ATTACHMENT D

ANALYSES SUPPORTING THE ADDITION OR REVISION OF ENERGY ECONOMY RATIO VALUES FOR THE PROPOSED LCFS AMENDMENTS

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ATTACHMENT D

This attachment to the “Notice of Public Availability of Modified Text and Availability of Additional Documents and Information,” related to Proposed Amendments to the Low Carbon Fuels Standard Regulation and to the Regulation on Commercialization of Alternative Diesel, is a supplement to Appendix H to the Initial Statement of Reasons supporting the proposed amendments released March 6, 2018.

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A. Energy Economy Ratios for Cargo Handling Equipment (Non-Yard Trucks) in the Low Carbon Fuel Standard

Many previous Energy Economy Ratio (EER) analyses have been performed by predicting emissions based on the average speed of the equipment (e.g., drayage and yard trucks). However, for some equipment types, namely non-yard truck cargo handling equipment (CHE), speed is a less relevant metric to characterize engine performance because a significant portion of the power is allocated for lifting and pushing cargo while equipment remains at a fixed location. Therefore, this analysis aims to quantify EERs for some of the more common CHE of the non-yard truck type operating in ports and rail yards (e.g., rubber tire gantry cranes, forklifts, container handlers, and bull dozers) using a method that does not rely on average equipment speed.

Combining real-world CHE activity data from a report compiled by the Starcrest Consulting Group, LLC[1], with recent internal work by CARB staff[2] where emissions data were collected from on-road engines with 350 to 500 peak brake horsepower, staff calculated EERs for selected CHE based on the modeled relationship between carbon dioxide (CO_2) emissions and real-time engine power along with prior estimates of CHE load factors used in the latest California Air Resources Board (CARB) emission inventory. [3] Briefly, this method includes calculating typical average horsepower for each equipment type, estimating CO_2 emissions, and calculating fuel consumption. Together, fuel consumed and equipment power output provides efficiency for the conventional engine, which can be used to relate the energy displaced for the potential switch to battery-electric alternatives.

1. Methods

a. Cargo Handling Equipment Power Requirements

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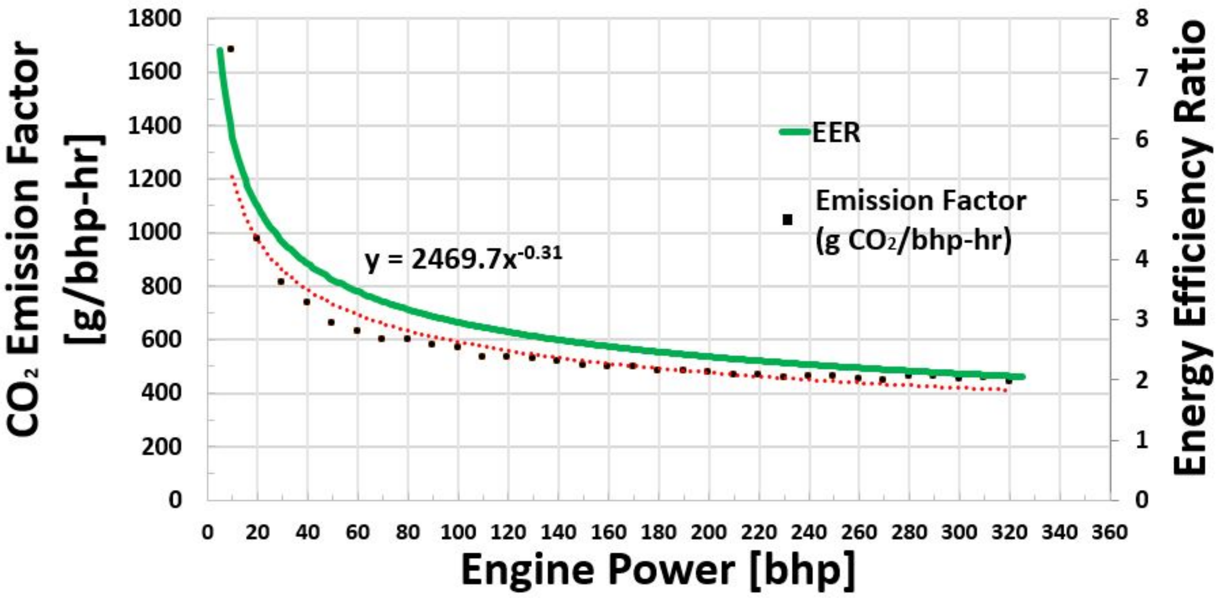
[1] Starcrest Consulting Group, LLC. July 2017. Port of Long Beach 2016 Air Emissions Inventory.

