

2021 Line-Haul Locomotive Emission Inventory



**Air Quality Planning and Science Division
Mobile Source Analysis Branch
February 2021**



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Executive Summary

Locomotives and rail systems are an important part of California's freight and passenger movement network and are significant contributors to harmful diesel emissions in California. This document summarizes the methodology utilized by the California Air Resources Board (CARB) to estimate emissions from Class I Line haul locomotives which include locomotives that provide interstate freight transportation for containers, liquid material, or bulk material in California. The Surface Transportation Board defines Class I Line hauls as operations that gross over \$450 million per year^{1,2}. There are six Class I Line haul operations in the United States, with two operating in California: Union Pacific (UP) Railroad and BNSF Railway. Additional locomotive categories not included in this inventory are Class II and III Line hauls, passenger locomotives, and switching locomotives that are used within rail yards.

This updated emissions inventory is developed using line haul activity and population supplied by both UP and BNSF railroads. The previous emissions inventory model was developed in 2011 based on 2007/2008 data and was later updated in 2016. Considering that previous inventories were created prior to the penetration of Tier 4 engines, they were not able to predict how railroads would adopt Tier 4 engines or respond to the new engine standards. Both releases predicted a relatively fast penetration of Tier 4 locomotives in the fleet - at a rate of up to 7 percent per year after 2015. In retrospect, the predicted penetration rate turned out to be very optimistic and has not materialized. According to the most recent data, Tier 4 locomotive engine penetration rates sit at under 1 percent per year on average because the railroads have been purchasing fewer than expected Tier 4 units for the past few years, instead choosing to operate remanufactured Tier 1+ and Tier 2+ units.

Figure 1 shows the updated emission projections and the previous emission inventory (shown in the red line) that was used for the 2016 South Coast State Implementation Plan. As shown, due to the lack of Tier 4 locomotive engine penetration in the fleet, the updated Class I Line-haul inventory shows increased emissions for both nitrogen oxides (NOx) and particulate matter (PM) compared to previous inventories. Barring a change in this behavior, either internal or due to regulation or incentive actions, locomotive emissions are projected to continue to increase through 2032. This trend will make locomotives an increasingly important mobile source sector for future air quality planning and policy development as emissions from other sources such as diesel trucks and construction equipment are decreasing significantly over the same period.

1 Freight Facts and Figures 2017, U.S. Department of Transportation and Bureau of Transportation Statistics, available at: https://www.bts.gov/sites/bts.dot.gov/files/docs/FFF_2017.pdf

2 Freight Railroads Background, Office of Rail Policy and Development, Federal Railroad Administration, April 2015, available at: https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/14497/Freight%20Railroads%20Background%20April_2015.pdf

Figure 1: Comparison of 2016 and 2020 Line Haul NOx Emissions Inventory (tpd)

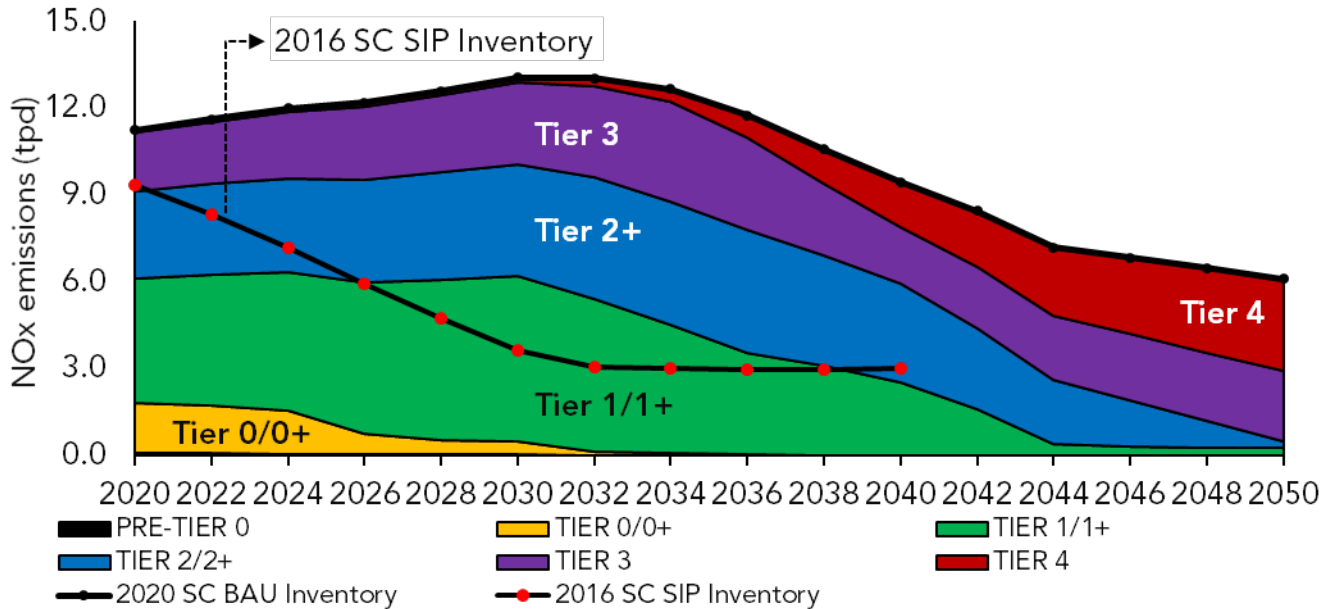
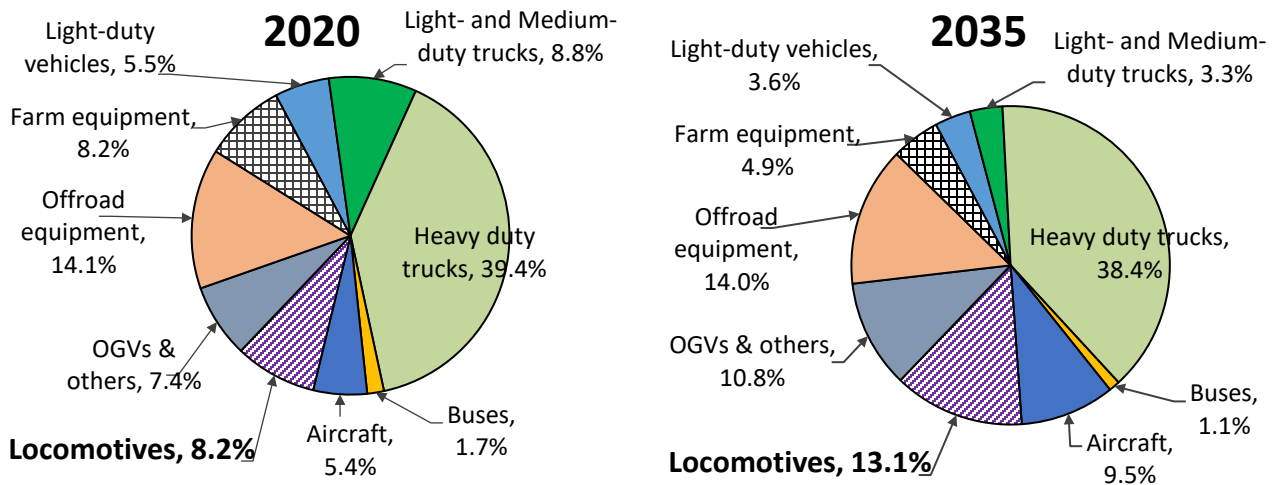


Figure 2 presents the relative emissions contribution of line haul locomotives compared to other mobile sources, demonstrating the increasing importance of line haul emissions over time. Separately from the direct contribution, it is notable that locomotives in freight movement offer substantially lower energy footprints than other freight transportation modes, such as road/trucks, pipeline, and waterways³ per gross ton-mile of cargo moved.

Figure 2: NOx Emission Contribution by Sector in 2020 and 2035⁴



³ Rail travel is cleaner than driving or flying, but will Americans buy in?, Andreas Hoffrichter, 2015, available at: <https://theconversation.com/rail-travel-is-cleaner-than-driving-or-flying-but-will-americans-buy-in-112128>

⁴ These charts do not account for recently adopted regulations such as HD Omnibus and Advanced Clean Trucks

Inventory Inputs and Methodology

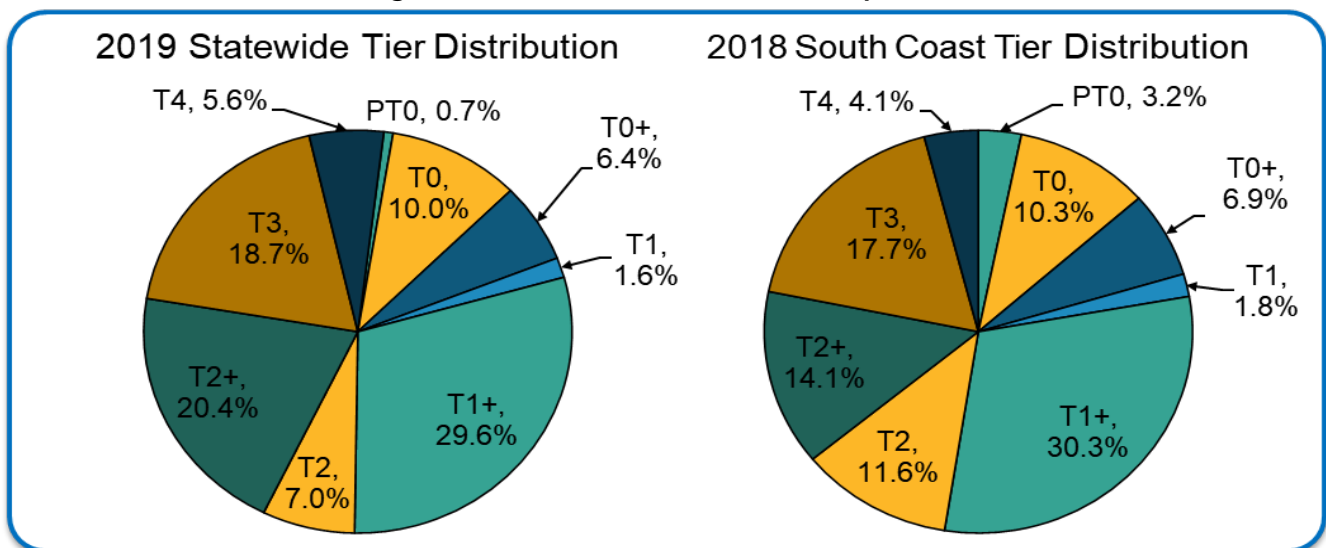
Line Haul Population and Activity Data

In 1998, CARB and California railroads (RRs) agreed to a memorandum of understanding (MOU) for accelerated adoption of cleaner locomotives in the South Coast region. In conjunction with the MOU and the locomotive engine emission standards, the RRs agreed to ensure the South Coast locomotive fleet met a Tier 2 engine average by 2010. To verify Fleet Average Targets in the MOU are being met, UP and BNSF must track and report locomotive activity in the South Coast Nonattainment Area by recording megawatts-hours (MWhrs) and fuel consumption.

The 2020 updated line haul model is developed primarily on the 1998 MOU data for locomotives operating in South Coast Air Basin (SCAB) supplied by BNSF and UP from 2010 to 2018. The 2018 data serves as the base year for population and activity, and the forecasting model is based on the remanufacturing behavior and MWhrs transition patterns between Tier groups observed between 2015 to 2018. This report discusses the methodology employed by CARB staff to determine future locomotive activity, Tier distribution, and resulting emissions.

