APPENDIX D

California Air Resources Board

Quantification Methodology

California Air Resources Board
Low Carbon Transportation
Advanced Technology Demonstration and Pilot Projects

California Climate Investments

FINAL
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List of Acronyms and Abbreviations

Acronym	Term
bhp	brake horsepower
CARB	California Air Resources Board
CCI	California Climate Investments
CHC	commercial harbor craft
CO_2	carbon dioxide
Demos & Pilots	Advanced Technology Demonstration and Pilot Projects
Diesel PM	diesel particulate matter
EER	energy efficiency ratio
g	gram
gal	gallon
GGRF	Greenhouse Gas Reduction Fund
GHG	greenhouse gas
hp	horsepower
hr	hour
kW	kilowatt
kWh	kilowatt-hour
lbs	pounds
LCT	Low Carbon Transportation
LTO	landing and takeoff
mi	mile
MJ	megajoule
MTCO2e	metric tons of carbon dioxide equivalent
NO_x	oxides of nitrogen
OGV	ocean-going vessel
PM	particulate matter
PM2.5	particulate matter with a diameter less than 2.5 micrometers
PM_{10}	particulate matter with a diameter less than 10 micrometers
ROG	reactive organic gas
scf	standard cubic foot
yr	year
ZEV	zero-emission vehicle or equipment

List of Definitions

Term	Definition
Activity	Annual operation of the equipment or vehicle, measured in annual average hours of use.
Baseline	The technology applied under normal business practices, such as the existing engine in a vehicle or conventional equipment for replacements, repowers, and retrofits. In other words, the vehicle/equipment that is either currently owned/in operation that will be repowered, retrofitted, or scrapped and replaced with a newer, cleaner piece of equipment; or the conventional vehicle/equipment that would otherwise have been purchased without the incentive.
Co-benefit	A social, economic, or environmental benefit as a result of the proposed project in addition to the GHG reduction benefit.
Cost-effectiveness	A measure of the dollars provided to a project for each annual ton of covered emission reduction.
Deterioration	The increased exhaust emissions over time, taking into account wear and tear on engines and emissions control devices.
Deterioration Life	A factor calculated from the period of time the engine has deteriorated, plus half the project life, used to estimate deterioration over the entire project life.
Deterioration Product	The result of multiplying the deterioration rate, equipment activity, and the deterioration life for a technology.
Deterioration Rate	Rates that estimate increased air pollutant emissions from engine wear and tear and other variables that increase engine emissions over time. On-road deterioration rates are established by weight class and engine model year, based on values in CARB's on-road emission inventory model. Off-road deterioration rates are established by horsepower and either Tier or model year, based on values in CARB category-specific inventory models.
Energy and Fuel Cost Savings	Changes in energy and fuel costs to the equipment/vehicle operator as a result of the project. Savings may be achieved by changing the quantity of energy or fuel used, conversion to an alternative energy or fuel source/vehicle, or renewable energy or fuel generation to displace existing fuel purchases.

Term	Definition
Key Variable	Project characteristics that contribute to a project's GHG emission reductions and signal an additional benefit (e.g., fossil fuel use reductions).
Load Factor	Average operational level of an engine in a given application as a fraction or percentage of the engine manufacturer's maximum rated horsepower.
Project Type	For the purposes of the LCT Demos & Pilots Quantification Methodology, eligible projects fall into seven project types that meet the objectives program and for which there are methods to quantify GHG emission reductions.
Quantification Period	Number of years that the equipment or vehicle will provide emission reductions that can reasonably be achieved and assured. Sometimes referred to as "Project Life" or "Useful Life."
Replacement	The new, retrofitted, or reconditioned vehicle/equipment that replaces or avoids the use of the baseline vehicle/equipment.

Section A. Introduction

California Climate Investments is a statewide initiative that puts billions of Cap-and-Trade dollars to work facilitating GHG emission reductions; strengthening the economy; improving public health and the environment; and providing benefits to residents of disadvantaged communities, low-income communities, and low- income households, collectively referred to as "priority populations." Where applicable and to the extent feasible, California Climate Investments must maximize economic, environmental, and public health co-benefits to the State.

The California Air Resources Board (CARB) is responsible for providing guidance on estimating the GHG emission reductions and co-benefits from projects receiving monies from the GGRF. This guidance includes quantification methodologies, co-benefit assessment methodologies, and benefits calculator tools. CARB develops these methodologies and tools based on the project types eligible for funding by each administering agency, as reflected in the program expenditure records available at: www.arb.ca.gov/cci-expenditurerecords.

For CARB's Low Carbon Transportation (LCT) Advanced Technology Demonstration and Pilot Projects (Demos & Pilots) Program, CARB developed this LCT Demos & Pilots Quantification Methodology to provide guidance for estimating the GHG emission reductions and selected co-benefits of each proposed project type. This methodology uses calculations to estimate GHG emission reductions from replacing older, higher-emitting equipment or vehicles with newer, more efficient equipment or vehicles; and GHG emissions reductions from capture and control systems.

The LCT Demos & Pilots Benefits Calculator Tool automates methods described in this document, provides a link to a step-by-step user guide with project examples, and outlines documentation requirements. Projects will report the total project GHG emission reductions and co-benefits estimated using the LCT Demos & Pilots Benefits Calculator Tool as well as the total project GHG emission reductions per dollar of GGRF funds awarded. The LCT Demos & Pilots Benefits Calculator Tool is available for download at: http://www.arb.ca.gov/cci-resources.

Using many of the same inputs required to estimate GHG emission reductions, the LCT Demos & Pilots Benefits Calculator Tool estimates the following co-benefits and key variables from LCT Demos & Pilots projects: $PM_{2.5}$ Reductions (lbs), NO_x Reductions (lbs), ROG Reductions (lbs), Diesel PM Reductions (lbs), Fossil Fuel Use Reductions (gallons), Fossil Fuel Based Energy Use Reductions (kWh), and Energy and Fuel Cost Savings (dollars). Key variables are project characteristics that contribute to a project's GHG emission reductions and signal an additional benefit (e.g., criteria pollutant emission reductions, fuel use reductions). Additional co-benefits for which CARB assessment methodologies were not incorporated into the LCT Demos & Pilots Benefits Calculator Tool may also be applicable to the project. Applicants should consult the Advanced Technology Demonstration and Pilot Projects grant solicitation materials to ensure they meet programmatic requirements.

Methodology Development

CARB developed this Quantification Methodology consistent with the guiding principles of California Climate Investments, including ensuring transparency and accountability[1]. CARB developed this LCT Demos & Pilots Quantification Methodology to be used to estimate the outcomes of proposed projects, inform project selection, and track results of funded projects. The implementing principles ensure that the methodology will:

- Apply at the project-level;
- Provide uniform methods to be applied statewide, and be accessible by all applicants;
- Use existing and proven methods;
- Use project-level data, where available and appropriate; and
- Result in GHG emission reduction estimates that are conservative and supported by empirical literature.

CARB assessed peer-reviewed literature and tools and consulted with experts, as needed, to determine methods appropriate for the LCT Demos & Pilots project types. CARB also determined project-level inputs available. The methods were developed to provide estimates that are as accurate as possible with data readily available at the project level. CARB released the Draft Demos & Pilots Quantification Methodology and Draft Demos & Pilots Benefits Calculator Tool for public comment in June 2023. This Final Demos & Pilots Quantification Methodology and accompanying Demos & Pilots Benefits Calculator Tool have been updated to address public comments, where appropriate, and for consistency with updates to the Demos & Pilots grant solicitation.

In addition, the University of California, Berkeley, in collaboration with CARB, developed assessment methodologies for a variety of co-benefits such as providing cost savings, lessening the impacts and effects of climate change, and strengthening community engagement. As they become available, co-benefit assessment methodologies are posted at: www.arb.ca.gov/cci-cobenefits.

Tools

The LCT Demos & Pilots Benefits Calculator Tool relies on CARB-developed emission factors. CARB has established a single repository for emission factors used in CARB benefits calculator tools, referred to as the California Climate Investments Quantification Methodology Emission Factor Database (Database), available at: http://www.arb.ca.gov/cci-resources. The Database Documentation explains how emission factors used in CARB benefits calculator tools are developed and updated.

[1] California Air Resources Board. CCI Funding Guidelines for Administering Agencies. www.arb.ca.gov/cci-fundingguidelines

The LCT Demos & Pilots Benefits Calculator Tool must be used to estimate the GHG emission reductions and co-benefits of the proposed project. The LCT Demos & Pilots Benefits Calculator Tool can be downloaded from: http://www.arb.ca.gov/cci-resources.

