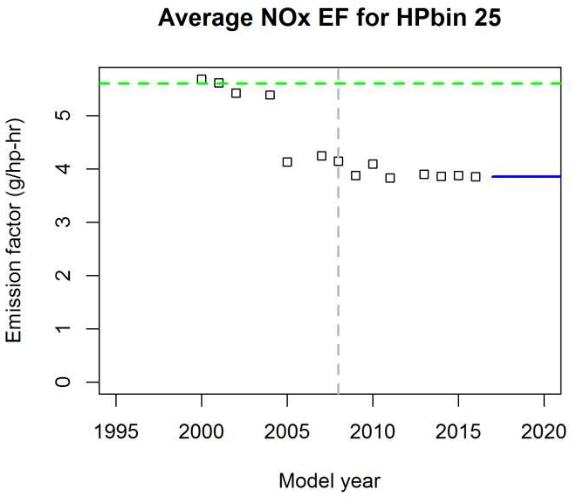
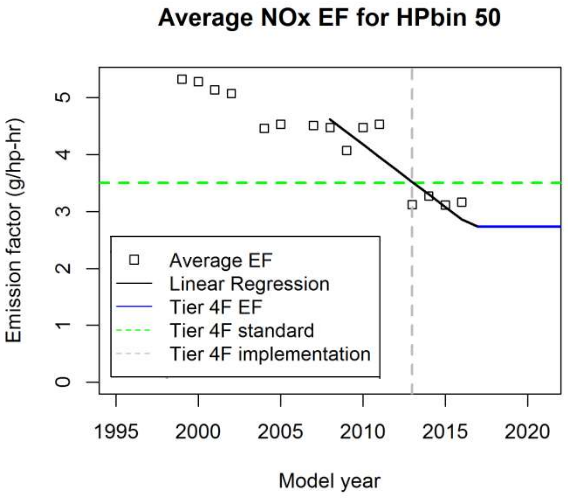
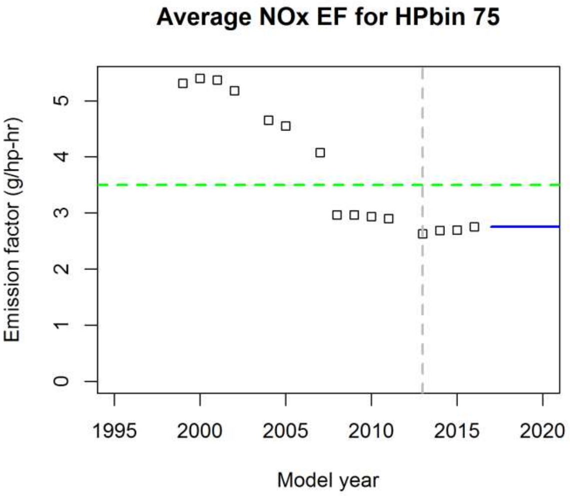
7. ARB. 2011. Diesel Fuel Comparison Study. https://www.arb.ca.gov/fuels/diesel/dieselcomp/dieselcomp.htm (Last accessed: Nov 2016)

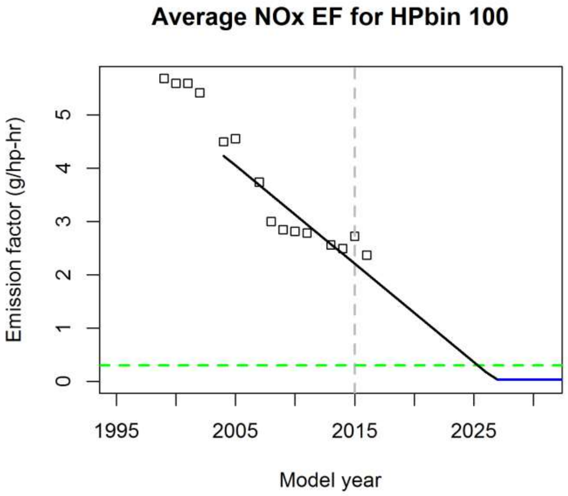
Appendix A

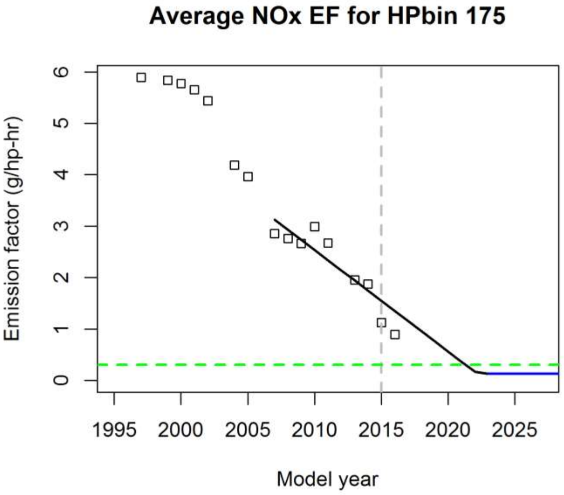
Projections of Emission Factors for Future Off-road Engines Using Linear Regression