Tier distribution and turnover patterns shown in the SCAB were used for determining Tier and turnover patterns for the remainder of the state. The SCAB data was used because the data set is significantly more robust, has more years represented, and has a higher temporal resolution. The activity, in MWhrs, for the remainder of the state, was based on data supplied by UP and BNSF. An overall Tier distribution for the remainder of the state was also supplied at a lower resolution; however, as shown in Figure 3, the statewide Tier distribution was not significantly different in 2018 than the one in South Coast. Hence the more robust South Coast data set was used to determine the activity and Tier transition patterns across the state.

Figure 3: Tier Distribution in Unit Population

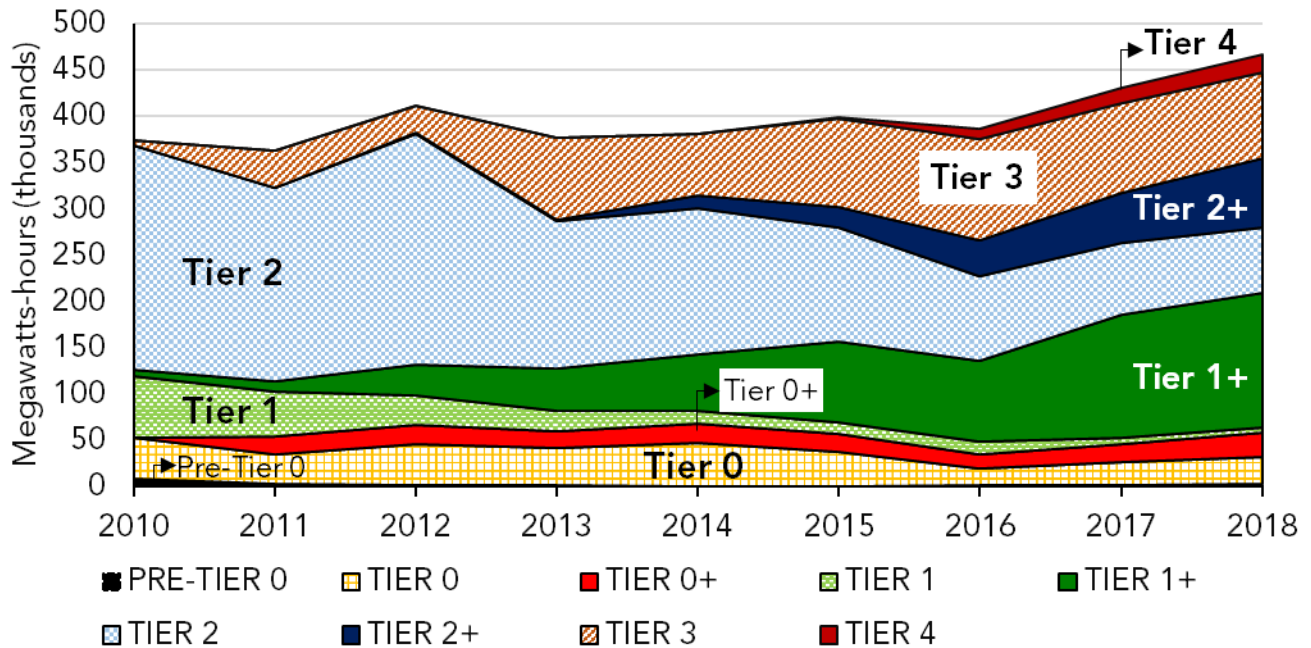


Remanufacturing a locomotive generally means replacing older, worn-out engine components with either newly manufactured power assemblies or refurbished assemblies. Remanufacturing includes engine replacements, upgrades, and conversion of engine emissions control systems; therefore, a locomotive's engine Tier can be changed from one Tier to another after the remanufacture. The emission standard of the remanufactured units depends on the remanufacture kit. These units are identified as different emission standards, such as Tier 1r, or 1+, 2r or 2+, etc. The following sections will cover the existing data, the observed pattern of transitions between Tiers, the projected overall growth, and lastly, how these inputs combine to form the forecast.

Tier Distribution of Locomotives in Source Data

Figure 4 shows the megawatt-hours (MWhrs) distribution of locomotive Tier groups operated in the South Coast Air Basin from 2010 to 2018. Between 2010 and 2018, the majority of Tier 1 and 2 units were replaced by Tier 1+ and Tier 2+ units, respectively. MWhrs of Tier 4 show a slow adoption rate from 2016 through 2018, while the MWhrs of Tier 3 have remained steady for between 2016 and 2018. Tier 1+ notably became the largest contributor to MWhrs in 2018. Tier 4 locomotive purchases have been steadily decreasing since Tier 4 standards went into effect in 2015, with no 2019 Tier 4 locomotive purchases as of May 31, 2019, which is again indicating the low adoption of Tier 4 locomotives by rail yards.

Figure 4: South Coast Air Basin Class I Line Haul Locomotive MWhrs Distribution from 2010 to 2018



Emission Factors

The updated emissions inventory model uses the line haul emission factors, by Tier, published by U.S. Environmental Protection Agency (U.S. EPA)⁵ as shown in Table 1. As illustrated in this table, Tier 4 engines offer significantly lower NOx and diesel PM2.5 emission rates compared to older Tiers. This shows the importance of Tier 4 engine adoption in reducing NOx emissions from the rail sector in California.

Table 1. U.S. EPA Line Haul Emission Factors for NOx and PM10 in g/bhp-hr

Tier	PM10	NOx
Pre-Tier 0	0.320	13
Tier 0	0.320	8.6
Tier 0+	0.200	7.2
Tier 1	0.320	6.7
Tier 1+	0.200	6.7
Tier 2	0.180	4.95
Tier 2+	0.080	4.95
Tier 3	0.080	4.95
Tier 4	0.015	1.0

Forecasting Methodology

Looking at the rail data from 2010 to 2018, the Tier distribution shows different activity levels and turnover patterns in each year. The turnover pattern will determine which engine Tiers are seeing increased activity, which ones are phasing out (also known as diminishing Tiers), which ones are being remanufactured, and what Tier they are being manufactured to. In addition, the available data covers only the South Coast Air Basin, and each railroad can assign any of their units to California operations from outside the state. Considering the Tier pattern over the past nine years, CARB inventory staff recognized that a conventional survival curve - or demographic data-based approaches for predicting locomotive turnover rates would not be the most appropriate modeling technique for this category. Conventional methods generally rely on a captive group of equipment that is retired and replaced on a predictable schedule, and engines are not remanufactured to different Tiers in a complex or shifting pattern.

Furthermore, conventional forecasting methods are limited to reflect work intensity per locomotive unit, while in reality, the workload per unit can, and does, change over time. A heavy heavy-duty truck is defined by the Federal Highway Administration (FHWA) as weighing 33,001 pounds and greater, while a modern railcar's gross capacity is around 286,000 pounds. Locomotives can stretch from 10,000 to 15,000 feet in length by pulling as

⁵ Emission Factors for Locomotives, United States EPA, April 2009, available at: <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100500B.txt>

many as one hundred railcars. As a result, the total weight pulled by Class I locomotives can vary significantly depending on the length of the train and the type of commodity being transported. Based on the aforementioned reasons, this inventory uses MWhrs (activity) as the basis for the inventory instead of the population of locomotives.

Traditional locomotive inventory methods generally focus on equipment turnover and neglect the impact of remanufacturing. Therefore, this new CARB inventory uses a replacement and remanufacture behavior-based modeling approach – essentially focusing on the shift between Tier groups in addition to equipment turnover cycles. This new inventory bases the Tier transition forecast on information for locomotives visiting the South Coast Air Basin because this is the most robust dataset provided to CARB by the rail companies. Assuming rail companies provide information at similar levels of detail for other parts of the state, CARB can update the inventory accordingly.

The basic model assumptions assumed for this inventory update are:

1. MWhrs from the South Coast MOU⁶ data are used to calculate fuel use and emissions (accounting for engine Tier) for each locomotive. This is the foundation for forecasting MWhrs and emissions for future years.
2. South Coast Air Basin line-haul operations are representative of statewide line-haul operations. This means that the model assumed other air basins have similar remanufacture and replacement behavior. The model presumes SCAB's pattern of diminishing MWhrs is identical to statewide fleet turnover patterns, which is supported by the similarity of Tier distributions between SCAB and the rest of California, as shown in Figure 3.
3. Railroads (RRs) will remanufacture the locomotive units in California operation in a similar pattern, as demonstrated over the past decade. As a result, the SC Tier distribution will change over time, but the MWhrs transition patterns between Tier groups will remain consistent in future years. The observed Tier transition patterns were used to predict incremental MWhrs per year and Tier distributions in the coming years.
 - a. The suggested model presumes that total MWhrs of old Tier groups, such as Pre-Tier 0, T1, T1+, etc., will start to diminish after the major turnover timing that the majority of each Tier group is retired or remanufactured (this is described in detail later in the document). This relies on the assumption that turnover patterns of the statewide fleet are similar to those of the nationwide fleet.
 - b. 1998 MOU data obtained from 2010 to 2018 reasonably presents the movement of MWhrs between Tier groups, and this inventory assumes that the transition patterns will continue in the next decades.

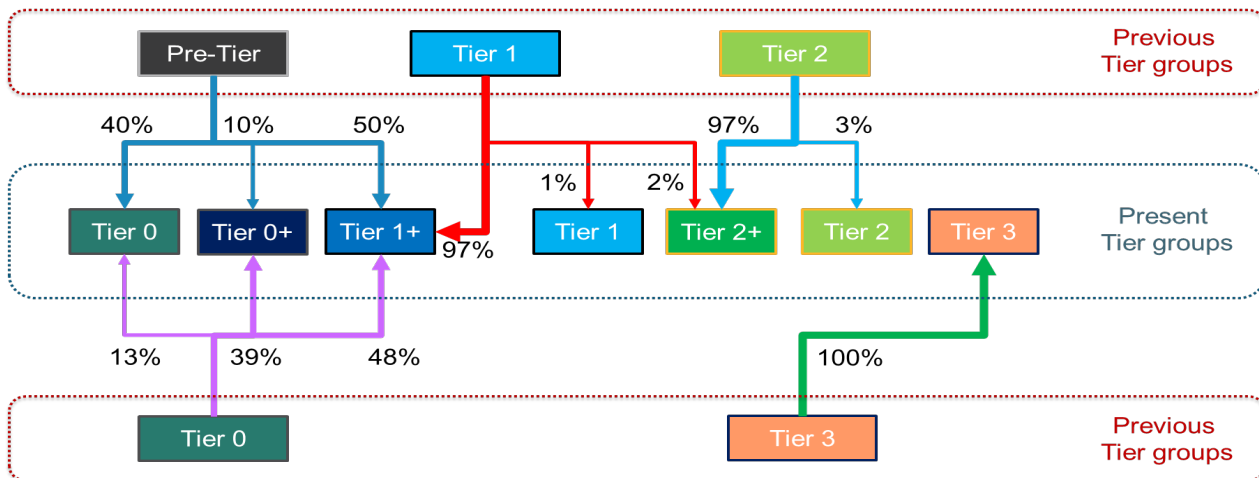
⁶ CARB Rail Emission Reduction Agreements, available at: <https://ww2.arb.ca.gov/resources/documents/rail-emission-reduction-agreements>

Transition Patterns between Tier Groups

The Tier distribution of locomotives in the South Coast from 2010 to 2018 is the basis for forecasting future Tier distributions. Figure 5 shows the observed MWhrs flows between Tier groups during this period. For example, 1,218 Pre-Tier locomotives were remanufactured to a Tier 0 emission standard. The most significant observed patterns of the MWhrs remanufactures are:

- From Pre-Tier 0 to Tier 0 and Tier 1+,
- Tier 0 to Tier 0+,
- Tier 1 to Tier 1+,
- Tier 2 to Tier 2+.