[2] California Air Resources Board. Data from the Pilot Truck and Bus Surveillance Program as submitted to the Journal of Air & Waste Management Association in March 2018: *"Deriving fuel-based emission factor thresholds to interpret heavy-duty vehicle roadside plume measurements."*

[3] California Air Resources Board. 2011. Cargo Handling Equipment Inventory, Appendix B: Emissions Inventory Methodology.

A function relating work (or brake)-specific CO_2 emissions to instantaneous brake horsepower has been constructed using recent emissions data from selected engines with 350 to 500 peak horsepower measured as part of CARB's Pilot Truck and Bus Surveillance Program. See **Figure 1**.

Figure 1: CO_2 emission factors and derived Energy Economy Ratio (EER) versus engine power (bhp) developed using internal CARB emissions data from Class 8 on-road trucks as part of CARB's Pilot Truck and Bus Surveillance Program.



For this analysis, staff suggest that the mass of CO_2 emitted for a given instantaneous horsepower for on-road truck engines will be similar for non-yard truck CHE operating under the same load. Therefore, CO_2 can be used as a surrogate to estimate the fuel consumed for CHE under average load factors. A line of best fit is represented as **eq. 1** where y is the CO_2 emission factor (g bhp-hr^{-1}) and x is the given engine power (bhp).

$$y=2469.7*x^{-0.31} \qquad \textbf{(1)}$$

The following assumptions can be used to estimate the EER for non-yard truck CHE based on the CO_2 emission factor (g bhp-hr^{-1}):

- Carbon Content of Diesel Fuel by Weight = 0.869
- Molecular Weight of Oxygen (O) = 16 grams/mole
- Molecular Weight of Carbon (C) = 12 grams/mole
- 0.832 kilograms Diesel Fuel = Liter of Diesel Fuel
- 3.785 Liters of Diesel Fuel = Gallon of Diesel Fuel

- 1 Horsepower = 0.7457 kilowatt
- 134.47 MJ = Energy Content in a Gallon of Diesel Fuel

Presently, CARB's EER calculation methods assume no losses of energy during battery charging or conversion of energy to useful work. To be consistent with prior calculation methods, staff assume no losses for non-yard truck equipment. Therefore, the inverse of conventional engine efficiency can be used to estimate EERs. For reference, the corresponding EERs associated with the brake-specific CO_2 emissions are shown on the right axis of **Figure 1**.

b. Application to Specific Cargo Handling Equipment

Table 1 presents real-world CHE power and activity data and expected average real-world CHE loads based on CHE type. The load factors were previously reported for various equipment types in CARB's CHE emissions inventory methodology.[37] The remaining data presented in the table is a subset of the CHE fleet-average data compiled by the Starcrest Consulting Group, LLC, for the Port of Long Beach.[35] Using load factors from previous CARB work, the arithmetic mean of the minimum and maximum engine power ratings, staff calculated the expected average operational horsepower. See next section for a discussion of the final column in **Table 1**.

Table 1. Horsepower, loads, and activity for evaluated cargo handling equipment types

Equipment Type	Average Engine Power Rating (BHP)[1]	Load Factor[3]	Calculated Average Operational Horsepower (BHP)	Hours of Operation[1]
Bulldozer	146	0.55	80	1,900
Forklift-Diesel	133	0.30	40	55,723
Loader	320	0.55	176	14,112
RTG Crane	653	0.2	131	140,154
Side Handler	211	0.59	124	10,276

Top Handler	306	0.59	181	401,633

EER values for non-yard truck CHE were estimated by combining the data presented in **Table 1** with the function presented in **Figure 1**. Specifically, we applied the average operational brake horsepower to **eq. 1**, and with the unit conversions listed in the above bullets, EERs were calculated for each CHE type as shown in **Table 2**.

