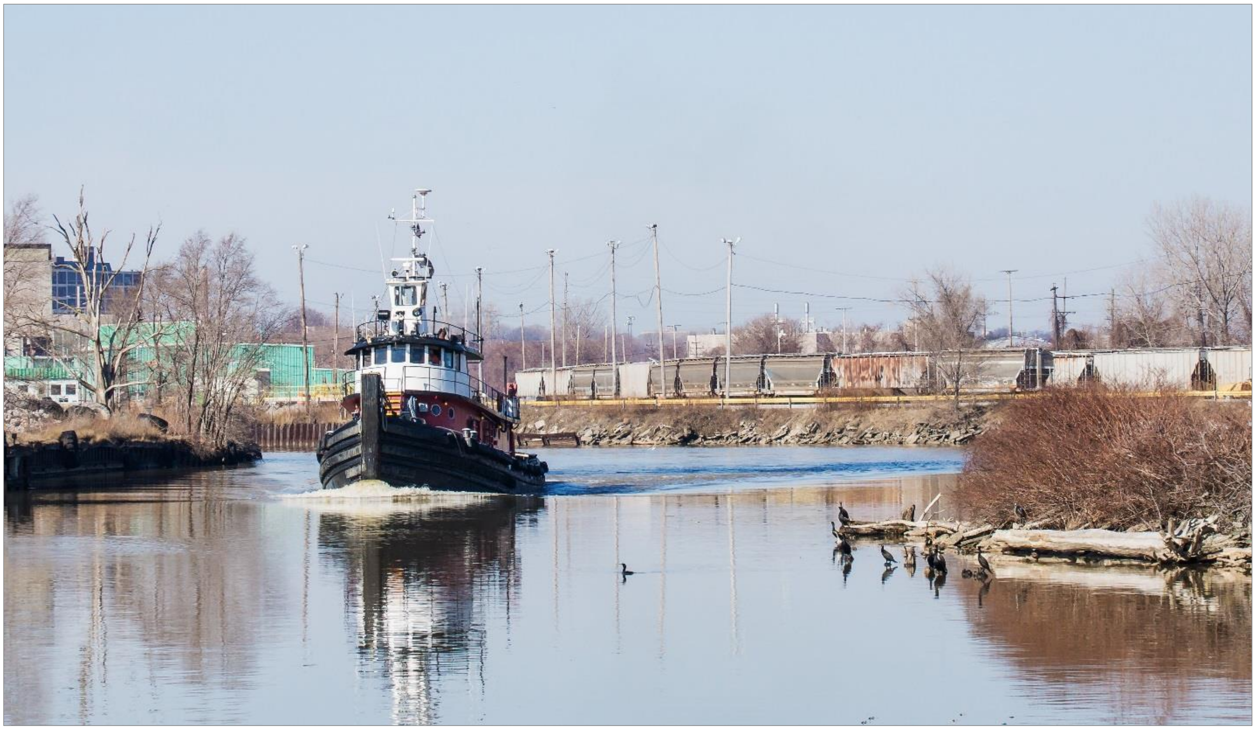

Impact of Updated Service Life Estimates on Harbor Craft and Switcher Locomotive Emission Forecasts and Cost-Effectiveness

Final Report

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Diesel Technology Forum and
Environmental Defense Fund

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PREFACE

The Diesel Technology Forum and the Environmental Defense Fund undertook this analysis to better understand the potential opportunity the Volkswagen $2.9 billion Environmental Mitigation Trust could have on reducing diesel emissions from older marine workboats and switcher locomotives. The Trust is established for the primary purpose of reducing emissions of oxides of nitrogen (NOx), an ozone or smog forming compound. States, as beneficiaries of the Trust, maintain an account with the Trust and the amount therein is determined by the population of passenger vehicles found to have been outfitted with technology to sidestep emission requirements. The Trust allows for the replacement or repower of heavy-duty vehicles and equipment as heavy-duty applications are the largest contributors to NOx emissions. Repowering large applications, including switch locomotives and marine workboats, is an eligible category of funding through the Trust.

While much is known about the useful life and cost effectivity for NOx reduction from heavy-duty trucks and buses, a similar understanding about these large applications is not as robust. This research seeks to better understand the useful life of these engines and cost effectiveness of reducing NOx when repowering older engines with new cleaner models that come with technology to meet recent emissions requirements. These workboats and switch locomotives operate at marine ports located in or adjacent to major cities and contribute to hazardous smog pollution. Replacing these older engines with new clean diesel models can have an immediate and significant beneficial impact in reducing emissions for sensitive communities.

Starting in 2015, new clean diesel engines used in marine applications and switcher locomotives in the United States are required to meet the most recent Tier 4 emissions standards for off-road engines. Relative to previous generations of technology, the latest clean diesel technologies can reduce emissions, including NOx and fine particle emissions (PM2.5), by 88 percent to 95 percent. While the latest clean diesel technologies are ready and available to reduce emissions, the U.S. Environmental Protection Agency (EPA) estimates that by 2020, unless additional action is taken, only 5 percent of the switch locomotive and 3 percent of the marine workboat fleets will be powered by these clean technologies.[1]

State governments now have an opportunity to get more of these clean technologies out in the field to deliver immediate emission reductions for communities near port operations. Through the Trust, states may use Trust revenue to fund up to 40 percent of the cost and installation of a new cleaner engines that power marine workboats and switch locomotives. Equipment owned by government agencies may receive up to 100 percent of the new engine cost. Other incentive programs are also available for states and others to pursue these projects. The Diesel Emission Reduction Act, managed by the EPA, is a federal program that provides grant funding to help with the cost and installation of new cleaner engines or upgrades to older engines that improves emission performance. Some states and port authorities also manage similar incentive programs to help vessel and switcher owners with the cost and installation of new

[1] U.S. EPA. *National Port Strategy Assessment: Reducing Air Pollution and Greenhouse Gases at U.S. Ports*. EPA-420-R-16-011. September 2016.

cleaner engines or retrofits. Incentive funds from these types of programs can be used in a cost-effective manner to provide significant emission reductions that benefit community health, as well as reduce climate impacts.

This research demonstrates that repowering older engines found in marine workboats and switch locomotives with newer cleaner models is one of the most cost-effective project types to reduce NOx emissions. This research also demonstrates that these engines are long lived and replacing these engines sooner would generate emission reduction benefits for many sensitive communities located near ports and rail yards.

Executive Summary

In this report, we discuss several factors that affect both costs and emission reductions from commercial marine vessels (CMVs) and switcher locomotive control projects, which are relevant to evaluating cost-effectives for the purposes of allocating VW mitigation funds and other diesel grants. One critical factor that is a major input for marine workboat emission reduction estimates, and was a primary focus of this analysis, is the expected remaining service life of the engine to be retrofitted or replaced. EPA regulates commercial marine engines using three categories based on engine cylinder displacement. Category 2 engines have displacements of 7 to 30 liters per cylinder and are installed primarily in larger workboats like push or towboats or off-shore support vessels. Category 1 engines have lower displacement volumes and are widely used. Not the subject of this study are Category 3 engines that have higher engines displacements and are used only in large ocean-going vessels.

The primary conclusions of this report are as follows:

- Available data suggests that the service life of Category 2 commercial marine vessels is 50 years, over two times longer than EPA's 23-year estimate. Additional research is needed to determine whether the 13-year service life estimate for Category 1 vessels with larger horsepower engines should be updated.
- EPA estimated that the 2008 Heavy Duty Locomotive and Marine Rule[2] would by 2040 reduce NOx and PM2.5 emissions for Category 2 vessels by 333,925 tons and 8,758 tons, respectively. Using the 50-year service life estimate, we calculate that the rule will only reduce NOx and PM2.5 emissions by 161,167 tons and 3,537 tons, respectively. Actual NOx and PM2.5 emission reductions are 51.7% and 59.6% less than predicted in EPA's Rule.
- NOx Emission inventories for Category 2 vessels could be underestimated by 8 tons per day in the New York City nonattainment area; 4 tons per day in Houston; and 0.3 tons per day in Baltimore. These additional NOx emissions represent a cost-effective opportunity to help local areas meet their air quality standards.
- The cost-effectiveness of repowering Category 2 vessels ranges from \$1,000 to \$5,000 per ton of NOx and is \$1,000 to \$20,000 per ton of NOx for switcher locomotives.
- Upgrading marine vessel and switcher locomotive engines is one of the most cost-effective ways to reduce NOx and PM2.5 emissions in the mobile source sector. These reductions can rapidly bring substantial health benefits to at-risk communities.

[2] U.S. EPA. *Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression-Ignition Engines Less Than 30 Liters per Cylinder.* 40 CFR Parts 9, 85, et al. June 30, 2008.

Service Life and Attrition for Category 1 and 2 Commercial Marine Vessels

Based on analysis of in-use surveys and vessel registration data, fleet turnover of Category 2 commercial marine engines has been slower than the EPA originally estimated, likely because the service life of the propulsion engines is much longer than originally estimated. Available data suggests that larger Category 2 commercial marine engines' service life is 50 years on average, substantially higher than the 23 years estimated by EPA. This 50-year service life is consistent with EPA's estimated service life for similarly powered switching locomotives.

A longer service life reduces fleet turnover rate to cleaner, lower emitting engines, and therefore increases future year emission estimates. Higher emission forecasts strengthen the case for and highlight the need to support additional programs to reduce commercial marine emissions. Figure ES-1 shows how revising the Category 2 service life affects forecasted Category 2 emission reductions compared with the EPA RIA forecast.

The EPA RIA estimated that NOx emissions from Category 2 vessels would be reduced from 432,539 tons in 2000 to 98,614 tons in 2040, based on a 23-year service life for these engines.[3] Using a 50-year service life, this analysis suggests that by 2040 NOx emissions will only be reduced to 271,372 tons. Ultimately, the EPA rule may only reduce NOx emissions by 37%, instead of the original forecasted 77% reduction.

For PM2.5 emissions, the EPA RIA estimated that emissions from Category 2 vessels would decline from 12,622 tons in 2000 to 3,864 tons in 2040. Using a 50-year service life, this analysis suggests that PM2.5 emissions in 2040 would be 9,085 tons. Therefore, the EPA rule may only reduce PM2.5 emissions by 28%, compared to the original forecasted 69% reduction.

Due to limited resources and data, this analysis did not re-evaluate the EPA RIA emissions from Category 1 vessels, which estimated that Category 1 vessels have an average service life of 13 years. According to the EPA RIA, the Category 1 vessels range in size from an average of 43kW (57hp) to 1,492kW (2001hp). The larger Category 1 engines (>560kW/750hp) represented 58% of the Category 1 fleet and had much longer average activity hours (943 vs 4,503).[4]

Based on our analysis of Category 2 engines, the service life of larger (>560kW) Category 1 commercial marine engines may also be longer than EPA estimates. Smaller Category 1 vessel engines (<560kW) may be more easily replaced through normal vessel maintenance, however, the complications involved in replacing the larger Category 1 engines (>560kW) could result in a service life greater than 13 years. A specific survey of vessels would be required to determine whether larger Category 1 engines have a longer service life than what was estimated in the EPA RIA.

[3] U.S. EPA. Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder.EPA420-R-08-001. March 2008. p.3-52 and 3-53.
[4] EPA RIA, p.3-9.

This analysis also did not re-assess the emissions from switcher locomotives. The EPA RIA assumed an average service life of 50 years for switcher locomotives, which appears to be consistent with industry standards.

While our analysis suggests that the emission reductions from Category 2 vessels was less than what had been forecasted by EPA, the 2008 Locomotive and Marine rule has nevertheless been tremendously successful in reducing diesel emissions. EPA estimated that by 2040 the rule would reduce annual emissions of NOx and PM2.5 by 1,144,000 and 37,000 tons, respectively.[5] The Category 2 vessels that we were able to analyse only represent a portion of the diesel fleet covered the 2008 rule. Our analysis of Category 2 vessels suggests that total emission reductions from the 2008 rule for NOx and PM2.5 would have been 172,758 (15%) and 5,221 (14%) tons less than EPA originally projected.

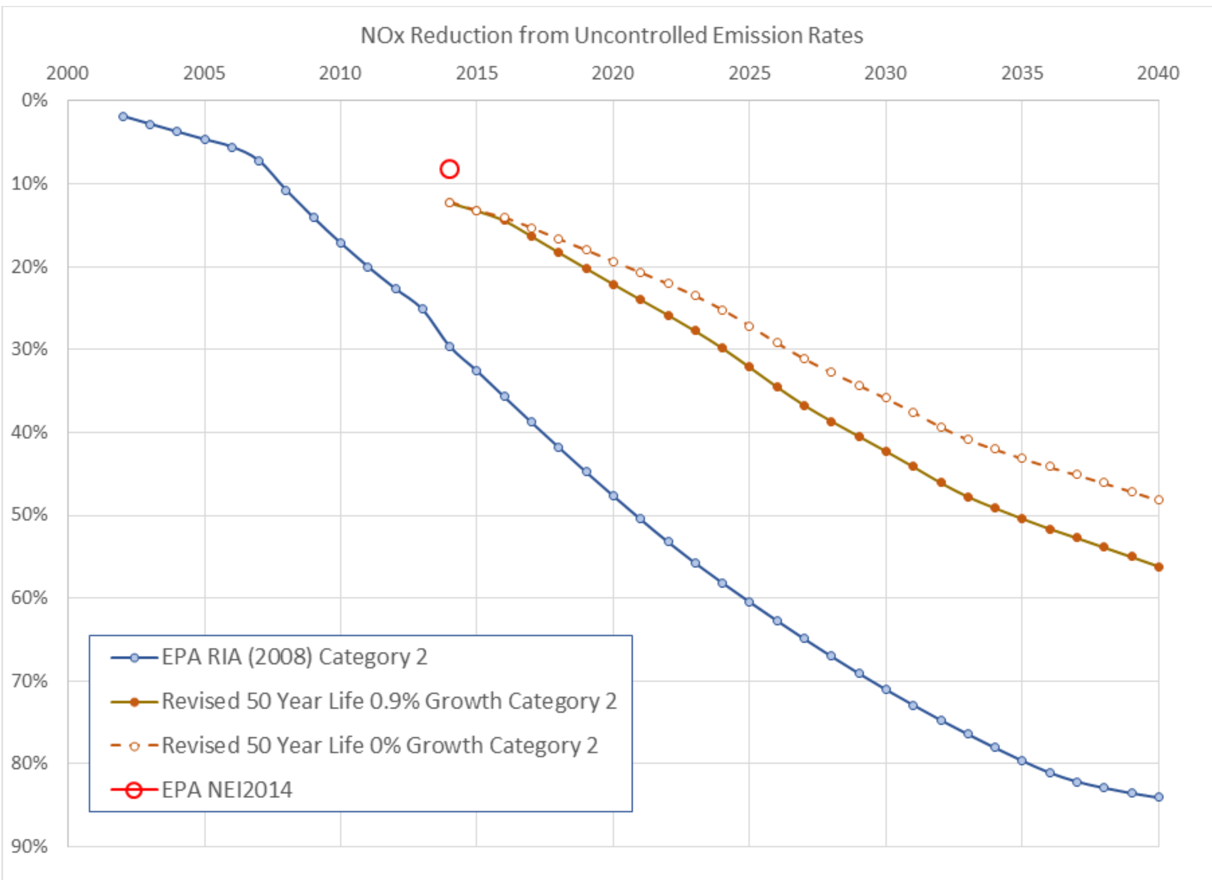

Figure ES-1. Revised NOx emission reduction from uncontrolled levels using surveyed and forecasted age distributions for Category 2 engines.

[5] EPA RIA, p.ES-6.