Section B. Methods

The following section provides details on the methods supporting emission reductions in the LCT Demos Benefits Calculator Tool.

Project Type

CARB developed the following project types that meet the objectives of the LCT Demos & Pilots solicitation and for which there are methods to quantify GHG emission reductions:

1. On-road Heavy-duty Vehicle Replacement and Repower Projects
    a. Applicable to 'Green Zones'
2. Off-road Equipment Replacement and Repower Projects
    a. Applicable to 'Green Zones'
    b. Applicable to 'Port Vehicles and Equipment'
    c. Applicable to 'Modular Zero-Emission Capable Cargo Handling Equipment Demonstration'
    d. Applicable to 'Zero-Emission Ground Support Equipment'
    e. Applicable to 'Off-Road Construction and Agriculture Equipment'
3. Zero-emission Lawn and Garden Landscaping Equipment
    a. Applicable to 'Green Zones'
4. Marine Commercial Harbor Craft Projects
    a. Applicable to 'Resilient Zero-Emission Vessel Charging Project'
    b. Applicable to 'Emission Reductions from Ocean Going Vessels'
    c. Applicable to 'Zero-Emission Capable Commercial Harbor Craft'
    d. Applicable to 'Tier-4 Commercial Harbor Craft'
5. Marine Ocean-Going Vessels Projects: Ship-side Power, Marine Capture and Control
    a. Applicable to 'Emission Reductions from Ocean Going Vessels'
6. Zero-emission Locomotives
    a. Applicable to 'Zero-Emission Intrastate Line Haul Locomotive'
    b. Applicable to 'Zero-Emission Rail'
7. Zero-emission Aviation
    a. Applicable to 'Zero-Emission Aviation'

General Approach

Methods used in the LCT Demos & Pilots Benefits Calculator Tool for estimating the GHG emission reductions and air pollutant emission co-benefits by project type are provided in this section. The Emission Factor Database Documentation explains how emission factors used in CARB benefits calculator tools are developed and updated. These methods account for GHG emission reductions from replacing older farm equipment with newer, more efficient equipment. In general, the GHG emission reductions are estimated in the LCT Demos & Pilots Benefits Calculator Tool using the approaches in Table 1. The LCT Demos & Pilots Benefits Calculator Tool also estimates air pollutant emission co-benefits and key variables using many of the same inputs used to estimate GHG emission reductions.

Table 1. General Approach to Quantification by Project Type

Zero-Emission Equipment and Vehicle Project Types (1, 2, 3, 4, 6, 7)
Emission Reductions = Baseline Equipment/Vehicle Emissions – Replacement Equipment/Vehicle Emissions
Emission Capture and Control Project Types (5)
Emission Reductions = (Baseline Equipment/Vehicle Emissions + Capture and Control Technology Emissions) * Percent Captured and Controlled

More specifically, the LCT Demos & Pilots Benefits Calculator Tool calculates estimates for GHG emissions reductions and air pollutant emission co-benefits using two methods for each of the project types:

1. Equations and methods from the Carl Moyer Program[2].
2. Equations and methods from previously existing CARB methodologies or Calculator Tools.

For all calculations, there are two pieces of equipment of interest:

1. The vehicle/equipment in use – i.e., the "baseline" vehicle/equipment.
2. The newer, replacement equipment/vehicle. Note: the Carl Moyer Guidelines often refer to these replacement vehicles/equipment as "reduced".

[2] CARB. Carl Moyer Program Guidelines. https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm

A. Weighted Emissions Reductions and Cost-effectiveness

1. Determine the Weighted Air Pollutant Emission Reductions

Total weighted air pollutant emission reductions from LCT Demo projects are determined by taking the sum of the project's annual air pollutant emission reductions using Equation 1. While NO_x and ROG emissions are given equal weight; emissions of combustion PM_{10} (such as diesel exhaust PM_{10} emissions) have been identified as a toxic air contaminant and thus carry a greater weight in the calculation, consistent with the Carl Moyer Guidelines (2017).[3]

Equation 1: Weighted Emission Reductions

$$WER = ER_{NOx} + ER_{ROG} + 20 \times ER_{PM}$$

Where,			Units
WER	=	Annual weighted emissions reductions	US tons/yr
ER_{NOx}	=	Annual NOx emission reductions	US tons/yr
ER_{ROG}	=	Annual ROG emission reductions	US tons/yr
ER_{PM}	=	Annual PM emission reductions	US tons/yr

2. Cost-Effectiveness Calculations

The cost-effectiveness of a project is determined by dividing the annualized cost of the potential project by the annual emission reductions that will be achieved by the project, as shown in Equation 2 below. Capital recovery factors are sourced from the Carl Moyer Guidelines (2017).

Equation 2: Emissions Reduction Cost-effectiveness

$$CE = \frac{CRF \times IC}{AER}$$

Where,			Units
CE	=	Emissions reduction cost-effectiveness	$\$/MTCO_2e$ or \$/lbs
CRF	=	Capital Recovery Factor	Unitless
IC	=	Incremental cost	\$
AER	=	Calculated annual emission reduction	$MTCO_2e$/yr or lbs/yr

Incremental cost is determined by subtracting the cost of a baseline vehicle from the cost from the advanced technology vehicle. Equation 3 is used to determine incremental

[3] CARB. Carl Moyer Program Guidelines. https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm

cost.

Equation 3: Incremental Cost

$$IC = C_{ATV} - C_{Baseline}$$

Where,			Units
IC	=	Incremental cost	$
C_{ATV}	=	Cost of advanced technology equipment or vehicle	$
$C_{Baseline}$	=	Cost of baseline equipment or vehicle	$

B. Emissions Reductions from Zero-Emission On-Road Heavy-Duty Vehicles

The LCT Demos & Pilots Benefits Calculator tool calculates estimates of GHG emissions reductions and air pollutant emission co-benefits for each of the project types. The following subsections presents the equations and methods from existing CARB methodologies or Calculator Tools used for Zero-Emission On-Road Heavy-Duty Vehicle projects.

1. GHG Equations

Equation 4 shows the GHG emission reductions that occur over the project's entire quantification period. Using Equation 5, the GHG emission reductions from on-road heavy-duty truck replacement and repower projects are estimated as the difference between the baseline and replacement scenarios. Equation 6 is used to determine the estimated annual fuel consumption in the baseline and replacement scenarios based on annual vehicle miles traveled.

Vehicle Category, Model Year, and Calendar Year are used as lookup inputs to ascertain fuel economy from CARB's EMission FACtors (EMFAC) model.

Equation 4: Total GHG Emission Reductions from On-Road Heavy-Duty Vehicles

$$ER_{GHG} = QP \times AER_{GHG}$$

Where,			Units
ER_{GHG}	=	GHG emission reductions over quantification period	$MTCO_2e$
QP	=	Quantification period	years
AER_{GHG}	=	Annual GHG emission reductions of replacing the baseline vehicle with the replacement vehicle	$MTCO_2e/yr$

Equation 5: Annual GHG Emission Reductions from On-Road Heavy-Duty Vehicles[4]

$$AER_{GHG} = ((FC_{baseline} \times CC_{baseline\ fuel}) - (FC_{replacement} \times CC_{replacement\ fuel})) \times \frac{1\ MTCO_2e}{1{,}000{,}000\ gCO_2e}$$

Where,			Units
AER_{GHG}	=	Annual GHG emission reductions of replacing the baseline vehicle with the replacement vehicle	$MTCO_2e$/yr
$FC_{baseline}$	=	Fuel consumption of the baseline vehicle	unit/yr
$CC_{baseline\ fuel}$	=	Carbon content of baseline fuel type	gCO_2e/unit
$FC_{replacement}$	=	Fuel consumption of the replacement vehicle	unit/yr
$CC_{replacement\ fuel}$	=	Carbon content of replacement fuel type	gCO_2e/unit

Equation 6: Fuel Consumption for the Baseline and Replacement Vehicle[4]

$$FC_i = \frac{AA}{MPG_i}$$

Where,			Units
FC	=	Fuel consumption	unit/yr
AA	=	Annual activity	miles/yr
MPG	=	Fuel economy	miles/unit
i	=	Baseline or Replacement	

2. Criteria and Toxic Air Pollutant Equations

Estimates of individual air pollutant emission reductions from on-road heavy-duty truck replacement and repower projects are calculated. Equation 7 shows the air pollutant emission reductions that occur over the project's entire quantification period. Based upon Carl Moyer Program methods, individual air pollutant emission reductions are estimated as the difference between the baseline and replacement scenarios using Equation 8.[5]

Vehicle Category, Model Year, and Calendar Year are used as lookup inputs to ascertain emission factors from CARB's EMFAC model. The following calculations are repeated for each type of pollutant – i.e., NO_x, ROG, and PM.