Figure 5: MWhrs Transition Between Tiers due to Remanufacturing



Baseline Growth Rate of Total MWhrs

The base MWhrs growth was predicted using the Freight Analysis Framework (FAF) version 4.5.1 data⁷, as well as the historic railroad growth rates. FAF is produced through a partnership between the Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA). It collects data from a variety of sources to create a comprehensive picture of freight movement among states and major metropolitan areas by all modes of transportation. The main sources of information are the Commodity Flow Survey (CFS) and international trade data from the Census Bureau. FAF provides forecasts as estimates for tonnage and value by regions of origin and destination, commodity type, and mode. The FAF forecast is used in forecasts by California Statewide Freight Forecasting Model (CSFFM) developed by CalTrans, as well as the Bay Area Metropolitan Transportation Commission for San Francisco Bay Area Goods Movement Plan⁸. Equation 1 shows how projections from FAF

⁷ Freight Analysis Framework Version 4 available at: <https://faf.ornl.gov/fafweb/>

⁸ Metropolitan Transportation Commission, San Francisco Bay Area Goods Movement Plan, February 2016, https://mtc.ca.gov/sites/default/files/RGM_Full_Plan.pdf

as well as the historic railroad growth rates were used to determine the future growth rates for rail activity in California. On the left of the equation, the historical FAF forecast rate (i.e., 2.249 percent growth per year) is compared to the observed growth rate of MWhrs in the railroad data (i.e., 2.777 percent per year). From this relationship, we can see that the railroad MWhrs experienced a higher growth rate than is forecasted by FAF. Applying this relationship to the current forecast for California rail in FAF 4.5 (1.773 percent per year), expected growth from the railroads will be 2.19 percent per year.

$$\frac{\text{FAF15, freight movement growth rate in past years (tons)}}{\text{Reported MWhrs growth rate for the past years}} = \frac{\text{FAF45, forecasted freight movement growth rate (tons)}}{\text{MWhrs growth rate for future years}}$$

$$\frac{2.249\%}{2.777\%} = \frac{1.773\%}{\text{MWhrs growth rate for future years}} = 2.1898\%$$

Table 2. Freight Movement-related Growth Rate Forecasts

Data sources	Time frame	Average Growth
Total Distillate Sales/Deliveries to Railroad Consumers (Thousand Gallons) ⁹	2013–2018	1.82%
CA State Rail Plan: Compound annual growth rates for carload service ¹⁰	2013–2040	1.70%
CA State Rail Plan: Compound annual growth rates for intermodal service ¹⁰	2013–2040	2.90%
ATA 2012 Rail Volume Forecast: Rail Carload & Intermodal Freight ¹¹	2012–2023	1.42%
2019 The Budget and Economic Outlook: GDP (Billions of dollars) ¹²	2013–2018	4.70%
2020 SCAG SoCal Connect – Goods Movement Plan ¹³	2020-2045	2.8%
Rail growth used for SCAG Regional Transportation Planning ¹⁴	2010–2018	3.30%
Class I Rail Freight Fuel Consumption and Travel (million gallons) ¹⁵	2010–2018	1.51%
Seasonally adjusted Rail Freight Intermodal Traffic (BTS & AAR) ¹⁵	2010–2018	3.17%
Port of Long Beach container counts (TEUs) ¹⁶	2010–2018	2.20%
Port of LA container counts (TEUs) ¹⁷	2010–2018	2.00%

⁹ U.S. Energy Information Administration, Sales of Distillate Fuel Oil by End Use, https://www.eia.gov/dnav/pet/pet_cons_821dst_dcu_nus_a.htm

¹⁰ California State Rail Plan, <https://dot.ca.gov/programs/rail-and-mass-transportation/california-state-rail-plan>

¹¹ <http://www.azttca.org/pdf/ATA-Freight-Forecast.pdf>

¹² The Budget and Economic Outlook: 2019 to 2029 of Congressional budget office (CBO), <https://www.cbo.gov/system/files/2019-03/54918-Outlook-3.pdf>

¹³ 2020 Connect SoCal Goods Movement Plan, Adopted on September 3, 2020, https://scag.ca.gov/sites/main/files/file-attachments/0903fconnectsocial_goods-movement.pdf?1606001690

¹⁴ 2012-2035 Regional Transportation Plan (RTP) of the Southern California Association of Governments, <http://rtpscs.scag.ca.gov/Pages/2012-2035-RTP-SCS.aspx>

¹⁵ Bureau of transportation statistics: Class I Rail Freight Fuel Consumption and Travel, <https://www.bts.gov/content/class-i-rail-freight-fuel-consumption-and-travel>

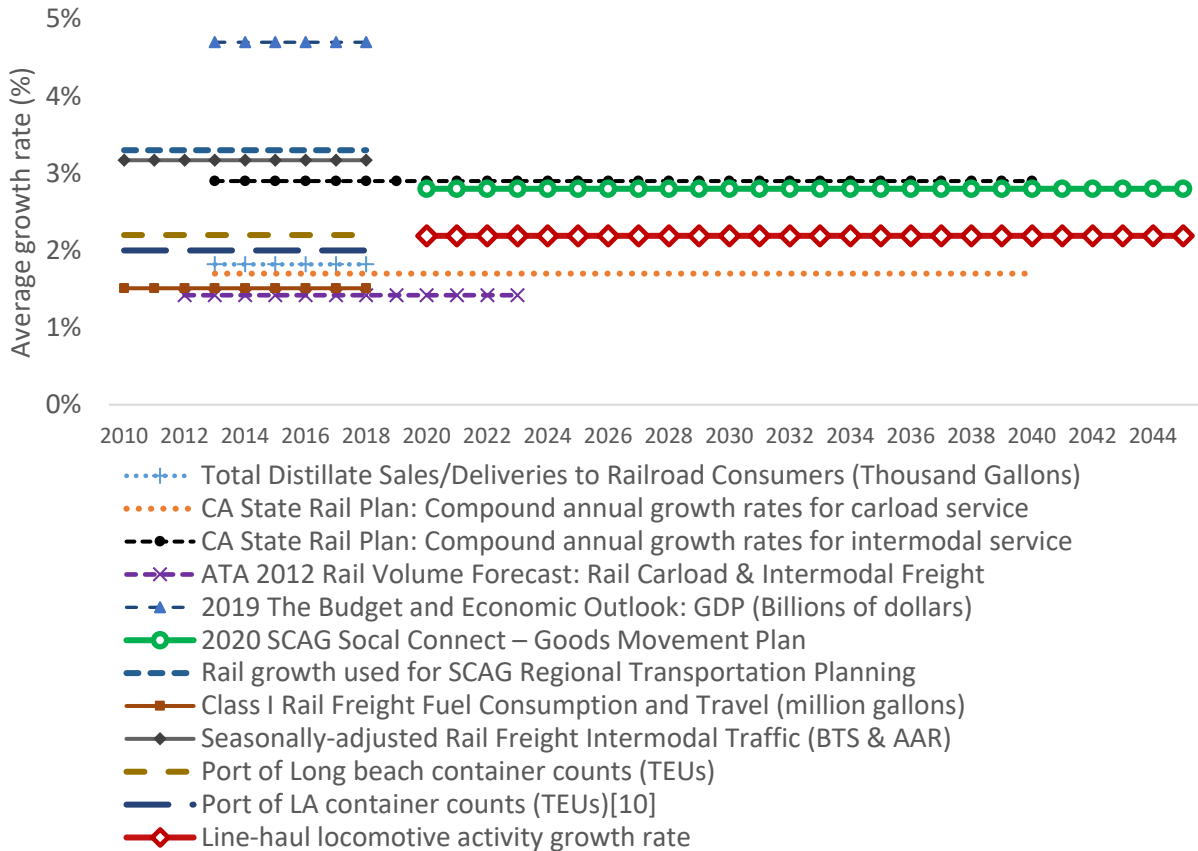
¹⁶ Port of Long Beach latest statistics, <https://www.polb.com/business/port-statistics/#latest-statistics>

¹⁷ Port of LA container statistics, <https://www.portoflosangeles.org/business/statistics/container-statistics>

In addition to reviewing FAF data, the data source is compared against a number of sources to determine if the FAF forecast was reasonable. Table 2 and Figure 6 present the calculated growth rates from multiple data resources and confirms the value from FAF is within a reasonable range of other data sources. It is notable that the growth used in this emissions inventory is significantly below those suggested by the State Rail Plan¹⁰, the Southern California Association of Governments (SCAG) 2020 regional transportation plan (2020 RTP)¹⁴, or the Bureau of Transportation Statistics and American Association of Railroads growth¹⁵ totals over the last decade, but instead is closer to the historical growth rates of fuel used by the railroads. For example, according to SCAG's Goods Movement Plan, between 2020 and 2045, freight train volumes are expected to more than double, and intermodal lift volumes are expected to grow by more than 140 percent. That is almost an average of 2.8% year over year growth for freight train volumes between 2020–2045 which is higher than the 2.19 percent growth assumed for this emissions inventory update.

There are some indications that efficiency may change from the current forecast, as the RRs are attempting to make a transition to precision scheduled railroading (PSR), which is expected to enhance the system efficiency. CARB will continue to monitor rail data to determine if rail efficiencies need to be reflected in future inventories.

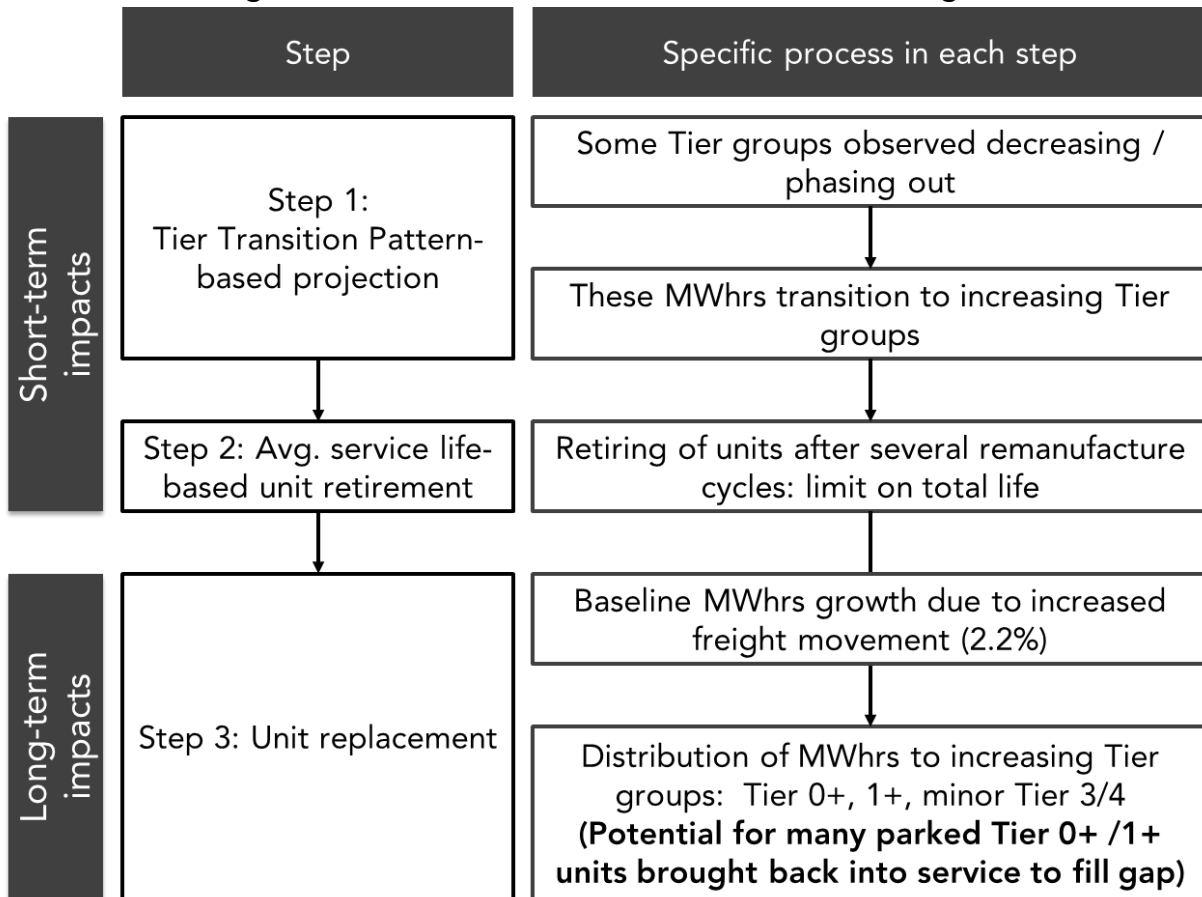
Figure 6. Freight Movement-related Growth Rate Forecasts



