# RENEWABLE DIESEL AS A MAJOR TRANSPORTATION FUEL IN CALIFORNIA:

## Opportunities, Benefits and Challenges

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## Authorship and Uses

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**Cover photo:** AltAir Fuels renewable diesel / jet fuel refinery in Paramount CA (photo courtesy of AltAir Fuels)

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# List of Terms

| ACRONYM | DEFINITION |
|---|---|
| **ADF** | Alternative Diesel Fuel |
| **AQMP** | Air Quality Management Plan |
| **ARB** | California Air Resources Board (Also “CARB") |
| **AB** | Assembly Bill |
| **BAAQMD** | Bay Area Air Quality Management District |
| **BEV** | Battery Electric Vehicle |
| **CO** | Carbon monoxide |
| **$CO_2$** | Carbon Dioxide |
| **CI** | Carbon Intensity |
| **CEC** | California Energy Commission |
| **CAA** | Federal Clean Air Act |
| **CWI** | Cummins Westport Inc. |
| **DGE** | Diesel Gallon Equivalent |
| **DOC** | Diesel Oxidation Catalyst |
| **DPF** | Diesel Particulate Filter |
| **DPM** | Diesel Particulate Matter |
| **EGR** | Exhaust Gas Recirculation |
| **EPA** | U.S. Environmental Protection Agency |
| **g/bhp-hr** | Grams per Brake Horsepower-Hour |
| **gCO2e/MJ** | Grams of carbon dioxide equivalent per mega Joule |
| **g/mi** | Grams per mile |
| **GHGs** | Greenhouse Gases |
| **HDE** | Heavy-Duty Engine |
| **HDV** | Heavy-Duty Vehicle |
| **HHDV** | Heavy-Heavy-Duty Vehicle |
| **HHDT** | Heavy-Heavy-Duty Truck |
| **ICCT** | International Council for Clean Transportation |
| **LCFS** | Low Carbon Fuel Standard (California) |
| **LED** | Low Emission Diesel regulation |
| **MSS** | Mobile Source Strategy (CARBB) |
| **NAAQS** | National Ambient Air Quality Standards |
| **$NO_x$** | Oxides of Nitrogen |
| **OEM** | Original Equipment Manufacturer |
| **NZEV** | Near-Zero-Emission Vehicle |
| **PM** | Particulate Matter |
| **$PM_{2.5}$** | PM smaller than 2.5 microns in size |
| **RD** | Renewable Diesel |
| **RDxx** | xx% (by volume) of RD blended with petroleum diesel |
| **RFS** | Renewable Fuel Standard (federal) |
| **RNG** | Renewable Natural Gas |
| **SCAQMD** | South Coast Air Quality Management District |
| **SCAB** | South Coast Air Basin |
| **SCR** | Selective Catalytic Reduction |
| **SFBAB** | San Francisco Bay Air Basin |
| **SIP** | State Implementation Plan |
| **SJVAB** | San Joaquin Valley Air Basin |
| **THC** | Total Hydrocarbons |
| **ULSD** | Ultra-Low Sulfur Diesel |
| **ZEV** | Zero-Emission Vehicle |

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## Executive Summary

Renewable diesel (RD) is doing its part to help ensure that heavy-duty vehicles (HDVs) with diesel engines can achieve the level of environmental performance needed to perpetuate their sales well into the 21st century. Any on-road HDV fuel-engine platform that will be sold in California beyond the 2030 timeframe will likely be required by the California Air Resources Board (CARB) to 1) achieve (at a minimum) near-zero-emissions of key air pollutants (especially oxides of nitrogen, or "NOx"), and 2) use a low-carbon-intensity renewable fuel. Although not all RD feedstock and production pathways offer reduced carbon intensity, RD used in California's transportation sector achieves a volume-weighted carbon intensity rating that is about 66 percent lower than petroleum diesel (mostly ultra-low sulfur diesel, or ULSD). This "drop-in" replacement for ULSD is already delivering major greenhouse gas (GHG) reductions, with RD consumption in California's transportation sector now exceeding *a quarter of a billion gallons per year*.

Thus – provided RD is made from environmentally benign feedstocks (as discussed in this report) – the fuel-related need for the diesel engine's future is being fully achieved today. However, the longer-term viability of heavy-duty diesel engines in California rests on the ability for diesel engine technology itself – possibly in combination with a hybrid-electric drivetrain – to achieve near-zero-emissions status. This is generally defined to be a NOx certification level at, or below, 0.02 g/bhp-hr.

This report describes how RD is enabling a "better side" of heavy-duty diesel engines. Over the last several years, California has become a test-bed for RD use, where it is allowing cities such as San Francisco, Oakland, San Diego and Los Angeles to achieve compelling GHG reductions, while also significantly contributing to much-needed improvements in ambient air quality. The latter is true because RD reduces tailpipe emissions of NOx and particulate matter (PM) when used to replace petroleum-derived diesel in 1) older on-road diesel HDVs, and 2) most diesel off-road HDVs and equipment.

Specific advantages offered by RD as a replacement for petroleum diesel include:

- It can be produced from a wide array of renewable, low-carbon-intensity feedstocks using existing oil refinery capacity; thus, extensive new production facilities will not be required for expanded RD use;
- It is substantially similar to ULSD in its physical and chemical characteristics; this means RD has no "blend wall" and can be directly used in existing diesel-powered vehicles and ULSD infrastructure without need for hardware and materials changes, even when used in its "neat" (100 percent) form (RD100);
- It has a high cetane number and other beneficial qualities that collectively enable HDVs to reduce their engine-out NOx and PM emissions by an average of 13 percent and 29 percent, respectively, while providing equivalent vehicle performance and near-equivalent fuel efficiency;
- It can deliver these benefits in any type of diesel engine application (on- or off-road, medium- or heavy-duty), subject to certain limitations described in the White Paper;
- It appears to significantly improve performance and reduce life-cycle costs of diesel particulate filters (DPFs), which are widely used to control PM emissions on post-2006 on-road HDVs (and some off-road HDVs).