Regional Emissions Inventories

To assess the impact Category 2 vessels could have on local areas, regional emission inventories for the Houston, Baltimore, and New York metropolitan areas were gathered from EPA and other published sources. Under the Clean Air Act, state air quality agencies develop emission forecasts for areas that are not in attainment with Federal air quality standards for ozone, PM2.5 and other pollutants. A longer service life for commercial marine engines would necessitate a revision of the forecast emission inventory for commercial marine vessels. With a longer service life for just Category 2 marine engines, we estimate a 20% increase in commercial marine NOx emissions from the Category 1 and 2 vessels in 2017 and 35% increase in emissions in 2023 compared to previous EPA estimates. The emission increases result in about 4 tons of NOx per day in the Houston metropolitan area, 8 tons per day or more in the New York metropolitan area, and substantially less than 1 ton per day in Baltimore.

Emission forecasts in Houston and New York regions indicate an opportunity for significant NOx reduction from commercial marine and locally-based (yard and/or short haul) locomotive projects. The Baltimore region had considerably lower marine and locomotive emissions, and therefore less, though still potentially important, opportunities for marine and locomotive emission reductions.

Engine Retrofit or Repower Project Cost Effectiveness

Previous emission reduction estimates from marine vessel engine repowers and retrofits are likely underestimated because remaining service life of the engine being replaced or retrofitted were underestimated. New data suggests that using a 50-year service life, each engine retrofit or repower project results in substantially greater project total emission reductions. Estimates of longer marine engine life developed in this work corresponds to EPA estimates of engine life for similarly powered yard locomotives. Based on greater project emission reductions, each project becomes more cost effective, which can make them more desirable for voluntary programs like DERA and the VW mitigation trust fund.

The cost effectiveness of the Category 2 commercial marine projects evaluated in the project range from less than $1,000 to $5,000 per ton of NOx removed, based on the revised 50-year service life. In addition to service life, the primary factors affecting commercial marine cost effectiveness is hours of operation and average engine load. Push boats that push large barges represent more cost-effective project opportunities because they work more hours and have higher engine loads, however, these vessels frequently operate on large waterways outside of nonattainment areas. Tugboats assisting larger ships and performing other general work more frequently operate in ports adjacent to metropolitan areas, many of which are nonattainment for EPA air quality standards. These tugboats represent a source category with substantial opportunities for cost-effective retrofit or repower projects.

For the switcher locomotive cost-effectiveness analysis, we used the EPA estimated service life of 50 years. Using the EPA estimate, switcher locomotive engine retrofit or repower project cost effectiveness range from $1,000 to $20,000 per ton of NOx removed. The low-end cost effectiveness is based on remanufacture of an existing engine, and higher cost effectiveness is based on engine repower during a locomotive rebuild.

Commercial marine and switching locomotive marine engine upgrade or repower projects are very cost-effective owing to high engine rated power, hours of operation, engine load, and long remaining service life. The emission benefits associated with these projects will accrue quickly and persist for many years.

1.0 ATTRITION, SERVICE LIFE AND IN-USE AGE DISTRIBUTION

1.1 Introduction

In this section, a review is presented of the service life, attrition curve shape, growth rate on the in-use age distribution of Category 1 and 2 commercial marine vessels (e.g., tugs, fishing vessels, work boats, ferries and excursion vessels) and switch locomotives, and the effect these factors have on the emissions inventory. This evidence suggests that the service life of commercial marine vessels is 50 years, and those engines may or may not be used in the same vessel throughout the engine lives. The choice of the NONROAD attrition curve used by EPA or alternative functions does not significantly affect age distribution estimates.

EPA regulates commercial marine engines using three categories based on engine cylinder displacement. EPA defined Category 2 engines, the primary focus of this analysis, to have engine displacements of 7 to 30 liters per cylinder and are installed primarily in larger workboats like push or towboats. Category 1 engines have lower displacement volumes and are widely used. Not the subject of this study are Category 3 engines that have higher engines displacements and are used in large ocean-going vessels.

A method is presented below to forecast fleet age distribution using a longer service life estimate, and revised emission reductions are presented and compared with previous age distribution estimation methods and recent surveys of smaller commercial marine vessels. The longer life results in lower emission reductions from natural fleet turnover than historically predicted by the EPA heavy duty locomotive and marine engine rule, and local forecasts by state air quality agencies.

1.2 Background

US national and regional commercial marine and locomotive emission inventories often rely on methodology from the EPA's Regulatory Impact Analysis (RIA) for the 2008 heavy duty locomotive and marine engine rule.

EPA RIA emission estimation methodology is typical of off-road engine emission inventories. Emissions are estimated as the product of aggregate work activity (in units of kilowatt-hours or horsepower-hours) and emission factors (grams per kilowatt). Kilowatt-hours is the product of engine population, hours of activity per engine and engine load. Engine load is estimated as the rated power of the engine multiplied by an equipment type specific load factor. To estimate locomotive work activity (work units in horsepower-hours is used more commonly with locomotives), EPA primarily relied on detailed fuel consumption data (separately for line-haul and switching engines), fleet size, and fleet composition provided by industry sources to estimate aggregate activity. Locomotive fuel consumption can be converted to horsepower-hours using typical work-specific fuel consumption rates (in units of gallons/hp-hr) and is directly related to engine power and load factor.

Activity (kW-hr) = Population x Hours x Engine Rated Power x Load Factor

Engine population can be difficult to estimate because offroad engines are typically not required to be registered. EPA RIA estimated the population of engines and locomotives by model year in base year 2002 for marine and 2005 for locomotive engines from historical sales or in-use population derived from a market research firm (Power Systems Research [PSR]) and industry sources, respectively. EPA applied attrition (scrappage) and growth assumptions to estimate the future year age distribution, which determines the effect of emissions standards on future year emissions.

In the EPA RIA, average hours of activity per engine (see Table 2-1) was estimated based on average activity estimates from equipment surveys. EPA did not include a use-by-age factor (annual hours of use typically declines with engine age) for commercial marine activity but did implement a use-by-age factor for older locomotives.

Table 2-1. EPA (2008) RIA annual hours of use.

Engine Type	Annual Activity (hours per year per engine)
Commercial Marine	
Category 1 Propulsion	<600 kW: 943 hours >600 kW: 4503 hours
Category 2[6]	Tow boats (tugs of all types): 3306 hours Ferries: 1356 hours Offshore Support: 6060 hours Average All: 3882 hours
Auxiliary	<600 kW: 742 hours >600 kW: 2500 hours
Locomotive[1]	
All	Line-Haul: 4350 hours Switch: 4450 hours

[1] Average estimates shown here. Activity is estimated to decline by age as described in this report.

Of all inputs to off-road engine activity, load factor estimates are the most uncertain because load factor estimates are often based on assumptions from marketing research studies. Special studies are required to accurately estimate engine loads across all modes of operation (including idling). EPA RIA assumptions for commercial marine engines were based on a single overall load factor to account for all in-use operating modes throughout an engine's life. EPA RIA locomotive load factors were based on in-use studies of time in mode (called notches on locomotives) performed in support of the EPA (1998b) initial locomotive rulemaking that informed test cycles for switching and line-haul locomotives.

Population multiplied by average annual hours of activity per engine is the most useful method to estimate activity of the marine or locomotive fleets. Activity attrition combines both expected reduction in (1) population and (2) activity as engines age. The combination of

[6] Backcalculated from hp-hr, load factor, total power, and utilization rate in Table 3-12 of the 2008 RIA.

population and activity attrition, from the EPA RIA, is summarized for commercial marine and locomotive engines:

- Commercial Marine Engine
  - Historic and Forecasted Sales
  - Annual Attrition
    - Attrition Function by Age Relative to the Median Life
    - Median (Service) Life
      - 13 years for Category 1 propulsion
      - 17 years for Category 1 auxiliary
      - 23 years for Category 2
  - Activity Attrition (no change in annual hours as the engine ages)
- Locomotives
  - Historic and Forecasted Sales
  - Population Attrition (End of Life: 40 years for Line-Haul; 50-year life with lower use by age until full attrition at 70 years for Switching)
  - Reduction Activity by Age (Line-Haul 8-40 years; Switch 50 – 70 years)

1.3 Attrition\Survivorship

In this section, engine attrition and survival rates are presented. Survival rate is different than age distribution because the in-use fleet age distribution characterizes the fleet's age by model year in a given calendar year and results from historic sales and survival rate. Age distribution can be used to infer average engine life, survival, and therefore relative annual attrition. Sales and attrition and therefore age distributions are influenced substantially by economic conditions and business considerations.

In the EPA NONROAD model (now part of the Motor Vehicle Emission Simulator [MOVES] model[7]), attrition rate is defined by service life (in years) and the shape of the attrition curve (which is a fixed curve shape as a function of age). The median service life is the primary variable affecting attrition of engines in NONROAD. NONROAD defines engine service life as the age when 50% of the original engines of that model year have been scrapped as described in the EPA (2008) RIA:

> ***"Engine Median Life (years) and Scrappage.*** *The engine median life defines the length of time engines remain in service. Engines persist in the population over two median lives; during the first median life, 50 percent of the engines are scrapped, and over the second, the remaining 50 percent of the engines are scrapped. Engine median lives also vary by category. The age distribution is defined by the median life and the scrappage*

[7] https://www.epa.gov/moves/moves2014a-latest-version-motor-vehicle-emission-simulator-moves

algorithm. For commercial marine diesel engines, the scrappage algorithm in the NONROAD model was used for all categories."[8]

NONROAD uses a scrappage curve to estimate year-by-year attrition; all engines of a given vintage are retired at twice the service life. It is also important to consider that, although not mentioned in the EPA (2008) RIA quote above, historic and forecasted engine sales in addition to the service life and scrappage algorithm determines in-use fleet age distribution.

The term 'service' life indicates the actual 50% median attrition age rather than 'useful' life, which is a legal definition of length of initial manufacturer's or remanufacturer's responsibility for the engine to meet its emission standard, after which the engine is typically rebuilt or scrapped. The service life is almost always much longer than the useful life because, as described in the EPA (1998b) rulemaking for locomotives quoted here, the useful life is set to the period until the first or next remanufacture (also known as rebuild), and the remanufacturer may not be the original engine manufacturer.

> *"A locomotive or locomotive engine covered by the standards contained in this action will be required to comply with the standards throughout its useful life….The minimum useful life value is intended to represent the expected median remanufacture interval for the Class I railroad locomotive fleet during the early part of the next century….For freshly manufactured locomotives it will be assumed for calculation of credits or debits that the remaining service life is 40 years, or seven useful life periods."* (EPA 1998b)

In our analysis, scrappage algorithms are compared to evaluate the impact of scrappage algorithm choice and service life and attrition rate estimates. Unfortunately, there is little evidence to support an informed choice of in-use age distribution and expected attrition rates of commercial marine, locomotive, or nonroad equipment engines. However, there have been many studies of in-use vehicles (such as passenger cars), which have sufficient historic sales and in-use registration data to compare scrappage algorithms.

One such in-use vehicle study (Jacobsen and van Benthem, 2013) was used to explore the effect that scrappage curve formulation has on attrition. Jacobsen and van Benthem (2013) estimated the year-by-year attrition rate from 1 to 19 years. We extended the study attrition estimate linearly from 19 to 32 years to complete the in-use age distribution using the simplifying assumption of no sales growth. The resulting vehicle survivorship by vehicle age and the 50% survivorship point demonstrates the result in the same form as the NONROAD model scrappage curve used in the EPA RIA.

Figure 2-1 shows the results of vehicle survivorship compared with the NONROAD scrappage curve, and best-fit versions of a Weibull, normal, and Bodek and Heywood (2008) distribution. In all cases, we estimated that the 50% scrappage point would be the same interpolated 15.7 year service life as shown in the blue circle in Figure 2-1. The NONROAD attrition curve shape is

[8] EPA, Regulatory Impact Analysis, page 3-4

fixed in NONROAD, and only service life can be adjusted to provide a best fit. The Weibull and normal distributions, and the Bodek and Heywood (2008) survival functions use two variables (one to estimate life and another that adjusts curve shape) allowing for a better fit than the NONROAD estimate. The Weibull distribution overestimates survival in early years and Heywood's function underestimates survival in early years. The NONROAD curve shows a more dramatic drop in survivorship at the service life of the vehicle, and both overestimates survival in early years and underestimates survival in later years.

It is important to note that a population distribution is not the same as an activity distribution in the case that activity declines with vehicle age. Multiplying in-use population by age specific MOVES estimates of vehicle miles travelled (VMT) results in a 50% activity survivorship point of about 12 years, or 3 years prior to the 50% population survivorship point of 15.7 years. EPA does not apply such a use-by-age function to nonroad equipment including commercial marine.

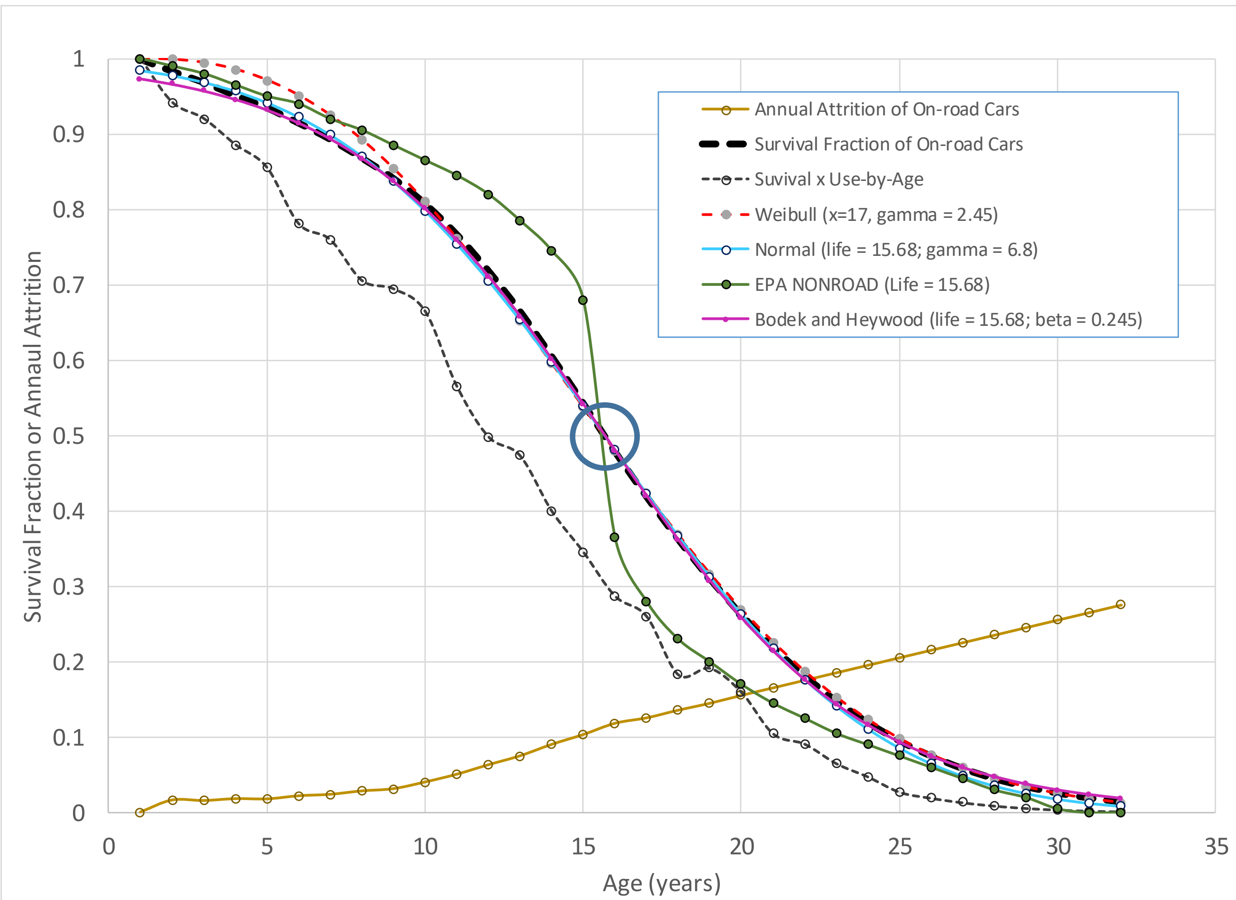

Figure 2-1. Survivorship of on-road vehicles. (Annual attrition and implied survival from Jacobsen and van Benthem (2013), Service Life indicated with a Blue Circle at 0.5 survival)

On-road vehicle survival rates are expected to differ considerably from commercial marine or locomotives for many reasons. On-road vehicles are more likely to be subject to early age attrition through higher rates of accidents, theft, or other reasons. However, on-road vehicles may also be retained longer than non-road equipment would be retained by businesses when operation becomes economically infeasible due to the risk of operational problems, lower fuel efficiency or power, and other durability problems.