[4] Unit is gallons for gasoline, diesel, LNG, and LNG; scf for CNG; kWh for electric; and kg for hydrogen.
[5] CARB. Carl Moyer Program Guidelines. https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm

Equation 7: Total Air Pollutant Emission Reductions from On-Road Heavy-Duty Truck Projects

$$ER_{pollutant} = QP \times AER_{pollutant} \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$ER_{pollutant}$	=	Emission reductions over quantification period	lbs
QP	=	Quantification period	years
$AER_{pollutant}$	=	Annual emission reductions of replacing the baseline vehicle with the replacement vehicle	US tons/yr

Equation 8: Annual Air Pollutant Emission Reductions from On-Road Heavy-Duty Truck Projects

$$AER_{pollutant} = \mathrm{AEP}_{baseline} - \mathrm{AEP}_{replacement}$$

Where,			Units
$AER_{pollutant}$	=	Annual emission reductions of replacing the baseline vehicle with the replacement vehicle	US tons/yr
$AEP_{baseline}$	=	Annual emissions for the baseline vehicle	US tons/yr
$AEP_{replacement}$	=	Annual emissions for the replacement vehicle	US tons/yr

Equation 9 is used to determine the estimated annual air pollutant emissions of the baseline and replacement vehicles, using respective values for emission factors. For zero-emission replacement vehicles, the air pollutant emission factors are zero.

Equation 9: Annual Emissions for Baseline and Replacement Vehicle

$$AEP_i = EF_i \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
AEP	=	Annual emissions for the vehicle	US tons/yr
EF	=	Zero-mile emission factor for the vehicle	gram/mile
AA	=	Annual activity	miles/yr
i	=	Baseline or Replacement	

C. Emissions Reductions from Off-Road Equipment and Vehicles

The LCT Demos & Pilots Benefits Calculator Tool calculates estimates for GHG emissions reductions and air pollutant emission co-benefits for each of the eligible project types. The following subsections present the equations and methods from the Carl Moyer Program and existing CARB methodologies or Calculator Tools used for Off-Road Equipment and Vehicle projects.

1. GHG Equations

Equation 10 shows the GHG emission reductions that occur over the project's entire quantification period. Using Equation 11, the GHG emission reductions from off-road equipment replacement projects are estimated as the difference between the emissions from the baseline and replacement equipment.

Equation 10: GHG Emission Reductions from Off-Road Equipment or Vehicles

$$ER_{GHG} = QP \times AER_{GHG}$$

Where,			Units
ER_{GHG}	=	GHG emission reductions over quantification period	$MTCO_2e$
QP	=	Quantification period	years
AER_{GHG}	=	Annual GHG emission reductions of replacing the baseline equipment with the replacement equipment	$MTCO_2e/yr$

Equation 11: Annual GHG Emission Reductions from Off-Road Equipment or Vehicles

$$AER_{GHG} = AEG_{baseline} - AEG_{replacement}$$

Where,			Units
AER_{GHG}	=	Annual GHG emission reductions of replacing the baseline equipment with the replacement equipment	$MTCO_2e/yr$
$AEG_{baseline}$	=	Annual GHG emissions for the baseline equipment	$MTCO_2e/yr$
$AEG_{replacement}$	=	Annual GHG emissions for the replacement equipment	$MTCO_2e/yr$

To determine GHG emissions for the baseline off-road equipment, fuel consumption is calculated for the baseline equipment and multiplied by the fuel's carbon content using Equation 12.

Equation 12: Annual GHG Emissions from Baseline Off-Road Equipment or Vehicle

$$AEG_{baseline} = FC_{baseline} \times CC_{baseline} \times \frac{1\ MTCO_2e}{1{,}000{,}000\ g}$$

Where,			Units
$AEG_{baseline}$	=	Annual GHG emissions of the baseline equipment	$MTCO_2e$/yr
$FC_{baseline}$	=	Annual fuel consumption of the baseline equipment	gal/yr or scf/yr
$CC_{baseline}$	=	Carbon content of the baseline equipment (depending on fuel type)	gCO_2e/gal or gCO_2e/scf

If the annual fuel consumption is not provided, Equation 13 is used to estimate the annual fuel consumption in the baseline scenario, using respective values for brake specific fuel consumption, maximum rated horsepower, load factor, and fuel efficiency factor. The load factors are sourced from the 2017 Carl Moyer Program Guidelines.

Equation 13: Annual Fuel Consumption of the Baseline Equipment, if Not Provided[6]

$$FC_{baseline} = BSFC_{baseline} \times HP_{max,baseline} \times LF \times AA$$

Where,			Units
$FC_{baseline}$	=	Annual fuel consumption of the baseline equipment	gal/yr
$BSFC_{baseline}$	=	Brake specific fuel consumption	gal/bhp-hr
$HP_{max,baseline}$	=	Maximum rated horsepower of the baseline equipment	bhp
LF	=	Load factor of the equipment	Unitless
AA	=	Annual Activity	hr/yr

To determine GHG emissions for the replacement zero-emission off-road equipment, fuel consumption is calculated for the replacement equipment and multiplied by the fuel's carbon content using Equation 14. The fuel consumption of the replacement equipment is calculated by converting the baseline fuel consumption on an energy-equivalent basis using Equation 15.

[6] The BSFC values used are as follows: 1) compression-ignited engines <= 100 hp: 0.408 lb/hp-hr, 2) compression-ignited engines >100 hp: 0.367 lb/hp-hr, 3) spark-ignited engines using CNG: 0.507 lb/hp- hr, and 4) 4-stroke spark-ignited engines using gasoline: 0.605 lb/hp-hr (sources: Exhaust Emission Factors for Nonroad Engine Modeling – Spark-Ignition, U.S. EPA, 2010; Off-Road Diesel Emission Factors, California Air Resources Board, 2018).

Equation 14: Annual GHG Emissions of the Zero-Emission Replacement Equipment

$$AEG_{replacement} = EU_{replacement} \times CC_{replacement} \times \frac{1\ MTCO_2e}{1{,}000{,}000\ g}$$

Where,			Units
$AEG_{replacement}$	=	Greenhouse gas emissions of the zero-emission replacement equipment	$MTCO_2e/yr$
$EU_{replacement}$	=	Electricity or hydrogen use of the zero-emission replacement equipment	kWh/yr or kg/yr
$CC_{replacement}$	=	Carbon content of electricity or hydrogen	gCO_2e/kWh or gCO_2e/kg

Equation 15: Annual Fuel Consumption of Zero-Emission Replacement Equipment

$$EU_{replacement} = \frac{FC_{baseline} \times ED_{baseline\ fuel}}{ED_{ZEV\ replacement} \times EER_{ZEV\ replacement}}$$

Where,			Units
$EU_{replacement}$	=	Annual fuel use of the zero-emission replacement	kWh/yr or kg/yr
$FC_{baseline}$	=	Annual fuel consumption of the baseline equipment	gal/yr
$ED_{baseline}$	=	Energy density of the baseline fuel type	MJ/gal or MJ/scf
$ED_{ZEV\ replacement}$	=	Energy density of the ZEV replacement fuel	MJ/kWh or MJ/kg
$EER_{ZEV\ replacement}$	=	Energy Efficiency Ratio of the ZEV replacement fuel type relative to baseline fuel type	Unitless

2. Criteria and Toxic Air Pollutant Equations

Equation 16 shows the individual air pollutant emission reductions that occur over the project's entire quantification period. The individual air pollutant emission reductions from off-road equipment replacement projects are estimated, based upon methods outlined in the Carl Moyer Program Guidelines, as the difference between the baseline and replacement scenarios using Equation 17.[7]

Horsepower, Engine Tier, and Model Year are used as lookup inputs to ascertain emission factors from the Carl Moyer Program Guidelines. The following calculations are repeated for each type of pollutant – i.e., NO_x, ROG, and PM.