MWhrs Forecasting Methodology

As described earlier, the forecasting model is based on the observed transition between Tiers, as well as the application of growth to the total MWhrs. The resulting MWhrs distribution for future years will show that some Tier groups will be phased out, while others will grow and take over the diminishing MWhrs of the Tier groups that are phasing out. The forecasting process is presented in Figure 7.

Figure 7: MWhrs of Line Haul Locomotive Forecasting Procedure



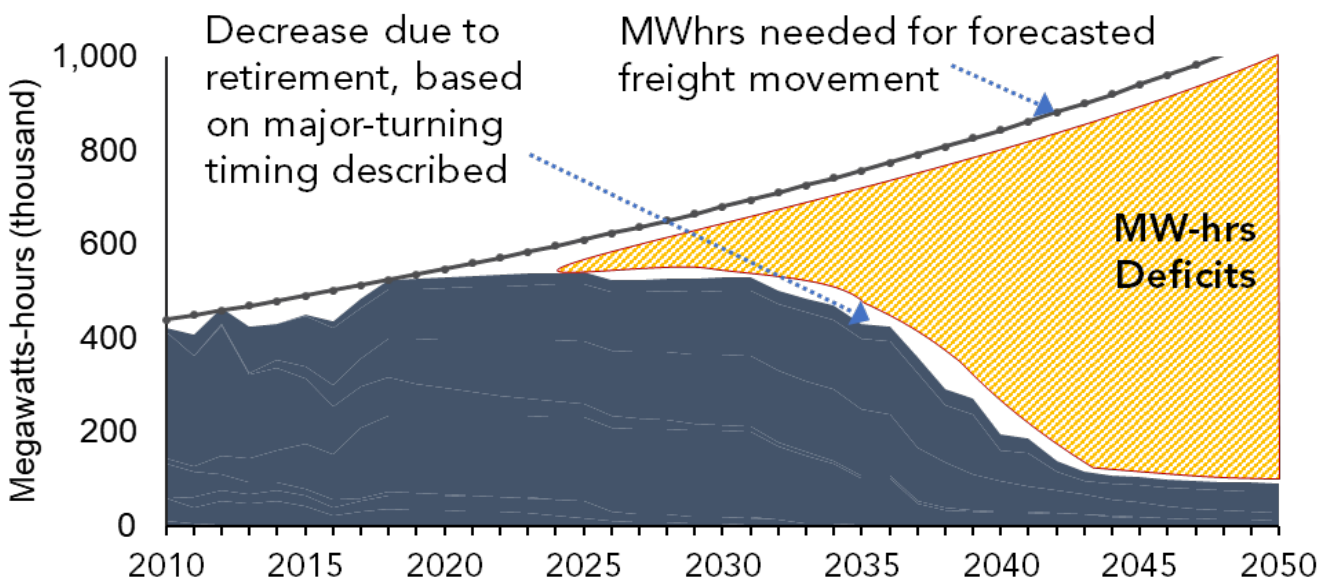
The updated model organizes the nine Tier groups into two bins that are expected to either grow or diminish based on observed trends. Increasing Tier groups (ITGs), including Tier 0+, 1+, 2+, 3, and 4, have increased in the past decade and are projected to increase in future years. The other Tiers are arranged into Decreasing Tier groups (DTGs), which have negative growth rates based on the 2010 to 2018 period. The MWhrs increase for ITGs is directly correlated to the MWhrs decreases of DTGs, such as Pre-Tier, Tier 0, Tier 1, and Tier 2. Incremental MWhrs of ITGs are calculated based on the process described below.

1. Future MWhrs of Tier 0+, 1+, and 2+ are equal to the sum of the previous year's MWhrs and MWhrs transferred from Decreasing Tier Groups.
 - a. For example, as shown in Figure 5, the sources of incoming MWhrs for Tier 0+ are Pre-Tier and Tier 0. The increase of MWhrs of Tier 0+ relies on the

- decreasing MWhrs of Pre-Tier and Tier 0 and then the percent of those Tier groups that are remanufactured to Tier 0+. Incremental MWhrs growth of Tier 0+ in a year (t) will be the same as the sum of decreased MWhrs of Decreasing Tier Groups in the previous year (t-1), in this case, 10% and 39% of reduced MWhrs of Pre-Tier 0 and Tier 0, respectively.
2. Pre-Tier, Tier 0, Tier 1, and Tier 2 will be phased out at their (negative) growth rate observed from the South Coast data.
 - a. MWhrs of the following Tier groups group decrease at a negative growth rate per year:
 - i. Pre-Tier 0: 14.0%
 - ii. Tier 0: 4.8%
 - iii. Tier 1: 26.6%
 - iv. Tier 2: 14.1%
 - b. The negative growth rate of Tier 0 is relatively low compared to the other groups, and as a result, Tier 0 would survive until 2040 at that rate. However, it is not likely that Tier 0 would phase out more slowly than (more recently manufactured) Tier 1 and Tier 2; therefore, the inventory assumes that Tier 0 would start being turned over at a rate similar to Tier 1 locomotives in 2025 and later years.
 3. For Tier 3 and 4, this model uses the baseline growth rate, 2.19%. The growth rates obtained from the MOU data are varied and inconsistent, and there was no Tier 3 or Tier 4 adoption for the most recent years. Therefore, this inventory maintains a conservative approach to estimate future MWhrs of Tier 3 and 4.

In addition, the total MWhrs of all locomotive activity increases at the growth rate described in the previous section. This creates a gap or deficit between expected MWhrs after the retirement and the initial forecast. In Figure 8, the black line indicates baseline MWhrs growth, and the diagonally striped area is representing the MWhrs deficit.

Figure 8: Deficits of the Total MWhrs of the Tier Groups Compared to the Base MWhrs Growth



Prediction of Major Turnover Timing

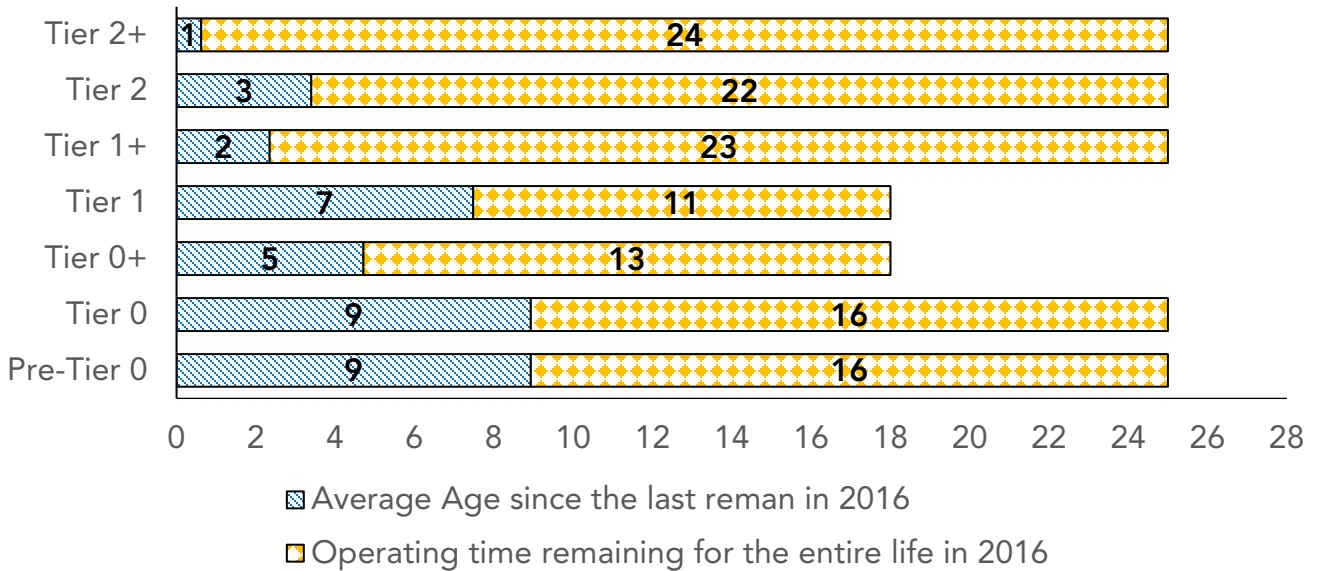
Locomotive units are typically scrapped, parked, converted to switchers, or replaced by new ones after a certain lifespan. According to the regulation impact analysis report from U.S. EPA, locomotives can run over 40 years¹⁸. Old units will eventually be retired and generally replaced by newer and cleaner units. As a result, total locomotive emissions will be reduced as railroads adopt a greater fraction of cleaner Tier units. Therefore, it is important to know the major turnover timing in which most retirements occur (referred to in other cases as total service life, the average time to retirement, average lifespan, etc.). The retirement year of each Tier can be anticipated by using the age distribution and remaining operating time of the current line-haul fleet.

The most recent data submittals provided to CARB by the RRs show that locomotives' average service life in the South Coast Air Basin operations is approximately 25 years which is different from U.S. EPA's¹⁸. The age distribution of the locomotives shows a significant drop in population and activity at 25 years of age. CARB staff discovered that 84% of 22 ~ 24-year-old SC locomotives disappeared after reaching 25 ~ 27 years. Twenty-five years of the total service life assumption was used to only predict the major fleet turnover schedule upcoming in the next decade. This is because the future Tier mix in California operations could change over time as railroads introduce more advanced and cleaner locomotive units. Since Tier 4 was officially introduced in 2015, railroads are still actively operating more Tier 1+ and Tier 2+ locomotives rather than adopting Tier 3 and Tier 4 locomotives. If railroads continue to run them in the next decade, the average total service life of these locomotives in 2030 would be longer than 25 years.