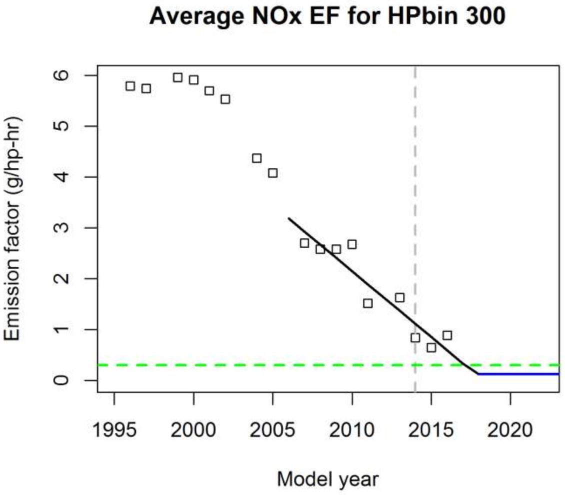





Average NOx EF for HPbin 75
Emission factor (g/hp-hr)
0
1
2
3
4
5
1995
2000
2005
2010
2015
2020
Model year


Average NOx EF for HPbin 100
Emission factor (g/hp-hr)
0
1
2
3
4
5
1995
2005
2015
2025
Model year


Average NOx EF for HPbin 175
Emission factor (g/hp-hr)
0
1
2
3
4
5
6
1995
2000
2005
2010
2015
2020
2025
Model year


Average NOx EF for HPbin 300
Emission factor (g/hp-hr)
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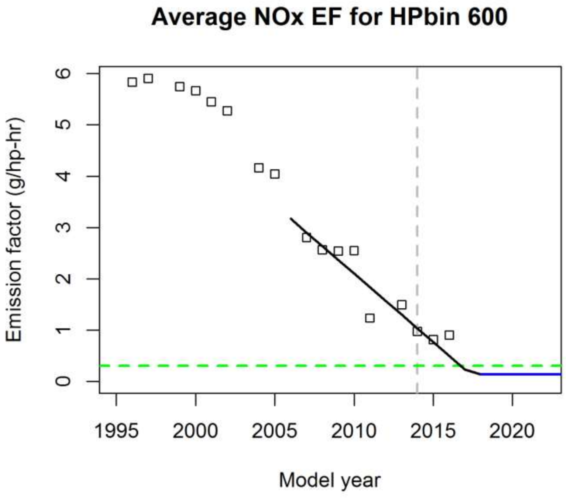
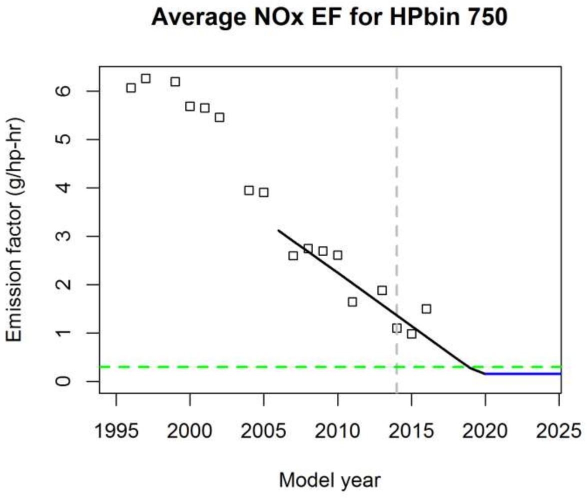
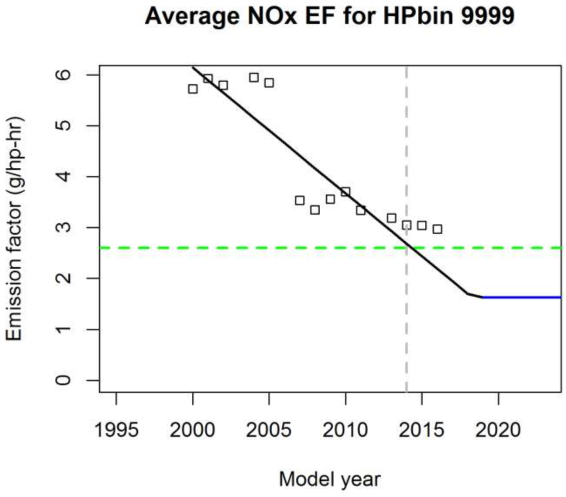
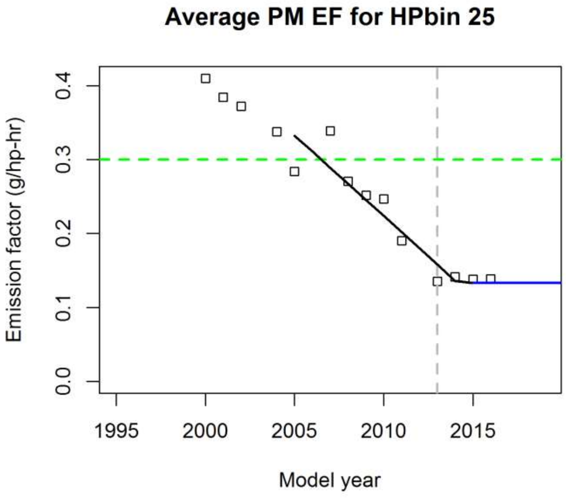
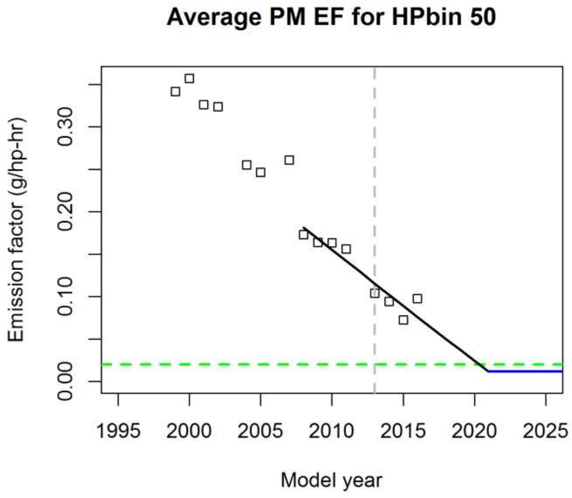
1
2
3
4
5
6
1995
2000
2005
2010
2015
2020
Model year

