Emissions from Diesel-Fueled Non-Road Equipment in California*

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April 19, 2010

Introduction

During 2004, the California Air Resources Board (CARB) began the development of a regulation intended to reduce emissions from in-use non-road Diesel-powered equipment. This process culminated in CARB's adoption in July 2007[1] of what is referred to as the "In-Use Off-Road Diesel Vehicle Regulation" (off-road regulation). The off-road regulation establishes emission reduction requirements for oxides of nitrogen (NOx) and particulate matter (PM) from existing fleets of off-road construction and mining equipment, airport ground support equipment (GSE), industrial equipment, and oil drilling equipment. In addition, the regulation requires that fleet owners report to CARB data characterizing each piece of equipment in their fleets.

In establishing the need for adoption of the off-road regulation, CARB developed a baseline inventory for NOx and PM emissions from the vehicles subject to regulation using the agency's OFFROAD2007 model.[2] As indicated in reference 2, of the industry sectors subject to the regulation, CARB estimated that the bulk of the equipment subject to the off-road regulation would be in the construction and mining sector.[†] The baseline NOx and PM emission inventories published by CARB in conjunction with the proposed off-road regulation are shown in Figures 1 and 2, respectively, for the period from 2009 through 2025.

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* It is intended that this manuscript will be submitted for publication in a peer-reviewed scientific journal and, if accepted, may be modified prior to publication in light of reviewer comments.

† Of the 164,250 pieces of off-road equipment that CARB estimated to fall into these four categories in 2000, 147,005 pieces, or 89.5% of the total, were construction and mining equipment. See Reference 2 at page E-2 (Table 1).

Figure 1
CARB Estimates of Baseline NOx Emissions from Vehicles Subject to the Off-Road Regulation

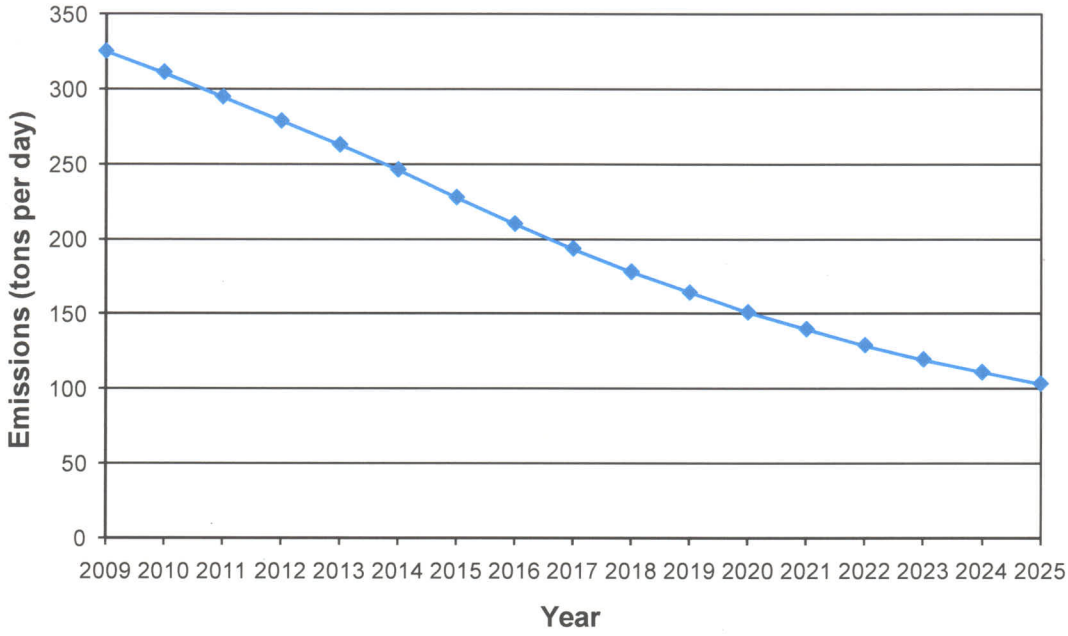
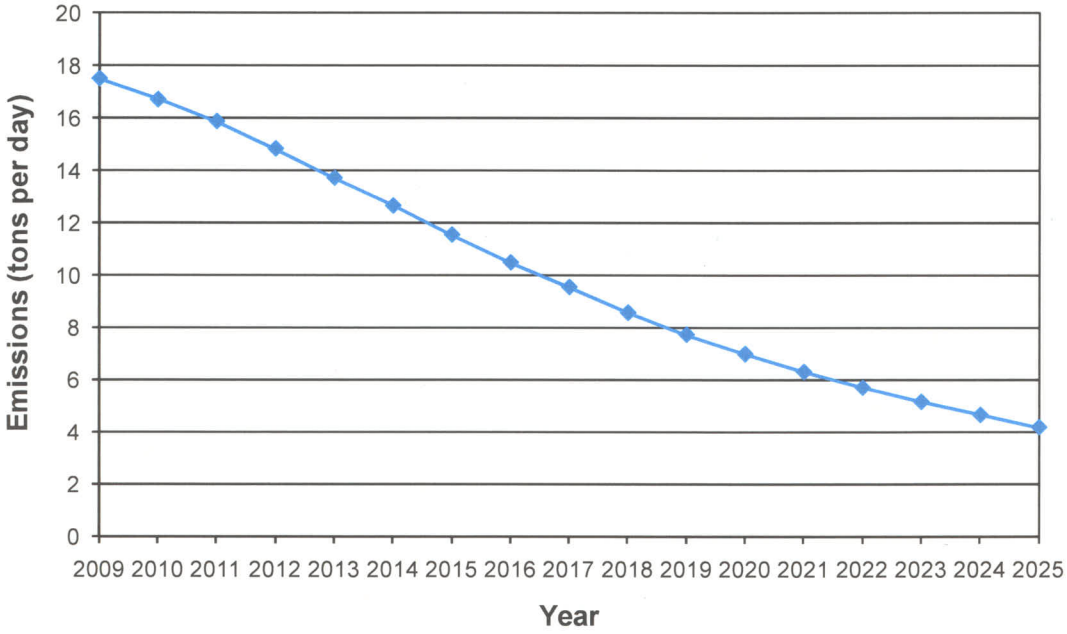