Assuming that railroads maintain the locomotive retirement patterns observed in recent years, the inventory calculates the operating time remained for each Tier by subtracting the average age per Tier from the average total service life. Figure 9 shows that the total service life consists of average age and the remained operating time. As shown in the figure, recently remanned (remanufactured) Tier groups, such as Tier 1+ and 2+, are likely to have longer periods of operating time remaining. The remaining operating time over total service life was used to estimate the possible number of remanufacturing cycles per Tier. Tier 0+ and Tier 1 groups show 18 years of average service life which is shorter than the observed fleet average. CARB staff presumed that this is because the majority of the two Tier groups were remanufactured to other Tiers before they reach their total service life. The inventory uses calendar year (CY) 2016 as the base year to calculate the average age of the locomotive fleet. Tier 4 was officially introduced into CA operations in 2015; therefore, CY2016 is the first year that all Tier groups were operated at the same time, and Tier 4 units turned 1-year-old in that CY.

¹⁸ Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder, <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P10024CN.txt>

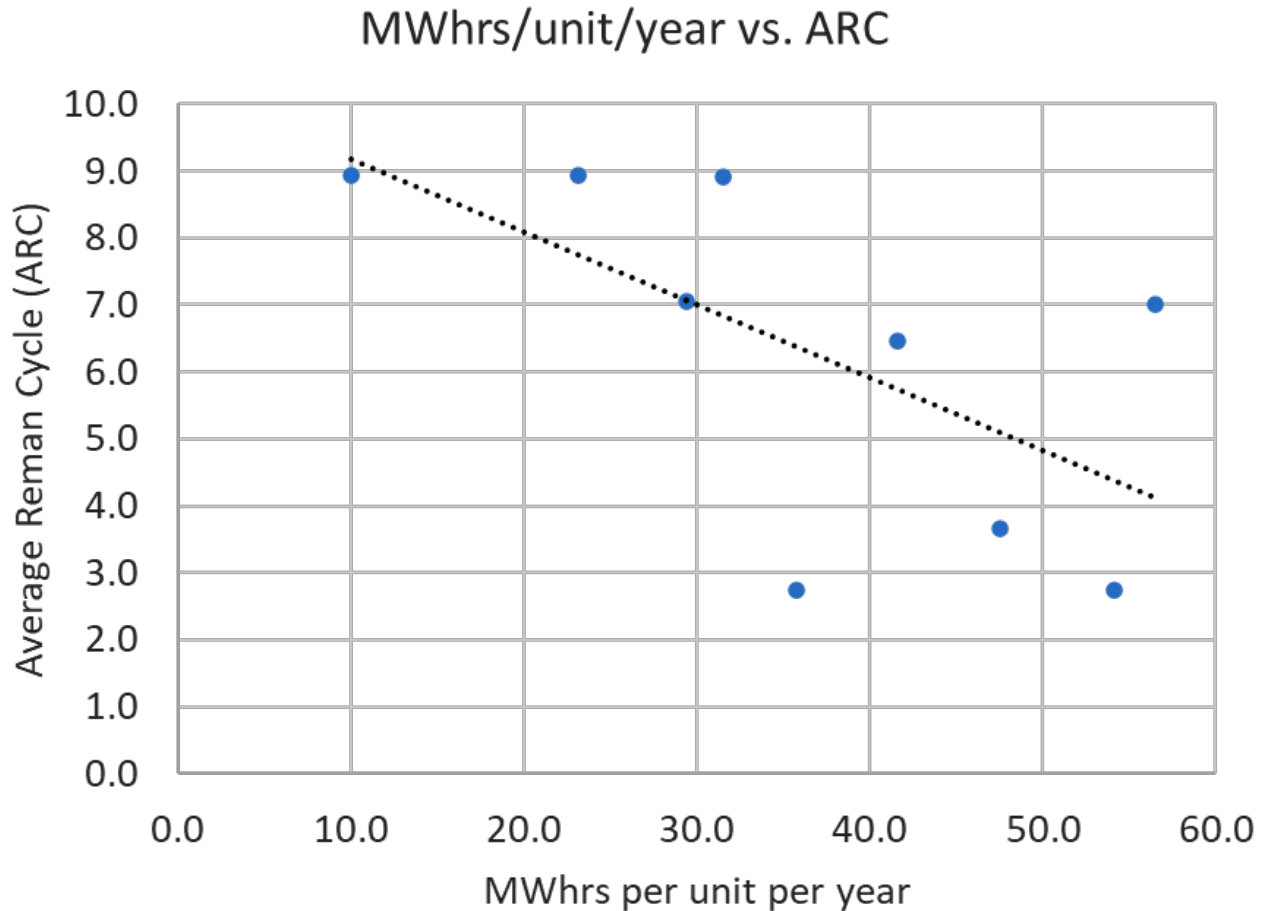
Figure 9: Total Service Life per Tier



Remanufacturing behavior also affects turnover patterns. Using the South Coast locomotive visit database, the inventory calculates the average remanufacturing cycle (ARC), which is the number of years between each major overhaul of a locomotive engine. Unlike other mobile sources, railroads can remanufacture locomotive units almost indefinitely. The model uses data from 2015 to 2018 submittals to determine the average time between remanufacturing to predict future remanufacturing cycles.

For example, if model year (MY) 2010 locomotives in CA operations have a remanufacture cycle of 10 years, the engine will be remanufactured in 2020 for the first time. Then, every ten years thereafter, assuming a functional limit of two remanufacturing cycles, the locomotive would be remanufactured in 2030 for a second time and then would likely be retired or removed from line-haul service in 2040. The predicted remanufacturing and retiring years could be slightly changed depending on the work intensity (MWhrs per unit) of individual units. If a line-haul locomotive operates more than average, the unit will be remanned earlier than the other units started at the same time.

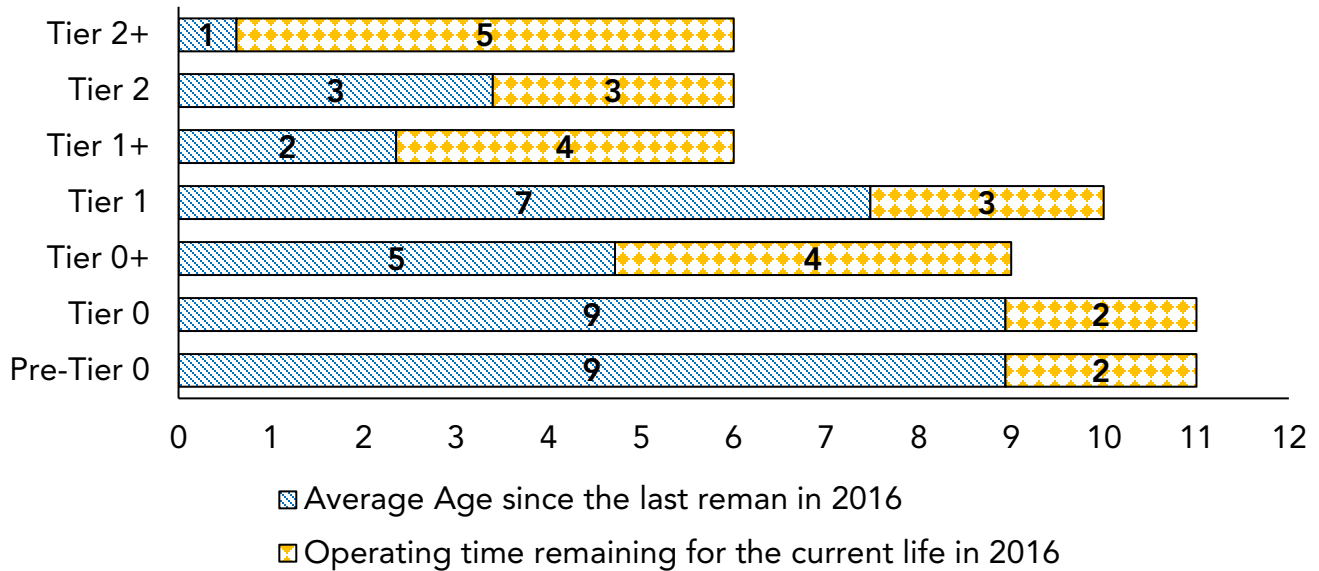
Figure 10: Distribution of MWhrs per Unit and Average Reman Cycle (ARC)



Average reman cycles (ARCs) vary by the annual activity of each Tier group. Tier groups with higher MWhrs per unit have a shorter reman cycle due to longer annual operating hours. Figure 10 supports this inverse relationship and indicates that the ARCs should be normalized by MWhrs per unit. Thus, the inventory adjusts ARC based on the difference between the average MWhrs per unit and the Tier groups' MWhrs per unit. Effectively, this means units with higher use are remanufactured more often, as remanufactures are based on hours of use, not calendar years.

The remaining useful life is defined as the operating time remaining for a locomotive group and is calculated by subtracting the average age (as shown in 9) from the average reman cycle (ARC) for each Tier group. Effectively this means comparing the age now to the average time a locomotive would retire after an average number of remanufacturing cycles. Figure 11 shows the operating time from the last remanufacture, as well as the forecasted remaining time before the next remanufacture based on the Tier-based ARC. Note that the average reman cycle is equal to the average time between remanufactures, with an additional year for the remanufacturing process to account for the time that the locomotive would be parked to complete the process.

Figure 11: Average Remanufacturing Cycle



From base year 2016, locomotives are expected to operate for the period including the remaining life before the following remanufacture and any remaining future service life based on the number of remanufactures possible. The length of this future service life depends on the age of locomotives and the remaining number of remanufactures. In other words, each Tier will have a different length of future service life depending on the potential number of remanufactures that they can undergo. The inventory determines how many times each Tier can be remanufactured in future years by considering the age distribution of the Tier groups. The average ages of Tier 1+ / Tier 2 / Tier 2+ groups are lower than the older Tiers and these Tier groups demonstrate the ability to have two remanufactures before retirement. The older Tiers have approximately one remaining remanufacture prior to retirement due to their older average age and resulting shorter remaining life.

Figure 12 presents how long the locomotives will continue to operate on average based on the predicted major turnover timing. For Tier 3 and 4 locomotives, the inventory assumes that a major turnover will occur 25 years after a locomotive is first introduced into service.