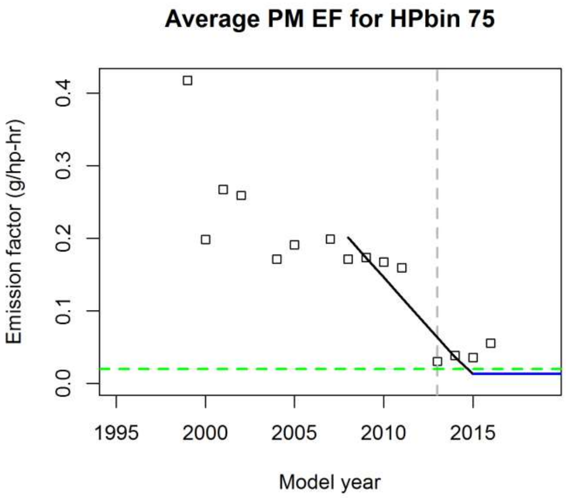

Average NOx EF for HPbin 600

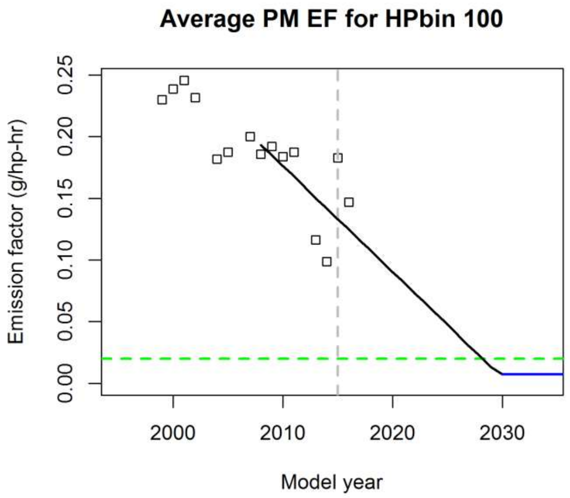

Average NOx EF for HPbin 750

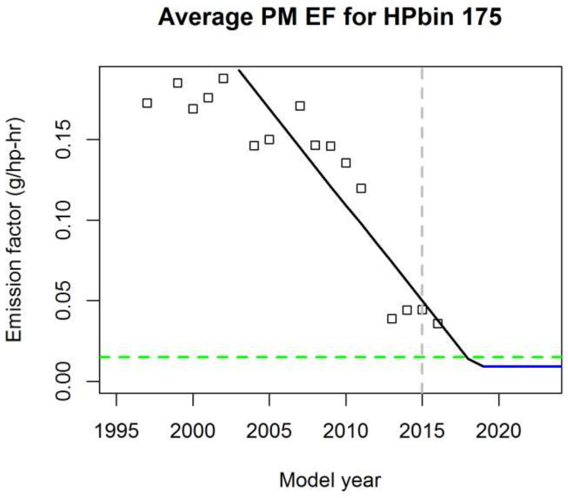

Average NOx EF for HPbin 9999

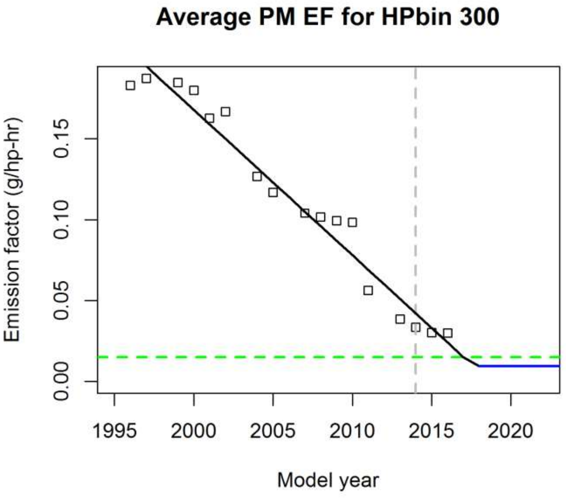

Average PM EF for HPbin 25
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
1995
2000
2005
2010
2015
Model year

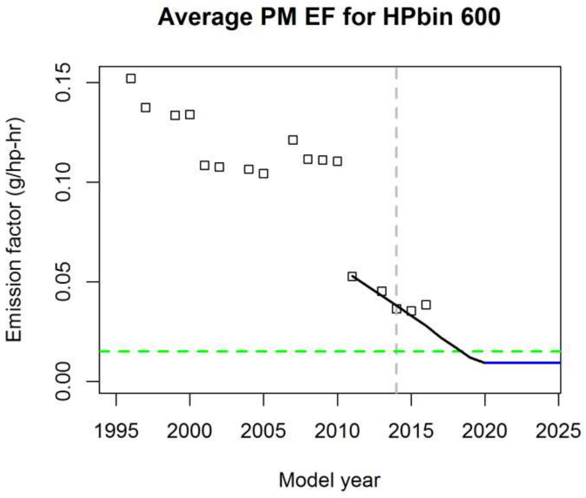