Figure 2
CARB Estimates of Baseline PM Emissions from Vehicles Subject to the Off-Road Regulation



The OFFROAD2007 model generates an emission inventory for the equipment subject to the regulation by compiling estimates for specific types of equipment (e.g., bulldozers, graders, backhoes) in a given calendar year. Although execution of the OFFROAD2007 model requires thousands of individual calculations to be performed, the basic calculations performed are relatively simple and given by the following equation:

$$\text{Emissions} = \text{EF}*\text{Pop}*\text{AvgHp}*\text{Load}*\text{Activity}*\text{Fuel} \qquad (1)$$

where:

- "Emissions" refers to emissions of a specific pollutant (e.g., PM or NOx) in tons per day for equipment of a given type and age;
- "EF" denotes an emission factor for the equipment in units of tons of pollutant emitted per brake-horsepower hour of operation;
- "Pop" means the number of pieces of equipment of the type and age;
- "AvgHP" means the average maximum rated brake-horsepower of the equipment;
- "Load" means the average load on the equipment during operation as a fraction of the maximum load;
- "Activity" refers to the number of hours per day that the equipment is in operation; and
- "Fuel" is a correction factor used to account for the emission impacts of differences in California Diesel fuel as compared to the federal Diesel fuel that the emission factors reflect.

As described in reference 2, the data used in the OFFROAD model for the factors "Pop," "AvgHP," "Load," and "Activity" are based on various surveys performed by CARB and other different organizations at different points in time. Data regarding emission factors ("EF") were developed by CARB and reflect appropriate CARB and U.S. Environmental Protection Agency (EPA) new engine emission standards. CARB also developed the values used for the "Fuel" parameter.

In addition to emissions, the OFFROAD2007 model estimates fuel consumption in the same manner in which it estimates emissions. In this case, the emission factor in Equation (1) is replaced by a brake specific fuel consumption factor with units of mass of fuel consumed per brake-horsepower hour of operation.

Although the OFFROAD2007 model was used by CARB as the basis for adoption of the off-road regulations, a recent study by Millstein and Harley[3] indicates that the OFFROAD2007 model may significantly overestimate NOx and PM emissions from vehicles subject to the off-road regulation. The Millstein and Harley study compared NOx and PM emission estimates for 2005 derived from Diesel fuel use data to 2005 NOx and PM emission estimates from the OFFROAD model. The authors reported that the NOx and PM emission estimates from the OFFROAD model for 2005 were 4.5 and 3.1 times higher than those derived from the 2005 Diesel fuel use data. It should also be noted that the basic approach used by Millstein and Harley had been used in a study published in 2000 to evaluate an old version of the U.S. EPA NONROAD emission inventory model.[4]

Given the implications of the Millstein and Harley study and the fact that the baseline inventory was a critical factor in CARB's evaluation of the need for the off-road regulation, the Associated General Contractors of America (AGC) commissioned an independent review of the baseline inventory following the general approach used by Millstein and Harley involving comparisons of OFFROAD2007 model results and fuel consumption data. The results of that review are documented in this paper.

Data Sources

As noted previously, the data germane to the off-road regulation upon which the OFFROAD2007 model is based were developed by CARB and other organizations using surveys and other means. In particular, the data regarding the "Pop" and "AvgHP" parameters were developed from survey data. As indicated by Millstein and Harley, a more recent survey performed under contract to CARB by Baker[5] reported results that differed substantially from the survey-based data in the OFFROAD2007 model.

However, as the result of the reporting requirements of the off-road regulation itself, detailed data characterizing the Diesel vehicle fleet operating in California have been provided to CARB through the Diesel Off-road On-line Reporting System (DOORS).[6] Pursuant to the off-road regulation, all fleets subject to the regulation were required to have completed their initial round of reporting of equipment operated in California[*] by August 1, 2009. CARB is pursuing a campaign to ensure complete reporting[7] and annual reporting updates are also required by the off-road regulation. Therefore, the DOORS database is not static. In this study, DOORS data provided by CARB[8] in February 2010 were used to characterize calendar year 2009 equipment populations and age distributions, and maximum rated engine power levels, as well as to identify "low-use" equipment. These data were then used to replace the existing survey-based data in the OFFROAD2007 model.