For all these positive attributes, many end users refer to RD as a "wonder fuel." Clearly, RD does offer important benefits for user fleets and the general population – especially by providing "across-the-board"

GHG reductions in all diesel engines that consume it instead of petroleum-derived diesel. However, RD does not constitute a widely impactful or sustainable strategy to improve ambient air quality, in California or the broader U.S. Its abilities to help reduce ozone-precursor NOx emissions and toxic air contaminants (especially DPM) are limited by the breadth of diesel-engine applications for which it can provide such benefits, and the time frame over which they can be derived. This is because, based on limited but robust data, RD does not significantly reduce NOx emissions from diesel engines equipped with selective catalytic reduction (SCR), nor PM emissions from diesel engines equipped with DPF technology.

However, most off-road diesel HDVs and equipment are not equipped with SCR and DPF technology, and it will take many years for this transition to occur. Thus, RD use in the off-road sector will likely be its most-important use to improve air quality in California, especially in the South Coast Air Basin (the greater Los Angeles area). CARB's proposed "Low-Emission Diesel" (LED) regulation seeks to direct more than a billion gallons of RD per year specifically to fuel heavy-duty off-road vehicles operating in the SCAB.

This switch from petroleum-derived diesel to RD in off-road HDVs and equipment will provide major GHG reductions from California's transportation sector. Localized NOx and PM reductions in the SCAB will be relatively small, but nonetheless important for improving ambient air quality and reducing street-level exposure to DPM and other air toxics. Gradually (over decades), all in-use diesel engines in the SCAB and throughout California will incorporate advanced emission controls like SCR and DPFs (or, they will be replaced by alternative fuel HDV platforms that achieve near-zero-emission or zero-emissions levels). Thus – based on current knowledge – this will apparently negate any additional significant benefits RD can contribute to NOx and PM reductions in California.

In effect, the San Francisco Bay Area and southern California are serving today as national testbeds for early RD consumption, with the primary focus being on-road HDVs. It appears that, on a trial basis, use of RD is beginning to expand into certain off-road applications (e.g., ferries, harborcraft, and in-State locomotives). This increasing demand is likely to push RD consumption in California well beyond the quarter-billion gallons that are currently being transacted under LCFS-covered transportation applications. In particular, CARB's draft LED regulation seems likely to direct most of the State's RD supply by 2030 away from on-road HDVs, for use in off-road applications operated in the SCAB.

There is sufficient volume of RD being imported into California today (at least 250 million gallons) to meet near-term demand. However, ability to meet longer-term demand is less certain. Over the next decade, RD demand in California is expected to grow by (roughly) an order of magnitude, possibly approaching two billion gallons per year. In preliminary assessments, CARB has identified multiple feasible pathways that can technically and economically meet such demand. CARB estimates that 2.6 billion gallons of RD supply for California will be possible by 2030. Notably, these types of estimates by CARB are intentionally designed to provide reasonable scenarios, but they are not meant to make hard projections.

California's Low Carbon Fuel Standard, and a similar program in Oregon, provide strong incentive for the production and use of low-carbon transportation fuels like RD. However, outside these markets, it can be very hard to obtain RD. National demand for RD appears to already be exceeding supply, especially in the eastern U.S. where some major HDV fleets like United Parcel Services and the New York City Department of Sanitation have not been able to purchase enough RD. When it is obtainable in such places, RD can cost much more than petroleum diesel, especially when purchased in small volumes. This can make RD unaffordable to HDV fleets as a GHG-reduction strategy. The challenges that make the RD-supply picture uncertain for California as well as nationwide include 1) the relatively small capacity of current production in the U.S. (particularly within California); 2) competing uses for RD's major feedstocks, and 3) concerns about non-sustainable and/or environmentally harmful feedstocks such as palm oil.

Given these current and future dynamics, there appears to be an important need for local air districts in both Southern and Northern California to better understand RD's impacts on NOx and PM emissions from a wide diversity of on- and off-road heavy-duty diesel engines and applications. This can help inform strategies involving RD's potential role in new regulatory efforts (e.g., indirect source regulations, facility cap requirements, incentives, etc.). From a statewide perspective, it also seems important to conduct further study about the dynamics of RD supply and demand in California (e.g., competing uses for feedstocks, where the supply will most be needed, etc.).

Specific recommendations of this White Paper include (but are not limited to) the following:

Conduct trials of RD in high-horsepower off-road applications and select on-road applications

- Air districts should consider funding trials of RD in high-horsepower off-road applications such as marine vessels and locomotives. In particular, the South Coast Air Quality Management District (SCAQMD) could work with railroads and other local stakeholders (e.g., the San Pedro Bay Ports) to conduct such a trial on one or more locomotives. The Bay Area Air Quality Management District (BAAQMD) and the City of San Francisco could work with ferry operators serving the San Francisco Bay to test RD in one or more ferry vessels. (This process has recently been initiated.)
- The BAAQMD and CARB may want to work with stakeholders associated with the Port of Oakland drayage truck fleet (e.g., licensed motor carriers, port authorities) to sponsor a controlled test on the use of RD in the fleet, specifically to determine if switching drayage trucks to run on RD can help improve DPF performance and durability.

Conduct further emissions studies on how RD impacts HDVs with state-of-the-art emissions controls

- CARB should continue working with air districts, academic institutions, the heavy-duty engine industry, and possibly RD producers / suppliers to conduct focused emissions testing programs designed to better characterize the impacts of RD on heavy-duty diesel engines with advanced emissions controls.

Conduct a focused assessment in California of RD supply and demand

- CARB and the California Energy Commission should take the lead to further study the potential future supply and demand dynamics for RD as a major transportation fuel in California.