Average PM EF for HPbin 50
Emission factor (g/hp-hr)
0.00
0.10
0.20
0.30
1995
2000
2005
2010
2015
2020
2025
Model year

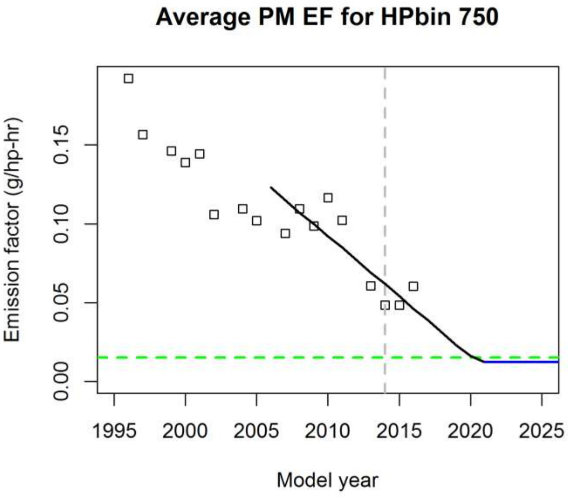

Average PM EF for HPbin 75
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
1995
2000
2005
2010
2015
Model year

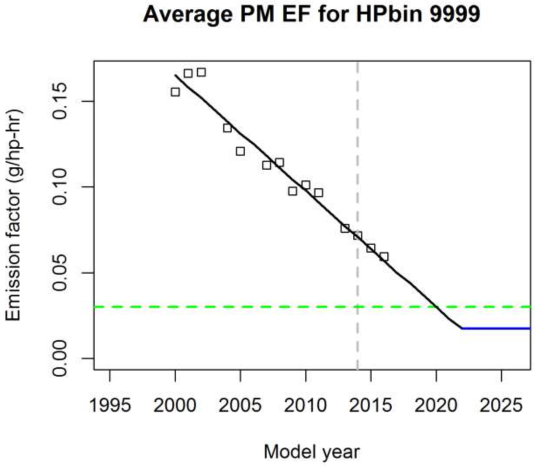

Average PM EF for HPbin 100
Emission factor (g/hp-hr)
0.00
0.05
0.10
0.15
0.20
0.25
2000
2010
2020
2030
Model year