This exercise was intended to show that the service life is the most important variable when predicting age distribution, and that there was no reason, based on available evidence, for us to change the NONROAD model attrition curve assumption used in the EPA RIA for our analysis. Alternative survival functions provide similar attrition rates, and evidence is not available to confidently choose one function over others. While the NONROAD attrition curve does not exactly match the survival rates for on-road vehicles, it only marginally errs due to a one coefficient fit and may better describe nonroad equipment in general accounting for the differences in the factors that determine when nonroad equipment and on-road vehicles are scrapped.

1.4 In-Use Age Distribution

In this section, age distributions are outlined, and a methodology is shown for using age distribution of commercial marine vessels to estimate engine service life. In-use age distribution and historic long-term growth rates are used to estimate average service life.

Historic sales and fleet growth affect in-use age distribution and can have a major impact on service life and the scrappage curve. To provide a basis for understanding the interplay between growth and age distribution, Figure 2-2 shows the expected age distribution using the NONROAD scrappage curve and a 50-year service life with different historic sales growth rates. With zero growth, the age distribution is exactly the NONROAD survival prediction. For a negative growth (declining sales) scenario, the age distribution shows an increase in the fleet fraction of older engines up to near the service life when attrition increases rapidly. The fleet-average age is about half the average service life when there has been a small growth rate in sales.

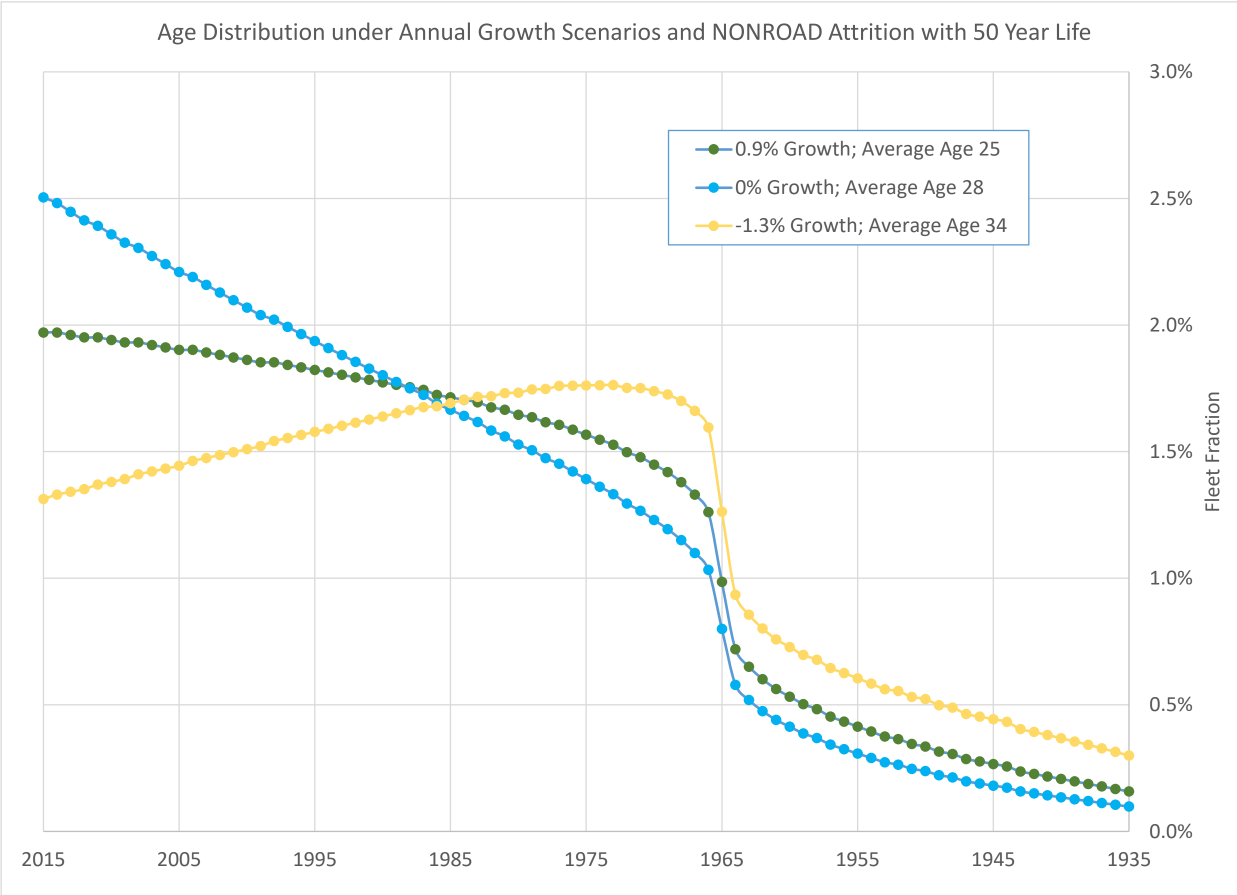

Figure 2-2. Expected age distribution with a service life of 50 years and the NONROAD attrition

1.4.1 Category 2 Commercial Marine Engines

Ramboll downloaded 2015 in-use vessel characteristics for commercial marine vessels to identify vessel population by age (Waterborne Transportation Lines of the United States (WTLUS); USACE, 2017)[9]. The vessels reviewed were tugs, push boats, offshore support, ferries, and other passenger vessels such as excursion vessels. Other vessel types in this dataset could have used Category 3 engines and therefore were not included in this analysis. The WTLUS does not identify if the original engine has been replaced during the vessel's life. In Figure 2-3, we segregated the vessels with installed propulsion power greater than 2600 hp as a proxy to estimate how Category 2 engine age distribution differs from the remaining commercial marine age distribution. We assumed that the total installed propulsion power of greater than 2600 hp for two engines together (1300 hp each) is a size proxy for Category 2 engines.

The EPA (2008) RIA estimated a long-term growth rate of Category 1 and 2 commercial marine engines of 0.9% population increase per year. However, river lock activity data indicators (USACE, 2017b) have shown that tons of material transported through inland waterways

[9] WLTUS, Calendar Year 2015, Volume 3: Vessel Characteristics.

(where push boats perform the work) has declined an average of 1.3% per year from 1999 through 2016. Because push boats are also employed near harbors and along intercoastal waterways without locks, it is uncertain if that activity has declined at all or at the same rate as the inland waterways. However, it is likely that push boat activity growth has been minimal or is in fact declining. Push boats are only one of many vessel types that may use Category 2 engines and represent about a third of the in-use Category 2 vessel population in 2015.

Based on Figure 2-2, for a positive growth rate, in-use average or median age for push boats is expected to be equal to about half the service life. However, a slower growth rate results in higher average age for the same service life.

Based on the substantial drop in fleet fraction for vessels at 50 years shown in Figure 2-3, a 50-year engine service life appears reasonable. Using the NONROAD model scrappage curve with a 50-year life and the estimated 0.9% per year growth estimate from the EPA (2008) RIA for Category 1 and 2 commercial marine engines, the predicted age distribution follows the general trend of the actual age distribution despite the peaks and valleys in historic sales as shown in Figure 2-3. In general, vessel age distributions for Category 2 vessels reflect a service life of 50 years based on the substantial drop in the fleet fraction at 50 years as well as the median and average age of the fleets, which are about half of the 50-year service life.

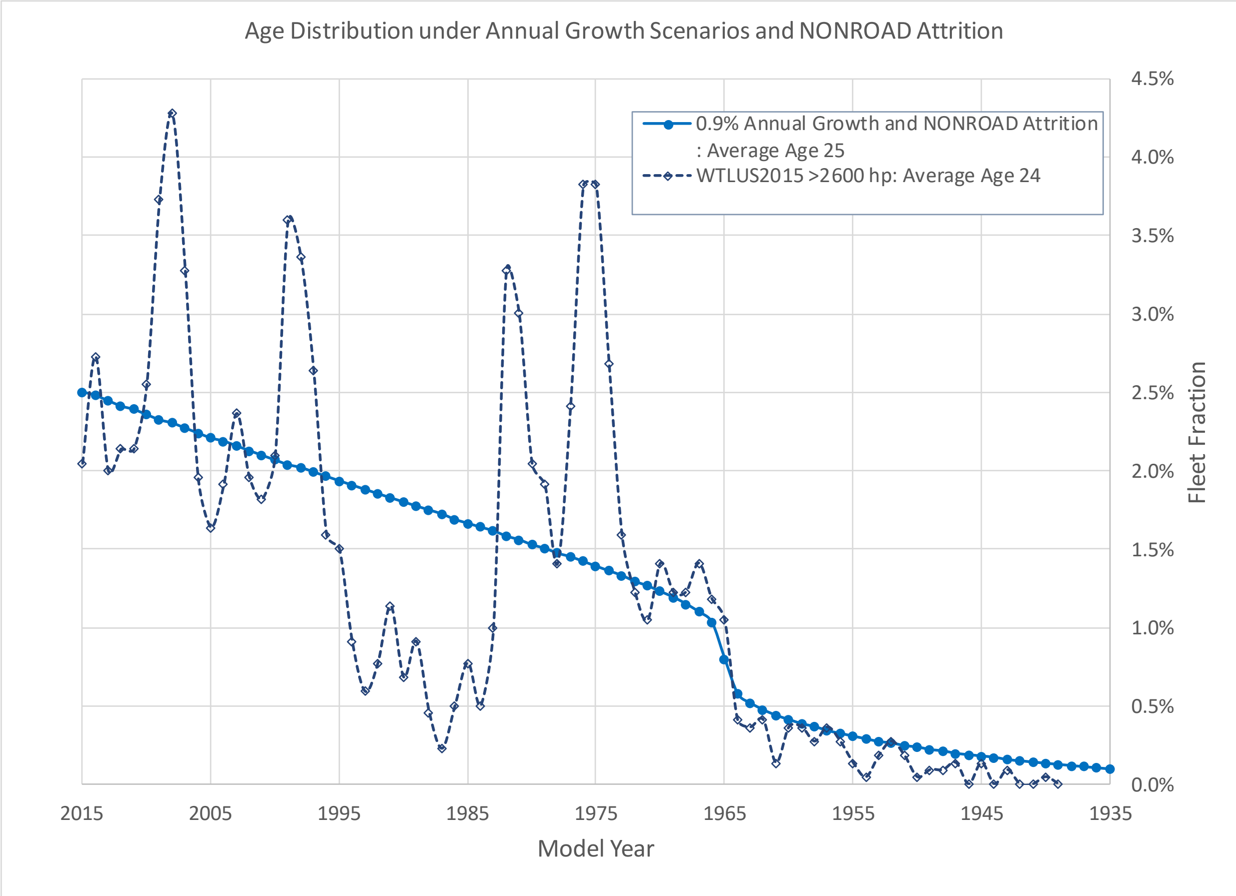

Figure 2-3. Age distribution of tugs, push boats, offshore support, ferries, and other passenger vessels >2600 hp installed power (assumed to be Category 2) from WTLUS2015 and predicted using the NONROAD scrappage curve with a 50-year life.

For comparison, EPA estimated the service life of Category 2 engines at 23 years. Under EPA's growth scenario of 0.9% per year, the fleet average engine age should be about 12 years based on the 23-year service life for Category 2 engines, and no vessel should be older than 46 years old or 1969 model year. The EPA RIA estimated the median service life of the Category 2 engines as 23 years citing an earlier EPA assessment of average age (EPA, 1998a). The fleet average age is much lower at close to half the service life, so the 23-year average age should have indicated at least a 46-year service life. The remaining question is if the engines in these vessels have been replaced during the vessel life or rebuilt to new emission standards in the vessel.

EPA (2008, 1998a) estimated commercial marine median service life based on the Power Systems Research (PSR) estimate for Category 1, and average age for Category 2[10] commercial marine engines. Because a fleet includes both new engines/vessels as well as older ones near the end of their service life, the average age of a fleet is much lower than the median or

[10] Table 15.

average service life of an engine. Likewise, EPA (1998a) noted that Category 2 commercial marine engines are similar (General Motors EMD, ALCO, and General Electric models) to those used in switching locomotives, which were estimated to have a service life of 50 years.

1.4.2 Category 1 Engines

The age distribution for the tug, push boats, offshore support, ferries, and other passenger vessels with less than 2600 horsepower installed propulsion power assumed to be a proxy for Category 1 engines is shown in Figure 2-4. The age distribution for Category 1 has an average age of 32 years owing to the large fraction (almost half) of vessels with model years from 1966 – 1982 or 49 to 33 years old in 2015. This is higher than the Category 2, which indicates that the conclusion that vessel ages are higher than expected would not change if Category 1 and 2 age distributions were combined.

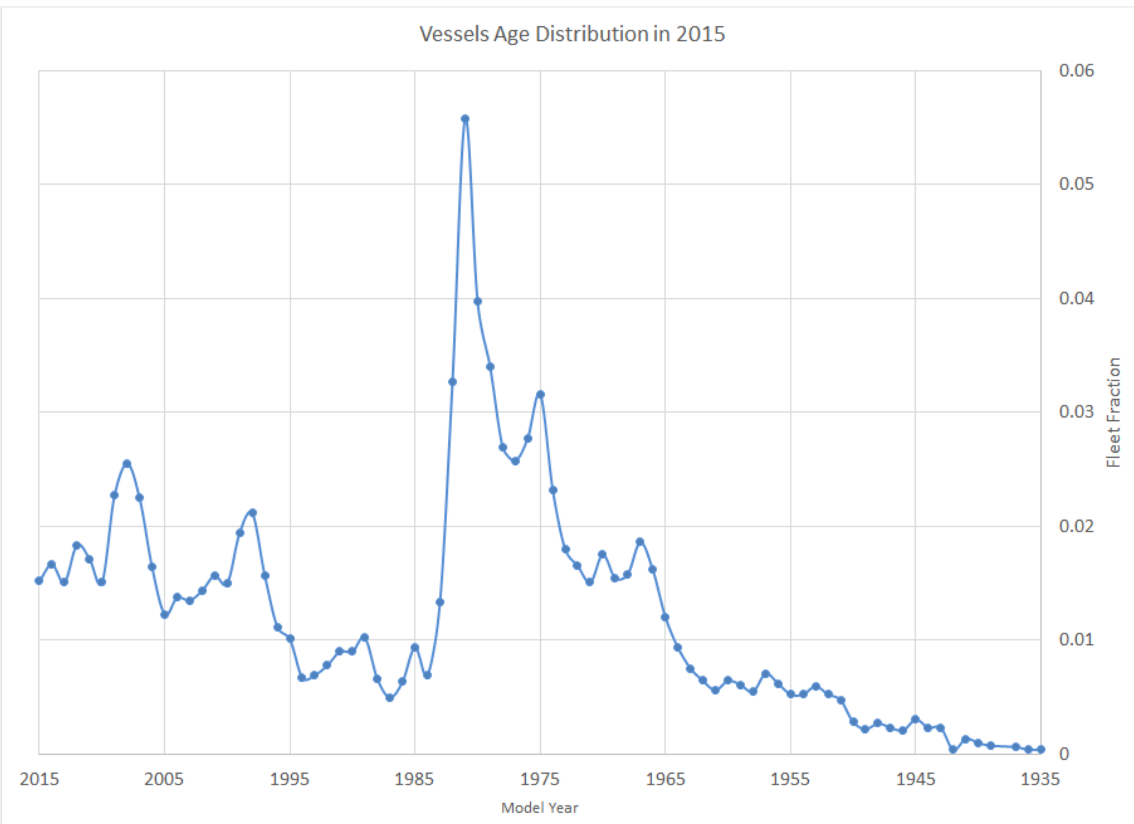

Figure 2-4. Age distribution of all tugs, push boats, offshore support, ferries, and other passenger vessels <2600 hp installed propulsion power (assumed to be Category 1).