In addition to the DOORS data, data from several other sources were used to estimate calendar year 2009 emissions from vehicles subject to the off-road regulation. The first of these data sources[9] were the hours of equipment operation reported by two locals of the Operating Engineers union: Local 12, which is in southern California; and Local 3, which is in northern California. Again as described in more detail below, these data were used to account for changes in the operating patterns of equipment in 2009 resulting from the current recession relative to years thought to be more representative of the activity data in the OFFROAD2007 model, such as 2005.

Diesel fuel sales data were also collected for comparison with OFFROAD2007 estimates of fuel consumption and potentially for use in adjusting the model's emission inventory estimates. The primary source of fuel sales data was the California Board of Equalization (BOE),[10] which provided information regarding total sales of tax-exempt Diesel fuel sold for use in off-highway applications as well as the volume of on-highway Diesel fuel that

[*]The off-road regulation applies broadly to equipment operated in California and covers equipment that is primarily operated in other states if it also operates for some portion of the year in California.

construction firms burned in off-road equipment. In addition, the most recent data regarding the relative consumption of Diesel fuel by vehicles subject to the off-road regulation compared to other off-highway applications in California, such as rail and marine operations, were obtained from the Energy Information Administration (EIA).[11]

The emission, fuel correction, and brake specific fuel consumption factors in the OFFROAD2007 model were not modified in this analysis.

Methodology and Results

The first step in updating the baseline inventory from the OFFROAD2007 was the incorporation of the DOORS data into the model in place of the existing survey-based data. Given that the DOORS data available were collected during 2009, this change was made for the 2009 calendar year. The DOORS data were tabulated by equipment type and age* in order to revise the total population estimates and useful life estimates in the OFFROAD2007 model. Once the DOORS data were jointly tabulated by equipment type and age, the age distributions were examined and updated age distributions were developed and incorporated into the OFFROAD2007 model. In addition, revised maximum rated horsepower values were computed from the DOORS database for each equipment type and these values were also substituted for the existing values in the OFFROAD2007 model.

The OFFROAD2007 model accounts for year-to-year equipment population growth (or contraction) through use of a growth factor file (growth.csv) read by the model. The growth factor file consists of relative factors used to project equipment populations forward or backward to a specific calendar year. Since the DOORS database reflected calendar year 2009, an alternative version of the growth factor file was created for use with the DOORS data to reflect this 2009 reference point. The remaining DOORS-based revisions were generally implemented by generating separate versions of some of the default input data files used by the OFFROAD2007 model during an execution.

The version of OFFROAD2007 updated to include the DOORS data was then run for an annual average day;† the results are presented in Table 1 along with those obtained from the unmodified OFFROAD2007 model.‡ As shown in Table 1, use of the DOORS data reduced the total 2009 population, activity, fuel consumption, and NOx and PM emission estimates for the vehicles subject to the off-road regulation.

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* Equipment age was calculated from model year recorded for each piece of equipment in the DOORS database subtracted from the 2009 calendar year during which these data were collected (e.g., equipment from model year 2005 had an age of four years).

† The OFFROAD model can be run for a number of different scenarios including different portions of the week and different seasons. All results presented here are based on annual average day runs.

‡ It should be noted that there are some small discrepancies in the baseline inventory results reported by CARB in reference 1 and the results from the OFFROAD2007 model. It should also be noted that similar discrepancies are observed in spreadsheets and other CARB documents related to the off-road regulation.

Table 1 Comparison of OFFROAD2007 and DOORS Based 2009 Inventory for Vehicles Subject to the Off-Road Regulation					
Source	Pop	Activity (hours/day)	Fuel Cons. (gal./day)	NOx (ton/day)	PM (ton/day)
OFFROAD	191,678	543,924	2,664,493	332.47	18.77
DOORS	156,929	479,839	2,438,305	304.28	16.38
DOORS LU	156,929	455,444	2,339,322	287.92	15.36

In addition to allowing for the adjustments described above, the DOORS data identify "low-use vehicles," which are defined as those operating 100 hours or less per year. In the DOORS data used in this analysis, 11,655 pieces of equipment, or about 7.5% of the total population, were identified as being low use. In order to account for the impact of low-use equipment, another run of the modified OFFROAD2007 model was done for 2009 using just the low-use populations. The results of this run were scaled using the ratio of activity based on 100 hours per year of operation to the activity estimated from the modified OFFROAD2007 model for the low-use equipment.[*†]

The results for 2009 following the low-use equipment adjustment are also shown in Table 1 with the source label "DOORS LU." As one would expect, the adjustment reduced all of the model outputs.