Figure 12: Predicted Average Service Time until Major Turnover

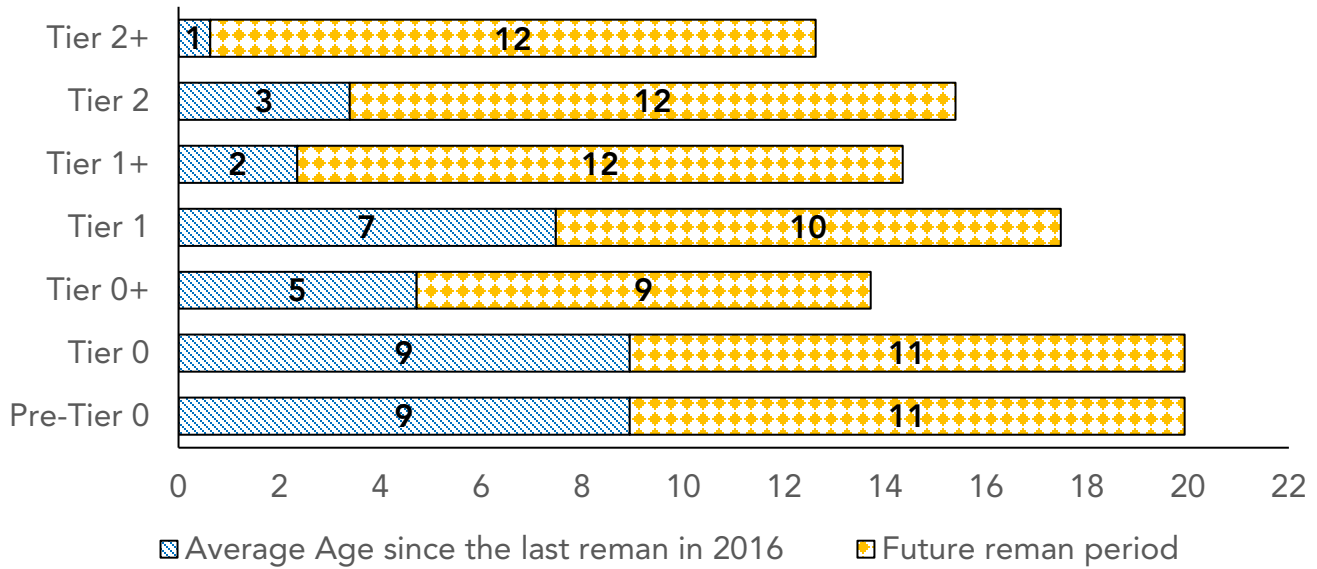


Table 3 shows the predicted time between turnovers. Note that the numbers provided in this table present the year that the bulk portion of each Tier is predicted to retire, while the phase-out starts several years earlier as the age distribution of each Tier is generally a normal distribution. Figure 9 shows that CARB staff calculated the remaining operating time for a given total service life by subtracting the average age (Column B) from the Average retirement age (Column D, total service life). Figure 11 shows the sum of columns (B) and (C) is equal to column (A) which is the average reman cycle. Column (F) of Major turnover timing is the sum of 2016 (base year) and the predicted average service time of Figure 12.

Table 3. Predicted Major Turnover Timing (years)

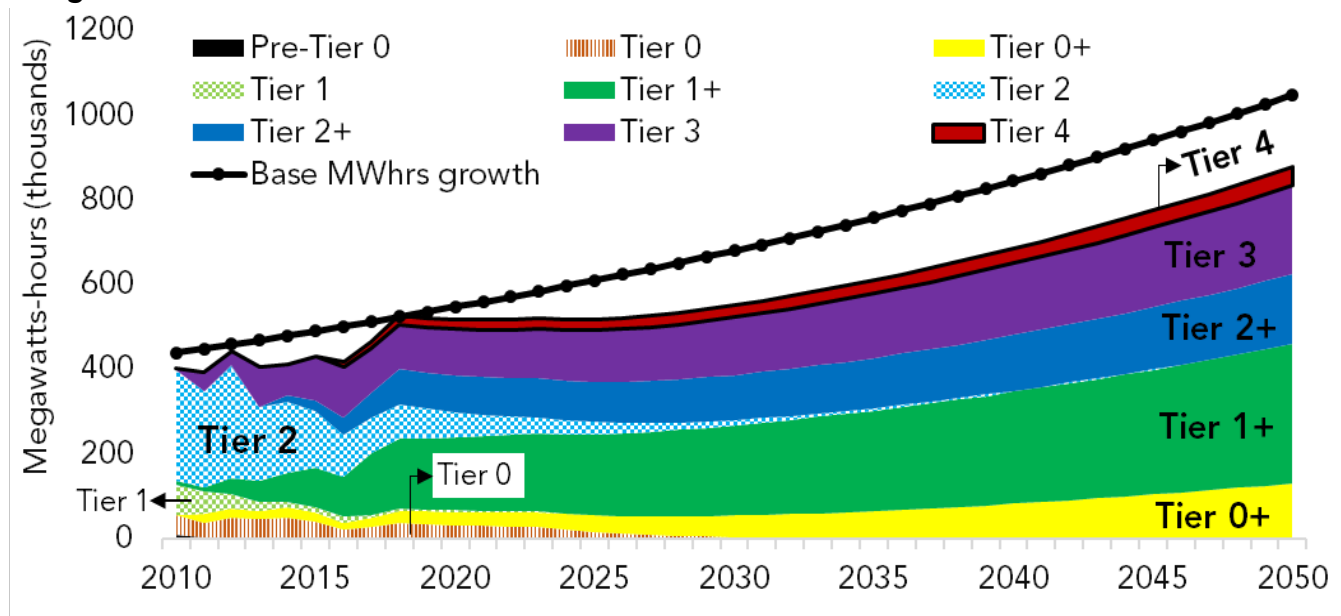
Tier	Activity-Adjusted ARC (A)	Average age since the last reman in 2016 (B)	Remaining useful life in 2016 (C=A-B)	Average retirement age (D)	Operating time remaining for the total service life in 2016 (E=D-B)	Major Turnover Timing (F)
Pre-Tier	11	9	2	25	16	2029
Tier 0	11	9	2	25	16	2029
Tier 0+	9	5	4	18	13	2029
Tier 1	10	7	3	18	11	2029
Tier 1+	6	2	4	25	23	2032
Tier 2	6	3	3	25	22	2031
Tier 2+	6	1	5	25	24	2033
Tier 3	-	-	-	-	-	2035
Tier 4	-	-	-	-	-	2039

Tier Distribution Baseline (BAU Case)

South Coast activity data shows that railroads (RRs) are likely to use older Tier locomotives than newer Tier locomotives in recent years. For instance, total MWhrs of Tier 1+ has been increased by 43.4 percent for the past nine years and became the largest contributing Tier group in 2017. Tier 2 accounted for 64 percent of the total MWhrs of the Tier groups in 2010, with the activity in MWhrs gradually migrating to Tier 2+. Until 2014, Tier 2 was the largest contributor to MWhrs among the Tier groups, however beginning in 2015, Tier 1+ became the largest single contributor. The Tier distribution of the 2018 South Coast MOU data shows that 30.3 percent of total units operated in the South Coast were Tier 1+. New Tier 3 units are no longer available for purchase, and the railroads have not purchased any new Tier 4 units for the last two years in California. The BAU scenario reflects these fleet turnover trends where the railroads operate Tier 1+ and Tier 2+ units more than the newer units.

Figures 13 and 14 present intermediate steps in the modeling process. Figure 13 shows the MWhrs projections solely based on the growth rates obtained from MOU data without considering the lifespan of locomotives or retirement. The Tier distribution presented in Figure 13 is an initial step only but is not used as a final Tier distribution because it neglects the life cycle of locomotives and could overestimate emissions. Figure 14 shows the MWhrs distributions adjusted by the Tier Transition Patterns (TTP) discussed in the previous section called Transition Patterns between Tier Groups. The MWhrs shifts in the Tier transition observed in the data forces some Tier groups to continue to decrease while shifting their workload to the observed increasing Tier groups. This is a basic framework for all scenarios considered in the forecasting process, and each analysis scenario will result in different Tier distributions based on the given conditions, such as ARCs and MWhrs deficit allocations.

Figure 13: MWhrs Distribution based on the Given MWhrs Growth Rates for the Past 9 Years



The BAU scenario assumes no In-Use Operating Regulation in the CA operations; however, the MWhrs of the Tier groups would naturally start to diminish in 2029, and the resulting MWhrs distribution will be as shown in Figure 15.

Figure 14: MWhrs Distribution based on Tier Transition Patterns (MWhrs Flows)

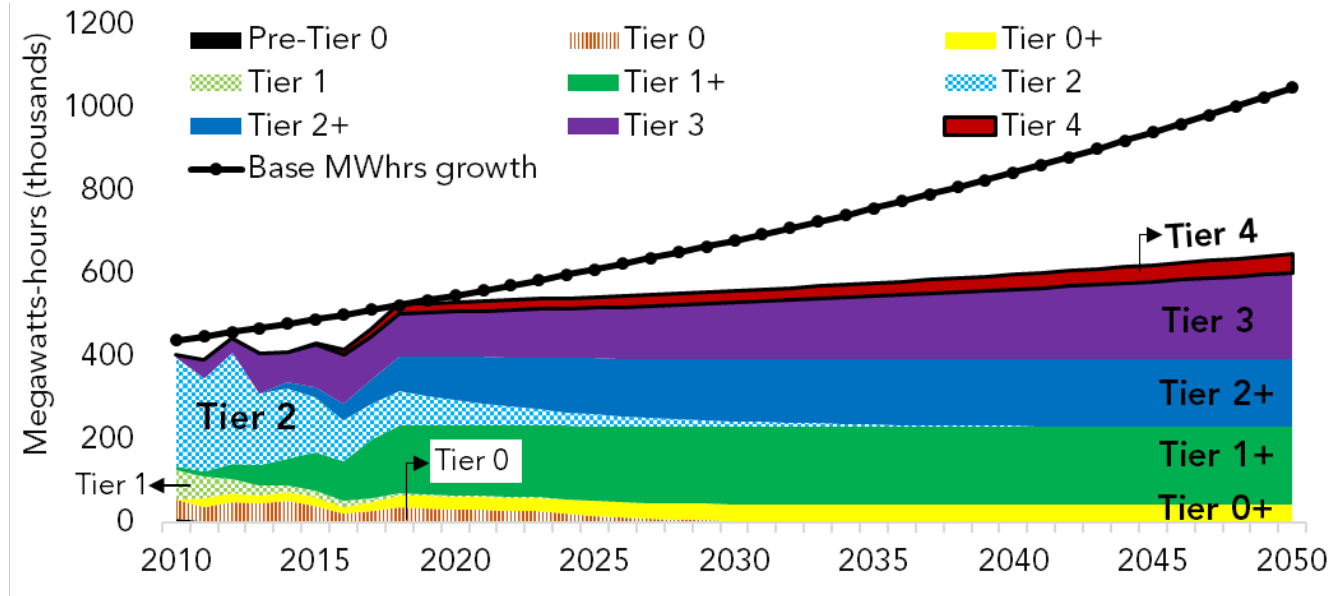
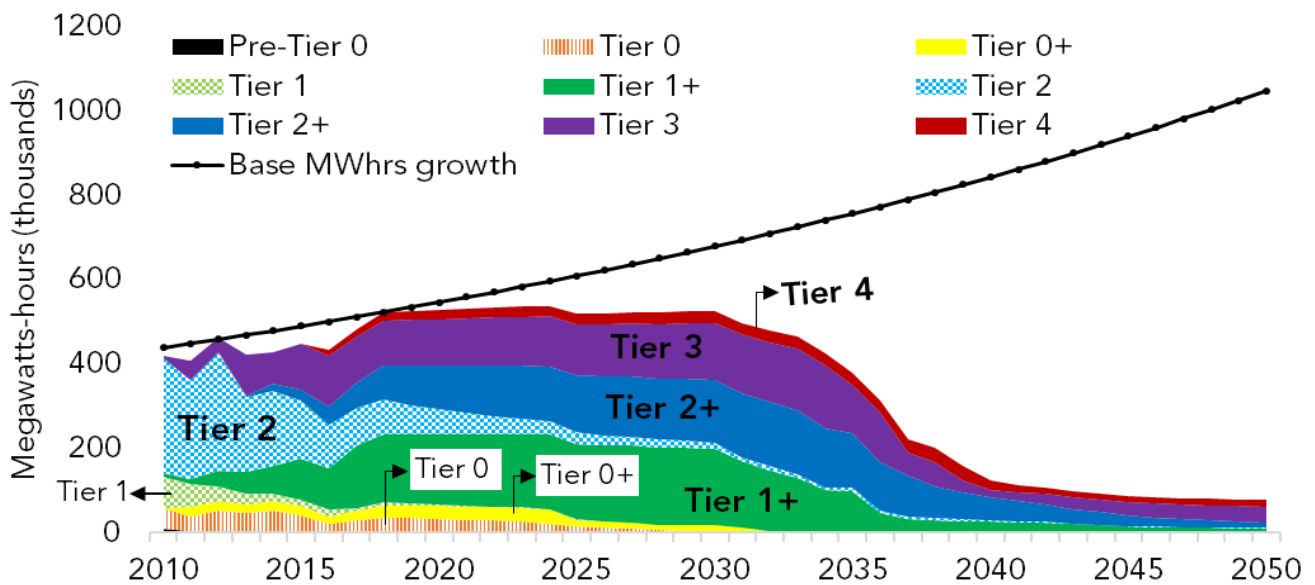