Ramboll is aware of instances when lower power engines have been replaced in older vessels. Therefore, despite the advanced age of vessels with lower powered engines, we cannot confidently verify or contradict the 13-year engine life that EPA (2008) has used for Category 1 propulsion engines without knowing a full history of upgrades to the vessels. Vessels may have two Category 1 propulsion engines with rated power greater than 1300 hp each, but those higher power Category 1 engines will be physically larger and more expensive and so may be rebuilt rather than replaced as discussed for Category 2 engines.

1.4.3 Commercial Marine Engine Surveys

Survey results have also shown that the turnover rate is slower than EPA (2008) had forecast. The turnover rate to new engines for Category 1 and 2 engines shown in Table 2-2 represents the calendar year (CY) 2014 National Emissions Inventory (NEI) (EPA, 2015) and those from the WTLUS Coast Guard (USACE, 2017)[11] registered vessels in 2015. According to the NEI, through 2014 only 24% of the engines were controlled (meeting the Tier 1 or better emission standard) engines whereas the WTLUS registered vessels indicated 38.6% in 2015. In addition, data from the Port Authority of New York and New Jersey (PANYNJ, 2016) shows a similar slower turnover rate compared to what was reported in the NEI2014.

Table 2-2. 2014 and 2015 Calendar Year Category 1 and 2 Engine by Tier Level.
(NEI, EPA, 2008)) (WTLUS, USACE 2015) (PANYNJ, 2016)

Estimate	Pre-control	Tier 1	Tier 2	Tier 3
NEI CY2014	76.0%	5.2%	17.8%	1.0%
WTLUS CY2015	60.1%	16.3%	18.3%	5.2%
PANYNJ CY2016	71.1%	10.5%	10.5%	7.8%

The Tier 1 standard began in 2000. It could take about one year to put a new vessel in service, so 2014 represents about 14 years of turnover. The NEI2014 turnover estimate is about 1.7% per year, and about 2.6% per year from the Category 2 WTLUS for registered vessels with greater than 2600 hp installed power. The NEI2014 reported tier level distribution combined Category 1 and Category 2 engine types.

Depending on the growth rate, a 50-year service life implies an average turnover rate of 2% per year or higher and a 23-year life (used by EPA, 2008, for Category 2) implies more than 4% per year turnover rate. The NEI, WLTUS, and PANYNJ turnover rate ranges from 1.7 to 2.6% per year. The survey results indicate that engines survive longer than the service life indicated in the EPA RIA (2008), and 50 years better represents the service life of a vessel and engine.

1.4.4 Locomotives

Locomotive emissions inventory discussion in the EPA RIA focused on locomotive activity, sales and attrition, not fleet average characteristics. Annual locomotive population by age was estimated based on the prior year's age distribution and the estimation year's sales added with growth and attrition. EPA assumed 100% attrition at the end of service life without the use of an attrition curve. EPA did reduce the hours of activity with engine age as outlined here:

[11] WLTUS, Calendar Year 2015, Volume 3: Vessel Characteristics.

- Line-Haul Locomotives
  - 4350 hrs/yr 0-8 years old;
  - Decreasing linearly from 4350 hrs/yr at 8 years to 1740 hrs/hr at life end 40 years
- Switch Locomotives
  - 4450 hrs/yr 0-50 years old;
  - Decreasing linearly from 4450 hrs/yr at 50 years to 3115 hrs/yr at life end 70 years (EPA, 2008)[12]

Figure 2-5 shows how overall activity (i.e., combined population and annual hours) attrition for switching locomotives. Sample switch projects shown in Section 4 estimated 3250 hours per year, which corresponds to the activity level during the last four years of the switching locomotive life according to EPA (2008) RIA methodology.

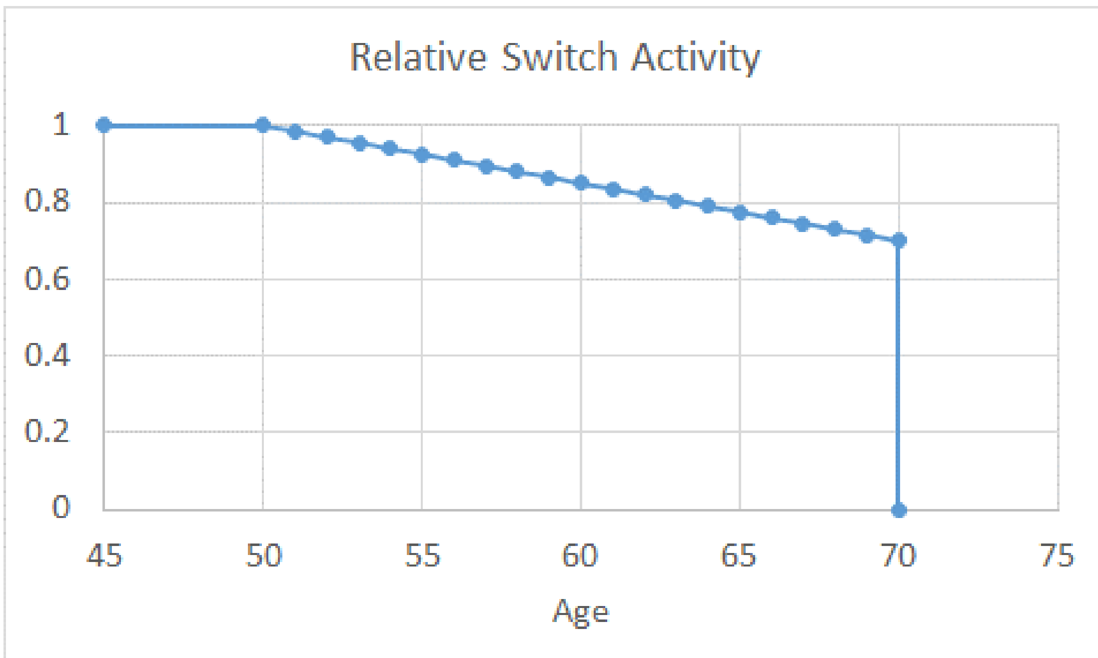

Figure 2-5. EPA (2008) RIA relative switch locomotive activity as a function of age.

Because many switching locomotive engine models (such as the EMD 645 engine) were the same as most of those identified as Category 2 commercial marine engines (EPA, 2008), the life of Category 2 commercial marine engines could be the same as switch locomotive engines.

1.5 National Emission Inventory

To revise the national inventory for commercial marine engines, we used a service life of 50 years for Category 2 marine engines. While there is an indication that vessels using Category 1 engines may also survive to 50 years on average, there is anecdotal information that some Category 1 engines have been replaced in vessels instead of being periodically rebuilt.

[12] EPA, Regulatory Impact Analysis, Table 3-70.

Therefore, we did not revise the Category 1 inventory; however, we would recommend that EPA investigate the engine service life of Category 1 vessels. Likewise, we did not revise the switching locomotive inventory because the engine service life is already at least 50 years, and there is no reliable information contradicting that estimate.

2.5.1 Fleet Age Distribution

To apply the revised engine service life adjustment to the Category 2 marine inventory, the age distribution taken from the WTLUS vessels for calendar year 2015 was used as an initial condition. The major vessel types with Category 2 propulsion engines were chosen using the International Classification of Ships by Type (ICST): Pushboats, tugboats, offshore support vessels, other carriers (Specialized) also indicated by Vessel Type Construction Characteristics (VTCC) codes as ferries, and passenger (other) identified as excursion/sightseeing.

Ramboll developed a dynamic age distribution model to account for attrition and growth for future year fleet age distributions. We use the term 'dynamic' to indicate the year-by-year change to the fleet composition, and to distinguished it from the use of a fixed age distribution. Starting with the 2015 vessel population by age, we used the NONROAD scrappage curve with the 50-year vessel service life, 0.9% growth rate (consistent with EPA RIA) and incrementally added sales to estimate fleet turnover and growth by year as described:

1. Started with calendar year 2015 Age Distribution from WTLUS
2. Applied NONROAD attrition methodology to estimate original historic sales by model year.
3. Applied one year of age to fleet and estimate remaining fleet in CY2016 after applying the NONROAD attrition rate for each age.
4. Estimated model year 2016 new sales such that fleet population is 1.009 multiplied by the calendar year 2015 population.
5. Repeated steps 3 and 4 for each new calendar year up to 2040.

For each subsequent year starting with calendar year 2016, the growth in the fleet was estimated by multiplying the total number of vessels in 2015 by 1.009 based on the assumption of EPA RIA activity growth. We incremented a year of age and applied the attrition to the 2015 fleet. The difference between the 2016 fleet total after the growth was added and the remaining 2015 fleet after one year of incremental attrition provides the expected new vessel sales in 2016. Using this same approach, each year's fleet population was estimated up to calendar year 2040. Table 2-3 show the age distribution results through 2020, and the first year's population in each calendar year represents new sales. We expect that a great majority of these vessels would employ two Category 2 propulsion engines per vessel though some may have four and others only one. We used decimal quantities for vessels when forecasting and accounting for attrition to maintain an accurate fleet total. Figure 2-6 provides a visual representation of the fleet age distribution results from this approach.

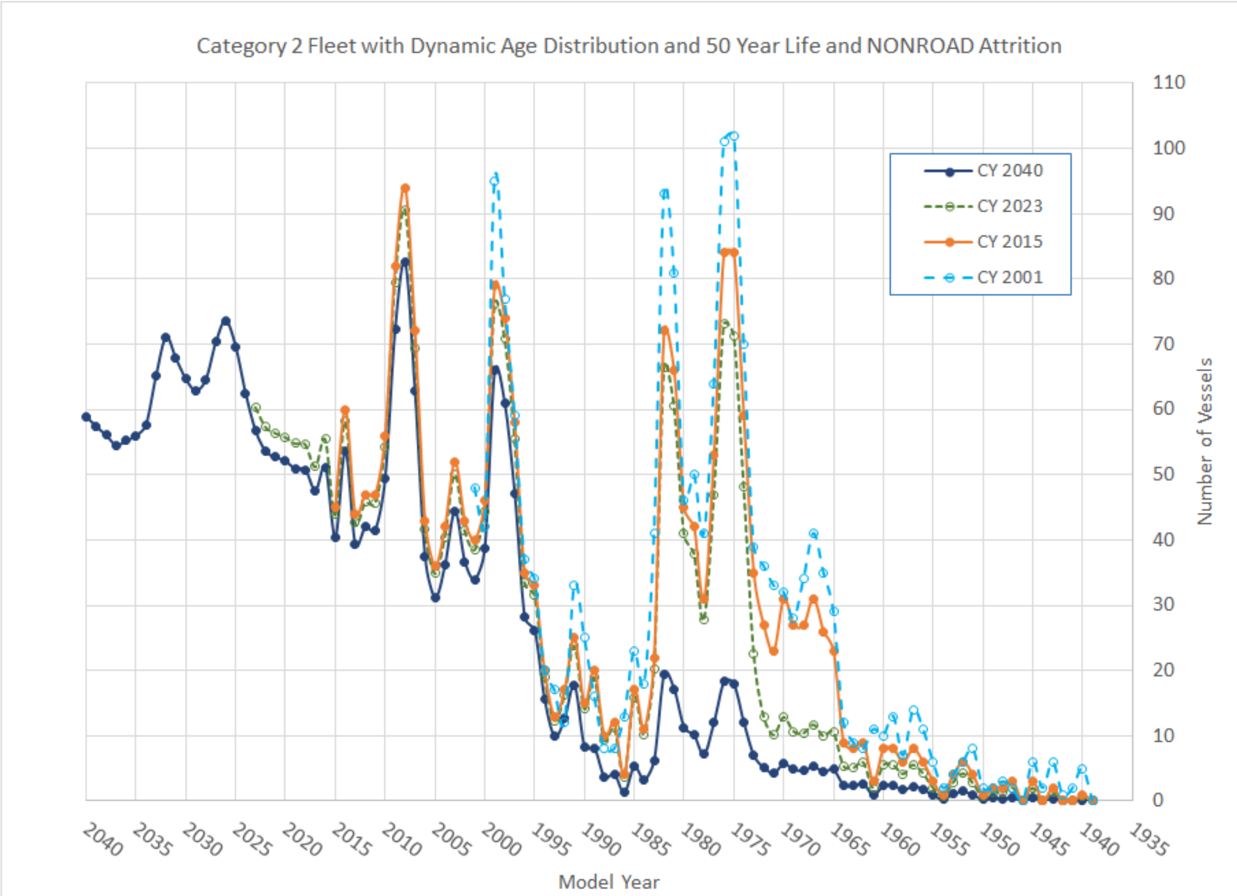

Figure 2-6. Fleet age distribution for Category 2 vessels. (CY2001 and CY2015 from WTLUS data, and CY2023 and CY2040 are forecasts)

Table 2-3. Category 2 Vessel Population. (2015 represents the WTLUS >2600 hp installed)

Model Year / Calendar Year --->	2014	2015	2016	2017	2018	2019	2020
Total	**2,177**	**2,197**	**2,217**	**2,237**	**2,257**	**2,277**	**2,298**
2020							56.32
2019						55.33	55.33
2018					55.49	55.49	55.21
2017				52.28	52.28	52.01	51.75
2016			56.54	56.54	56.26	55.98	55.98
2015		45	45.00	44.78	44.55	44.55	44.33
2014	60.00	60	59.70	59.40	59.40	59.10	58.80
2013	44.22	44	43.78	43.78	43.56	43.34	43.34
2012	47.24	47	47.00	46.76	46.53	46.53	46.29
2011	47.00	47	46.76	46.53	46.53	46.29	46.05
2010	56.28	56	55.72	55.72	55.43	55.15	54.86
2009	82.42	82	82.00	81.58	81.16	80.74	80.74
2008	94.00	94	93.52	93.04	92.56	92.56	92.08
2007	72.37	72	71.63	71.26	71.26	70.89	70.52
2006	43.22	43	42.78	42.78	42.56	42.34	42.11
2005	36.19	36	36.00	35.81	35.63	35.44	35.25
2004	42.00	42	41.78	41.56	41.35	41.13	40.91