As noted above, data related to the activity of vehicles subject to the off-road regulation are available from two California Operating Engineers unions. These data are presented in Figure 3. As shown in Figure 3, Operating Engineer hours are down by approximately 39.5% in 2009 relative to 2005,[‡] with this change being attributed to the current economic recession. There are two potential factors that contribute to this decline: (1) changes in the number and types of pieces of equipment in operation in 2009 relative to 2005, and (2) changes in the number of hours that each piece of equipment is being operated. In order to adjust for the first factor, the ratio of 2009 DOORS LU activity to that for the 2005 OFFROAD2007 results was computed. This ratio is 0.891 and again accounts for the change in activity expected from the change in equipment populations and types in 2009 relative to 2005. The remaining change in activity shown in the Operating Engineers data is likely due to reduced use of equipment. The factor that accounts for the reduction in equipment use is then 0.680,[§] and it is applied directly to the DOORS LU results; the results are shown in Table 2.

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[*] Note again that the OFFROAD2007 model results presented here are for annual average days and, as such, reflect appropriately weighted weekend day and weekend activity. Given this, they are converted to annual values based on a 365-day year.

[†] For 2009, this scaling factor was 0.16.

[‡] 2005 was chosen as the point of reference because it is near the peak of California construction activity and was used by CARB as a point of reference in developing the baseline inventory for the off-road regulation, as shown in reference 1.

[§] This value is computed by dividing the total remaining activity value of 0.606 in 2009 from the Operating Engineers data by the value of the remaining activity after accounting for change in equipment populations and types, which is 0.891.

Figure 3
Changes in Operating Engineer Hours Over Time

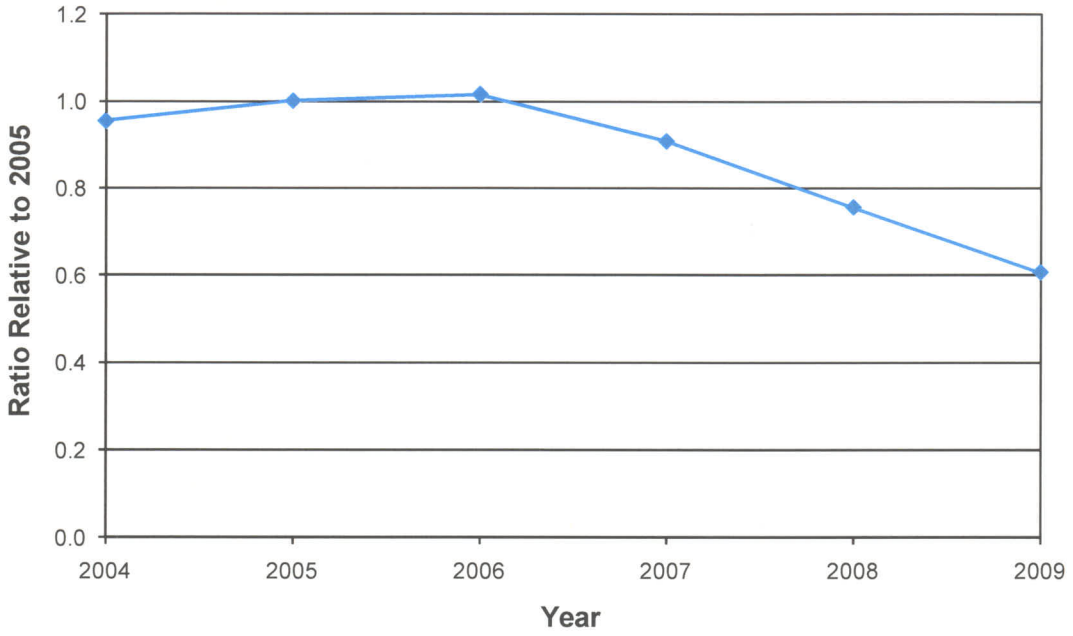

Table 2
Impact of Accounting for Reduced Operation of Vehicles Subject to the Off-Road Regulation in 2009

Source	Pop	Activity (hours/day)	Fuel Cons. (gal./day)	NOx (ton/day)	PM (ton/day)
DOORS LU	156,929	455,444	2,339,322	287.92	15.36
DOORS LU-A	156,929	309,702	1,590,739	195.79	10.44

Having adjusted the OFFROAD2007 model results for 2009 for vehicles subject to the off-road regulation to reflect the actual population and characteristics of those vehicles and also to account for the relative decrease in equipment operation in 2009 associated with the economic recession, the remaining question in light of Millstein and Harley is whether the adjusted OFFROAD2007 fuel consumption estimate is reasonable in light of actual 2009 California Diesel fuel sales data for vehicles subject to the off-road regulation. The first point of comparison is between the OFFROAD2007 fuel consumption value shown in Table 2 and 2009 sales of dyed Diesel fuel sales for use in off-road applications in California. As noted above, this value of 727,111,419 gallons is available from the California BOE. Converting the daily fuel consumption value in Table 2 into an annual value yields a value of 580,619,735 gallons for 2009, or about 80% of the total dyed Diesel fuel sales in California in 2009.