Average PM EF for HPbin 175

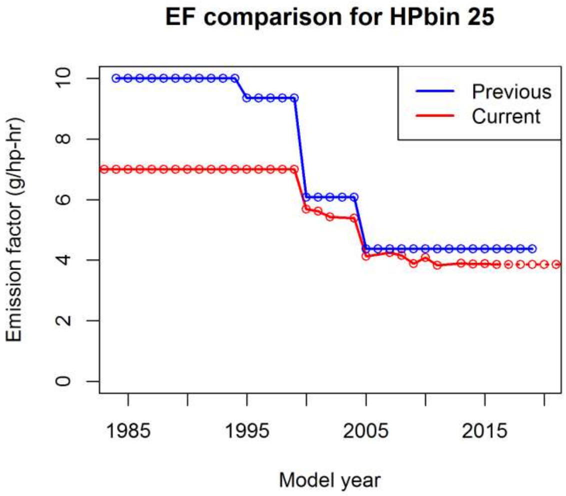

Average PM EF for HPbin 300

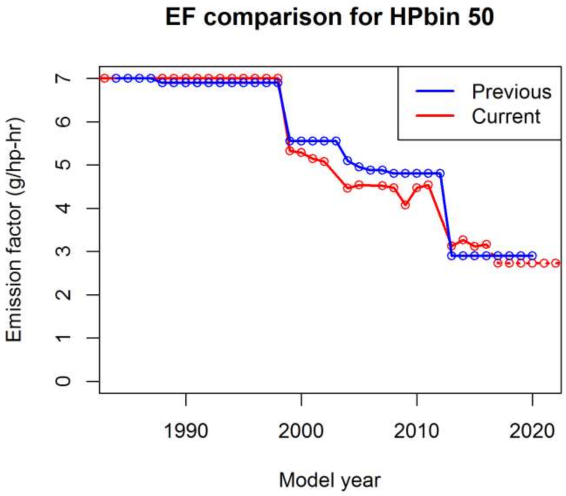

Average PM EF for HPbin 600

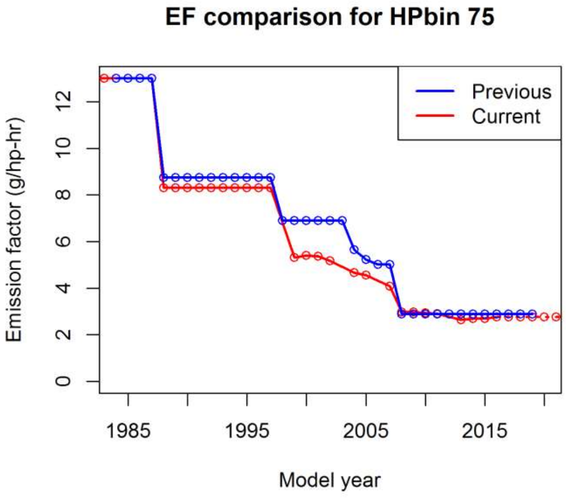

Average PM EF for HPbin 750

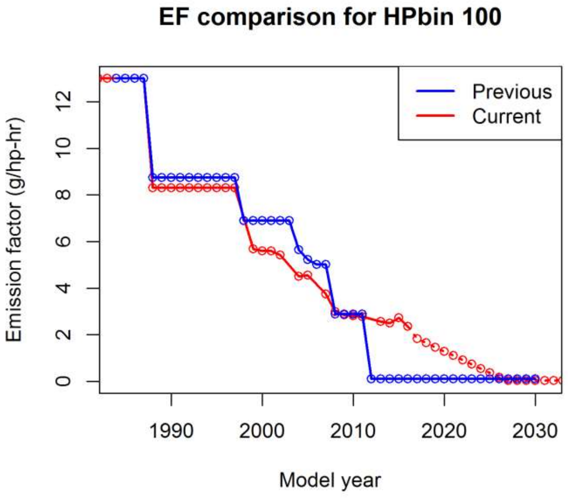


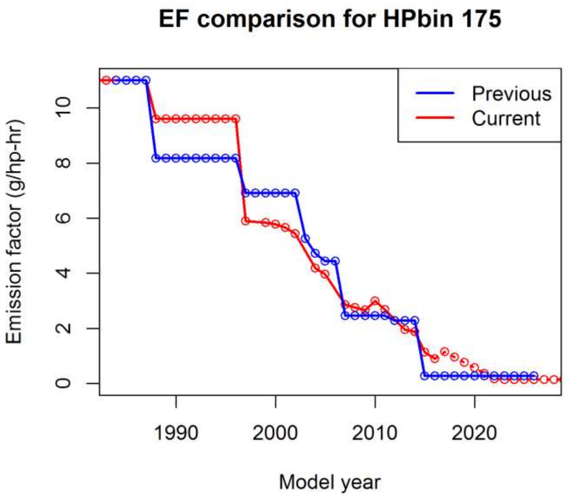
Comparison of Previous and Current NO_x and PM Emission Factors