Model Year / Calendar Year --->	2014	2015	2016	2017	2018	2019	2020
2003	52.27	52	51.73	51.46	51.19	50.92	50.92
2002	43.23	43	42.77	42.55	42.32	42.32	42.10
2001	40.21	40	39.79	39.58	39.58	39.37	39.16
2000	46.24	46	45.76	45.76	45.51	45.27	45.03
1999	79.42	79	79.00	78.58	78.16	77.74	77.32
1998	74.00	74	73.61	73.21	72.82	72.43	72.03
1997	58.31	58	57.69	57.38	57.07	56.76	56.45
1996	35.19	35	34.81	34.62	34.44	34.25	34.06
1995	33.18	33	32.82	32.64	32.46	32.29	32.11
1994	20.11	20	19.89	19.78	19.67	19.57	19.46
1993	13.07	13	12.93	12.86	12.79	12.72	12.64
1992	17.09	17	16.91	16.81	16.72	16.63	16.53
1991	25.14	25	24.86	24.72	24.59	24.45	24.17
1990	15.08	15	14.92	14.83	14.75	14.58	14.50
1989	20.11	20	19.89	19.78	19.55	19.44	19.33
1988	10.06	10	9.94	9.83	9.78	9.72	9.66
1987	12.07	12	11.86	11.80	11.73	11.66	11.53
1986	4.05	4	3.98	3.95	3.93	3.89	3.86
1985	17.10	17	16.90	16.80	16.61	16.51	16.32
1984	11.06	11	10.94	10.81	10.75	10.62	10.55
1983	22.13	22	21.74	21.62	21.36	21.23	20.98
1982	72.85	72	71.58	70.73	70.31	69.46	69.04
1981	66.39	66	65.22	64.83	64.05	63.66	62.88
1980	45.54	45	44.73	44.19	43.92	43.38	42.84
1979	42.25	42	41.49	41.24	40.73	40.23	39.72
1978	31.38	31	30.81	30.43	30.05	29.68	29.30
1977	53.33	53	52.35	51.70	51.05	50.40	49.42
1976	85.04	84	82.96	81.91	80.87	79.30	78.26
1975	85.06	84	82.94	81.89	80.30	79.25	77.66
1974	59.75	59	58.25	57.12	56.37	55.24	54.11
1973	35.45	35	34.32	33.87	33.19	32.52	31.61
1972	27.53	27	26.64	26.11	25.58	24.87	23.98
1971	23.31	23	22.54	22.08	21.47	20.70	19.63
1970	31.63	31	30.37	29.52	28.47	26.99	21.09
1969	27.56	27	26.25	25.31	24.00	18.75	13.69
1968	27.77	27	26.04	24.69	19.29	14.08	12.73
1967	32.15	31	29.39	22.96	16.76	15.16	14.01
1966	27.42	26	20.31	14.83	13.41	12.39	11.58
1965	29.44	23	16.79	15.18	14.03	13.11	12.42
1964	12.33	9	8.14	7.52	7.03	6.66	6.29
1963	8.85	8	7.39	6.91	6.55	6.18	5.94
1962	9.74	9	8.41	7.97	7.52	7.23	6.79
1961	3.21	3	2.84	2.68	2.58	2.42	2.32
1960	8.44	8	7.56	7.26	6.81	6.52	6.22
1959	8.47	8	7.69	7.22	6.90	6.59	6.27
1958	6.24	6	5.63	5.39	5.14	4.90	4.65
1957	8.52	8	7.65	7.30	6.96	6.61	6.43
1956	6.27	6	5.73	5.45	5.18	5.05	4.77
1955	3.14	3	2.86	2.71	2.64	2.50	2.43
1954	1.05	1	0.95	0.93	0.88	0.85	0.80
1953	4.21	4	3.89	3.68	3.58	3.37	3.26
1952	6.16	6	5.68	5.51	5.19	5.03	4.70
1951	4.23	4	3.89	3.66	3.54	3.31	3.20

Model Year / Calendar Year --->	2014	2015	2016	2017	2018	2019	2020
1950	1.03	1	0.94	0.91	0.85	0.82	0.79
1949	2.13	2	1.94	1.81	1.75	1.69	1.63
1948	2.06	2	1.87	1.81	1.74	1.68	1.55
1947	3.21	3	2.90	2.79	2.69	2.48	2.38
1946	0.00	0	0.00	0.00	0.00	0.00	0.00
1945	3.11	3	2.89	2.67	2.56	2.44	2.33
1944	0.00	0	0.00	0.00	0.00	0.00	0.00
1943	2.17	2	1.92	1.83	1.75	1.67	1.58
1942	0.00	0	0.00	0.00	0.00	0.00	0.00
1941	0.00	0	0.00	0.00	0.00	0.00	0.00
1940	1.05	1	0.95	0.90	0.86	0.81	0.76

2.5.2 Revised Fleet Emissions

Once the fleet distribution for any year was estimated, the emission factors for Category 2 engines shown in Table 2-4 were applied to each model year. The application of the emission factors by model year multiplied by the accompanying fleet fraction, power, and EPA RIA hours of use and load factor provided the emission rates for each calendar year. We assumed that the engine model year would be one year older than the vessel model year because of the time required to build each vessel and put it in service, so a 1999 engine would have been installed in a year 2000 vessel.

Table 2-4. Category 2 Engine Emission Factors by Tier Level. (Tables 3-16 and 3-41 in EPA (2008) RIA)

Model Year			Emission Factor (g/kW-hr)			
Start	End	Tier Level	HC	NOx	PM	CO
1900	1999	Uncontrolled	0.134	13.36	0.32	2.48
2000	2006	Tier 1	0.134	10.55	0.32	2.48
2007	2012	Tier 2	0.134	8.33	0.32	2
2013	2015	Tier 3	0.07	5.97	0.11	2
2016	2050	Tier 4	0.02	1.3	0.03	2

To determine the impact of a revised service life for Category 2 engines, the baseline inventory from the EPA RIA was adjusted to determine the emissions inventory estimate in the absence of the Tier 1 and Tier 2 emission standards. The 2002 inventory was assumed to have included two years of growth (0.9% per year) and Tier 1 fleet turnover (21% NOx reduction per engine resulting from turnover of an uncontrolled engine to a Tier 1 engine and 4.4% per year fleet turnover) to estimate the uncontrolled 2000 base year inventory. The 2000 base year inventory in the absence of any controlled engine was grown by 0.9% per year to estimate an uncontrolled emission inventory. Table 2-5 shows the results from the RIA, and the results with the revised Category 2 engine life estimate and reductions relative to the uncontrolled inventory.

Table 2-5. Category 2 and Total Commercial Marine Emissions and NOx Emission Reductions with and without Revised Life (0.9% Growth)

	Category 2				Overall Reduction Category 1 and 2 Total	
Year	RIA (tons)	RIA Reduction	Revised Life (tons)	Revised Life Reduction	RIA	Revised Cat. 2 Life
2000	432,539	0.0%	432,539	0.0%	0.0%	0.0%
2002	432,306	1.8%	436,661	0.8%	1.6%	1.1%
2014	345,213	29.6%	430,103	12.3%	30.3%	21.3%
2015	333,586	32.6%	429,264	13.2%	33.3%	23.3%
2016	320,992	35.7%	427,177	14.4%	36.7%	25.6%
2017	308,346	38.8%	421,515	16.3%	40.1%	28.4%
2018	295,746	41.8%	415,366	18.3%	43.5%	31.2%
2019	283,222	44.8%	409,268	20.2%	46.7%	34.0%
2020	270,832	47.7%	403,147	22.1%	49.8%	36.5%
2021	258,585	50.5%	396,924	24.0%	52.7%	38.9%
2022	246,543	53.2%	390,812	25.8%	55.4%	41.2%
2023	235,176	55.8%	384,108	27.7%	57.9%	43.4%
2024	224,475	58.1%	376,362	29.8%	60.3%	45.6%
2025	213,984	60.5%	367,313	32.1%	62.6%	47.9%
2026	203,629	62.7%	357,690	34.5%	64.7%	50.0%
2027	193,441	64.9%	348,763	36.7%	66.7%	52.0%
2028	183,404	67.0%	341,089	38.6%	68.5%	53.8%
2029	173,555	69.1%	333,970	40.5%	70.2%	55.3%
2030	164,024	71.0%	326,787	42.3%	71.7%	56.7%
2031	154,845	72.9%	319,101	44.1%	73.0%	58.0%
2032	145,870	74.7%	310,835	46.1%	74.2%	59.3%
2033	137,176	76.4%	303,778	47.7%	75.3%	60.4%
2034	128,777	78.0%	298,409	49.1%	76.3%	61.3%
2035	120,726	79.6%	293,506	50.4%	77.2%	62.1%
2036	113,237	81.0%	288,918	51.6%	78.1%	62.8%
2037	107,705	82.1%	284,813	52.7%	78.8%	63.5%
2038	104,042	82.9%	280,462	53.9%	79.2%	64.1%
2039	101,058	83.5%	276,043	55.0%	79.6%	64.8%
2040	98,614	84.1%	271,372	56.2%	79.9%	65.4%

Table 2-6. Category 2 and Total Commercial Marine Emissions and PM Emission Reductions with and without Revised Life

	Category 2				Overall Reduction Category 1 and 2 Total	
Year	RIA (tons)	RIA Reduction	Revised Life (tons)	Revised Life Reduction	RIA	Revised Cat. 2 Life
2000	12,622	0.0%	12,622	0.0%	0.0%	0.0%
2002	12,850	0.0%	12,850	0.0%	0.0%	0.0%
2014	12,231	14.5%	14,003	2.1%	31.9%	26.5%
2015	11,378	21.2%	13,941	3.4%	37.3%	29.6%
2016	11,293	22.5%	13,835	5.0%	40.5%	32.9%
2017	10,973	25.3%	13,663	7.0%	44.1%	36.2%
2018	10,680	28.0%	13,476	9.1%	47.5%	39.3%
2019	10,361	30.8%	13,291	11.2%	50.5%	42.0%
2020	10,067	33.3%	13,105	13.2%	53.2%	44.5%
2021	9,831	35.5%	12,916	15.2%	55.5%	46.8%
2022	9,580	37.7%	12,729	17.2%	57.7%	48.9%
2023	9,298	40.1%	12,526	19.2%	59.9%	50.9%
2024	8,990	42.6%	12,292	21.5%	62.1%	52.9%
2025	8,670	45.1%	12,018	23.9%	64.2%	55.0%
2026	8,340	47.7%	11,728	26.4%	66.1%	56.9%
2027	8,001	50.2%	11,460	28.7%	68.0%	58.6%
2028	7,653	52.8%	11,229	30.8%	69.7%	60.2%
2029	7,301	55.4%	11,013	32.7%	71.4%	61.5%
2030	6,943	58.0%	10,795	34.6%	72.9%	62.8%
2031	6,581	60.5%	10,561	36.6%	74.3%	63.9%
2032	6,216	63.0%	10,311	38.7%	75.6%	65.0%
2033	5,852	65.5%	10,097	40.5%	76.9%	66.0%
2034	5,488	67.9%	9,931	42.0%	78.1%	66.8%
2035	5,128	70.3%	9,780	43.4%	79.2%	67.5%
2036	4,795	72.5%	9,637	44.7%	80.3%	68.2%
2037	4,504	74.4%	9,507	45.9%	81.1%	68.8%
2038	4,244	76.1%	9,370	47.2%	81.9%	69.4%
2039	4,022	77.5%	9,231	48.4%	82.6%	70.0%
2040	3,864	78.6%	9,085	49.7%	83.1%	70.6%

The results from our revised emission reduction estimates, relative to the uncontrolled inventory, are like the NEI estimates through 2014. The revised Category 2 50-year life predicts higher turnover than the NEI2014. The NOx emission reduction using the NEI survey fleet fractions were lower at 7 – 8% as shown in Table 2-6 compared with 12.3% predicted in this work as shown in Table 2-5 for calendar year 2014. Table 2-6 shows the NEI2014 emission estimates (NEI Table 4-22 results) and what the NEI Table 4-21 fleet fraction would estimate using the NEI Table 4-20 emission factors. The NEI2014 emission reduction estimate (using either the fleet fraction or the total emissions) is much lower than the EPA RIA estimated for calendar year 2014. The NEI also did not distinguish between Category 1 and 2, so the results presented in Table 2-6 combines both engines types.

Table 2-6. NEI2014 Fleet Distribution and Estimated Emissions.

Reference	Emission Standard	NEI Table 4-20 NOx Emission Factor (g/kW-hr)	NEI Table 4-21 Fleet Fraction	NEI Table 4-22 Result
Table 4-22	Category 1 & 2 Power			41,009,501,736 kW-hr
Table 4-22	Category 1 & 2 NOx			561,463 tons NOx
Table 4-21	Base Uncontrolled	13.36	76.0%	
Table 4-21	Tier 1	10.55	5.2%	
Table 4-21	Tier 2	8.33	17.8%	
Table 4-21	Tier 3	5.97	1.0%	
Table 4-21 / Table 4-22	Average EF g/kW-hr		12.24	12.42
Overall	Reduction from Uncontrolled		8.3%	7.0%

Figure 2-7 compares the predicted Category 2 NOx emission reduction (based on total NOx emissions including growth) using the EPA RIA and revised service life with the Ramboll dynamic age distribution estimates and two growth estimates compared with the NEI2014 reduction estimates. For an expected life of 50 years there were lower emissions reductions compared to EPA estimated in the 2008 RIA. The emission reduction based on an expected life of 50 years are more consistent with recent surveys of engine tier level fleet fractions.

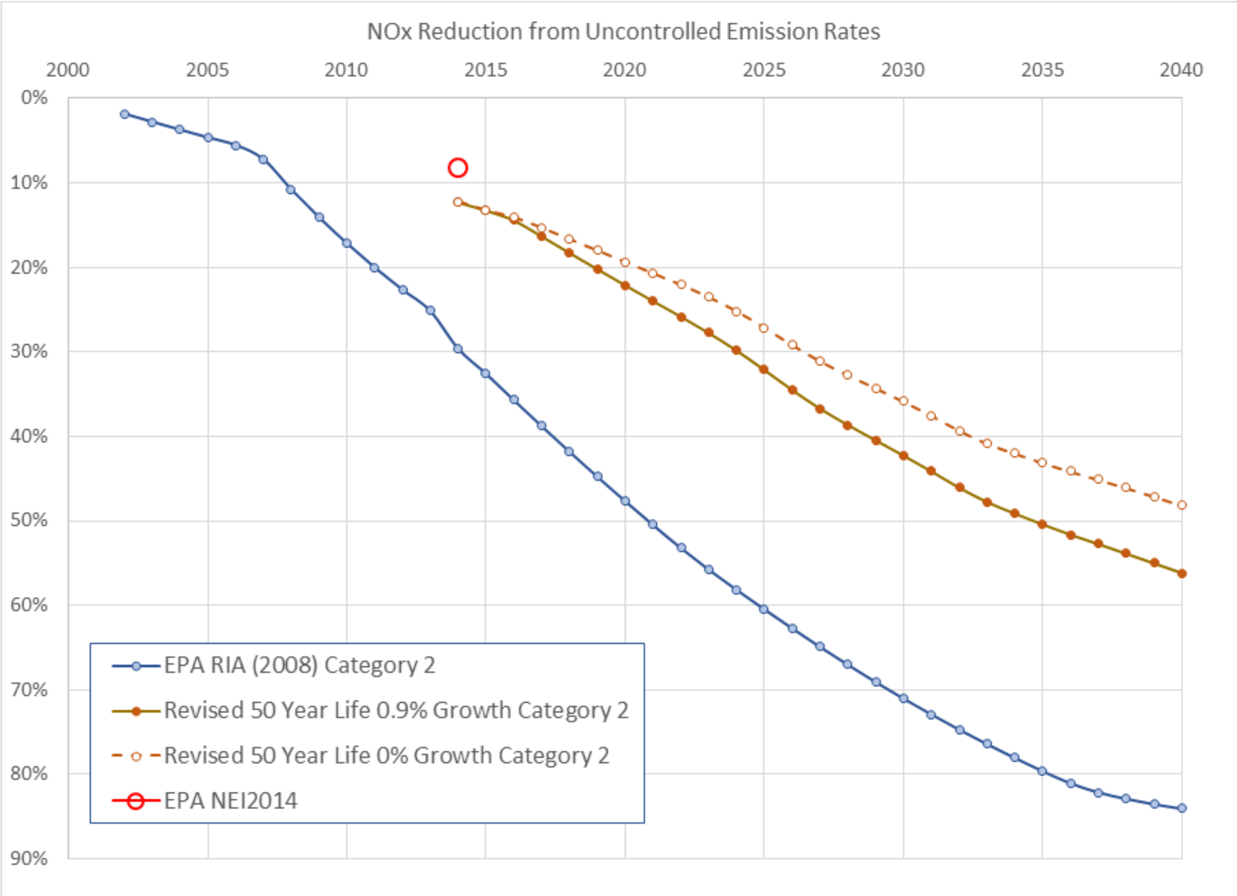

Figure 2-7. Predicted NOx emission reduction from uncontrolled level using surveyed and forecasted age distributions for Category 2 engines.

2.0 REGIONAL EMISSION INVENTORY CASE STUDIES

Using the revised national average emission reductions with a longer Category 2 engine life, we investigated the impact that these changes would have on regional emission inventories. The regions chosen were the greater Houston, New York/New Jersey, and Baltimore metropolitan areas.