# 1. Background / Introduction to Renewable Diesel

## 1.1. California's Dependence on Conventional Diesel Fuel

California's heavy-duty on- and off-road mobile source sectors annually consume approximately 3.6 billion gallons of diesel fuel (see Figure 1). This level of consumption is expected to remain relatively constant over the next 15 years.[1] California is making solid progress to decrease use of "fossil" diesel fuel by displacing it with non-petroleum alternatives. Alternative fuels used in California currently include biomass-based diesel (BBD) fuels (biodiesel and renewable diesel), natural gas (both fossil and renewable[2]), propane, electricity and hydrogen. However, more than 90 percent of diesel fuel sold today in California is still produced from fossil crude oil.

This dominance by fossil petroleum fuel in America's transportation sector—particularly its near-total use by very-high-fuel-use "heavy-heavy-duty" trucks—has major adverse economic and environmental consequences. In California, expeditious, wide-scale displacement of fossil diesel with alternatives that

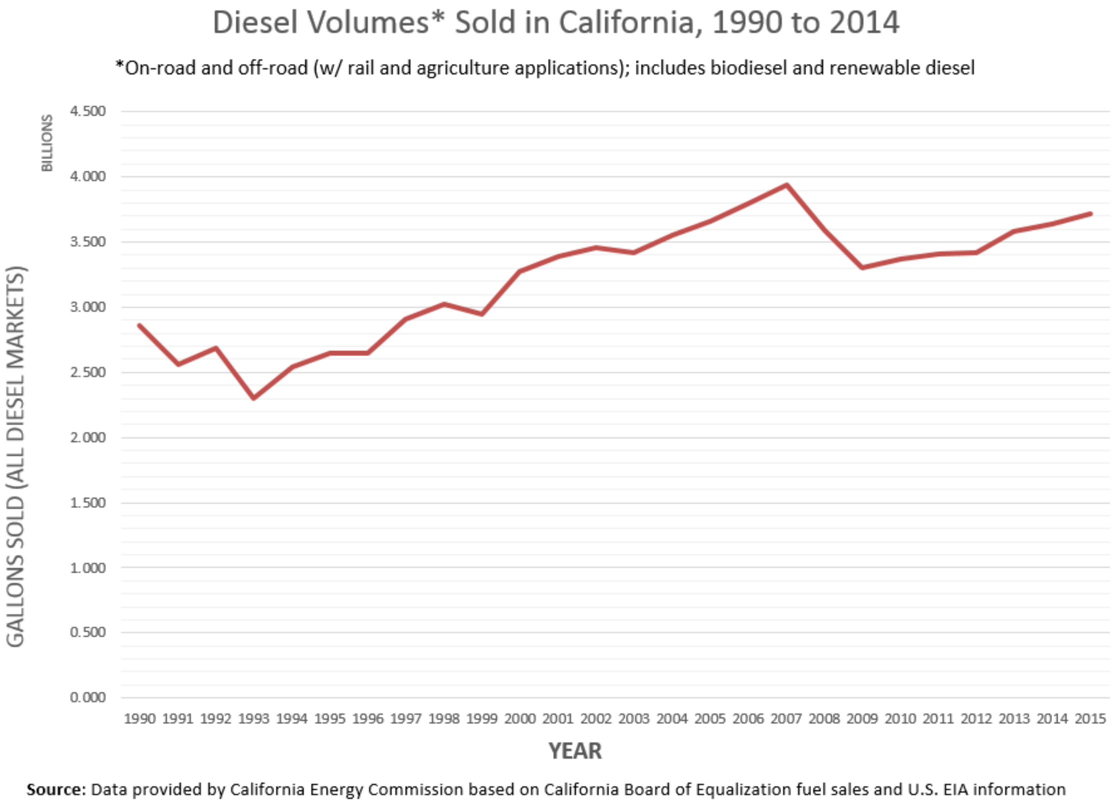

Figure 1. Volume of diesel fuel sold in California, 1990 to 2015

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[1] California Energy Commission, "California Fuels Used in Transportation Energy Assessment Division," spreadsheet provided to GNA dated January 4, 2017.

[2] Approximately 60 percent of the natural gas used in California today for vehicle applications is renewable natural gas (RNG).

are more environmentally benign is a top priority for the California Air Resources Board (CARB) and the California Energy Commission (CEC), as well as for local air quality regulatory agencies such as the South Coast Air Quality Management District (SCAQMD) and the Bay Area Air Quality Management District (BAAQMD).

## 1.2. General Description and Properties of Renewable Diesel

Renewable diesel (RD)[3] is a broad term that essentially refers to any diesel fuel 1) that is produced from a renewable feedstock, 2) predominantly consists of hydrocarbons (not oxygenates), 3) and meets key requirements established for diesel engine fuels (see below). As further described in this study, RD can be produced through various processes using a wide array of feedstocks. The most prevalent method of producing RD is called "hydrotreating," by which feedstocks such as vegetable oils or animal fats are reacted with hydrogen. This process produces RD, renewable propane and other light hydrocarbons.