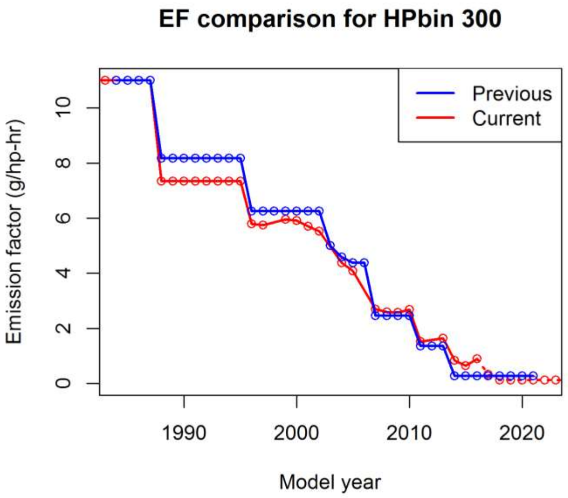


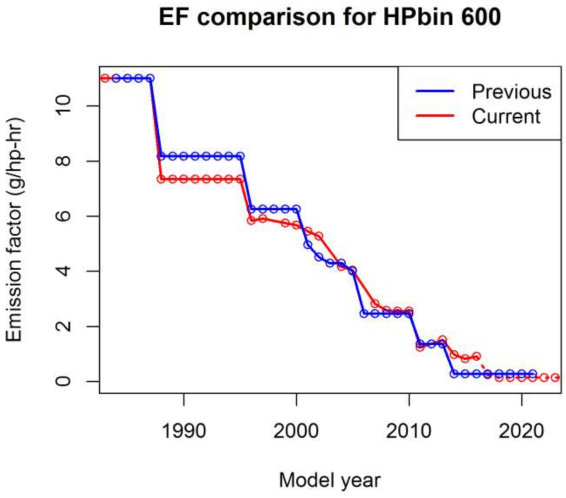


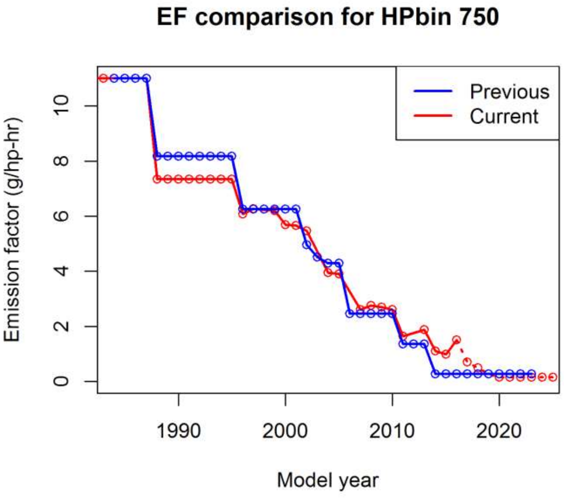

EF comparison for HPbin 75

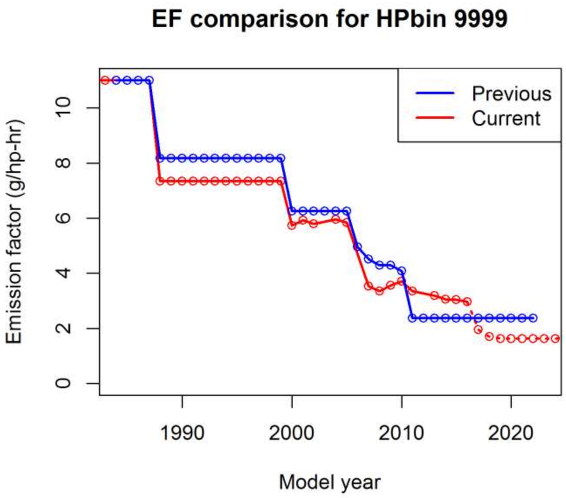

EF comparison for HPbin 100

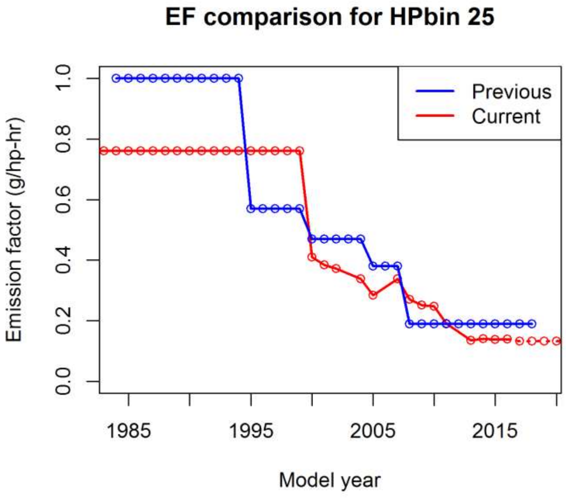

EF comparison for HPbin 175

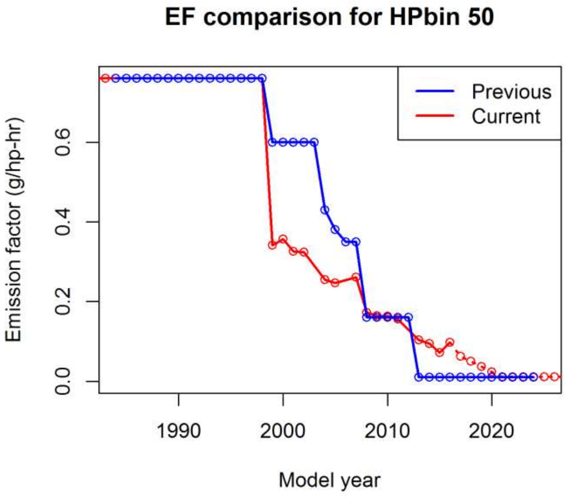

EF comparison for HPbin 300

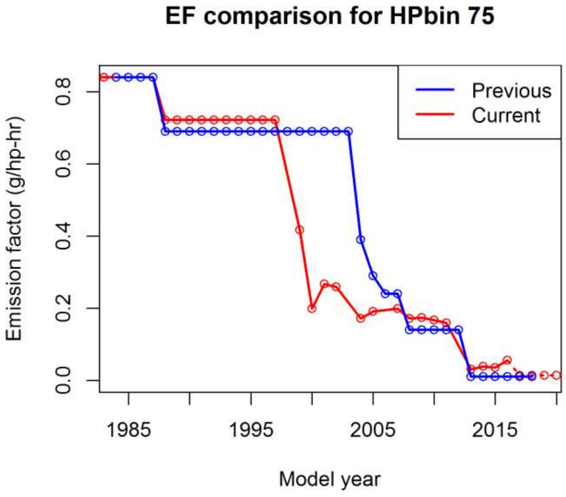

EF comparison for HPbin 600

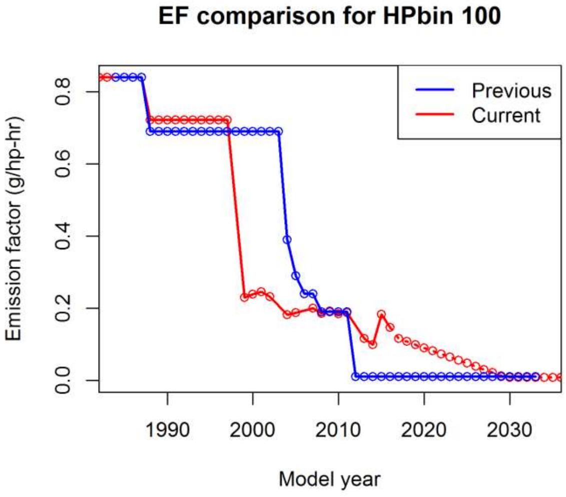

EF comparison for HPbin 750