Ramboll investigated the State Implementation Plans (SIP), individual reports, and NEI for base year and forecast year emission inventories up to calendar year 2023. The NEI2014 is the most recent NEI available; EPA's most recent forecasts were for 2017 and 2023 based on NEI2011 estimates.

Emission inventories forecasted from the NEI2014 emissions inventory would incorporate the same expected change from 2014 to future years based on the EPA RIA estimates despite evidence showing that the fleet turnover for commercial marine vessels is slower than forecasted.

2.1.1 National Emission Inventory (NEI)

The NEI Category 2 commercial marine vessel emission estimate relies on EPA's national emission estimates based on the RIA for areas for which emissions were not provided by a state/local/tribal agency. For areas in which a state/local/tribal agency provided emissions based on efforts to identify specific sources operating in their region, the NEI is based on the state/local/tribal agency emission submission. NEI2014 included state/local/tribal updates for many states based on special studies and other input from the States including Texas and New Jersey.

In the published emissions from the NEI2014, we assumed that the main source category codes (SCC) for commercial marine vessels using Category 1 and 2 engines were 2280002200 and 2280002100 denoting transiting and harbor marine diesel vessels. Other SCCs for marine residual vessels were assumed to be related to the larger ocean-going ships using Category 3 engines. The locomotive emissions included in this summary were SCC 2285002007 for Class II/III regional railroads and 2285002010 for Diesel Locomotive Yard Operations to correspond to locomotives most likely to be locally based and be available for engine retrofit or repower projects.

However, at the time of this report, the latest EPA forecasts of emissions for modeling purposes (Modeling Platforms for 2017 and 2023[13]) relied on the 2011 as the base year and applied simple multipliers to address growth and emission control for future calendar years. EPA used the growth and controlled emission estimates from the RIA to adjust emission totals.

The revised emission reduction estimates for Category 2 engine emissions were combined with the original Category 1 engine emissions to revise the forecasted emissions from the smaller

[13] https://www.epa.gov/air-emissions-modeling/emissions-modeling-platforms

(non-Category 3) commercial marine emissions. The previous section described how the Category 2 fleet turnover was estimated. No change to the Category 1 engine emissions was estimated despite evidence showing vessels with Category 1 engines are older than EPA forecasted because it was uncertain how often smaller engines are replaced in those vessels. Table 3-1 shows the revised emissions totals relative to the EPA RIA estimates that can be used to adjust the EPA forecasts for each region. Because Category 2 engine life was revised, fleet turnover to lower emitting engines was not as rapid, increasing fleet average emissions.

Table 3-1. Revised Category 1 and 2 Emission Inventory Relative to EPA RIA

Year	VOC	CO	NOx	PM
2014	100.5%	101.7%	112.9%	107.9%
2015	101.3%	102.0%	115.1%	112.3%
2016	102.0%	102.3%	117.5%	112.7%
2017	102.9%	102.5%	119.5%	114.2%
2018	103.9%	102.8%	121.6%	115.6%
2019	105.0%	103.1%	124.0%	117.2%
2020	106.2%	103.3%	126.5%	118.7%
2021	107.5%	103.6%	129.1%	119.8%
2022	108.9%	103.8%	131.9%	121.0%
2023	110.4%	104.0%	134.6%	122.5%
2024	111.9%	104.2%	137.1%	124.1%
2025	113.4%	104.3%	139.3%	125.7%
2026	114.9%	104.4%	141.5%	127.2%
2027	116.6%	104.5%	143.9%	129.1%
2028	118.5%	104.6%	146.8%	131.6%
2029	120.4%	104.7%	149.8%	134.4%
2030	122.4%	104.7%	152.7%	137.3%
2031	124.3%	104.6%	155.3%	140.3%
2032	126.2%	104.5%	157.6%	143.3%
2033	128.2%	104.4%	160.2%	146.9%
2034	130.4%	104.3%	163.4%	151.3%
2035	132.6%	104.2%	166.7%	156.2%
2036	134.8%	104.1%	169.8%	161.0%
2037	136.5%	104.1%	171.9%	165.5%
2038	137.4%	104.0%	172.6%	169.4%
2039	138.1%	103.9%	172.7%	172.6%
2040	138.4%	103.8%	172.2%	174.2%

2.1.2 Houston-Galveston-Brazoria (HGB) Area

The Houston area consists of eight counties, Brazoria, Chambers, Galveston, Harris, Fort Bend, Waller, Liberty, and Montgomery of which the first four have nearly all the commercial marine activity.

In Houston, the commercial marine emissions inventory has been evolving as better data are becoming available to assess activity. Updated Category 1 and 2 vessel inventories (Eastern Research Group (ERG), 2015) revealed higher activity which, taken together with adjustments to growth and emission rates, produced higher emissions compared to previous SIP and NEI estimates. The ERG report was cited as the commercial marine emission inventory for the Reasonable Further Progress (RFP) SIP for HGB. (TCEQ 2016). Table 3-2 presents the ERG emission results for Category 1 and 2 commercial marine vessel emissions.

Revising the Category 2 engine life results in higher emissions in general from this segment and amounts to an increase of about 4 tons NOx per day or a 34% increase over the projected 2023 emissions. For comparison purposes, the increase in Category 2 emissions from the 50-year service life equals about 44% of the 9.2 tpd of NOx RFP SIP[14] contingency emission reduction for 2018 from 2017.

Table 3-2. Houston Area 2016 RFP SIP, NEI2011, NEI2011 Forecasts, NEI2014, and Revised TCEQ Category 1 and 2 Commercial Marine Emissions

	Emissions (tpd)			
Calendar Year	**VOC**	**CO**	**NOx**	**$PM_{2.5}$**
2014 for RFP SIP (ERG, 2015 Report)	0.40	4.9	15.3	0.25
2023 Growth and Control Applied (ERG, 2015 Report)	0.33	5.8	12.0	0.10
2023 Revised Emissions	0.36	6.0	16.1	0.12
2023 Emission Increase due to Category 2 Revised Fleet Turnover	0.03	0.2	4.1	0.02

2.1.3 Baltimore

Due to a revision in the geographic boundaries between the NEI2011 and NEI2014, we were not able to determine the implications of the longer Category 2 service life on the Baltimore area SIP. Using the 2011 NEI data for Category 1 and 2 marine engines, we estimate that the 2023 Baltimore are controlled emissions to equal approximately 0.90 tpd of NOx. Using the 50-year service life for the Category 2 engines would have resulted in a 1.2 tpd of NOx, and increase of

14 https://www.tceq.texas.gov/assets/public/implementation/air/sip/hgb/HGB_2016_AD_RFP/RFP/Adoption/16017SIP_HGBRFP_Ado.pdf

0.3 tpd, which is a relatively small proportion of area emissions. The Baltimore area RFP SIP[15] identified the RFP contingency emission reduction for 2012 to be 11.9 tpd NOx to reach the minimum target level. The 0.3 tpd of increased NOx emissions appears to represent a small proportion of the RFP contingency for Baltimore. These emission estimates are shown in Table 3-3.

Table 3-3. Baltimore 2011 SIP, NEI2011 and NEI2014 Smaller Commercial Marine Emissions.

Calendar Year	Emissions (tpd)			
	VOC	CO	NOx	$PM_{2.5}$
2023 Projection (Based on NEI2011)	0.03	0.12	0.90	0.017
2023 Revised Fleet Turnover Category 1 and 2 Emissions	0.04	0.13	1.21	0.021
2023 Emission Increase due to Revised Fleet Turnover	0.00	0.00	0.31	0.004

2.1.4 New York/New Jersey

The emissions for the New York metropolitan area comprise of counties in New York, New Jersey and Connecticut were derived from many sources and compared. For the New York counties, the NY Department of Environmental Conservation (NYDEC)[16] stated in their SIP that both commercial marine vessel and locomotive emission inventories were based on the NEI2011. New Jersey[17] modified the NEI2011 forecast to 2017 revising their estimates and adding additional categories of smaller commercial marine vessels including ferries, government, dredges, and harbor and navigation projects.

Like Baltimore, EPA revised the spatial allocation of Category 1 and 2 marine vessel emissions for the NEI2014 emissions inventory for the New York metropolitan area SIP. This made it difficult project the impact of a 50-year service life on current and future marine vessel inventories. Therefore, the emissions shown in Table 3-4 are New Jersey-modified NEI2011 forecasts.

The results in Table 3-4 show that revising 2017 SIP projection, based on the NEI2011 platform, shows an increase of 8.2 tons of NOx per day. The RFP SIP[18] forecasted contingency emission reduction requirement in 2017 was calculated to be 89.4 tpd NOx reductions. The additional emissions from a 50-year service life for Category 1 and 2 marine vessels equals approximately 9.2% of the RFP requirements.

[15] http://mde.maryland.gov/programs/Air/AirQualityPlanning/Documents/SIPDocuments/FINAL%20BNAA%20O3%20SERIOUS%20BumpUp%20SIP.pdf
[16] NYDEC 2017. "Ozone (2008 8-Hour NAAQS) Attainment Demonstration for NY Metro Area," November 2017, https://www.dec.ny.gov/chemical/110727.html
[17] NJDEP 2017. "State Implementation Plan (SIP) Revision for the Attainment and Maintenance of the 75 ppb and 84 ppb Ozone National Ambient Air Quality Standards, Ozone Attainment Demonstration and Nonattainment New Source Review (NNSR) Program Compliance Certification." October 2017. http://www.state.nj.us/dep/baqp/ozoneppb.html
[18] https://www.dec.ny.gov/docs/air_pdf/sip2008o3nymafinal.pdf

Table 3-4. New York Metropolitan Area Smaller Commercial Marine Emissions.

Calendar Year	Emissions (tpd)			
	VOC	CO	NOx	$PM_{2.5}$
2017 SIP Total: Modelling Platform 2017 for NY and CT with Revised New Jersey Estimates	1.20	10.10	42.07	1.28
Revised Fleet Turnover Category 1 and 2 2017 Emissions	1.23	10.35	50.27	1.46
2017 Emissions Increase with Revised Fleet Turnover	0.03	0.25	8.20	0.18

3.0 COST EFFECTIVENESS

3.1 Introduction

This section summarizes our general approaches to emissions reduction and cost effectiveness (CE) calculations for engine and equipment replacement/modernization or retrofits projects associated with locomotives or commercial marine vessels for discussion and provides example calculations based on input data from stakeholders.

We followed EPA guidance and emission inventory calculations and the States of Texas and California cost effectiveness approaches to develop a tool to evaluate cost effectiveness and emissions reductions for locomotive and commercial marine vessel projects.

3.2 Emission and Cost-Effectiveness Analysis Methodologies

EPA guidance for estimating emission reductions is described generally in EPA (1997). EPA (1997) is a documents EPA Guidance for incorporating voluntary mobile source emission reductions (VMEPs) into State Implementation Plans (SIPs) EPA (1997) describes the goals and key criteria for evaluating and crediting emissions reductions from VMEPs. The evaluation criteria are briefly described below along with descriptions of how proposed locomotive and marine projects meet the EPA guidance.

1. Quantifiable: Essentially, emissions reductions must be able to be measured. Engine certifications essentially guarantee the emission reductions. Emissions are quantified using the same approach that EPA or individual states (e.g. Texas or California) use when developing emission inventories for air quality SIPs.
2. Surplus: This criterion is meant to demonstrate that emissions reductions would not have occurred without the project.
3. Enforceable: A SIP measure must be enforceable by the State or the Federal government. Again, the engine certification meets this criterion.
4. Permanent: This criterion is meant to ensure that the emission reduction persists during life of the project. For example, replacing the engine and scrapping the older engine ensures that this criterion is met, though there are other methods to meet the "permanent" criterion.
5. Adequately Supported: Staff oversight and enforcement administration is a necessary component of a VMEP. For example, adequately funding is needed to oversee the installation of new engines and provide program oversight and accounting to ensure that new engines are being used and that the replaced older engines are removed from service or recertified to new emission standards.

Cost effectiveness is determined using the Texas Emission Reduction Plan (TERP) guidance described in equations 1-4. The TERP guidance provides a method and a discount rate to converted project cost to an annualized cost using the capital recovery factor (CRF) to amortize the project. (TCEQ, 2017) The amortization depends upon project (or activity) life, which for engine replacement programs is the estimated remaining life of the vehicle to be replaced.

*Annual emission reduction = Activity * (Emission Ratebefore – Emission Rateafter)* [Eqn. 1]

Cost Effectiveness = Annualized Cost / Annual NOx Emission Reduction [Eqn. 2]

*Annualized Cost = Project Cost * CRF* [Eqn. 3]

$CRF = [(1 + i)^n (i)] / [(1 + i)^n - 1]$ [Eqn. 4]

Where:

i = discount rate (0.03) (This discount rate will be easily manipulated in our product.)
n = activity life

To evaluate the emission reductions from locomotive and commercial marine vessel projects, we will follow EPA guidance and other documentation to calculate locomotives and commercial marine vessels emission inventories. In many cases, SIP emission inventories have relied on the EPA approaches and emission results.

3.2.1 Locomotive Emissions

The basic EPA guidance for developing locomotive emissions estimates are found in two documents (EPA 2008; 2009a). EPA has used two different methods to estimate emissions, one based on fuel consumption (gallons) and another based on the hours of operation and average load factor. We are providing both options in our emission reduction benefit and cost effectiveness calculator tool.

The fuel consumption method relies on the locomotive operator to provide fuel consumption activity of the locomotives. For line-haul locomotives, some railroads will know or can accurately estimate fuel consumption based on gross ton-miles of train activity. For switching locomotives that are locally refuelled, railroads may have records of gallons dispensed to the locomotive. EPA provides factors to convert gallons of fuel consumed to work performed by type of locomotive as shown in Table 4-1.

Table 4-1. Locomotive Conversion Factors (Hp-hr/gallon).[4]

Locomotive Application	Conversion Factor
Class 1 Railroad Line-Haul	20.8
Small Railroad Line-Haul	18.2
Switching	15.2

Emissions for locomotives are then estimated by applying emissions factors in Tables 4-2 and 4-3 as follows:

Emissions = Fuel consumption * Conversion Factor * Emission Factor

Table 4-2. Locomotive – EPA projected emissions factors (g/hp-hr) for line-haul engines.

Engine Type	Applicable Year	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
Unregulated (Uncontrolled)	**Pre-1973**	**0.48**	**1.28**	**13.0**	**0.32**
Tier 0 – original	1973 – 2001	0.48	1.28	8.60	0.32
Tier 0+ – final[1]	2010	0.30	1.28	7.20	0.20
Tier 1 – original	2002 – 2004	0.47	1.28	6.70	0.32
Tier 1+ – final[1]	2010	0.29	1.28	6.70	0.20
Tier 2 – original	2005	0.26	1.28	5.50	0.18
Tier 2+ – final[1]	2013	0.13	1.28	4.95	0.08
Tier 3	2012 – 2014	0.13	1.28	4.95	0.08
Tier 4	2015+	0.04	1.28	1.00	0.015

[1] These are estimated emissions at the time of rebuild with many exceptions for older Tier 0 engines.

Table 4-3. Locomotive – EPA projected emission factors for switching (duty cycle) engines.

Engine Type	Applicable Year	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
Uncontrolled (Uncontrolled)	**Pre-1973**	**1.01**	**1.83**	**17.4**	**0.44**
Tier 0 – original	1973 – 2001	1.01	1.83	14.0	0.44
Tier 0+ – final[1]	2010	0.57	1.83	10.62	0.23
Tier 1 – original	2002 – 2004	1.01	1.83	9.9	0.43
Tier 1 – final[1]	2010	0.57	1.83	9.9	0.23
Tier 2 – original	2005	0.51	1.83	7.3	0.19
Tier 2 – final[1]	2013	0.26	1.83	7.3	0.11
Tier 3	2011 – 2015	0.26	1.83	4.5	0.08
NREC Gen. Set	<2015	0.10	1.09	2.67	0.065
Tier 4	2015+	0.08	1.83	1.00	0.015

[1] These are estimated emissions at the time of rebuild with many exceptions for older Tier 0 engines.