[7] CARB. Carl Moyer Program Guidelines. https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm

Equation 16: Air Pollutant Emission Reductions from Off-Road Equipment or Vehicles

$$ER_{pollutant} = QP \times\ AER_{pollutant}\ \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$ER_{pollutant}$	=	Emission reductions over quantification period	lbs
QP	=	Quantification period	years
$AER_{pollutant}$	=	Annual emission reductions	US tons/yr

Equation 17: Annual Emission Reductions from Off-Road Equipment or Vehicles

$$AER_{pollutant} = \mathrm{AEP}_{baseline} - \ \mathrm{AEP}_{replacement}$$

Where,			Units
$AER_{pollutant}$	=	Annual emission reductions	US tons/year
$AEP_{baseline}$	=	Annual emissions for the baseline equipment	US tons/year
$AEP_{replacement}$	=	Annual emissions for the replacement equipment	US tons/year

Equation 18 is used to determine the estimated annual air pollutant emissions in the baseline scenarios, using respective values for emission factors. For zero-emission replacements, the replacement air pollutant emissions equal zero.

Equation 18: Annual Air Pollutant Emissions of the Baseline Equipment

$$AEP_{baseline} = EF_{baseline} \times LF_{baseline} \times HP_{baseline} \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
$AEP_{baseline}$	=	Annual air pollutant emissions of the baseline equipment	US tons/year
$EF_{baseline}$	=	Zero-mile emission factor of the baseline equipment	g/bhp-hr
$LF_{baseline}$	=	Equipment Load Factor	Unitless
$HP_{baseline}$	=	Maximum rated horsepower of the baseline equipment	bhp
AA	=	Annual Activity	hours/year

D. Emission Reductions from Commercial Landscaping Equipment

The LCT Demos & Pilots Benefits Calculator tool calculates estimates of GHG emissions reductions and air pollutant emission co-benefits for each of the project types. The following subsections presents the equations and methods from existing CARB methodologies or Calculator Tools used for Commercial Landscaping Equipment (i.e., lawn and garden equipment).

1. GHG and Criteria and Toxic Air Pollutant Equations

Equation 19 is used to estimate GHG and air pollutant emission reductions from landscaping equipment, calculated as the difference in fuel and energy use between the baseline and replacement scenarios over the quantification period. The quantification period is selected based on the needs of the air districts and communities and must not exceed a maximum value of average equipment life sourced from the 2020 Emissions Model for Small Off-Road Engines (SORE2020).[8] Also note that there are two sources of emissions from landscaping equipment, exhaust and evaporative. However, the following calculations only account for the exhaust emissions. Including evaporative emissions would increase the emission reductions.

Equation 19: Emission Reductions from Landscaping Equipment

$$ER_{Lawn} = LGEF \times N \times QP$$

Where,			Units
ER_{Lawn}	=	Emission reductions from lawn and garden equipment	$MTCO_2e$ or lbs
$LGEF$	=	Lawn and garden equipment-specific emission factor	$MTCO_2e$/yr or lbs/yr
N	=	Quantity of particular lawn and garden equipment	Unitless
QP	=	Quantification period	yr

The emission reduction factor for NOx, ROG, and PM from landscaping replacement projects are estimated as the difference between the emissions of the baseline and reduced equipment over the quantification period using Equation 20.

[8] CARB. 2020 Emissions Model for Small Off-Road Engines. https://ww2.arb.ca.gov/our-work/programs/mobile-source-emissions-inventory/road-documentation/msei-documentation-road-0

Equation 20: Annual Air Pollutant Emission Reduction Factor from Landscaping Equipment

$$LGEF_{pollutant} = \left(AEP_{baseline} - AEP_{replacement}\right) \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$LGEF_{pollutant}$	=	Lawn and garden equipment-specific air pollutant emission factor	lbs/yr
$AEP_{baseline}$	=	Annual emissions for the baseline equipment	US tons/yr
$AEP_{replacement}$	=	Annual emissions for the replacement equipment	US tons/yr

Annual air pollutant emissions for the baseline equipment are calculated based on Carl Moyer Program methods using Equation 21. Only zero-emission replacements are allowable for landscaping equipment, so the replacement equipment emissions will always equal zero. Therefore, only the emissions for the baseline units will need to be determined, and that will be equal to the emission reductions per unit replaced. PM_{10} is assumed to be equivalent to PM, and $PM_{2.5}$ is assumed to be 76 percent of PM. For ROG, the calculation must include the ROG fraction to convert from total hydrocarbons (THC) to ROG.

Equation 21: Annual Air Pollutant Emissions from Baseline Landscaping Equipment

$$AEP_{baseline} = (EF_{ZH} + DP) \times HP \times LF \times Act \times RF \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
$AEP_{baseline}$	=	Annual emissions of the baseline equipment	US tons/yr
EF_{ZH}	=	Zero-hour emission factor	g/bhp-hr
DP	=	Deterioration product	g/bhp-hr
HP	=	Engine horsepower	hp
LF	=	Load factor	Unitless
Act	=	Annual usage or activity	hr/yr
RF	=	ROG fraction (conversion from THC to ROG), only applicable for calculating ROG emissions	g_{ROG}/g_{THC}

The deterioration product accounts for the increase in emissions over time as the integrity of the specific equipment degrades from usage, calculated using Equation 22. In the deterioration product, the deterioration rate is specific to each criteria pollutant, and the annual usage should match the value used in Equation 21 and the quantification period should match the value used in Equation 19.

Equation 22: Deterioration Product for Landscaping Equipment

$$DP = DR \times Act \times \frac{QP}{2}$$

Where,			<u>Units</u>
DP	=	Deterioration product	g/bhp-hr
DR	=	Deterioration rate	$g/bhp\text{-}hr^2$
Act	=	Annual usage or activity	hr/yr
QP	=	Quantification period	yr

The zero-hour emission factor, deterioration rate, engine horsepower, load factor, and annual usage were determined from equipment-specific population weighting of the year 2025 data available from SORE2020. The year 2025 was selected to serve as a representative year between 2020 – 2030. Population weighting was performed for both commercial and residential sectors; the vendor sector was included with the commercial sector. This population weighted data was used to establish a representative and conservative estimate of individual equipment.

E. Emissions Reductions from Marine Commercial Harbor Craft

The LCT Demos & Pilots Benefits Calculator Tool estimates GHG emissions reductions and air pollutant emission co-benefits for each of the project types. The following subsections present the equations and methods from the Carl Moyer Program and existing CARB methodologies or Calculator Tools used for marine commercial harbor craft.

1. GHG Equations

Equation 23 is used to estimate GHG emission reductions from marine vessel projects, calculated as the difference in annual emissions between the baseline and replacement scenarios over the quantification period.

Equation 23: GHG Emission Reductions from Non-Hybrid Marine Vessels

$$ER_{GHG} = QP \times \left(AEG_{baseline} - AEG_{replacement}\right) \times \frac{1\ MTCO_2e}{1{,}000{,}000\ gCO_2e}$$

Where,			Units
ER_{GHG}	=	GHG emission reductions from marine vessel replacement over quantification period	$MTCO_2e$
QP	=	Quantification period (project-specific project life used in Moyer Program)	yr
$AEG_{baseline}$	=	Annual GHG emissions of the baseline marine vessel	gCO_2e/yr
$AEG_{replacement}$	=	Annual GHG emissions of the replacement marine vessel	gCO_2e/yr

Equation 24 is used to estimate annual GHG emissions reductions from the baseline and replacement marine vessels, calculated as the product fuel/energy use and carbon content of the respective fuel, summed for all propulsion and auxiliary engines of the marine vessel.

Equation 24: Annual GHG Emissions of Marine Vessels[9]

$$AEG_i = \left(Fuel_{prop,i} \times CC_{prop,i} \times N_{prop,i}\right) + \left(Fuel_{aux,i} \times CC_{aux,i} \times N_{aux,i}\right)$$

Where,

			Units
AEG_i	=	Annual GHG emissions of the baseline or replacement marine vessel	gCO_2e/yr
$Fuel_{prop,\,i}$	=	Annual fuel usage of baseline or replacement marine vessel propulsion engine	unit/yr
$CC_{prop,\,i}$	=	Carbon content of baseline or replacement propulsion engine fuel type	gCO_2e/unit
$N_{prop,\,i}$	=	Number of baseline or replacement propulsion engines	Unitless
$Fuel_{aux,\,i}$	=	Annual fuel usage of baseline or replacement marine vessel auxiliary engine	unit/yr
$CC_{aux,\,i}$	=	Carbon content of baseline or replacement auxiliary engine fuel type	gCO_2e/unit
$N_{aux,\,i}$	=	Number of baseline or replacement auxiliary engines	Unitless
i	=	Baseline or replacement	

Equation 25 is used to determine the equipment fuel use in the baseline scenario. If hourly fuel consumption is not provided, the baseline annual fuel consumption is calculated using Equation 26.