Like all transportation fuels in the U.S., RD must meet motor vehicle fuel specifications set by agencies like CARB and the U.S. Environmental Protection Agency (EPA). Specifically, RD meets the same standards and specifications as conventional diesel for aromatics, sulfur, lubricity, and other key chemical or physical properties encumbered under ASTM[4] International Standard D975-12a.[5] This makes RD a "drop in" replacement fuel for conventional diesel. Consequently, RD can be blended with conventional diesel in any amount and used with existing infrastructure and diesel engines. This has officially been corroborated in a 2013 joint statement by CARB and the (California) State Water Control Board, which declared that RD *"should be treated no differently"* than conventional diesel that is legally sold in California.[6] Federal agencies like EPA and the U.S. Department of Energy (DOE) have also approved RD as a replacement for conventional diesel, noting that "consumers who purchase renewable diesel are unlikely to notice any difference between renewable

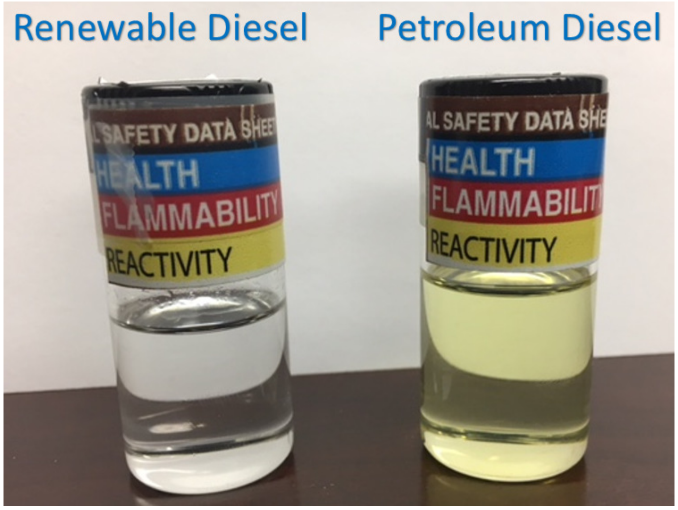

Figure 2. Clarity of RD compared to petroleum diesel (photo from AltAir Fuels)

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[3] RD is also sometimes called "renewable hydrocarbon diesel," "green diesel," HEFA (hydrogenated esters and fatty acids) diesel, and "hydrogenation derived renewable diesel (HDRD).

[4] ASTM, formerly the American Society for Testing and Materials, develops international standards for materials, products, systems, and services used in construction, manufacturing, and transportation.

[5] California Environmental Protection Agency, "Staff Report: Multimedia Evaluation of Renewable Diesel," prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf.

[6] California Air Resources Board and State Water Resources Control Board, "Renewable Diesel Should Be Treated the Same as Conventional Diesel," joint letter to various industry "stakeholders," July 31, 2013.

diesel and petroleum-derived diesel fuel."[7]

Table 1 summarizes key fuel properties of RD compared to petroleum-based diesel (in this case, California ultra-low sulfur diesel, or ULSD). As the table shows, RD has excellent general properties for use as a substitute diesel fuel. This includes a very high cetane number (typically above 70, and as high as 90), very low sulfur content, almost no aromatics, and a very low cloud point compared to ULSD. A slight downside is that RD has a volumetric energy content that is about 3 to 4 percent lower than ULSD. This means that a given volume of RD holds less energy than the same volume of ULSD, resulting in proportionally lower fuel economy and a reduced driving range for an HDV using RD instead of ULSD with RD (all else being equal). On the other hand, RD has a carbon-specific energy density (more energy per pound of fuel-borne carbon), which results in lower tailpipe $CO_2$ emissions (see Section 6).

## 1.3. Carbon Intensity and GHG-Reduction Potential

RD's primary environmental benefit is that it provides a cost-effective, compelling GHG-reduction strategy for ubiquitous diesel engines, which are worldwide workhorses for transporting both goods and people. CARB has noted that "sustainably sourced" RD pathways can achieve GHG reductions of 30 to 60 percent relative to conventional (petroleum-derived) diesel. CARB measures the GHG-reduction potential of all transportation fuels by their "carbon intensity" value in grams of carbon dioxide equivalent per mega

Table 1. Comparison of key properties for CARB diesel and RD

| **Key Fuel Property** | **Typical Fuel Property Measurements** | |
|---|---|---|
| | **CARB Diesel** | **Renewable Diesel** |
| Flash Point, oC | 148 | 146 |
| Typical Cetane Number[a] | 55.8 | 72.3 |
| Total Aromatic Content[b] (%) | 18.7 to 19.9 | 0.4 to 0.9 |
| Polycyclic Aromatic Hydrocarbon (PAH) Content[b] | 1.5 | 0.01 |
| Volumetric Energy Contentc (Btu/gallon) | 128,662 | 124,276 |
| Sulfur content (ppm) | 3.8 to 4.7 | 0.3 to 1.5 |
| Carbon (wt %) | 86.05 | 85.13 |
| Cloud Point[d] (oC) | -6.6 | -27.1 |

**Source:** UC-Riverside College of Engineering, Center for Environmental Research and Testing, including citations by CARB and State Water Board (https://www.arb.ca.gov/fuels/lcfs/20130731arbwaterboardjointstatementrd.pdf)

[a] Cetane number measures how quickly a fuel auto-ignites inside a compression ignition (diesel) engine. The RD cetane number is the average of three different Neste NExBTL batches.

[b] A high aromatics content contributes significantly to formation of unhealthful emissions, and lowers fuel quality. PAH compounds occur naturally in crude oil and are released when burned. Health effects are not fully defined.

[c] Volumetric energy content (heating value): measures heat released when a known quantity of fuel is burned under specific conditions. A lower energy content for a given volume of fuel will reduce a vehicle's driving range (all else being equal). This value for RD may vary from batch to batch.

[d] Cloud point: Measures low-temperature operability. A fuel with a lower cloud point will operate better in low temperatures (below freezing).