Figure 15: MWhrs Distribution Considering Anticipated Retirement Patterns



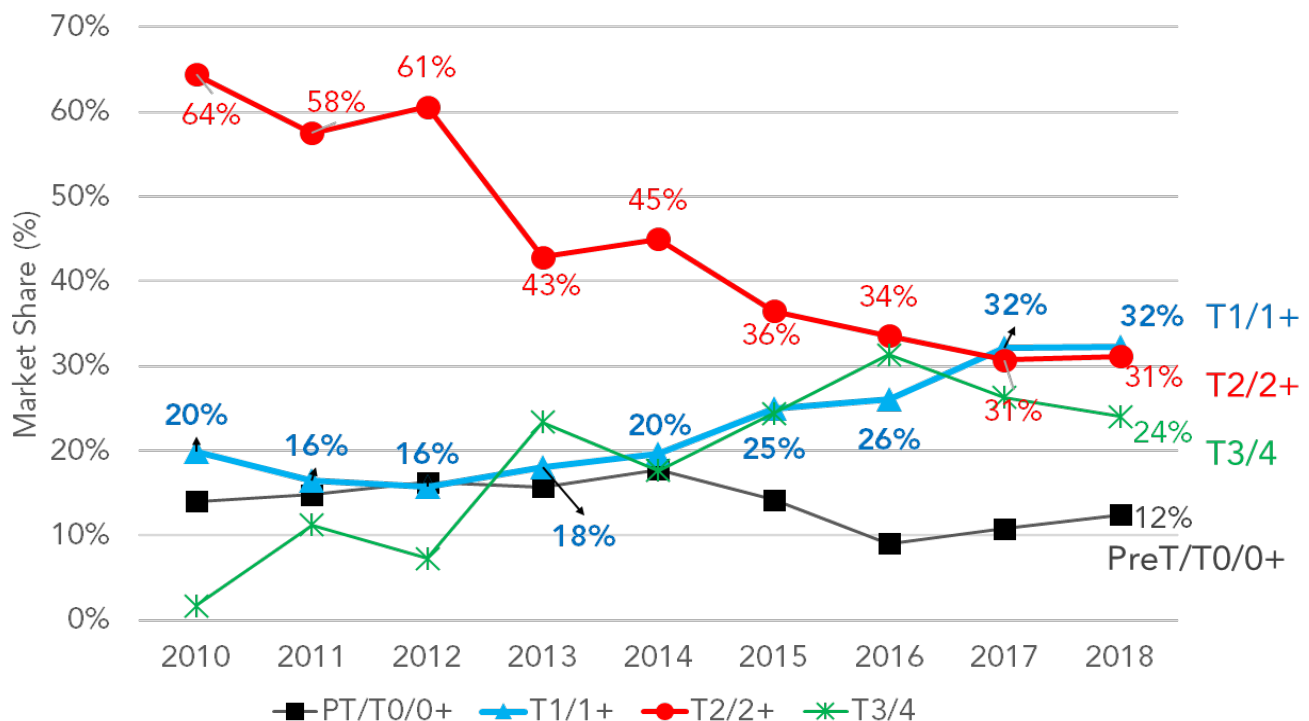
The observed Tier mix and activity patterns indicate that RRs have extended the use of Tier 1+ and Tier 2+ units rather than adopting relatively newer Tier units, such as Tier 3 and Tier 4. Considering the recent information that:

1. There has been no purchase of Tier 4 recently based on CARB communication with RRs and a review of draft 2019 MWhrs submittals;

2. Tier 3 purchase is not available;
3. RRs have no limitation in remanufacturing their current units; and,
4. RRs have parked numerous locomotives that could be pulled back into service later,

the inventory forecast reflects that the current primary Tier groups (Tier 1+ and Tier 2+) may be used to maintain the total workload for the next few decades. As a result, the forecast shows units needed to meet the projected MWhrs for accommodating expected freight movement growth (and to replace the locomotives that are phasing out) to include a large number of Tier 1+ and 2+ units, either remanufactured with service life extended or brought back into service after being stored. This trend is assumed to continue until these older Tier groups reach their maximum service life. In this case, the maximum service life reflects the U.S. EPA's assumption of 40 years, as discussed in their 2008 rulemaking^{18,18}. As Tier 1+ and Tier 2+ locomotives reach 40 years of age, the workload share of the Tier 4 group is projected to increase while the other Tier groups are assumed to diminish. Figure 16 shows the MWhrs share (%) of the Tier groups that have been operating in CA for the past nine years. Pre-Tier 0/Tier 0/Tier 0+ units are likely to be retired in the near future as their average ages reach their effective unit lifetime^{18,19}, and the other Tier units will absorb the MWhrs of units retired. The total MWhrs of Tier 1/1+ and Tier 2/2+ locomotives currently make up around 31% and 32% of the total market share, respectively.

Figure 16: MWhrs Share (%) of the Tier Groups



¹⁹ CFR 2008 - Title40 - Vol31 - Subchapter U – Air pollution controls - Part 1033, <https://www.govinfo.gov/content/pkg/CFR-2008-title40-vol31/pdf/CFR-2008-title40-vol31-chap1-subchapU.pdf>

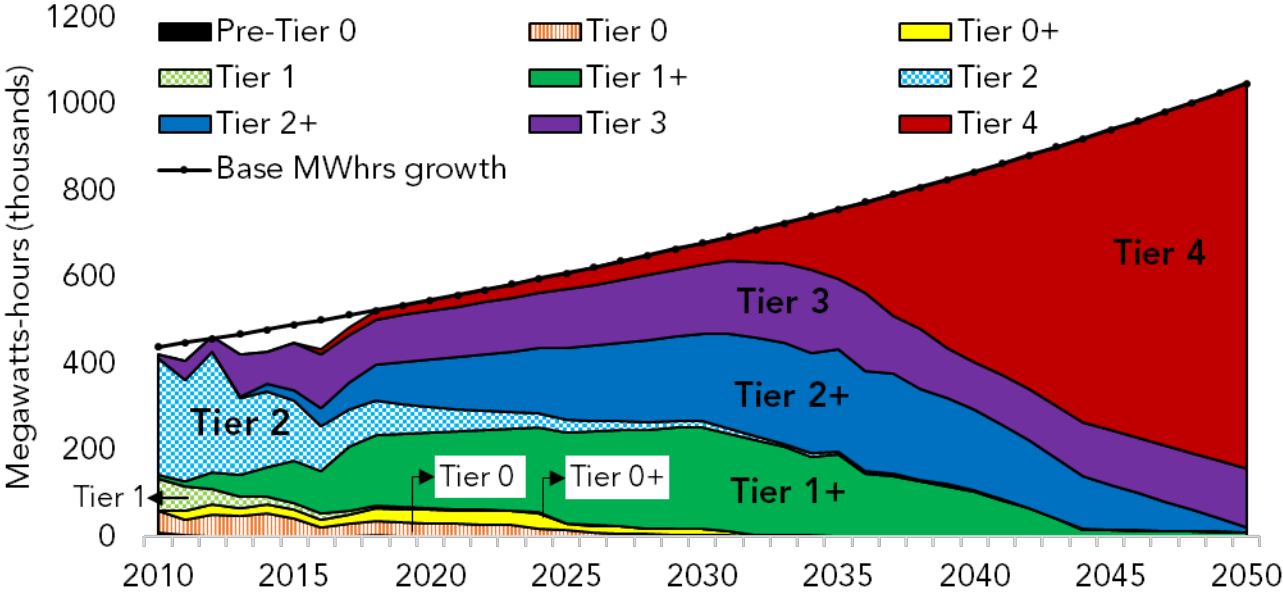
Figure 17 shows the trend in workload share as well as MWhrs deficit allocation ratio. The percent allocation of Pre-Tier 0/Tier 0/ Tier 0+ was distributed to the other ITGs, such as Tier 1+/2+/3/4. The model maintains the initial allocation ratio until 2030 which is the major turnover timing of the fleet and then gradually changes ratio shifts toward a higher fraction of Tier 4 in 2050.

Figure 17: Tier Allocation of Replacement in Business-As-Usual Scenario

Tier	Workload share (%) for the past 9 years	Tier	Percent of Deficit MWhrs	
			Until 2030	CY 2050
Tier 1/1+	30%	Tier 1+	35%	0% (in 2044)
Tier 2/2+	30%	Tier 2+	35%	0%
Tier 3/4	25%	Tier 3	15%	10%
Tier PT0/T0/0+	15%	Tier 4	15%	90%

Since new Tier 3 purchases are no longer available, most replacements would be Tier 4 locomotives between 2040 and 2050. Most Tier 1 units were remanufactured to Tier 1+, as those units were mostly sold between 2002 and 2004. The model reflects that the last model year of Tier 1 would be retired in 2044, which is 40 years after the last year of its sales period (as noted previously this is the maximum life assumed by U.S. EPA in their 2008 rulemaking). Thus, the MWhrs deficit allocation for Tier 1+ drops to zero percent in 2044. Tier 4 and 3 will eventually account for 90% and 10% of the MWhrs deficit in 2050, respectively. Figure 18 shows the resulting Tier distribution by 2050.

Figure 18: BAU Scenario Tier Distribution



Tier 3 locomotives are expected to be able to take an increased share of the workload without an increase in their population by expanding MWhrs per unit within California. Currently, the Tier 3 units are averaging slightly more than half of the maximum observed MWhrs compared to the maximum observed from 2013 to 2018, showing they could expand their activity significantly without exceeding levels already observed in the data.

Scaling South Coast to Statewide Emissions

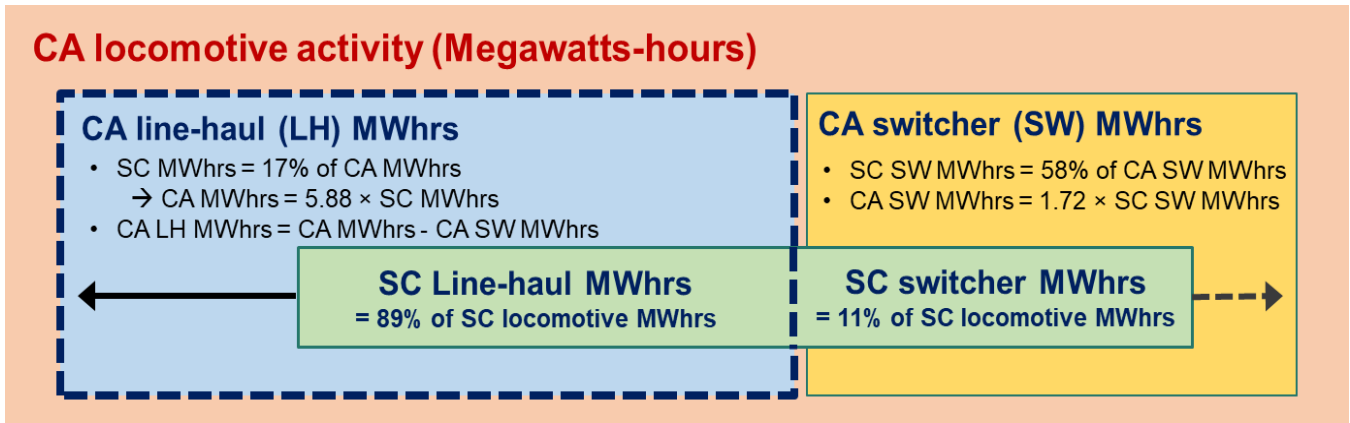
As the MOU data only covers locomotive activities in the South Coast Air Basin, the updated model uses the conversion factors provided in Table 4 to estimate statewide MWhrs and emissions from the South Coast (SC) MOU data. SC switchers account for 11% of total SC locomotive activity. SC line-hauls contribute 17% of total CA line-haul activity in MWhrs, while the contribution from SC switchers is about 58% of total CA switcher MWhrs. One of the reasons for the higher fraction of SC switchers over the total statewide switcher activity is the Ports of Los Angeles and Long Beach in the South Coast region require an increased number of rail yards and activity to organize containers and build trains.