Equation 25: Marine Vessel Annual Fuel Use

$$Fuel_{j,i} = HFC_{j,i} \times AA_{j,i}$$

Where,

			Units
$Fuel_{j,\,i}$	=	Annual fuel usage of baseline or replacement marine vessel propulsion or auxiliary engine	unit/yr
$HFC_{j,\,i}$	=	Hourly fuel consumption of baseline or replacement marine vessel propulsion or auxiliary engine	unit/hr
$AA_{j,\,i}$	=	Annual activity of baseline or replacement marine vessel propulsion or auxiliary engine	hr/yr
j	=	Propulsion or auxiliary	
i	=	Baseline or replacement	

[9] Unit is gallons for gasoline, diesel, LNG, and LNG; scf for CNG; kWh for electric; and kg for hydrogen.

Equation 26: Marine Vessel Annual Fuel Use, if Hourly Fuel Use not Provided

$$Fuel_{j,i} = \frac{BSFC_{j,i} \times LF_{j,i} \times HP_{j,i} \times AA_{j,i}}{FD_{j,i}}$$

Where,			Units
$Fuel_{j,i}$	=	Annual fuel usage of baseline or replacement marine vessel propulsion or auxiliary engine	unit/yr
$BSFC_{j,i}$	=	Brake specific fuel consumption factor of baseline or replacement marine vessel propulsion or auxiliary engine	lbs/bhp-hr
$LF_{j,i}$	=	Load factor of baseline or replacement marine vessel propulsion or auxiliary engine	Unitless
$HP_{j,i}$	=	Horsepower of baseline or replacement marine vessel propulsion or auxiliary engine	hp
$AA_{j,i}$	=	Annual activity of baseline or replacement marine vessel propulsion or auxiliary engine	hr/yr
$FD_{j,i}$	=	Fuel density of baseline or replacement marine vessel propulsion or auxiliary engine fuel	lb/unit
j	=	Propulsion or auxiliary	
i	=	Baseline or replacement	

For projects that operate using zero-emission technology, Equation 27 is used to determine annual energy use.

Equation 27: Zero-Emission Replacement Marine Vessel Annual Fuel Use

$$Fuel_{j,replacement} = Fuel_{j,baseline} \times \frac{ED_{baseline}}{ED_{ZE\ replacement}} \times \frac{1}{EER}$$

Where,			Units
$Fuel_{j,\ replacement}$	=	Annual energy usage for replacement marine vessel propulsion or auxiliary engine	kWh
$Fuel_{j,\ baseline}$	=	Annual fuel usage for baseline marine vessel propulsion or auxiliary engine	gal or scf
$ED_{baseline}$	=	Energy density of baseline fuel	MJ/gal or MJ/scf
$ED_{ZE\ replacement}$	=	Energy density of zero-emission replacement fuel	MJ/kWh or MJ/kg
EER	=	Energy Efficiency Ratio relative to baseline equipment fuel type	Unitless
j	=	Propulsion or auxiliary	

For hybrid marine vessel projects, Equation 28 is used to directly estimate GHG emission reductions from hybrid system marine vessel projects based on the reduced technology verification percentage (a default value of 70% may be used, assuming a default CO_2 reduction factor of 30%).[10]

Equation 28: GHG Emission Reductions from Hybrid Marine Vessels

$$ER_{hybrid} = \left(\frac{BSFC_{baseline} \times LF_{baseline} \times HP_{baseline} \times AA}{FD_{baseline}} \times FSEF \times RTVP\right) \times QP \times \frac{1\ MTCO_2e}{1{,}000{,}000\ gCO_2e}$$

Where,			Units
ER_{hybrid}	=	Emission reductions from hybrid marine vessel	$MTCO_2e$
$BSFC_{baseline}$	=	Brake specific fuel consumption factor	lbs/bhp-hr
$LF_{baseline}$	=	Load factor of baseline marine vessel engine	Unitless
$HP_{baseline}$	=	Horsepower of baseline marine vessel engine	hp
AA	=	Annual hours of marine vessel engine usage	hr/yr
$FD_{baseline}$	=	Fuel density of marine vessel engine equipment fuel	lb/unit of fuel
$FSEF$	=	Fuel-specific emission factor	g/unit of fuel
$RTVP$	=	Reduced technology verification percentage (default value of 70%, assuming 30% operation on hybrid system)	%
QP	=	Quantification period (project-specific project life used in Moyer Program)	yr

2. Criteria and Toxic Air Pollutant Equations

Equation 29 is used to estimate the air pollutant emission reductions that occur over the marine vessel's entire quantification period. The following calculation is repeated for each type of pollutant – i.e., NO_x, ROG, and PM. Equation 30 is used to calculate the annual air pollutant emissions of the baseline and replacement marine vessels. For zero-emission technology replacements, the annual emissions of the replacement vessel are assumed to be zero. For hybrid marine vessels, Equation 31 is used to estimate the annual emissions of each propulsion and auxiliary engine. For all other technologies, Equation 32 is used. The air pollutant emission factors for the baseline and replacement engines are pulled directly from CARB's 2021 Commercial Harbor Craft Baseline Model, based on engine tier, horsepower, displacement and model year.[11] PM_{10} is assumed to be equivalent to PM, Diesel PM is assumed to be equivalent to PM, $PM_{2.5}$ is assumed to be 95.6 percent of PM, and ROG is assumed to be 121% of hydrocarbons.

[10] CARB. Technology Assessment: Ocean-going Vessels. https://ww3.arb.ca.gov/msprog/tech/techreport/ogv_tech_report.pdf
[11] CARB. 2021 Commercial Harbor Craft Model: Baseline. https://ww2.arb.ca.gov/our-work/programs/mobile-source-emissions-inventory/road-documentation/msei-documentation-road

Equation 29: Air Pollutant Emission Reductions from Marine Vessel Projects

$$ER_{pollutant} = QP \times \left(AEP_{baseline} - AEP_{replacement}\right) \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$ER_{pollutant}$	=	Air pollutant emission reductions over quantification period	lbs
QP	=	Quantification period	yr
$AEP_{baseline}$	=	Annual emissions of the baseline marine vessel	US tons/yr
$AEP_{replacement}$	=	Annual emissions of the replacement marine vessel	US tons/yr

Equation 30: Annual Air Pollutant Emissions from Marine Vessels

$$AEP_i = \left(AEP_{prop,i} \times N_{prop,i}\right) + \left(AEP_{aux,i} \times N_{aux,i}\right)$$

Where,			Units
AEP_i	=	Annual air pollutant emissions of the baseline or replacement marine vessel	US tons/yr
$AEP_{prop,\ i}$	=	Annual air pollutant emissions of the baseline or replacement marine vessel propulsion engine	US tons/yr
$N_{prop,\ i}$	=	Number of propulsion engines	Unitless
$AEP_{aux,\ i}$	=	Annual air pollutant emissions of the baseline or replacement marine vessel auxiliary engine	US tons/yr
$N_{aux,\ i}$	=	Number of auxiliary engines	Unitless
i	=	Baseline or replacement	

Equation 31: Annual Air Pollutant Emissions from Hybrid Marine Vessel Engines

$$AEP_{j,i} = EF_{j,i} \times LF_{j,i} \times HP_{j,i} \times RTVP \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
$AEP_{j,\,i}$	=	Annual air pollutant emissions of hybrid marine vessel propulsion or auxiliary engine	US tons/yr
$EF_{j,\,i}$	=	Emission factor of the conventional baseline or replacement marine vessel propulsion or auxiliary engine	g/bhp-hr
$LF_{j,\,i}$	=	Load factor of the conventional baseline or replacement marine vessel propulsion or auxiliary engine, by vessel type	Unitless
$HP_{j,\,i}$	=	Maximum rated horsepower of the conventional baseline or replacement marine vessel propulsion or auxiliary engine	bhp
RTVP	=	Reduced technology verification percentage (default value of 70%, assuming 30% operation on hybrid system)	%
AA	=	Annual activity	hr/yr
j	=	Propulsion or auxiliary	
i	=	Baseline or replacement	

Equation 32: Annual Air Pollutant Emissions from Marine Vessel Engines

$$AEP_{j,i} = EF_{j,i} \times LF_{j,i} \times HP_{j,i} \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
$AEP_{j,\,i}$	=	Annual air pollutant emissions of the baseline or replacement marine vessel propulsion or auxiliary engine	US tons/yr
$EF_{j,\,i}$	=	Emission factor of the baseline or replacement marine vessel propulsion or auxiliary engine	g/bhp-hr
$LF_{j,\,i}$	=	Load factor of the baseline or replacement marine vessel propulsion or auxiliary engine, by vessel type	Unitless
$HP_{j,\,i}$	=	Maximum rated horsepower of the baseline or replacement marine vessel propulsion or auxiliary engine	bhp
AA	=	Annual activity	hr/yr
j	=	Propulsion or auxiliary	
i	=	Baseline or replacement	

F. Emissions Reductions from Marine Ocean-Going Vessels

The LCT Demos & Pilots Benefits Calculator tool calculates estimates for GHG emissions reductions and air pollutant emission co-benefits for each of the project types. The following subsections present the equations and methods from existing CARB methodologies or Calculator Tools used for Ship-side Power and Marine Capture and Control Systems.