The alternative method relies on the locomotive rated power, hours of operation and a load factor to estimate the work (hp-hr) performed. EPA (2008) estimates of average annual activity and load factor estimates can be used. Emission estimates are based on the work performed by each locomotive as shown in the following equation:

Work = H × LF × N × P × RUF

Where,

Work = Combined annual work output for all locomotives remaining in the fleet that were originally manufactured in model year i.

H = Number of hours per year that a newly manufactured locomotive is projected to be used.

LF = Typical average load factor (0.275 line-haul or 0.1 switch)[5] or (26.891% for line-haul or 8.2715% for switch). (EPA, 2017)

N_i = Number of locomotives remaining in the fleet that were originally manufactured in model year i.

P_i = Average rated power of locomotives remaining in the fleet that were originally manufactured in model year i.

RUF_i = Relative use factor for locomotives remaining in the fleet that were originally manufactured in model year i.

RUF_i = [H – Relative Use Adjustment x (Age – Threshold Age)] / H

RUF = 1 until threshold age is reached
Hours (new) = Adjusted to Fleet Fuel Consumption
Relative Use Adjustment = 81.6 hours/year for line-haul; 66.75 hours/year for switch
Threshold Age = 8 years for line-haul; 50 years for switch

EPA assumed that hours per year depend upon the age of the locomotive according to the relative use factor (RUF). EPA estimated that the line-haul locomotives are used 4350 hours per year when new, and, after the first 8 years of use (threshold age), annual activity declines by 81.6 hours per year to the end of life at 40 years. Likewise, EPA estimated that switch locomotives are used at a rate of 4450 hours per year for the first 50 years of use (threshold age) and then annual use declines by 66.75 hours per year until the end of life, assumed to be 70 years.

Of course, for any specific project, the actual number of hours that a locomotive operates may be known. Once the work performed has been estimated, emissions are estimated by multiplying by the emission factor for the older engine(s) and the new replacement engine(s).

Example Locomotive Project

From the Texas TERP 2015 project list, one precontrolled 1500 hp switcher locomotive had its engine replaced with a Tier 3 compliant engine. A ten-year remaining life was estimated with a grant of $785,750 out of a total cost of $948,438. Current annual activity was estimated at 42500 gallons of fuel consumed or about 2800 hours per year using the EPA conversion factor.

Emission Reduction = 1500 x 0.1 x 2800 x (17.4 – 5.4) = 5.56 tons per year

Cost = $78,575 per year (0% interest rate)

Cost Effectiveness = $14, 132 per ton

In addition, stakeholders provided the cost for three switch locomotive projects; two retrofit and an engine replacement to new certified engines. The retrofit projects included engine upgrades to meet Tier 0+ or, for a select engine model, upgrade to meet Tier 3 emission standards. Tier 4 engines are available for direct replacement in locomotives.

The engine retrofit projects are cost effective because they are significantly less expensive than a full engine replacement despite not meeting the lowest emission standard. The cost effectiveness for retrofit or replacement projects depend on what standard the original engine met prior to retrofit. Older engines are not required to be upgraded to the original Tier 0 or final Tier 0+ emission standards and so can demonstrate benefits with an upgrade. Likewise, older engines that can meet Tier 0+ standards could benefit from an upgrade to Tier 3, which is available for some engine models, or a full engine replacement to Tier 4.

Table 4-4 provides the cost effectiveness estimates for the projects supplied by the stakeholders. The primary inputs are the cost of the engine upgrade or repower, the engine power and activity, and initial and final emission standards that the engine meets. As described in this memorandum, EPA estimates that engines can remain in service up to 70 years, so the estimate of remaining service life in the table could be considerably longer making these projects proportionally more cost effective.

Table 4-4. Locomotive projects summaries.

Project Description			Engine Input Data				Emission Factor (EF)		Results			Cost Effectiveness	
Original Engine Tier Level	New Engine Tier Level	Parts and Labor Cost	Average Power (hp)	Load Factor	Activity (hr/yr)	Remaining Service Life (years)	Original EF (g/hp-hr)	New EF (g/hp-hr)	Original Engine NOx (tons/year)	New Engine NOx (tons/year)	NOx Reduction (tons/year)	Full Cost ($/ton)	40% of Full Cost ($/ton)
Unreg.	Tier 0+ [a]	$210,000	3,150	0.10	3,250	20	17.4	10.6	19.64	11.96	7.67	$1,368	$547
Unreg.	Tier 3 [a]	$275,000	3,150	0.10	3,250	20	17.4	4.5	19.64	5.08	14.56	$945	$378
Tier 0	Tier 3 [a]	$275,000	3,150	0.10	3,250	20	12.6	4.5	14.22	5.08	9.14	$1,504	$602
Tier 0+	Tier 3 [a]	$275,000	3,150	0.10	3,250	20	10.6	4.5	11.96	5.08	6.88	$1,997	$799
Unreg.	Tier 4	$2,600,000	2,000	0.10	3,250	20	17.4	1	12.47	0.72	11.75	$11,063	$4,425
Tier 0	Tier 4	$2,600,000	2,000	0.10	3,250	20	12.6	1	9.03	0.72	8.31	$15,641	$6,256
Tier 0+	Tier 4	$2,600,000	2,000	0.10	3,250	20	10.6	1	7.59	0.72	6.88	$18,900	$7,560

a – Tier 2 Engine retrofit upgrades (all others are full engine replacements)

The cost of a new engine retrofitted into a rebuilt locomotive is relatively high, however the emission reduction rate is expected to be sufficient to have comparable or lower cost effectiveness than other nonroad emission reduction projects.

3.2.2 Commercial Marine Vessel Emissions

For commercial marine vessel emissions estimates, we relied on the EPA best practice for emission inventory development (EPA, 2009b) and EPA regulatory impact analysis (EPA, 2008)[19] for input and emissions factors. The emission factors provided by EPA[8] are expressed in units of gram per kW-hr, so it is necessary to estimate the kW-hrs work performed.

Work = Rated Power * Load Factor * Hours of Operation

The load factor is least understood input factor because estimates have relied on personal experience rather than in-use activity estimates. EPA has provided estimates which did not distinguish between vessel types. (EPA, 2009b) ARB provided alternative load factors by unique vessel type (ARB, 2017). EPA and ARB load factor estimates are shown in Table 4-5.

[19] Reviewed via personal communication with Penny Carey, EPA 2011.

Table 4-5. Harbor Craft load factor estimates.

Vessel / Aux Engine	Vessel Type	Load Factor
EPA Estimates		
Category 2 (Propulsion)	Various	0.85
Category 1 (Propulsion) <805 Hp	Various	0.45
Category 1 (Propulsion) >805 Hp	Various	0.79
Category 1 (Auxiliary) <805 Hp	Various	0.56
Category 1 (Auxiliary) >805 Hp	Various	0.65
California Air Resources Board		
Propulsion	Commercial Fishing	0.27
Propulsion	Charter Fishing	0.52
Propulsion	Ferries	0.42
Propulsion	Crew and Supply	0.38
Propulsion	Pilot Vessels	0.51
Propulsion	Tug Boats	0.50
Propulsion	Tow Boats / Push Boats	0.68
Propulsion	Work Boats	0.45
Propulsion	Others	0.52
Propulsion	Barges	0.45
Propulsion	Dredges	0.45
Auxiliary Engine	Commercial Fishing Generator	0.43
Auxiliary Engine	Charter Fishing Generator	0.43
Auxiliary Engine	Ferries Generator	0.43
Auxiliary Engine	Crew and Supply Generator	0.32
Auxiliary Engine	Pilot Vessels Generator	0.43
Auxiliary Engine	Tug Boats Generator	0.31
Auxiliary Engine	Tow Boats / Push Boats Generator	0.43
Auxiliary Engine	Work Boats Generator	0.43
Auxiliary Engine	Others Generator	0.43
Auxiliary Engine	Compressor	0.54
Auxiliary Engine	Crane	0.42
Auxiliary Engine	Deck Door Engine	0.89
Auxiliary Engine	Dredger	0.51
Auxiliary Engine	Barge/Dredge Generator	0.75
Auxiliary Engine	Hoist Swing Winch	0.31
Auxiliary Engine	Other	0.80
Auxiliary Engine	Pump	0.71

Annual hours of operation can be difficult to estimate especially for auxiliary engines. Often vessels have twin propulsion and twin auxiliary engines, so each engine does not necessarily work the same number of hours as its twin. Auxiliary engines may also be used more than propulsion engines because they may operate when the vessel is at-dock as well as when the vessel is transiting or away from dock.

EPA[8] provided emission factors that reflect the regulation standards and are parsed by cylinder displacement, model year, and power density (kW/liter displacement). The emission factors for smaller commercial marine engines are found in the Appendix A. Emission factors multiplied by engine work results in the emission estimate for any vessel.

Example Marine Project

For the example project, the EDF report on Clean Vessels for Texas Waters presents example projects with activity and other input factors (EDF, 2012). In this example, the propulsion engines are replaced with newer updated technology Tier 3 engines from the same manufacturer. The project life could be longer than 10 years given that the engines were less than 15 years old; for example, the historic TERP projects for marine engine replacement range from 5 to 14 years remaining life on the old engine. The approximate cost based on similar TERP projects would be $100,000 per engine for new Tier 3 engines.

Replaced Engines – 2 x 2003 Cummins KTA-19M

(bore 159 mm, stroke 159 mm, 3.2 l/cylinder)

(6 cylinders at 53 – 87 kW/cylinder or total power of 316 – 522 kW)

Activity – 3,500 hours per year; 92,400 gallons

Fuel Consumption, 92,400 gallons = 316 kW x 2 x Load Factor x 3500 hours x 213.089 g/kW-hr / 3200 grams/ gallon

Load Factor = 0.627

Emissions = 316 x 2 x 3500 x 0.627 x (9.1 - 4.69 g/kW-hr) = 6.7 tons per year

Cost Effectiveness = $200,000 / 10 years / 6.7 tons per year = $2,966/ton

While the final emission standard for smaller engines (those less than 600 kW) is not as low as for larger engines (at 1.3 g/kW-hr), the emission reduction is still cost effective.

In addition, stakeholders provided input data for engine replacement projects on commercial marine vessels. The input data included sample projects for push (also called tow) boats and harbor tugs. The push boats function is to push barges on river and inland waters over long distance, and harbor tugs assist in moving ships or barges near docks. For this reason, the push boats typically have higher load factors and more operational time.

The stakeholders described the replacement projects in terms emission standard that the replacement engine would meet, which have been translated into expected model year. Pre-controlled (unregulated) engines are any year 1999 or earlier, so we have assumed that the model year of the engine being replaced is 1998. Likewise, we have assumed that engines have a service life of 50 years for the original engines without an initiative to replace these engines, so the project life was calculated as the difference between 50 years and the age of the engine in 2018. As we have shown in Section 2, the service life for commercial marine vessels is probably closer to 50 years than substantially lower than the EPA RIA estimates.

Table 4-6 provides the summary inputs, emissions reductions, and cost effectiveness estimates by project. The push boat projects were more cost effective because the load factor and activity (hours/year) were higher than those for harbor tugs. Conservative estimates of the average load factor have been used resulting in lower emissions and emission reductions. The push boats load factor is assumed to be 0.6, less than EPA's estimate of 0.85 or ARB's estimate of 0.68 from ARB. The tugs load factor is assumed to be 0.3, less than EPA's estimate of 0.45 – 0.85 or ARB's estimate of 0.50.

Table 4-6. Harbor Craft Load Factor Estimates.

Project Description							Engine Input Data				Emission Factor		Results			Cost Effectiveness	
Vessel Type	Original Engine Tier and Model Year		Retrofit or Replacement New Engine Tier and Model Year		Engine Cylinder Displacement	Parts and Labor Cost	Engine Rated Power (kW)	Load Factor	Activity (hr/yr)	Remaining Service Life (years)	Original (g/kW-hr)	New (g/kW-hr)	Original Engine NOx (tons/year)	New Engine NOx (tons/year)	NOx Reduction (tons/year)	Full Cost ($/ton)	40% Cost ($/ton)
Push Boats	Unreg.	1998	Tier 3	2013	11.6	$1,100,000	3,729	0.60	6000	30	13.36	8.33	197.7	123.3	74.43	$493	$197
Push Boats	Unreg.	1998	Tier 2a	2012	10.4	$545,000	1,417	0.60	6000	30	13.36	8.33	75.1	46.8	28.28	$642	$257
Push Boats	Unreg.	1998	Tier 2a	2010	4.9	$468,000	1,570	0.60	6000	30	11	6	68.5	37.4	31.15	$501	$200
Push Boats	Tier 2	2010	Tier 4	2018	11.6	$1,400,000	2,983	0.60	6000	42	8.33	1.3	98.6	15.4	83.22	$401	$160
Push Boats	Unreg.	1998	Tier 3	2017	2.7	$650,000	746	0.60	6000	30	10	4.69	29.6	13.9	15.72	$1,378	$551
Tug Boats	Unreg.	1998	Tier 3	2013	11.6	$1,100,000	3,729	0.30	2500	30	13.36	8.33	41.2	25.7	15.51	$2,365	$946
Tug Boats	Unreg.	1998	Tier 2a	2010	10.4	$620,000	2,289	0.30	2500	30	13.36	8.33	25.3	15.8	9.52	$2,171	$868
Tug Boats	Tier 2	2010	Tier 4	2018	11.6	$1,400,000	2,983	0.30	2500	42	8.33	1.3	20.5	3.2	17.34	$1,923	$769
Tug Boats	Unreg.	1998	Tier 3	2015	4.9	$1,700,000	2,350	0.30	2500	30	11	4.81	21.4	9.3	12.03	$4,712	$1,885
Tug Boats	Tier 1	2005	Tier 2a	2010	4.9	$468,000	1,870	0.30	2000	37	9.2	6	11.4	7.4	3.96	$3,196	$1,278

a – Tier 2 Engine retrofit upgrades (all others are full engine replacements)

3.3 Summary

Overall switching locomotive and commercial marine engine (non-Category 3) upgrade or repower projects are very cost-effective owing to high engine rated power, activity, and long remaining service life. The benefit of these projects will accrue quickly and be maintained for many years. The cost effectiveness of these projects is lower (1/10th the cost per ton in many cases) than many other projects reducing emissions from mobile sources including a typical heavy-duty vehicle engine replacement project with a cost effectiveness of about $17,000 per ton of NOx removed (USDOT, 2015). Mobile source projects with a lower cost effectiveness compared to switching locomotive a commercial marine engine upgrade or replacement projects are limited to idle reduction and other projects with limited emission reduction potential.

Also, because each switching locomotive and commercial marine engine project provides large emission reductions, fewer projects are needed to produce the same emission reductions as with smaller engines and vehicles. Fewer projects would reduce the unquantified administration costs and effort relative to other project types that involve many more vehicles or pieces of equipment to reduce emissions by the same amount.

Commercial marine and locomotive source categories should be a primary focus of future emission reduction efforts for retrofit/repower programs based on cost effectiveness.

4.0 SUMMARY AND CONCLUSIONS

The focus of this analysis was to evaluate emission reduction opportunities from Category 1 and 2 smaller commercial marine vessels (e.g., tugs, fishing vessels, work boats, ferries and excursion vessels i.e., not including ocean-going ships) and short haul or switcher/yard locomotives as well as costs and cost-effectives of benefits of emission reduction projects for these source categories.

In this report, we analysed factors that are involved in estimating costs and benefits relative to existing factors which were developed a decade or more ago. One critical factor affecting estimated project total emission reductions is the expected remaining service life of the engine to be retrofitted or replaced. Another factor is the in-use activity both in terms of hours of operation and typical engine operation loads.

Based on in-use surveys and vessel registration data, fleet turnover of commercial marine vessels and engines has been slower than EPA originally estimated likely because the service life of these engines is much longer than original data estimated. Data suggests that the larger Category 2 commercial marine engines' service life is 50 years on average, higher than the 23 years estimated by EPA. 50 years is the EPA estimated service life of similarly powered switching locomotives, reinforcing the conclusion of a similar service life.