Table 4. The Conversion Factor Used for MWhrs Extrapolation

Conversion	Conversion factor	Note	Reference
SC line haul MWhrs to CA line haul MWhrs	17%	SC line hauls are responsible for 17% of total MWhrs of CA line-hauls	CA rail yard operation and gross-Ton-mile (GTM) data provided by UP and BNSF
SC switcher MWhrs to SC total MWhrs	11%	SC switchers account for 11% of total MWhrs of locomotive units operated in the South Coast Air Basin	CA rail yard data
SC switcher MWhrs to CA switcher MWhrs	58%	SC switchers contribute 58% of total CA switcher MWhrs	CA rail yard data

Figure 19 presents the MWhrs allocations of switchers and line hauls in SC and CA, respectively. Effectively, the SC MWhrs, including line hauls and switchers, are multiplied by 5.88 to reflect statewide operations, based on the value of 17 percent of the statewide total MWhrs occurring in the South Coast ($100 \div 17 = 5.88$). 11% of SC MWhrs, which is the fraction of SC switchers, was multiplied by 1.72 to obtain the switchers' statewide impact. Subtracting the CA switcher MWhrs from the total CA MWhrs provides the CA line-haul MWhrs.

Figure 19: Allocations of SC Line Haul and Switcher MWhrs over Statewide MWhrs



Emissions Results (BAU Case)

Figure 20 shows South Coast NO_x projections of the BAU scenario, and Figure 21 shows the statewide NO_x forecast. The total NO_x emissions per year are compared to the NO_x emission estimates where the 2016 South Coast SIP inventory is represented by a red line. The BAU scenario reflects the latest market information and locomotive activity patterns from the South Coast MOU data. The resulting NO_x distribution by Tier indicates that Tier 1+ and 2+ will be the major source of NO_x emissions for the next two decades, and they will be gradually replaced by Tier 4 locomotives.

Figure 21 provides NO_x emissions at the statewide level. Detailed NO_x and PM emissions data for South Coast (SC), San Joaquin Valley (SJV), and Statewide (CA) can be found in Table 5.

Figure 20: Projected South Coast NOx Emissions (tpd) by Tier vs. 2016 SC SIP Inventory

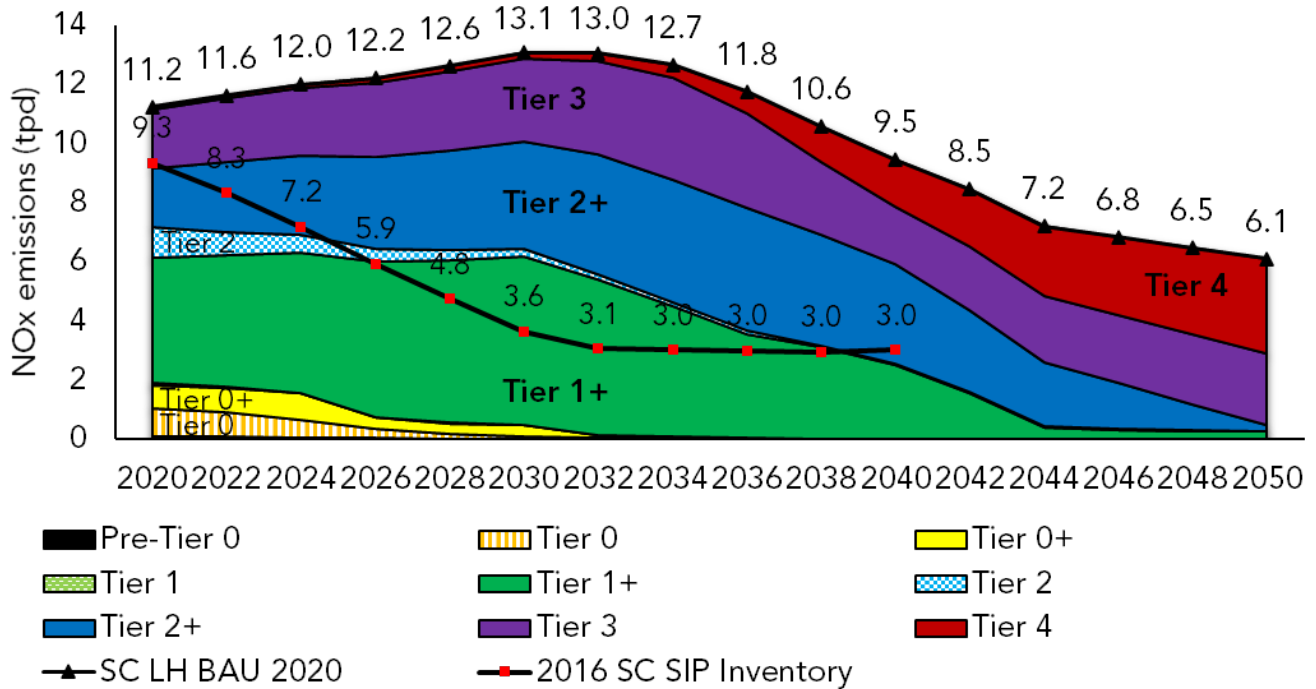


Figure 21: Statewide NOx Projections by Tier and 2016 SIP NOx Values

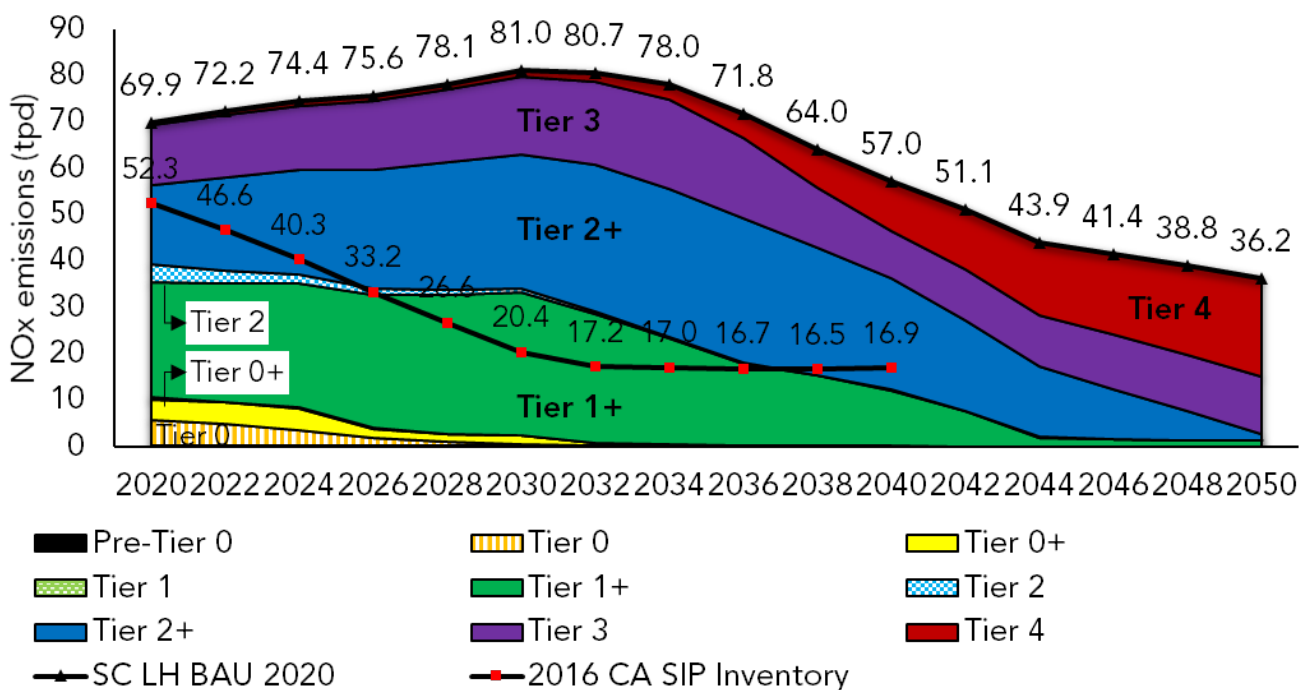


Table 5. Line-haul Locomotive NOx and PM emissions (tpd) in South Coast (SC), San Joaquin Valley (SJV), and California Statewide (CA)

Year	SC NOx	SJV NOx	CA NOx	SC PM	SJV PM	CA PM
2020	11.236	12.864	69.913	0.293	0.318	1.729
2021	11.426	13.065	71.007	0.293	0.318	1.728
2022	11.622	13.277	72.156	0.294	0.319	1.733
2023	11.824	13.497	73.355	0.295	0.320	1.741
2024	11.993	13.684	74.372	0.294	0.320	1.737
2025	12.011	13.702	74.467	0.288	0.313	1.700
2026	12.194	13.909	75.595	0.289	0.314	1.707
2027	12.409	14.152	76.915	0.292	0.317	1.722
2028	12.603	14.374	78.119	0.293	0.319	1.735
2029	12.838	14.640	79.563	0.297	0.323	1.757
2030	13.064	14.895	80.952	0.300	0.327	1.777
2031	13.115	14.954	81.272	0.295	0.321	1.745
2032	13.039	14.842	80.663	0.288	0.313	1.704
2033	12.944	14.705	79.918	0.281	0.305	1.659
2034	12.666	14.348	77.976	0.268	0.291	1.584
2035	12.463	14.039	76.298	0.266	0.287	1.559
2036	11.753	13.215	71.820	0.240	0.259	1.405
2037	11.000	12.303	66.866	0.225	0.240	1.307
2038	10.567	11.768	63.954	0.213	0.228	1.237
2039	9.949	11.053	60.072	0.199	0.212	1.153
2040	9.451	10.493	57.028	0.186	0.198	1.078
2041	8.977	9.967	54.169	0.172	0.184	0.999
2042	8.457	9.401	51.093	0.157	0.168	0.916
2043	7.833	8.743	47.519	0.138	0.150	0.818
2044	7.195	8.084	43.935	0.120	0.132	0.720
2045	7.010	7.849	42.657	0.116	0.128	0.695
2046	6.828	7.616	41.389	0.112	0.123	0.671
2047	6.650	7.384	40.129	0.109	0.119	0.647
2048	6.472	7.148	38.847	0.105	0.115	0.624
2049	6.291	6.908	37.543	0.102	0.111	0.601
2050	6.108	6.664	36.219	0.099	0.106	0.578