Unfortunately, the BOE does not have records regarding the volumes of dyed Diesel fuel that are burned by the different categories of non-road sources where its use is allowed (e.g., off-road equipment, ships, and trains). Such estimates for California are, however, available from the EIA. Specifically, EIA publishes estimates of non-road Diesel fuel use for four categories:

1. Farm;
2. Marine;
3. Rail; and
4. Off-highway.

EIA indicates that the off-highway category includes construction, logging, and other sources such as transportation refrigeration units. As discussed below, the off-highway category does not include mining and other sectors subject to the off-road regulation. The most recent EIA data are for 2008; they indicate that the off-highway category accounted for 14.59% of fuel used in these four categories. Using this value and the 2009 California BOE sales data, the off-highway fuel consumption of dyed Diesel in 2009 is estimated at 106,054,957 gallons.

Another issue is that significant amounts of non-dyed or "clear" on-highway Diesel fuel are burned in off-highway equipment in addition to dyed fuel. In this case, the issue can be addressed using data that are available from the California BOE for the construction industry taken from forms that must be submitted in order for firms to obtain a refund of the fuel tax paid on clear fuel. As firms have up to three years to submit these refund forms, data regarding the actual clear fuel used in off-road equipment in 2009 are not directly available; however, historical data are available. In this study, California BOE refund volumes for clear fuel burned in off-highway construction equipment for 2005 were compared to dyed fuel consumed by off-highway equipment in 2005 using 2005 California BOE dyed fuel data and EIA data for 2005.[12] The clear fuel volume for construction reported by BOE in 2005 was 44,631,475 gallons and represented 25% of total fuel estimated to be consumed in off-highway equipment. Using this same 25% value for 2009 increased the estimated off-highway equipment fuel consumption in 2009 to 132,568,697 gallons.

A final issue with respect to the 2009 fuel consumption estimate is ensuring that it reflects fuel consumed in vehicles subject to the regulation other than that used in the off-highway sector. As noted above, the off-highway sector does not include mining, and separation of mining and construction fuel use is not possible in the OFFROAD2007 model. Recent survey data for California published in reference 5* indicate that mining equipment accounts for about 1% of the total Diesel-fueled equipment in the construction and mining sector. However, it is likely to be used more frequently than construction equipment. In order to be conservative, it is assumed here that Diesel fuel use in mining equipment subject to the off-road regulation is 10% of that used in the off-highway category and the total 2009 fuel use estimate increases to 145,825,567 gallons.

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* See Table 70.

To account for fuel used in vehicles subject to regulation in sectors other than construction and mining, the ratio of total fuel consumed in vehicles subject to the regulation estimated using the DOORS version of OFFROAD2007 relative to that estimated using the model for the construction and mining sector was determined.* This value was 1.124. Application of this value raises the 2009 fuel consumption estimate to a final value of 163,907,937 gallons.

Recalling that the adjusted OFFROAD2007 fuel consumption for 2009 was 580,619,735 gallons, the ratio between that value and the independently derived fuel consumption estimate of 163,907,937 gallons is 3.54. The conclusion to be drawn from this result is that even after all of the updates described above are made to OFFROAD2007, the model overestimates off-road vehicle activity, and therefore NOx and PM emissions, by a factor of 3.54. The only alternative explanations are (1) that there are substantial errors in the OFFROAD2007 brake specific fuel consumption values, or (2) that far more fuel is being consumed than estimated above.

If the brake specific fuel consumption factors in the OFFROAD model are too high, then fuel specific emission factors (e.g., grams of pollutant emitted per kilogram of fuel burned) would have to be changed to be much higher than they are currently. As shown in Table 1 of Millstein and Harley, the current fuel-specific emission factors from OFFROAD are in reasonable agreement with those developed independently by others. Therefore, it is highly unlikely that errors in the brake specific fuel consumption factors in OFFROAD2007 are the cause of the observed over-estimation of fuel consumption.

In order for the volume of fuel being used in the vehicles subject to the off-road regulation to be 3.54 times higher than the volume estimated here, the relative amount of dyed Diesel fuel used in off-highway vehicles would have to be much higher relative to that used in farm, rail, and marine applications than reported by EIA, or much more clear fuel than the California BOE reports as being claimed for tax refunds would have to be burned in vehicles subject to the off-road regulation

Given the other changes made to the OFFROAD2007 model, the most likely source of error that leads to the overstatement of fuel consumption is the product of the hours of operation and the load factors used in the model. Although changes in activity were accounted for using the Operating Engineer hours, those changes adjusted only 2009 activity relative to 2005 activity and did not address any problems associated with the absolute values of the annual operating hours assumed in the OFFROAD2007 model. There were no changes made here to the OFFROAD2007 load factors given the dearth of suitable data.

The results of the updates to the OFFROAD2007 estimates described above and the reconciliation of those estimates with actual fuel consumption data are summarized in Figures 4 and 5 for NOx and PM emissions, respectively. The fuel consumption related

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* While it might seem to be inappropriate to use the DOORS version of the OFFROAD2007 model for this purpose, the question being investigated is whether the absolute fuel consumption and emission values are reasonable, not whether the model estimates of relative fuel consumption between sectors are reasonable. It is the latter that is being used to make this adjustment.