Table 2: Energy Economy Ratios for Selected Cargo Handling Equipment.

Equipment Type	EER
Bulldozer	3.2
Forklift-Diesel	3.9
Loader	2.5
RTG Crane	2.7
Side Handler	2.8
Top Handler	2.5
Operational-Hour-Weighted Average EER	**2.7**

2. Recommendation

The EERs shown in **Table 2** represent a wide range of equipment operations with contributions that vary in proportion to overall activity and emissions. Thus, the final recommendation for all non-yard truck CHE is an operational-hour-weighted EER of 2.7, which reflects the average of the EERs for each of the different CHE types weighted based on operational hours reported as shown in **Table 1**. This recommendation assumes 100 percent efficiency of battery-electric versions of this equipment, to be consistent with other estimates of EERs.

Finally, staff note that these load factors used in existing emission inventories are vetted through the public rulemaking process. However, they are highly sensitive parameters in determining final EER estimates. This is because staff assume average operational horsepower is a function of load and peak horsepower, and the efficiency of a conventional diesel engine is a function of vehicle power. Moreover, staff lack fleet-representative logged data that are more comprehensive and/or unequivocal than the values used in the existing inventory. Therefore, this analysis also uses load factors used in the latest CHE emission inventories developed by CARB and third-party consultants.

B. Energy Economy Ratios for Ocean-Going Vessels (OGVs) in the Low Carbon Fuels Standard

1. Background

Ocean-going vessels (OGVs) are commercial ships that are greater than or equal to 400 feet in length, weigh 10,000 gross tons or greater, or are propelled by a marine compression ignition engine with a displacement of at least 30 liters per cylinder. While there are fewer OGVs visiting California than the numbers of equipment operating in other sectors covered by LCFS, the vessels and engines are large and consume a large proportion of fuel relative to their numerical population. Therefore, there could be a benefit to incentivize the adoption of zero-emission technologies with lower carbon intensities. At this time, there are no viable technology options that would permit intercontinental propulsion of OGVs using advanced battery-electric or fuel-cell engine technologies. However, there are existing requirements that already apply to OGVs within “Regulated California Waters” (or 24 nautical miles of the California coast for OGVs); for example, the reduction of emissions from auxiliary engines while vessels are “at-berth.” For the case when OGVs are “at-berth,” or docked in a harbor, an auxiliary engine(s) powers vital equipment that must continue to operate even when the ship is not moving. Power needs while at-berth include support for any of the following: on-board electronics, lighting, ballast pumps, ventilation systems, and controlling the temperature of containers on container vessels.

This analysis quantifies an aggregated EER value for a wide range of auxiliary engines on all types of ships that call California ports, but does not include/pertain to boilers. The recommended EER broadly expresses the increased energy efficiency of using shore power instead of using the conventional on-board auxiliary engine(s). The analysis assumes all of the electric energy would be provided by the local utility even though some California ports are able to generate a portion of their own electricity, which may be associated with a different carbon intensity. For consistency with prior EER calculations, staff also assumed that shore power is 100% energy efficient.

Generally, diesel engines operate with 30 to 35 percent thermal efficiency where roughly 65 to 70 percent of energy is rejected as waste heat without being converted to useful work.[4] Auxiliary engines for all OGVs are generally medium speed 4-stroke engines. Despite a wide range of peak power outputs of auxiliary engines, this analysis

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[4] Thermal Efficiency for Diesel Cycle. https://www.nuclear-power.net/nuclear-engineering/thermodynamics/thermodynamic-cycles/diesel-cycle-diesel-engine/thermal-efficiency-for-diesel-cycle/.

will provide a fleet-average efficiency that is likely a close representation of most engines. Furthermore, although auxiliary power draw varies drastically among various types of OGVs, credits applied through the recommended OGV at-berth EER will be dependent on the power consumption reported to CARB by the particular company. For instance, a cruise ship may consume more energy when at-berth versus a container vessel; however, our analysis calculates a single EER applicable to all OGV types.