The service life of smaller Category 1 commercial marine engine may also be longer than EPA estimates, but smaller engines may be replaced during normal vessel maintenance. A specific survey of vessels would be required to confirm or contradict EPA estimated service life of 13 or 17 years. The EPA (NEI2014) survey reported a lower fraction of new (those with model years 2000 or later) engines than predicted and did not distinguish between large (Category 2) and smaller (Category 1) engines.

Increasing the service life reduces the expected fleet turnover to lower emitting engines and therefore increases predicted future year emissions. Higher potential emissions from Category 1 and Category 2 commercial marine vessel engines highlights the need for additional programs to reduce emissions from these sources.

Compared to other mobile source emission reduction projects, projects to reduce emission rates from commercial marine vessel engines typically have a longer project life based on the remaining service life which produces greater project total emission reductions. Greater project emission reductions results in more cost-effective projects. Locomotives also provide an opportunity for cost-effective emission reduction projects.

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APPENDIX A

EPA Commercial Marine Engine Emission Factors

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APPENDIX A EPA Commercial Marine Engine Emission Factors

A. Commercial Marine Propulsion Engines

Tier	Year <=Last Applied	Displacement (l/cylinder)		Power (kW)		Power Density	Emission Factors (g/kW-hr)				
		Low	<High	Low	<High	kW/l	HC	CO	NOx	PM10	Fuel
0	1999	0	0.9	0	8		2.01	6.71	13.41	1.21	248.3961
0	1999	0	0.9	8	19		2.28	6.71	11.4	1.08	248.3961
0	1999	0	0.9	19	37		2.41	6.71	9.25	0.94	248.3961
0	1999	0	0.9	37	100000		0.41	1.6	10	0.43	213.0849
0	1999	0.9	1.2	0	100000		0.32	1.6	10	0.36	213.0849
0	1999	1.2	2.5	0	100000		0.27	1.6	10	0.23	213.0849
0	1999	2.5	3.5	0	100000		0.27	1.6	10	0.19	213.0849
0	1999	3.5	5	0	100000		0.27	1.8	11	0.19	216.4091
0	1999	5	15	0	100000		0.134	2.48	13.36	0.21	213.0849
0	1999	15	20	0	100000		0.134	2.48	13.36	0.21	213.0849
0	1999	20	25	0	100000		0.134	2.48	13.36	0.21	213.0849
0	1999	25	30	0	100000		0.134	2.48	13.36	0.21	213.0849
1	2004	0	0.9	0	8		1.02	5.51	7.013	0.47	248.3961
1	2004	0	0.9	8	19		0.59	2.9	5.95	0.23	248.3961
1	2003	0	0.9	19	37		0.375	2.05	6.34	0.33	248.3961
1	2004	0	0.9	37	100000		0.41	1.6	9.8	0.43	213.0849
1	2003	0.9	1.2	0	100000		0.32	1.6	9.8	0.36	213.0849
1	2003	1.2	2.5	0	100000		0.27	1.6	9.8	0.23	213.0849
1	2006	2.5	3.5	0	100000		0.27	1.6	9.1	0.19	213.0849
1	2006	3.5	5	0	100000		0.27	1.8	9.2	0.19	213.0849
1	2006	5	15	0	100000		0.134	2.48	10.55	0.21	213.0849

Tier	Year <=Last Applied	Displacement (l/cylinder) Low	<High	Power (kW) Low	<High	Power Density kW/l	Emission Factors (g/kW-hr) HC	CO	NOx	PM10	Fuel
1	2006	15	20	0	100000		0.134	2.48	10.55	0.21	213.0849
1	2006	20	25	0	100000		0.134	2.48	10.55	0.21	213.0849
1	2006	25	30	0	100000		0.134	2.48	10.55	0.21	213.0849
2	2008	0	0.9	0	8		0.91	5.51	5.89	0.50	248.3961
2	2008	0	0.9	8	19		0.28	2.9	4.87	0.24	248.3961
2	2008	0	0.9	19	37		0.724	2.05	4.98	0.29	248.3961
2	2008	0	0.9	37	75		0.41	1.6	5.7	0.22	213.0849
2	2011	0	0.9	75	100000		0.41	1.6	5.7	0.22	213.0849
2	2012	0.9	1.2	0	100000		0.32	0.9	6.1	0.11	213.0849
2	2013	1.2	2.5	0	100000		0.19	1.1	6	0.12	213.0849
2	2012	2.5	3.5	0	100000		0.19	1.1	6	0.12	213.0849
2	2011	3.5	5	0	100000		0.19	1.1	6	0.12	213.0849
2	2011	5	7	0	100000		0.134	2	8.33	0.31	213.0849
2	2012	7	15	0	3700		0.134	2	8.33	0.31	213.0849
2	2013	7	15	3700	100000		0.134	2	8.33	0.31	213.0849
2	2013	15	20	0	100000		0.134	2	8.33	0.31	213.0849
2	2013	20	25	0	100000		0.134	2	8.33	0.31	213.0849
2	2013	25	30	0	100000		0.134	2	8.33	0.31	213.0849
3	2050	0	0.9	0	8		0.58	5.51	5.89	0.32	213.0849
3	2013	0	0.9	8	19		0.282	2.9	4.87	0.26	213.0849
3.1	2050	0	0.9	8	19		0.282	2.9	3.11	0.26	213.0849
3	2013	0	0.9	19	37		0.55	2.05	4.975	0.24	213.0849
3.1	2050	0	0.9	19	37		0.55	2.05	3.11	0.24	213.0849
3	2013	0	0.9	37	75		0.3	1.6	5.7	0.17	213.0849
3.1	2050	0	0.9	37	75		0.3	1.6	3.56	0.17	213.0849
3	2050	0	0.9	75	100000	35	0.14	1.6	4.08	0.08	213.0849

Tier	Year <=Last Applied	Displacement (l/cylinder) Low	<High	Power (kW) Low	<High	Power Density kW/l	Emission Factors (g/kW-hr) HC	CO	NOx	PM10	Fuel
3	2050	0.9	1.2	0	100000	35	0.13	0.9	4.54	0.05	213.0849
3	2017	1.2	2.5	0	600	35	0.1	1.1	4.69	0.07	213.0849
3.1	2050	1.2	2.5	0	600	35	0.1	1.1	4.69	0.06	213.0849
3	2050	0	0.9	75	100000	1000	0.15	1.6	4.38	0.08	213.0849
3	2016	0.9	1.2	0	100000	1000	0.14	0.9	4.89	0.05	213.0849
3	2050	1.2	2.5	0	600	1000	0.11	1.1	4.81	0.08	213.0849
3	2017	1.2	2.5	601	1000		0.1	1.1	4.69	0.07	213.0849
4	2050	1.2	2.5	601	1000		0.04	1.1	1.3	0.03	213.0849
3	2016	1.2	2.5	1001	100000		0.1	1.1	4.69	0.07	213.0849
4	2050	1.2	2.5	1001	100000		0.04	1.1	1.3	0.03	213.0849
3	2017	2.5	3.5	0	600		0.1	1.1	4.69	0.07	213.0849
3.1	2050	2.5	3.5	0	600		0.1	1.1	4.69	0.06	213.0849
3	2017	2.5	3.5	600	1000		0.1	1.1	4.69	0.07	213.0849
4	2050	2.5	3.5	600	1000		0.04	1.1	1.3	0.03	213.0849
3	2016	2.5	3.5	1000	100000		0.1	1.1	4.69	0.07	213.0849
4	2050	2.5	3.5	1000	100000		0.04	1.1	1.3	0.03	213.0849
3	2017	3.5	5	0	600		0.1	1.1	4.81	0.07	213.0849
3.1	2050	3.5	5	0	600		0.1	1.1	4.81	0.06	213.0849
3	2017	3.5	5	600	1000		0.1	1.1	4.81	0.07	213.0849
4	2050	3.5	5	600	1000		0.04	1.1	1.3	0.03	213.0849
3	2016	3.5	5	1000	1400		0.1	1.1	4.81	0.07	213.0849
4	2050	3.5	5	1000	1400		0.04	1.1	1.3	0.03	213.0849
3	2015	3.5	5	1400	100000		0.1	1.1	4.81	0.07	213.0849
4	2050	3.5	5	1400	100000		0.04	1.1	1.3	0.03	213.0849
3	2050	5	15	0	600		0.07	1.1	5.97	0.11	213.0849
3	2017	5	15	600	1000		0.07	2	5.97	0.11	213.0849

Tier	Year <=Last Applied	Displacement (l/cylinder)		Power (kW)		Power Density	Emission Factors (g/kW-hr)				
		Low	<High	Low	<High	kW/l	HC	CO	NOx	PM10	Fuel
4	2050	5	15	600	1000		0.02	2	1.3	0.03	213.0849
3	2016	5	15	1000	1400		0.07	2	5.97	0.11	213.0849
4	2050	5	15	1000	1400		0.02	2	1.3	0.03	213.0849
3	2015	5	15	1400	2000		0.07	2	5.97	0.11	213.0849
4	2050	5	15	1400	2000		0.02	2	1.3	0.03	213.0849
3	2013	5	15	2000	3700		0.134	2	8.33	0.11	213.0849
3.1	2015	5	15	2000	3700		0.02	2	1.3	0.11	213.0849
4	2050	5	15	2000	3700		0.02	2	1.3	0.03	213.0849
3	2016	5	15	3700	100000		0.06	2	1.3	0.10	213.0849
4	2050	5	15	3700	100000		0.03	2	1.3	0.04	213.0849
3	2015	15	20	0	2000		0.09	2	6.77	0.30	213.0849
4	2050	15	20	0	2000		0.01	2	1.3	0.04	213.0849
3	2015	15	20	2000	3700		0.01	2	1.3	0.30	213.0849
4	2050	15	20	2000	3700		0.01	2	1.3	0.04	213.0849
3	2016	15	20	3700	100000		0.07	2	1.3	0.23	213.0849
4	2050	15	20	3700	100000		0.01	2	1.3	0.05	213.0849
3	2016	20	30	0	100000		0.07	2	1.3	0.23	213.0849
3	2050	20	30	0	100000		0.01	2	1.3	0.05	213.0849

B. Commercial Marine Auxiliary Engines

Tier	Year <= Last Applied	Displacement (l/cyl)		Power (kW)		Power Density	Emission Factors (g/kW-hr)				
		Low	<High	Low	<High	kW/l	HC	CO	NOx	PM10	Fuel
0	1999	0	0.9	0	8		2.01	6.71	13.41	1.21	248.3961
0	1999	0	0.9	8	19		2.28	6.71	11.4	1.08	248.3961
0	1999	0	0.9	19	37		2.41	6.71	9.25	0.94	248.3961
0	1999	0	0.9	37	100000		0.41	2	11	0.73	213.0849
0	1999	0.9	1.2	0	100000		0.32	1.7	10	0.42	213.0849
0	1999	1.2	2.5	0	100000		0.27	1.5	10	0.23	213.0849
0	1999	2.5	3.5	0	100000		0.27	1.5	10	0.21	213.0849
0	1999	3.5	5	0	100000		0.27	1.8	11	0.19	213.0849
1	2004	0	0.9	0	8		1.02	5.51	7.013	0.47	248.3961
1	2004	0	0.9	8	19		0.59	2.9	5.95	0.23	248.3961
1	2003	0	0.9	19	37		0.375	2.05	6.34	0.33	248.3961
1	2004	0	0.9	37	100000		0.41	2	9.8	0.73	213.0849
1	2003	0.9	1.2	0	100000		0.32	1.7	9.8	0.42	213.0849
1	2003	1.2	2.5	0	100000		0.27	1.5	9.8	0.23	213.0849
1	2006	2.5	3.5	0	100000		0.27	1.5	9.1	0.21	213.0849
1	2006	3.5	5	0	100000		0.27	1.8	9.2	0.19	213.0849
2	2008	0	0.9	0	8		0.91	5.51	5.89	0.50	248.3961
2	2008	0	0.9	8	19		0.28	2.9	4.87	0.24	248.3961
2	2008	0	0.9	19	37		0.724	2.05	4.98	0.29	248.3961
2	2008	0	0.9	37	75		0.41	1.6	5.7	0.22	213.0849
2	2011	0	0.9	75	100000		0.41	1.6	5.7	0.22	213.0849
2	2012	0.9	1.2	0	100000		0.32	0.8	5.4	0.20	213.0849
2	2013	1.2	2.5	0	100000		0.21	0.9	6.1	0.14	213.0849
2	2012	2.5	3.5	0	100000		0.21	0.9	6.1	0.14	213.0849

Tier	Year <= Last Applied	Displacement (l/cyl)		Power (kW)		Power Density	Emission Factors (g/kW-hr)				
		Low	<High	Low	<High	kW/l	HC	CO	NOx	PM10	Fuel
2	2011	3.5	5	0	100000		0.21	0.9	6.1	0.14	213.0849
3	2013	0	0.9	0	75		0.3	1.6	5.7	0.17	213.0849
3.1	2050	0	0.9	0	75		0.3	1.6	3.56	0.17	213.0849
3	2050	0	0.9	75	100000	35	0.14	1.6	4.08	0.08	213.0849
3	2050	0	0.9	75	100000	1000	0.15	1.6	4.38	0.08	216.4091
3	2050	0.9	1.2	0	600		0.13	0.8	4.02	0.08	213.0849
3	2016	0.9	1.2	600	100000		0.13	0.8	4.02	0.08	213.0849
4	2050	0.9	1.2	600	100000		0.04	0.8	1.3	0.03	213.0849
3	2017	1.2	2.5	0	600		0.11	0.9	4.77	0.08	213.0849
3.1	2050	1.2	2.5	0	600		0.11	0.9	4.77	0.07	213.0849
3	2017	1.2	2.5	600	1000		0.11	0.9	4.77	0.08	213.0849
4	2050	1.2	2.5	600	1000		0.04	0.9	1.3	0.03	213.0849
3	2016	1.2	2.5	1000	1400		0.11	0.9	4.77	0.08	213.0849
4	2050	1.2	2.5	1000	1400		0.04	0.9	1.3	0.03	213.0849
3	2015	1.2	2.5	1400	100000		0.11	0.9	4.77	0.08	213.0849
4	2050	1.2	2.5	1400	100000		0.04	0.9	1.3	0.03	213.0849
3	2017	2.5	3.5	0	600		0.11	0.9	4.77	0.08	213.0849
3.1	2050	2.5	3.5	0	600		0.11	0.9	4.77	0.07	213.0849
3	2017	2.5	3.5	600	1000		0.11	0.9	4.77	0.08	213.0849
4	2050	2.5	3.5	600	1000		0.04	0.9	1.3	0.03	213.0849
3	2016	2.5	3.5	1000	100000		0.11	0.9	4.77	0.08	213.0849
4	2050	2.5	3.5	1000	100000		0.04	0.9	1.3	0.03	213.0849
3	2017	3.5	5	0	600		0.11	0.9	4.89	0.08	213.0849
3.1	2050	3.5	5	0	600		0.11	0.9	4.89	0.07	213.0849
3	2017	3.5	5	600	1000		0.11	0.9	4.89	0.08	213.0849

Tier	Year <= Last Applied	Displacement (l/cyl)		Power (kW)		Power Density	Emission Factors (g/kW-hr)				
		Low	<High	Low	<High	kW/l	HC	CO	NOx	PM10	Fuel
4	2050	3.5	5	600	1000		0.04	0.9	1.3	0.03	213.0849
3	2016	3.5	5	1000	1400		0.11	0.9	4.89	0.08	213.0849
4	2050	3.5	5	1000	1400		0.04	0.9	1.3	0.03	213.0849
3	2015	3.5	5	1400	100000		0.11	0.9	4.89	0.08	213.0849
4	2050	3.5	5	1400	100000		0.04	0.9	1.3	0.03	213.0849