Figure 4
Impacts of Updates to 2009 Baseline OFFROAD2007
NOx Emission Inventory

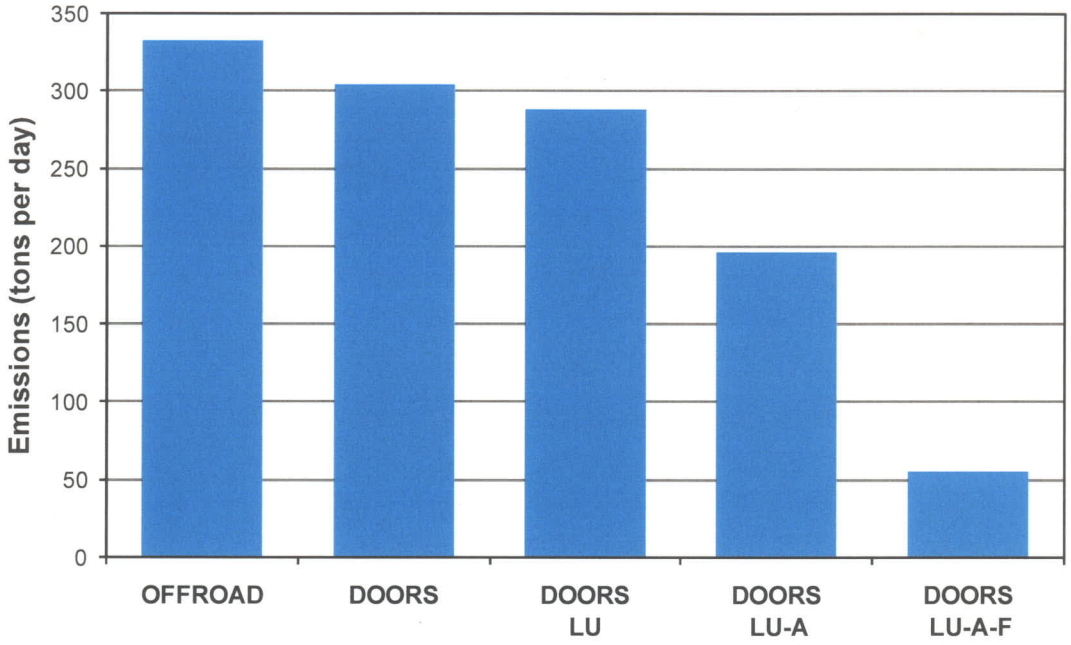
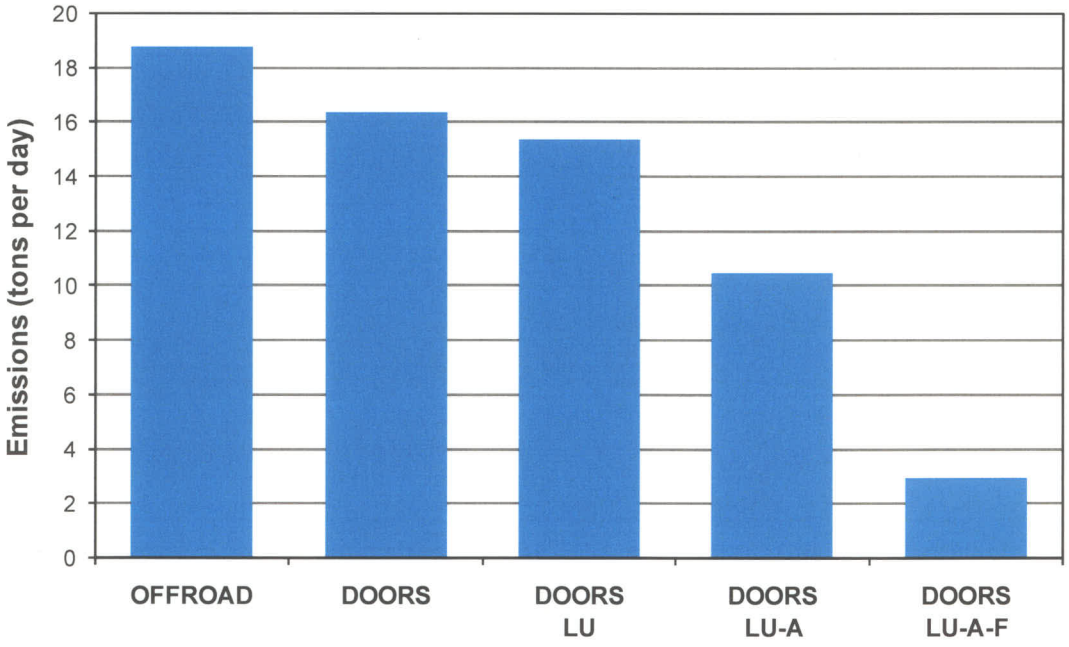


Figure 5
Impacts of Updates to 2009 Baseline OFFROAD2007
PM Emission Inventory



adjustments, labeled "DOORS LU-A-F," are shown in the rightmost columns in these two figures.