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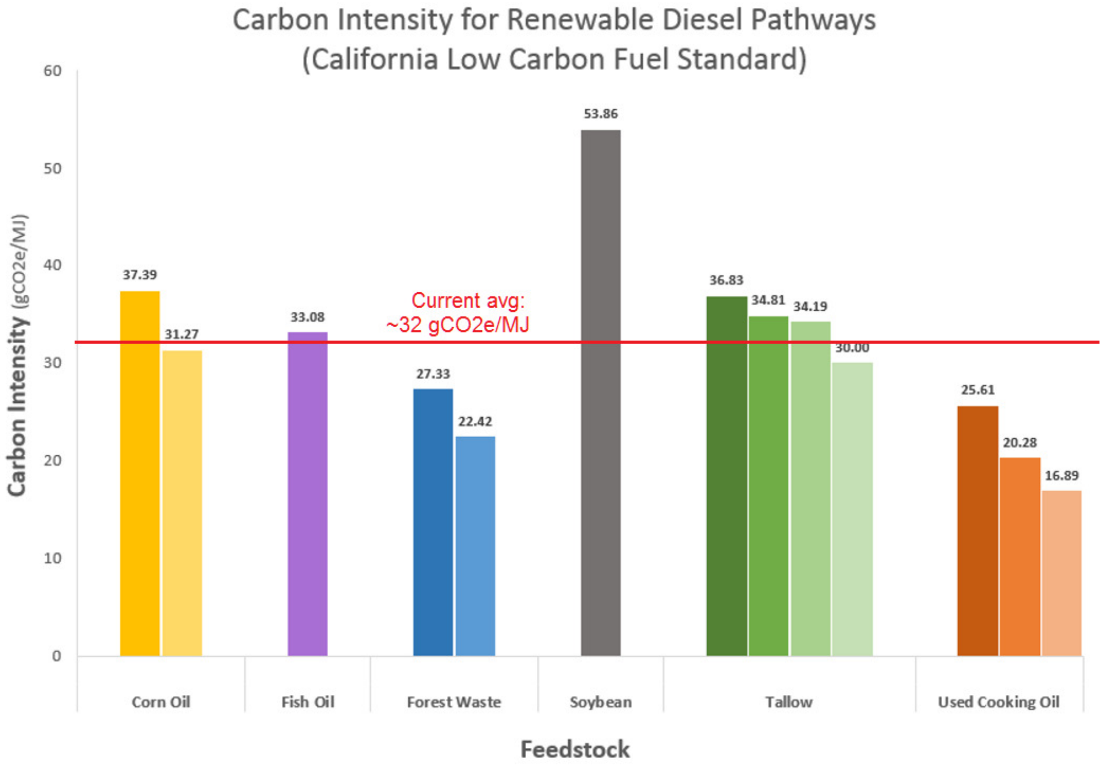
[7] U.S. Environmental Protection Agency, Renewable Fuel Standard Program: Standards for 2017 and Biomass-Based Diesel Volume for 2018," https://www.noticeandcomment.com/Renewable-Fuel-Standard-Program-Standards-for-2017-and-Biomass-Based-Diesel-Volume-for-2018-fn-386796.aspx.

Joule (gCO2e/MJ). The baseline fuel to compare heavy-duty vehicle (HDV) fuels is California ULSD, which currently has a CI value of 102.01 gCO2e/MJ.

In fact, RD can provide GHG reductions beyond 30 to 60 percent when used as a substitute for ULSD to power heavy-duty vehicles and equipment. Under California's landmark Low Carbon Fuel Standard (LCFS), at least 13 different low-CI RD-production pathways have been certified using six different feedstock types (corn oil, fish oil, forest waste, soybean oil, tallow, and used cooking oil). While many fuel-cycle factors contribute to a given fuel's CI value, feedstock plays the most prominent role.[8] As shown in Figure 3, the CI values for these RD pathways range from 53.86 gCO2e/MJ for the "soybean" pathway (a CI reduction of 47 percent), to 16.89 gCO2e/MJ for one of the three "used cooking oil" (UCO) pathways (an 83 percent CI reduction). The current average CI value for RD generating credits in the LCFS is approximately 32 gCO2e/MJ, although the volume-weighted average CI is 36 gCO2e/MJ. This is consistent with the fact that most of the RD being used in California currently is made from tallow feedstock (CI values that range from 36.83 to 30.00 gCO2e/MJ, as shown in the figure).



**Source:** CARB List of Certified LCFS pathways, 3/20/17

Figure 3. Carbon intensity ratings for RD production pathways under California LCFS

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[8] The type of feedstock for a given type of transportation fuel largely dictates the full suite of processes and procedures used to produce, extract, process and transport the fuel for final end use. For example, RD and other current-generation biofuels are typically derived from farmed crops or livestock, which can entail a series of complex direct and indirect land uses (e.g., how a crop was grown, the fertilizers uses, what alternative land use was avoided, etc.). Land use factors can make very significant contributions to the fuel's total carbon intensity value, which is derived using a comprehensive life-cycle analysis model such as Argonne National Laboratory's GREET (see https://greet.es.anl.gov/).

## 1.4. Combustion Characteristics and General Effect on Emissions of Harmful Air Pollutants

In addition to strong GHG-reduction benefits, substitution of RD for petroleum diesel can provide important improvements in ambient air quality. RD's properties such as its high cetane number, lack of aromatic hydrocarbons and very low sulfur content generally help reduce diesel engine exhaust emissions of criteria pollutants and toxic air contaminants. Specifically, RD can reduce oxides of nitrogen ($NO_x$) emissions, which are the key precursor to forming tropospheric ozone (photochemical smog). $NO_x$ emissions also react in the atmosphere to cause formation of harmful secondary organic aerosols (SOA) and fine particulate matter ($PM_{2.5}$). RD's benefits are not just NOx related. It burns with less soot than fossil diesel (see Figure 4) which helps to significantly reduce cancer-causing diesel particulate matter (DPM) emitted at the tailpipe of heavy-duty diesel vehicles and engines.

Graphic no longer available.

Figure 4. Clean-burning property of RD (left, produced by Neste)

In California's most-severely polluted airsheds (e.g. the South Coast Air Basin and San Joaquin Valley Air Basin), emissions from diesel engines must be drastically and rapidly reduced to meet National Ambient Air Quality Standards (NAAQS) for ozone[9] and $PM_{2.5}$. As a drop-in replacement for petroleum fuel, RD can help reduce formation of ozone and $PM_{2.5}$ in the atmosphere, while also helping reduce people's street-level exposure to carcinogenic DPM. However, there are significant caveats and limitations on the extent to which RD can do this.