2. Methods

The Starcrest Consulting Group, LLC, reported 2016 information for OGVs operating near and at the Port of Long Beach, including ships at-berth.[1] However, as a result of the existing At-Berth Regulation, a portion of the direct emissions from OGVs in 2016 have already been reduced by using shore power while at-berth. To eliminate the possible bias that could occur from quantifying fuel consumption for an OGV fleet comprising a fraction of auxiliary engines that are already plugged in, staff analyzed auxiliary engine data for OGVs while at-anchorage. Ships at-anchorage are stationary and waiting to enter the port terminal to be loaded or unloaded; therefore, the conditions under which the auxiliary engines are operating at-anchorage and at-berth are assumed to be similar. Since the fraction of vessels utilizing shore power cannot be quantified for vessels at-berth, data for OGVs at-anchorage are instead used as a surrogate for auxiliary engine fuel consumption (and efficiency) of OGV auxiliary engines at-berth. **Table 3** presents average at-anchorage data based on 890 OGVs of many types in 2016, which were used to calculate the recommended OGV at-berth EER.

Table 3: Ocean-going vessel (OGV) at-anchorage energy consumption and emissions data reported cumulatively from 890 vessels calling the Port of Long Beach in 2016[1]

Metric	Value
Auxiliary Energy Generated On-Board (kWh)	2.84×10^7
CO_2 emission (Metric Tons)	20,028
Number of Total OGVs (Unitless)	890
Calculated Fuel Energy Consumed by the Conventional Diesel Engine (MJ)	2.68×10^8

Staff estimated the fuel consumed at anchorage using CO_2 as a surrogate similar to previous analyses. The following assumptions can be used to estimate the EER for OGV auxiliary engine based on the CO_2 emission factor (g bhp-hr^{-1}):

- Carbon Content of Diesel Fuel by Weight = 0.869
- Molecular Weight of Carbon (C) = 12 grams/mole
- Molecular Weight of CO_2 = 44 grams/mole
- 0.832 kilograms Diesel Fuel = Liter of Diesel Fuel
- 3.785 Liters of Diesel Fuel = Gallon of Diesel Fuel
- 1 Horsepower = 0.7457 kilowatt
- 134.47 MJ = Energy Content in a Gallon of Diesel Fuel

Staff accounted for differences in physical properties (mass and energy density) of marine diesel oil (MDO) compared to traditional CARB ultra-low sulfur diesel (ULSD) fuel. For reference, **Table 4** provides quantitative differences in these properties.
The Calculated Fuel Energy Consumed by the Conventional Diesel Engine (MJ) based on CO_2 emissions is shown below:

$$\text{Calculated Fuel Energy Consumed by the Conventional Diesel Engine} = [20{,}028 \text{ tons of } CO_2 \text{ emission} \times 1{,}000 \times 12/44 \times (1/0.869) \times (1/0.872) \times (1/3.785) \times 140.55]$$

$$= 2.68 \times 10^8 \text{ (MJ)}$$

Table 4: Comparison of the physical properties of marine diesel oil and diesel fuel

Fuel Type/Metric	Mass Density (kg per Liter)	Energy Density MJ per Gallon
Marine Diesel Oil	0.872	140.55
CARB Diesel Fuel (ULSD)	0.832	134.47

Through unit analysis, staff calculated the energy (MJ) displaced by switching to the electric alternative at-anchorage.

$$EER_{\text{OGV-at-anchorage}} = [(2.68 \times 10^8 \text{ MJ})/((3.60 \text{ MJ kWh}^{-1})*(2.84 \times 10^7 \text{ kWh}))]$$

$$EER_{\text{OGV-At-Anchorage}} = 2.6$$

Given $EER_{\text{OGV-At-Anchorage}} \sim EER_{\text{OGV-At-Berth}}$, therefore:

$$EER_{\text{OGV-At-Berth}} = \boxed{2.6}$$

***Comparison with Fuel Rule Data** - *An EER value of 2.6 aligns with past emission inventory developments for CARB's OGV Fuel Rule. Documents in support of this rulemaking reported emission factors of 690 to 722 (g CO_2 kWh^{-1}), which translate into OGV auxiliary engine EERs ranging from 2.45 to 2.56 depending on fuel property assumptions.*

3. Recommendation

An EER of 2.6 is proposed as a single value representing the energy benefits associated with using shore power instead of operating auxiliary engines aboard the vessel.