As shown in Figure 4, the updates made to the 2009 baseline NOx inventory from the OFFROAD2007 model reduce the emission estimate from 332 tons per day to 55 tons per day. The final updated inventory value is approximately 6 times lower than the baseline value estimated using OFFROAD. Similarly, as shown in Figure 5, the baseline 2009 PM inventory is reduced from about 19 tons per day to about 3 tons per day and the final updated inventory is about 6.4 times lower than estimated using OFFROAD.

The adjustments made to the OFFROAD2007 model following incorporation of the DOORS data and the adjustment for low-use equipment described above can be cast in simplified mathematical form by revising Equation (1), as shown in Equation (2) below.

$$\text{Emissions} = [(EF*Pop*AvgHp*Load*Activity*Fuel)- (EF_{LU}*POP_{LU}*LOAD_{LU}*Activity_{LU}*Fuel*A_{LU})]*A_A*A_{FC} \qquad (2)$$

where:

- Subscript LU denotes low-use equipment;
- A_{LU} is the ratio of 100 hours per year of operation to the default OFFROAD2007 hours of operation (determined here to 0.161 for 2009);
- A_A is the ratio of the average actual hours of operation per piece of equipment to the default OFFROAD2007 average (determined here to be 0.680 for 2009); and
- A_{FC} is the ratio of actual fuel consumption to fuel consumption estimated by the OFFROAD2007 model (determined here to be 0.282 or 1/3.54).

Forecasting Future Emissions

As shown in Figures 1 and 2, the baseline emission inventory for the off-road regulation includes forecasts of future emissions through the year 2025. These forecasts, like the 2009 emission inventory, are based on the OFFROAD2007 model and reflect CARB assumptions regarding growth of the vehicle fleet subject to the off-road regulation over time. As noted in reference 1, OFFROAD2007 is based on assumed monotonic growth factors for Diesel vehicles in the different industry sectors subject to the regulation. The emission forecasts also reflect the impact of more stringent emission standards that apply to new vehicle engines in the future. Overall, the result is that despite growth in the vehicle population, baseline emissions will decline over time due to the impact of the more stringent emission standards that apply to newer vehicles.

In forecasting emissions forward from the updated 2009 baseline, there is no reason to alter the updates related to the DOORS and low-use-vehicle data. In addition, there is no reason to alter the changes made to reconcile the over-estimation of fuel consumption inherent in the OFFROAD2007 model's activity and load factors. There is, however, uncertainty related to the question of whether the update made in 2009 to relative activity made to account for the economic recession should remain in place for future years.

Given the monotonic growth rates upon which the OFFROAD2007 model is based and the uncertainties associated with vehicle growth forecasts in the sectors subject to the regulation, the simplest approach to highlighting the impact of the updates on future emissions is to assume no change in relative activity (e.g., set $A_A = 1$ in Equation 2) and to rely on the growth rates already in the OFFROAD2007 model. This approach is also consistent with that used by CARB to create the baseline inventory.

The updated baseline emissions forecast using this approach are shown in Figures 6 and 7 for NOx and PM, respectively, along with the CARB baseline inventory values from Figures 1 and 2. In order to maintain consistency of assumptions over time, the relative activity adjustment shown for 2009 in Figures 4 and 5 has been omitted for 2009 in Figures 6 and 7. As a result, the inventory values shown for that year in Figures 6 and 7 are higher than the available data indicate they should be. Also shown in these figures are the emission reduction targets CARB established at the time the off-road regulation was adopted, taken from reference 2.

As shown, the updated baseline emission inventory for NOx is far lower than either the CARB baseline or the CARB emission targets over the entire period through 2025. The same general trend is observed for the PM inventory until 2016, at which point the updated baseline and CARB emission targets converge.