Some producers, distributors and end users of RD have made specific claims about how much RD can reduce NOx and DPM. Often, they fail to differentiate between RD's use in older HDVs (without modern emission controls), versus its use in newer vehicles equipped with state-of-the-art emissions controls. As this paper discusses further, the actual effects of RD on emissions from heavy-duty diesel engines is a complex topic. Emissions benefits (where applicable) tend to be dependent on the specific application, technology and pollutant type. Section 6 provides a detailed discussion about what is currently known, unknown, or poorly documented regarding the exhaust emission implications of substituting RD for petroleum diesel in heavy-duty vehicles and engines.

It is very important to emphasize that <u>RD is not biodiesel</u>. While these two fuels are made from the same renewable feedstocks – and both are considered to be "biomass-based diesel" (BBD) fuels – RD and biodiesel have very different production pathways, which strongly impact end-use characteristics and

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[9] Ozone is not directly emitted by motor vehicles; it is formed when NOx and volatile organic compounds (VOCs) react in the presence of sunlight.

emissions of criteria pollutants (especially NOx). A key difference is that RD has been found to decrease NOx relative to conventional diesel, while biodiesel can have the opposite effect on NOx emissions.[10] The major differences between RD and biodiesel are further discussed below and in Section 2.2.

## 1.5. Materials Compatibility, Labeling Requirements and Other End User Issues

RD is considered a "drop-in" substitute for petroleum-based diesel because it can be used at any blend level (i.e., up to 100 percent RD), without causing detrimental material effects to engines that use it, or the fueling infrastructure used to store and dispense it. In 2013, CARB joined with the (California) State Water Resources Control Board to make it clear for potential end users that RD it is indeed a "drop-in replacement" for diesel:

> *Despite renewable diesel being comparable to conventional CARB diesel, there have been questions regarding the ability of marketers and others to store renewable diesel in USTs [underground storage tanks]. Further, questions have been raised about the compatibility of renewable diesel with leak detection systems used in USTs currently storing conventional CARB diesel. We consider renewable diesel to be a "drop in" fuel that can be blended with conventional CARB diesel in any amount and used with existing infrastructure and diesel engines. Accordingly, renewable diesel that meets the requirements for conventional CARB diesel and ASTM D975-12a should be treated no differently than conventional CARB diesel that is legal for sale in California.*[11]

Some engine/fuel experts have expressed modest concern that RD's lack of aromatics may be problematic for heavy-duty engines, from a materials compatibility and/or lubricity perspective. However, they note that more data are needed. Also, some have noted that selling or using RD can entail potentially confusing pump labeling requirements. For example, unlike neat RD (typically RD98 or RD99), mid-level RD blends may require special labeling, despite the above decree that the two fuels are essentially identical for blending purposes. However, issues like these do not appear to be a significant impediment to RD's wider use.[12]

## 1.6. Acceptance by Heavy-Duty Vehicle and Engine Manufacturers

As described, key government agencies (e.g., CARB, EPA, and DOE) deem RD (even at 100 percent) to be a drop-in, market-ready replacement for petroleum-based diesel. Partly, this is because major original equipment manufacturers (OEMs) of heavy-duty engines and trucks generally approve use of pure RD in their products as an alternative diesel fuel. According to leading RD producer Neste Corporation, at least

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[10] California Air Resources Board, Proposed Strategy for Achieving California's 2030 Greenhouse Gas Target: Appendix F Draft Environmental Impact Assessment," January 17, 2017, https://www.arb.ca.gov/cc/scopingplan/app_f_draft_environmental_analysis.pdf.

[11] California Air Resources Board and State Water Resources Control Board, "Renewable Diesel Should Be Treated the Same as Conventional Diesel," joint letter to various industry "stakeholders," July 31, 2013.

[12] National Renewable Energy Laboratory, "Renewable Diesel Fuel," Robert McCormick and Teresa Alleman, July 18, 2016, https://cleancities.energy.gov/files/u/news_events/document/document_url/182/McCormick___Alleman_RD_Overview_2016_07_18.pdf.

11 HDV and engine OEMs worldwide have "specifically approved/endorsed" the use of RD (up to 100 percent) in their products.[13]

Volvo Trucks North America appears to have been the first heavy-duty engine OEM in the U.S. to officially embrace use of RD as a substitute fuel for its diesel engines. After conducting truck and engine testing on RD, in 2015 Volvo announced that its customers can substitute RD for petroleum diesel in all Volvo diesel engines, with "no risk" of losing warranty coverages. Soon after, Mack Trucks (owned by Volvo) made a similar announcement. Based on "extensive truck and engine testing," Mack concluded that RD delivers similar performance to conventional diesel, while providing customers with reduced emissions of both GHGs and particulate matter (NOx benefits were not addressed). The Mack press release noted that RD will also help fleets reduce their maintenance costs.[14] This is a reference to growing reports by end users that they experience less-frequent (or zero) need to implement costly "forced" regeneration events on DPFs equipped on their HDVs, when operating on RD (see Section 6.3).