1. GHG Equations for Ship-side Power

Equation 33 shows the GHG emission reductions that occur over the ship-side power project's entire quantification period. Using Equation 34, annual activity is calculated based on the vessel's berthing time and annual number of visits to the ship-side power system.

Equation 33: GHG Emission Reductions from Ship-side Power

$$ER_{GHG} = QP \times P \times AA \times ED_{elec} \times (CC_{dsl} \times EER_{marine} - CC_{elec}) \times \frac{1\ MTCO_2e}{1{,}000{,}000\ gCO_2e}$$

Where,			Units
ER_{GHG}	=	GHG emission reductions from ship-side power system over quantification period	$MTCO_2e$
QP	=	Quantification period	yr
P	=	Shore power default power requirement, by vessel category and type/size	kW
AA	=	Annual activity of the ship-side power system	hr/yr
ED_{elec}	=	Energy density of electricity	MJ/kWh
CC_{dsl}	=	Carbon content of diesel	gCO_2e/MJ
EER_{marine}	=	Energy economy ratio of electricity relative to diesel, for ocean-going vessels	Unitless
CC_{dsl}	=	Carbon content of electricity	gCO_2e/MJ

Equation 34: Annual Activity of the Ship-side Power System

$$AA = BT \times V$$

Where,			Units
AA	=	Annual activity of the ship-side power system	hr/yr
BT	=	Berthing time per vessel visit	hr/visit
V	=	Annual number of visits	visit/yr

2. Criteria and Toxic Air Pollutant Equations for Ship-side Power

Equation 35 shows the individual air pollutant emission reductions that occur over the ship-side power project's entire quantification period, accounting for avoided emissions of the marine vessel and emissions generated from the use of ship-side power. The annual air pollutant emission reductions from ship-side power are estimated as a proportion of the default emissions from conventional ship-side power using Equation 36.

For the ship-side power system, vessel category and size/type are used as lookup inputs to ascertain emission factors from the Carl Moyer Program Guidelines.[12] The following calculations are repeated for each type of pollutant – i.e., NO_x, ROG, and PM.

Equation 35: Air Pollutant Emission Reductions from Ship-side Power

$$ER_{pollutant} = QP \times AER_{pollutant} \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$ER_{pollutant}$	=	Air pollutant emission reductions over quantification period	lbs
QP	=	Quantification period	yr
$AER_{pollutant}$	=	Annual air pollutant emission reductions	US tons/yr

Equation 36: Annual Air Pollutant Emission Reductions from Ship-side Power

$$AER_{pollutant} = AA \times DER \times P \times ERF \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
$AER_{pollutant}$	=	Annual air pollutant emission reductions	US tons/yr
AA	=	Annual activity of the ship-side power system	hr/yr
DER	=	Shore power default emission rate	g/kW-hr
P	=	Shore power default power requirement, by vessel category and type/size	kW
ERF	=	Emission reduction factor	%

[12] CARB. Carl Moyer Program Guidelines. https://www.arb.ca.gov/msprog/moyer/guidelines/current.htm

3. GHG Equations for Marine Capture and Control Systems

Equation 37 shows the GHG emissions that occur over the marine capture and control system's entire quantification period. Using Equation 38 and Equation 39, GHG emissions are calculated based on fuel usage and annual activity.

Equation 37: GHG Emissions of the Capture and Control System

$$E_{GHG} = QP \times (1 - Eff) \times AEG_{CC}$$

Where,			Units
E_{GHG}	=	GHG emissions over quantification period	$MTCO_2e$
QP	=	Quantification period	years
Eff	=	Capture system control efficiency	%
AEG_{CC}	=	Annual GHG emissions of the capture and control system	$MTCO_2e$/yr

Equation 38: Annual GHG Emissions of the Capture and Control System

$$AEG_{CC} = FC_{CC} \times CC_{CC} \times AA \times \frac{1\ MTCO_2e}{1{,}000{,}000\ g}$$

Where,			Units
AEG_{CC}	=	Annual greenhouse gas emissions of the capture and control system	$MTCO_2e$/yr
FC_{CC}	=	Hourly fuel consumption of the capture and control system	gal/hr or scf/hr
CC_{CC}	=	Carbon content of the capture and control system (depending on fuel type)	gCO_2e/gal or gCO_2e/scf
AA	=	Annual activity of the capture and control system	hr/yr

Equation 39: Annual Activity of the Marine Vessel

$$AA = BT \times V$$

Where,			Units
AA	=	Annual activity of the capture and control system	hr/yr
BT	=	Berthing time per vessel visit	hr/visit
V	=	Annual number of visits	visit/yr

4. Criteria and Toxic Air Pollutant Equations for Marine Capture and Control Systems

Equation 40 shows the individual air pollutant emission reductions that occur over the project's entire quantification period, accounting for emissions captured from the marine vessel and emissions generated from the control system's operation. The air pollutant emissions of the marine vessel are estimated as the sum of emissions from the vessel's auxiliary engines and boilers using Equation 41. The air pollutant emissions of the capture and control system's operation are estimated akin to off-road equipment using Equation 42.

For the marine vessel, vessel type, location (at berth or at anchor), fuel type, fuel sulfur content, and engine tier are used as lookup inputs to ascertain emission factors from CARB's 2019 Update to Inventory for Ocean-Going Vessels At Berth: Methodology and Results.[13, 14] For the capture and control system operation, fuel type, horsepower, and engine tier are used as lookup inputs to ascertain emission factors from the Carl Moyer Program Guidelines. The following calculations are repeated for each type of pollutant – i.e., NO_x, ROG, and PM.

Equation 40: Air Pollutant Emission Reductions from Marine Capture and Control

$$ER_{pollutant} = QP \times \left[(Eff \times AEP_{OGV}) - \left((1 - Eff) \times AEP_{CC}\right)\right] \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,

			Units
$ER_{pollutant}$	=	Air pollutant emission reductions over quantification period	lbs
QP	=	Quantification period	years
Eff	=	Capture system control efficiency	%
AEP_{OGV}	=	Annual criteria pollutant emissions of the ocean-going vessel	US tons/yr
AEP_{CC}	=	Annual criteria pollutant emissions of the capture and control system	US tons/yr

[13] CARB. 2019 Update to Inventory for Ocean-Going Vessels At Berth: Methodology and Results. https://ww2.arb.ca.gov/rulemaking/2019/ogvatberth2019

[14] Per the California Ocean-going Vessel Fuel Regulation, only 0.1% sulfur distillate fuels are allowed in California.

Equation 41: Annual Air Pollutant Emissions of the Ocean-Going Vessel

$$AEP_{OGV} = \frac{ED}{D} \times \frac{(EF_{Aux} \times EP_{Aux} + EF_{Boiler} \times EP_{Boiler})}{EER_i} \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
AEP_{OGV}	=	Annual air pollutant emissions of the ocean-going vessel	US tons/yr
ED	=	Energy density of diesel	MJ/gal
D	=	Density of diesel	g_{dsl}/gal
EF_{Aux}	=	Emission factor of the baseline OGV auxiliary engines, specific to fuel type, sulfur content, and engine tier	g/kWh
EP_{Aux}	=	Effective power of the baseline OGV auxiliary engines at berth or anchor, specific to vessel type	kW
EF_{Boiler}	=	Emission factor of the baseline OGV boilers, specific to fuel type, sulfur content, and engine tier	g/kWh
EP_{Boiler}	=	Effective power of the baseline OGV boilers at berth or anchor, specific to vessel type	kW
EER_i	=	Energy Economy Ratio of the baseline or shore power system relative to diesel	Unitless
AA	=	Annual activity of the capture and control system	hr/yr
i	=	Baseline or shore power system	

Equation 42: Annual Air Pollutant Emissions of the Capture and Control System

$$AEP_{CC} = EF_{CC,pollutant} \times LF \times HP \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
AEP_{CC}	=	Annual air pollutant emissions of the capture and control system	US tons/yr
$EF_{CC,\ pollutant}$	=	Emission factor of the capture and control system	g/bhp-hr
LF	=	Load factor	Unitless
HP	=	Maximum rated horsepower	bhp
AA	=	Annual activity	hr/yr

G. Emissions Reductions from Zero-Emission Locomotives

The LCT Demos & Pilots Benefits Calculator tool calculates estimates of GHG emissions reductions and air pollutant emission co-benefits for each of the project types. The following subsections presents the equations and methods from existing CARB methodologies or Calculator Tools used for Zero-Emission Locomotives.