Figure 6
NOx Emissions from Vehicles Subject to the Off-Road Regulation

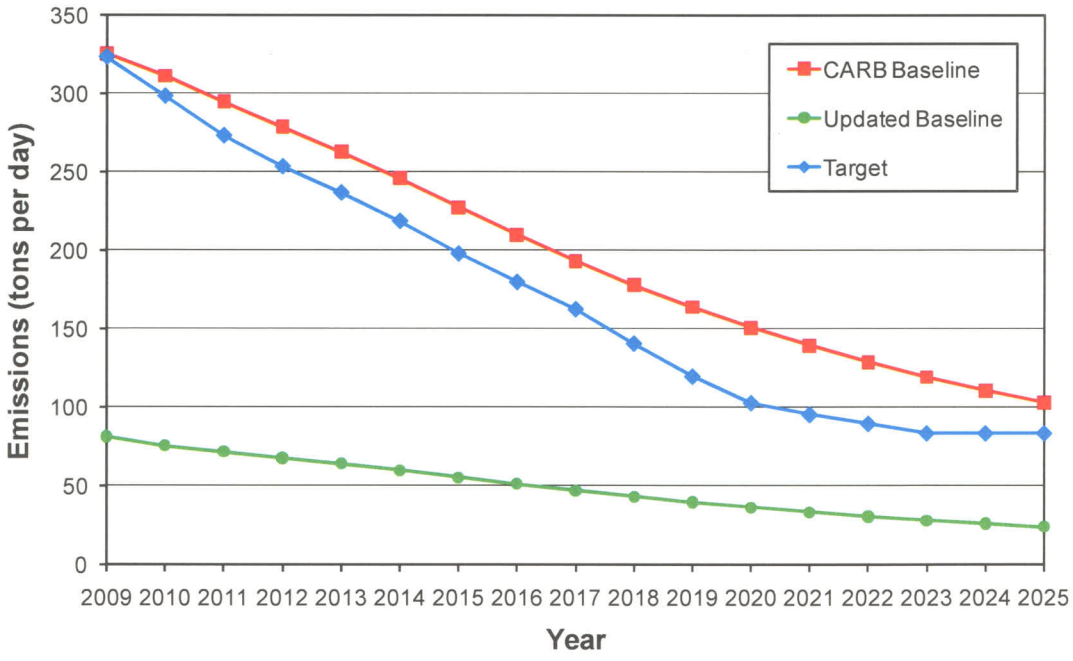
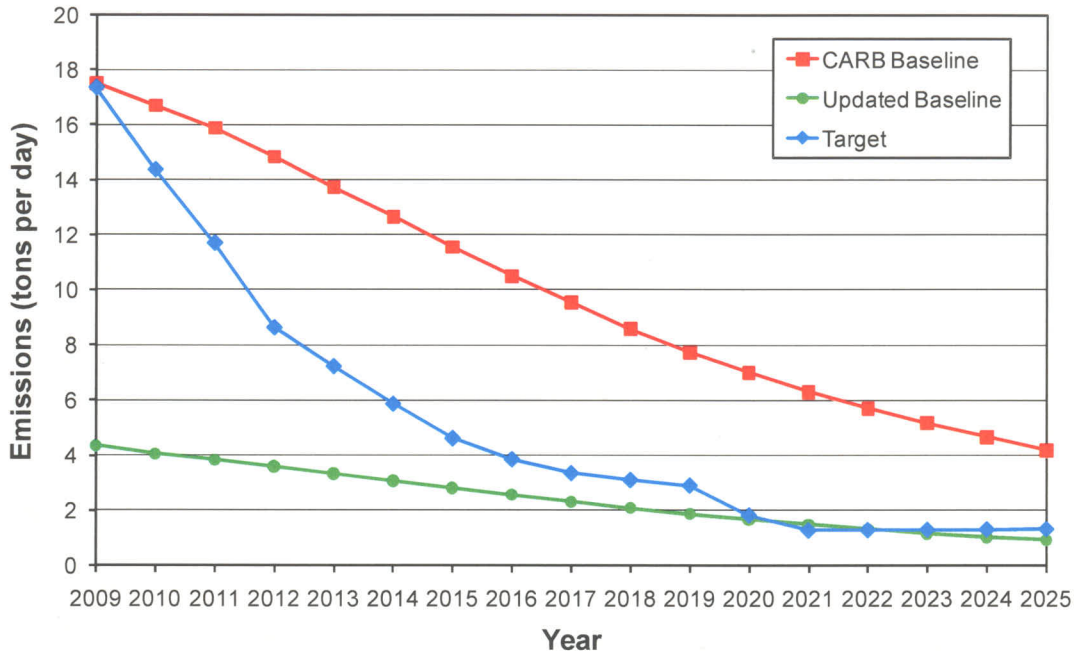


Figure 7
PM Emissions from Vehicles Subject to the Off-Road Regulation



References

1. State of California Air Resources Board, Resolution 07-19, July 26, 2007.

2 State of California Air Resources Board, Initial Statement of Reasons, Technical Support Document, and Appendices, Proposed Regulation for In-Use Off-Road Diesel Vehicles, April 2007.

3. Millstein, D.E., and Harley, R.A., "Revised estimates of construction activity and emissions: Effects on ozone and elemental carbon concentrations in southern California," *Atmospheric Environment* 43:6328-6335, 2009.

4. Kean, A., et al., "A Fuel-Based Assessment of Off-Road Diesel Engine Emissions," *J. Air & Waste Manage. Assoc.* 50:1929-2939, 2000.

5. Baker, R., "Characterization of the Off-Road Equipment Population," Eastern Research Group, Final Report to the California Air Resources Board

6. See https://secure.arb.ca.gov/ssldoors/doors_reporting/reporting.php

7. CARB Enforcement Division Advisory, Number 394, Revised November, 2009.

8. Personal Communication with Mike Terris, CARB, February 17, 2010.

9. Personal Communication with Mike Kennedy, AGC, March 31, 2010.

10. Personal communication with Philip Bishop, California Board of Equalization, April 7, 2010.

11. "Fuel Oil and Kerosene Sales 2008," Energy Information Administration, December 2009.

12. "Fuel Oil and Kerosene Sales 2005," Energy Information Administration, December 2006.