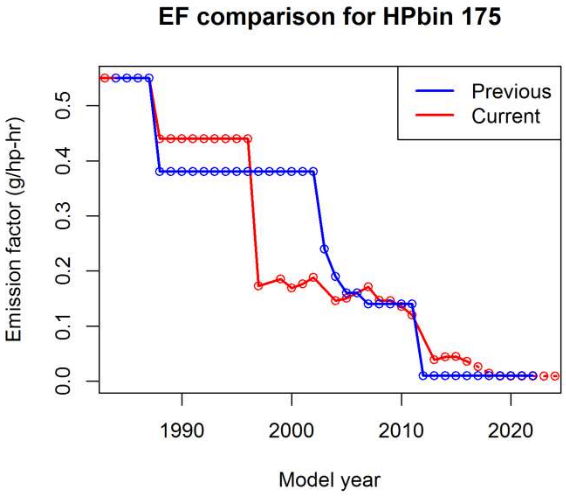

EF comparison for HPbin 9999

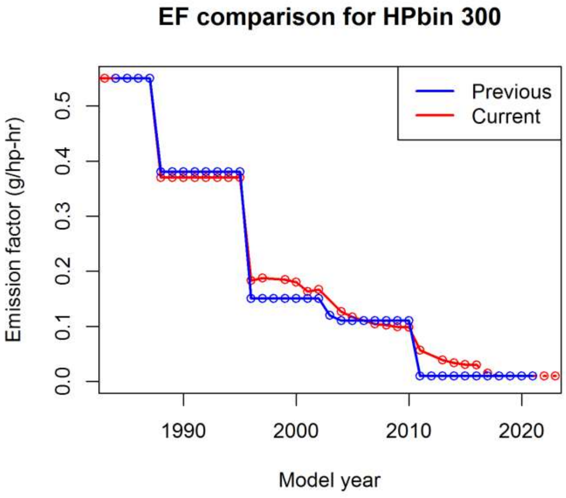

EF comparison for HPbin 25

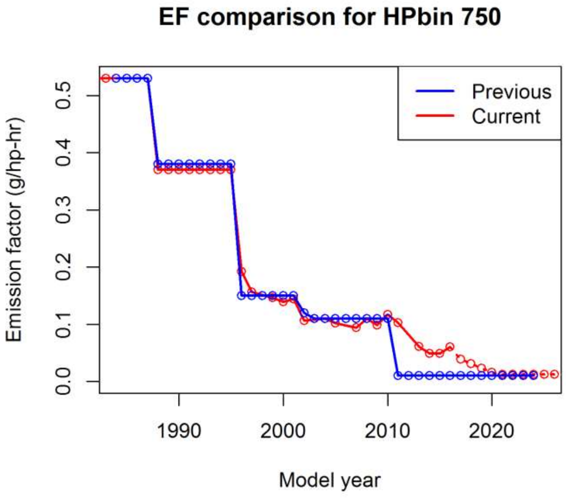

EF comparison for HPbin 50

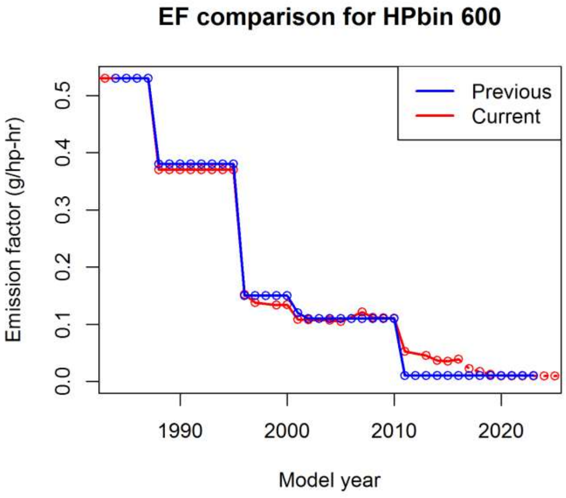

EF comparison for HPbin 75

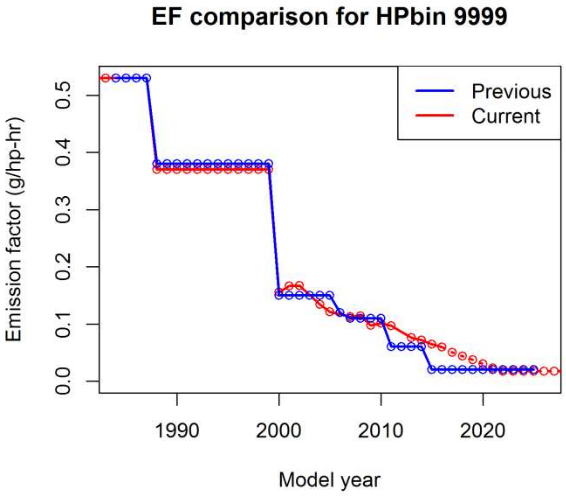

EF comparison for HPbin 100


EF comparison for HPbin 175
Previous
Current
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
0.5
1990
2000
2010
2020
Model year


EF comparison for HPbin 300
Previous
Current
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
0.5
1990
2000
2010
2020
Model year


EF comparison for HPbin 750
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
0.5
1990
2000
2010
2020
Model year
Previous
Current


EF comparison for HPbin 600
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
0.5
1990
2000
2010
2020
Model year
Previous
Current


EF comparison for HPbin 9999
Emission factor (g/hp-hr)
0.0
0.1
0.2
0.3
0.4
0.5
1990
2000
2010
2020
Model year
Previous
Current