1. GHG Equations

Equation 43 is used to estimate GHG emission reductions from locomotive projects, calculated as the difference in fuel and energy use between the baseline and replacement scenarios over the quantification period.

Equation 43: GHG Emission Reductions from Locomotives

$$ER_{GHG} = (AEG_{baseline} - AEG_{replacement}) \times Op \times QP \times \frac{1\ MTCO_2e}{1{,}000{,}000\ gCO_2e}$$

Where,			Units
ER_{GHG}	=	GHG emission reductions from locomotive replacement	$MTCO_2e$
$AEG_{baseline}$	=	Annual GHG emissions of the baseline locomotive	gCO_2e/yr
$AEG_{replacement}$	=	Annual GHG emissions of the replacement locomotive	gCO_2e/yr
Op	=	Percent operation in California	%
QP	=	Quantification period	yrs

Annual GHG emissions of the baseline locomotive are calculated using hourly fuel consumption and fuel carbon content with Equation 44. The GHG emissions calculation for the replacement locomotive is then calculated using Equation 45. The replacement locomotive is assumed to use the same amount of energy as the baseline locomotive, and proportions the carbon content by fuel type if the technology is dual electric-hydrogen.

Equation 44: Annual GHG Emissions of the Baseline Locomotive

$$AEG_{baseline} = Fuel_{baseline} \times EF_{GHG,baseline} \times AA$$

Where,			Units
$AE_{baseline}$	=	Annual GHG emissions of the baseline locomotive	gCO_2e/yr
$Fuel_{baseline}$	=	Hourly fuel consumption of the baseline locomotive	gal/hr or scf/hr
$EF_{GHG,\ baseline}$	=	Fuel-specific GHG emission factor for the baseline locomotive	gCO_2e/gal or gCO_2e/scf
AA	=	Annual activity	hr/yr

Equation 45: Annual GHG Emissions of the Replacement Locomotive

$$AEG_{replacement} = Fuel_{baseline} \times ED_{baseline} \times \left[\left(\frac{P_1 \times EF_{GHG,replacement\ 1}}{ED_{replacement\ 1} \times EER_{replacement\ 1}}\right) + \left(\frac{(1 - P_1) \times EF_{GHG,replacement\ 2}}{ED_{replacement\ 2} \times EER_{replacement\ 2}}\right)\right] \times AA$$

Where,			Units
$AEG_{replacement}$	=	Annual GHG emissions of the replacement locomotive	gCO_2e/yr
$Fuel_{baseline}$	=	Hourly fuel consumption of the baseline locomotive	gal/hr or scf/hr
$ED_{baseline}$	=	Energy density of the baseline fuel type	MJ/gal or MJ/scf
P_1	=	Percent primary fuel type of the replacement locomotive	%
$EF_{GHG,\ replacement\ 1}$	=	Fuel-specific GHG emission factor for the primary replacement fuel type	gCO_2e/kWh or gCO_2e/kg
$ED_{replacement\ 1}$	=	Energy density of the primary replacement fuel type	MJ/kWh or MJ/kg
$EER_{replacement\ 1}$	=	Energy Efficiency Ratio of the primary ZEV replacement fuel type relative to baseline fuel type	Unitless
$EF_{GHG,\ replacement\ 2}$	=	Fuel-specific GHG emission factor for the secondary replacement fuel type, if applicable	gCO_2e/kWh or gCO_2e/kg
$ED_{replacement\ 2}$	=	Energy density of the secondary replacement fuel type, if applicable	MJ/kWh or MJ/kg
$EER_{replacement\ 2}$	=	Energy Efficiency Ratio of the secondary ZEV replacement fuel type relative to baseline fuel type, if applicable	Unitless
AA	=	Annual activity	hr/yr

2. Criteria and Toxic Air Pollutant Equations

Equation 46 is used to estimate the air pollutant emission reductions that occur over the locomotive's entire quantification period. The following calculation is repeated for each type of pollutant – i.e., NO_x, ROG, and PM. The annual air pollutant emissions for the baseline locomotive are calculated using Equation 47. Alternatively, hourly fuel consumption and annual activity may be substituted with annual fuel consumption. PM_{10} is assumed to be equivalent to PM, Diesel PM is assumed to be equivalent to PM if the fuel is diesel or an alternative diesel fuel, and $PM_{2.5}$ is assumed to be 92 percent of PM if the fuel is diesel or a diesel substitute or 76 percent of PM if the fuel is gasoline or a gasoline substitute. The replacement locomotive uses zero-emission technology, so there are no air pollutant emissions to deduct for the replacement locomotive.

Equation 46: Air Pollutant Emission Reductions from Zero-Emission Locomotives

$$ER_{pollutant} = QP \times AEP_{baseline} \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$ER_{pollutant}$	=	Air pollutant emission reductions over quantification period	lbs
QP	=	Quantification period	yr
$AEP_{baseline}$	=	Annual air pollutant emissions of the baseline locomotive	US tons/yr

Equation 47: Annual Air Pollutant Emissions of Baseline Locomotives

$$AEP_{baseline} = EF_{pollutant,baseline} \times FCR_{baseline} \times FC_{baseline} \times AA \times \frac{1\ US\ ton}{907{,}200\ g}$$

Where,			Units
$AEP_{baseline}$	=	Annual air pollutant emissions of the baseline locomotive	US tons/yr
$EF_{pollutant,\ baseline}$	=	Air pollutant emission factor of the baseline locomotive, by locomotive class and engine tier	g/bhp-hr
$FCR_{baseline}$	=	Fuel consumption rate of the baseline locomotive, by locomotive class	bhp-hr/gal
$FC_{baseline}$	=	Hourly fuel consumption of the baseline locomotive	gal/hr
AA	=	Annual activity	hr/yr

H. Emissions Reductions from Zero-Emission Aviation

The LCT Demos & Pilots Benefits Calculator tool calculates estimates of GHG emissions reductions and air pollutant emission co-benefits for each of the project types. The following subsections presents the equations and methods from existing CARB, air district, and federal methodologies or Calculator Tools used for Zero-Emission Aviation.

1. GHG Equations

Equation 48 is used to estimate GHG emission reductions from aviation projects, calculated as the difference in fuel and energy use between the baseline and replacement scenarios over the quantification period.

Equation 48: GHG Emission Reductions from Aviation

$$ER_{GHG} = (AEG_{baseline} - AEG_{replacement}) \times QP \times \frac{1\ MTCO_2e}{1{,}000{,}000\ gCO_2e}$$

Where,			Units
ER_{GHG}	=	GHG emission reductions from aircraft replacement	$MTCO_2e$
$AEG_{baseline}$	=	Annual GHG emissions of the baseline aircraft	gCO_2e/yr
$AEG_{replacement}$	=	Annual GHG emissions of the replacement aircraft	gCO_2e/yr
QP	=	Quantification period	yrs

Annual GHG emissions of baseline commercial, air taxi, and general aviation aircraft are calculated using hourly fuel consumption and fuel carbon content with Equation 49. The GHG emissions of the replacement commercial, air taxi, and general aviation aircraft is then calculated using Equation 50. The replacement aircraft is assumed to use the same amount of energy as the baseline aircraft, accounting for energy efficiency improvements. Average fuel consumption rates and annual flight hours by aircraft type was derived from Federal Aviation Administration survey data. The fuel consumption rate data is assumed to include all cycles of flight (i.e., landing and takeoff cycle; climb, cruise, and descent cycle).

Equation 49: Annual GHG Emissions of the Baseline Commercial, Air Taxi, and General Aviation Aircraft

$$AEG_{baseline} = Fuel_{baseline} \times EF_{GHG,baseline} \times AA$$

Where,			Units
$AEG_{baseline}$	=	Annual GHG emissions of the baseline aircraft	gCO_2e/yr
$Fuel_{baseline}$	=	Hourly fuel consumption of the baseline aircraft	gal/hr
$EF_{GHG,\ baseline}$	=	Fuel-specific GHG emission factor for the baseline aircraft	gCO_2e/gal
AA	=	Average annual flight hours	hr/yr

Equation 50: Annual GHG Emissions of the Replacement Commercial, Air Taxi, and General Aviation Aircraft

$$AEG_{replacement} = Fuel_{baseline} \times \frac{ED_{baseline}}{ED_{replacement}} \times \frac{1}{EER_{replacement}} \times EF_{GHG,replacement} \times AA$$

Where,			Units
$AEG_{replacement}$	=	Annual GHG emissions of the replacement aircraft	gCO_2e/yr
$Fuel_{baseline}$	=	Hourly fuel consumption of the baseline aircraft	gal/hr
$ED_{baseline}$	=	Energy density of the baseline fuel type	MJ/gal
$ED_{replacement}$	=	Energy density of the replacement fuel type	MJ/kWh or MJ/kg
$EER_{replacement}$	=	Energy Efficiency Ratio of the ZEV replacement fuel type relative to baseline fuel type	Unitless
$EF_{GHG,\ replacement}$	=	Fuel-specific GHG emission factor for the replacement fuel type	gCO_2e/kWh or gCO_2e/kg
AA	=	Average annual flight hours	hr/yr

For agricultural aircraft (e.g., crop dusters), GHG emissions are instead estimated based on the number of treated acres. As part of a study performed for the San Joaquin Valley Air Pollution Control District, Sonoma Technology Inc (STI) estimated fuel consumption from crop dusting aircraft activity based on treated acreage. STI, with the aid of a local crop dusting company, determined that an Air Tractor aircraft with a Pratt & Whitney PT6A-45 turboprop engine could be used as a surrogate for all crop dusting aircraft. Annual GHG emissions of baseline agricultural aircraft are calculated using Equation 51. The GHG emissions of the replacement agricultural aircraft are then calculated using Equation 52, assuming the replacement aircraft uses the same amount of energy as the baseline aircraft, accounting for energy efficiency improvements.

Equation 51: Annual GHG Emissions of the Baseline Agricultural Aircraft

$$AEG_{baseline} = Fuel_{baseline,ag} \times EF_{GHG,baseline} \times Ac \times Op$$

Where,			Units
$AEG_{baseline}$	=	Annual GHG emissions of the baseline aircraft	gCO_2e/yr
$Fuel_{baseline,\ ag}$	=	Fuel consumption of the baseline agricultural aircraft per acre treated	gal/acre
$EF_{GHG,\ baseline}$	=	Fuel-specific GHG emission factor for the baseline agricultural aircraft	gCO_2e/gal
Ac	=	Number of acres treated per operation	acres/operation
Op	=	Number of operations per year	operations/yr

Equation 52: Annual GHG Emissions of the Replacement Agricultural Aircraft

$$AEG_{replacement} = Fuel_{baseline,ag} \times \frac{ED_{baseline}}{ED_{replacement}} \times \frac{1}{EER_{replacement}} \times EF_{GHG,replacement} \times Ac \times Op$$

Where,			Units
$AEG_{replacement}$	=	Annual GHG emissions of the replacement aircraft	gCO_2e/yr
$Fuel_{baseline,\ ag}$	=	Fuel consumption of the baseline agricultural aircraft per acre treated	gal/acre
$ED_{baseline}$	=	Energy density of the baseline fuel type	MJ/gal
$ED_{replacement}$	=	Energy density of the replacement fuel type	MJ/kWh or MJ/kg
$EER_{replacement}$	=	Energy Efficiency Ratio of the ZEV replacement fuel type relative to baseline fuel type	Unitless
$EF_{GHG,\ replacement}$	=	Fuel-specific GHG emission factor for the replacement fuel type	gCO_2e/kWh or gCO_2e/kg
Ac	=	Number of acres treated per operation	acres/operation
Op	=	Number of operations per year	operations/yr

2. Criteria and Toxic Air Pollutant Equations

The evaluation of air pollutant emissions impacts from aircraft operations focuses on the emission characteristics of this source relative to the vertical column of air that affects ground-level pollutant concentrations. This portion of the atmosphere, which begins at the earth's surface and is simulated in air quality models, is often referred to as the mixing zone. For the purposes of this methodology the mixing zone extends from the earth’s surface to a mixing height of 3,000 feet. For commercial, air taxi, and general aviation aircraft, the operations of interest within this layer are defined as the landing and take-off (LTO) cycle. The LTO cycle begins when the aircraft approaches the airport on its descent from cruising altitude, lands, and taxis to the gate. It continues as the aircraft starts back up, taxis back out to the runway for subsequent takeoff, and ascends back up to cruising altitude (climbout). Thus, the six specific operating modes in an LTO are: approach, taxi/idle-in, startup, taxi/idle-out, take-off, and climbout. The LTO cycle can provide a basis for calculating aircraft emissions. During each mode of operation, the aircraft engine(s) operates at different power settings for a given aircraft category. Emissions for one complete LTO cycle for a given aircraft are calculated by knowing emission factors for specific aircraft engines at those power settings. The emission factors used in the LCT Demos & Pilots Benefits Calculator are national averages by aircraft type provided by the 2020 US EPA National Emissions Inventory.[15]

Equation 53 is used to estimate the air pollutant emission reductions that occur over the aircraft's entire quantification period. The following calculation is repeated for each type of pollutant – i.e., NO_x, ROG, and PM. The annual air pollutant emissions for baseline commercial, air taxi, and general aviation aircraft are calculated using Equation 54. VOC emissions are assumed to be equivalent to ROG. The replacement aircraft uses zero-emission technology, so there are no air pollutant emissions to deduct for the replacement aircraft.

Equation 53: Air Pollutant Emission Reductions from Zero-Emission Aircraft

$$ER_{pollutant} = QP \times AEP_{baseline} \times \frac{2{,}000\ lbs}{1\ US\ ton}$$

Where,			Units
$ER_{pollutant}$	=	Air pollutant emission reductions over quantification period	lbs
QP	=	Quantification period	yr
$AEP_{baseline}$	=	Annual air pollutant emissions of the baseline aircraft	US tons/yr

[15] US EPA (2022). 2020 National Emissions Inventory. https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

Equation 54: Annual Air Pollutant Emissions of Baseline Commercial, Air Taxi, and General Aviation Aircraft

$$AEP_{baseline} = EF_{pollutant,baseline} \times LTO$$

Where,			Units
$AEP_{baseline}$	=	Annual air pollutant emissions of the baseline aircraft	US tons/yr
$EF_{pollutant,\ baseline}$	=	Air pollutant emissions per landing and takeoff cycle, by aircraft type	US tons/LTO
LTO	=	Annual number of annual landing and takeoff cycles	LTO/yr

Air pollutant emissions from agricultural aircraft cannot be calculated using the methods applied to commercial or general aviation aircraft. Crop dusters are believed to operate in their cruising modes exclusively within the 3,000 foot high mixing zone. Thus, these emissions from the cruising modes of crop dusting aircraft must be accounted for. Due to this unique characteristic of crop dusters (and a lack of available data on crop duster activity), emissions from these aircraft were estimated based on the number of harvested acres. Although the number of acres and applications per year varies widely depending on a number of factors, including crop type, the prevalence of weeds and insects in a given year, and farmer preferences, the STI study assumes a rough average of 60 acres per treatment and 5 applications per year. The annual air pollutant emissions for baseline agricultural aircraft are calculated using Equation 55. The replacement agricultural aircraft uses zero-emission technology, so there are no air pollutant emissions to deduct for the replacement aircraft.

Equation 55: Annual Air Pollutant Emissions of Baseline Agricultural Aircraft

$$AEP_{baseline} = EF_{crit,baseline,ag} \times Ac \times Op$$

Where,			Units
$AEP_{baseline}$	=	Annual air pollutant emissions of the baseline aircraft	US tons/yr
$EF_{crit,\ baseline,\ ag}$	=	Air pollutant emissions per acre of farmland treated	US tons/acre
Ac	=	Number of acres treated per operation	acres/operation
Op	=	Number of operations per year	operations/yr

Section C. References

The following references were used in the development of this Quantification Methodology and the LCT Demos & Pilots Benefits Calculator Tool:

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