Volvo and Mack collectively sell about 20 percent of the on-road heavy-duty engines sold in North America. The largest market share in this space is held by Cummins Inc.; which sells about 37 percent. Cummins was the last major engine OEM to formally approve RD to power its engines sold in the U.S., although (so far) this approval applies only to "select engines" used in medium-duty applications. Specifically, in mid-2017 Cummins announced that it has officially approved its B6.7 and L9 engine platforms (both on- and off-highway versions) to use "paraffinic diesel fuels" (RD) in North America. Cummins cited RD's potential to reduce GHG emissions "by 40 percent to 90 percent over the total life cycle of the vehicle" when compared with conventional fossil-based diesel. [15]

Prior to this long-anticipated announcement, Cummins conducted an 18-month field trial on HDVs running on RD100. The objective was to better understand potential changes in engine performance, aftertreatment effects and fuel system durability. Based on that test program, Cummins reported the following (emphasis added):

- Engine performance remained stable and consistent while using RD. Cummins' customers "should not expect to see any differences" when using it instead of petroleum diesel, except they may experience a "fuel economy detriment of 0 percent to 6 percent" when using neat RD, depending on the specific application and engine duty cycle.
- Advanced emissions control systems (diesel oxidation catalyst, diesel particulate filter, selective catalytic reduction) equipped on the 2010-emissions-compliant diesel engines Cummins tested "remained stable" and provided similar performance as when operated on petroleum diesel fuel. [16]

This U.S. announcement did not directly discuss how RD impacts criteria pollutant emissions. In a similar European announcement (2016), Cummins indicated that NOx and PM emissions "are no higher" when

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[13] Jeremy Baines, Vice President Sales, Neste US, Inc., presentation to 2017 ACT Expo, May 2017.

[14] Mack, "Mack Trucks Green-Lights Renewable Diesel Fuel for Use in Mack Engines, press release, January 7, 2016, https://www.macktrucks.com/community/mack-news/2016/mack-trucks-green-lights-renewable-diesel-fuel/.

[15] Cummins Inc., "Cummins Announces Compatibility with Select Renewable Diesel Fuels for B6.7 and L9 Engines," Press release, May 31, 2017, https://cumminsengines.com/cummins-announces-compatibility-with-select-r.

[16] Ibid.

using RD.[17] One Cummins engineer in the U.S. told the authors that RD can lead to very significant PM emissions reductions for vehicles and equipment powered by diesel engines that are not equipped with diesel particulate filters.

The Engine Manufacturers Association (EMA), which represents worldwide manufacturers of both heavy-duty engines and on-road HDVs, has taken a "cautiously optimistic" approach on RD. EMA cites positive attributes of RD and its petroleum-like properties, noting that "certain engine manufacturers" approve its use, provided that it meets ASTM D975 and other appropriate standards. EMA also notes that some heavy-duty OEMS have concerns that neat RD or high-RD blends "may cause engine malfunctions." EMA notes that its member companies continue to evaluate RD "to determine potential concerns and consider additional standard recommendations."[18] However, now that Cummins has announced its approval of RD for use in its own North American medium-duty engines, it seems likely that EMA will also formally endorse RD use as a drop-in replacement for petroleum diesel.

The next section discusses the many types of feedstock that can be used to produce RD, and how these same feedstock can also be used to produce biodiesel. EMA makes an important point – from the engine manufacturers' point of view – about feedstock choice (<u>emphasis added</u>):

> *Engine manufacturers must evaluate an engine's capability to perform using biodiesel or (RD) fuels. To date, they have not expressed a preference regarding the feedstock used to produce (either biodiesel or RD). The <u>critical performance factors of any diesel fuel</u> — petroleum-based or biomass-based — <u>are derived from the end product and not from the source or characteristics of the feedstock</u>.*[19]

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[17] Cummins Inc., "Cummins Announces Euro 6 Engine Compatibility with HVO Renewable Diesel and Other Paraffinic Fuels," Press release, September 21, 2016, https://cumminsengines.com/euro-6-compatibility-with-hvo.

[18] Engine Manufacturers Association, "Facts You Should Know About Biomass-Based Diesel Fuels," October 2015, http://www.truckandenginemanufacturers.org/file.asp?F=Facts+You+Should+Know+About+Biomass-Based+Diesel+Fuels%2Epdf&N=Facts+You+Should+Know+About+Biomass-Based+Diesel+Fuels%2Epdf&C=documents.

[19] Ibid.

## 2. Feedstock, Production and Cost / Price

### 2.1. Feedstock Types

RD can be produced from a wide variety of non-petroleum renewable resources. These include animal fats and wastes, vegetable oils, municipal solid waste, plant and algae oils, sludge and oils derived from wastewater, and other wastes. Figure 5 shows 10 different renewable feedstock to make RD, cited by Neste in its world-leading RD-production capabilities.

(Note: original Figure replaced with the following list.)

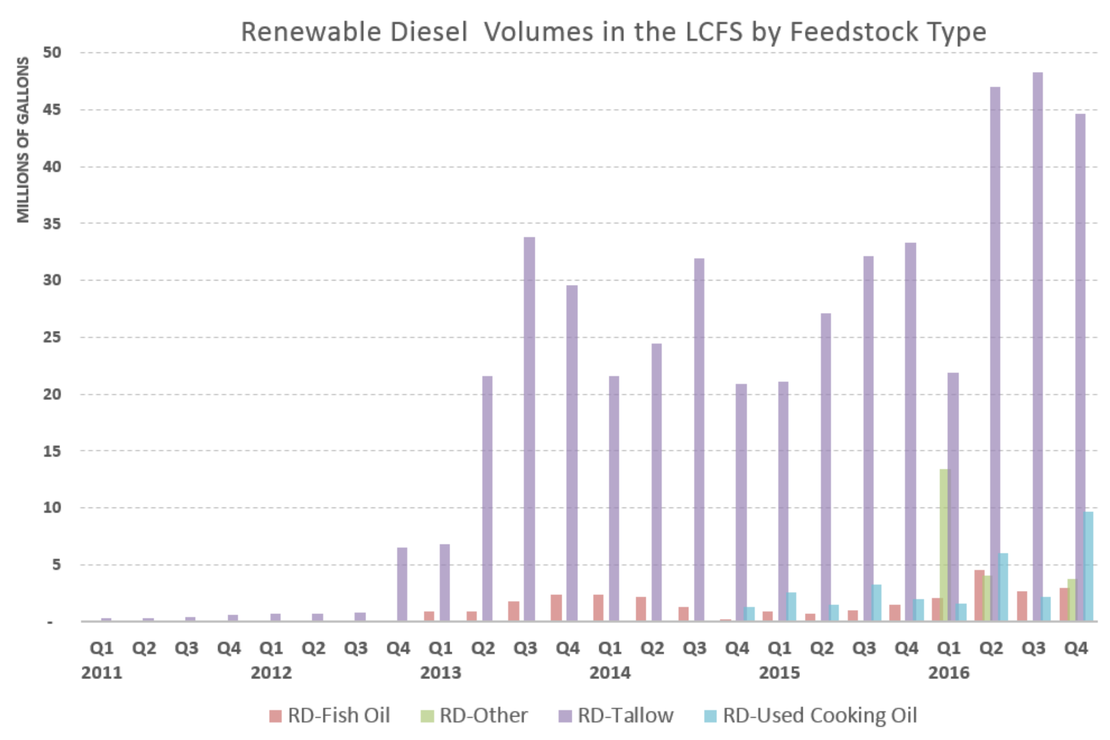
Possible Feedstock Sources* for RD or Biodiesel Include:

- Animal fat from food industry waste
- Fish fat from fish processing waste
- Vegetable oil processing waste and residues
- Used cooking oil
- Technical corn oil
- Crude palm oil
- Rapeseed oil
- Soybean oil
- Camelina oil
- Jatropha oil

*Note: not all feedstocks and pathways are environmentally sustainable; see text for details.

Figure 5. Broad range of renewable raw materials Neste uses to produce RD

RD pathways that generate credits under California's LCFS are predominately produced from tallow, used cooking oil, and fish oil (see Figure 6). Unspecified "other" feedstocks collectively make up 10 percent. Currently, none of the "other" feedstocks used to make RD for California are believed to be palm oil, which is a controversial pathway to produce RD (or other biofuels). The issue of palm oil as a potentially non-sustainable, controversial RD feedstock is further discussed in Section 8.2.



**Source:** California Air Resources Board, "LCFS Quarterly Data, April 9, 2017, https://www.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm.

Figure 6 Major feedstocks used for RD generating California LCFS credits

As the graph shows, tallow (from beef or sheep processing) is currently the leading feedstock used to make RD for use in California transportation markets. Animal tallow is a triglyceride material recovered by a rendering process. The animal residues are cooked, and the fat is recovered as it rises to the surface. Since animal tallow is a waste by-product, it is an inexpensive RD feedstock that is widely available in the U.S. It can be harvested sustainably, as long as robust markets exist for meat and other animal products. CARB has indicated that soybean oil may be one of the main feedstocks of the future for California's RD supply.[20] Figure 7 compares the "look" of these two

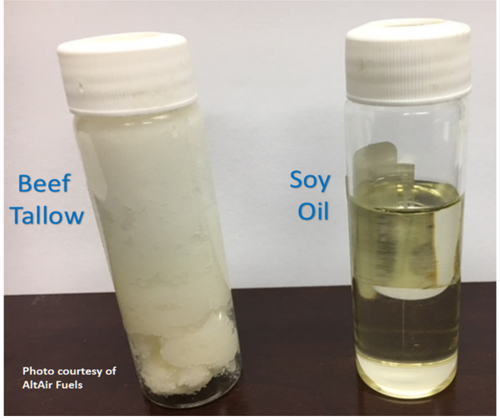


Photo courtesy of AltAir Fuels

Figure 7. Current and potential feedstock for California RD

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[20] Notably, as was demonstrated in Figure 3, soybean-derived RD has one of the highest CI values under the California LCFS. Thus, it's unclear why it would be economical to pursue this pathway, unless producing RD from soybeans is a significantly less-expensive process than other pathways with much lower CI values (e.g., beef tallow).

current and potential future feedstocks for RD in California.

It's important to note that many of the same feedstocks for RD are also used to produce biodiesel (see Figure 8). However, the processing methods for RD and biodiesel are very different. Consequently, these two fuels differ markedly in their physical and chemical characteristics, resulting in important implications about their end use as transportation fuels (see next section).

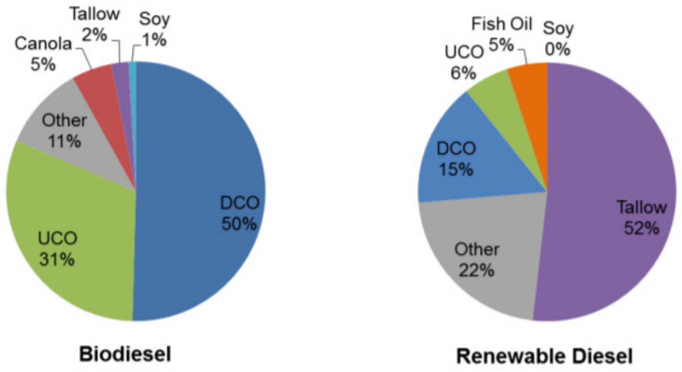

Figure 8. Biodiesel and RD feedstock for LCFS pathways

## 2.2. RD Production Processes and Difference from Biodiesel

Various biomass-to-liquid processes can be used to produce RD; these are very distinct from the process to make biodiesel. Currently, hydrotreatment (see Figure 9) is the most common method to produce RD. This process reacts animal fat or vegetable oil (triglycerides) with hydrogen[21] to remove oxygen and other elements, and to split the triglyceride molecules in three separate chains. The resulting fuel is substantially similar to fossil diesel, but it consists of pure hydrocarbons and paraffinic compounds, with very low aromatics and no sulfur. By comparison, biodiesel is produced through a process called transesterification, in which methanol (or ethanol) and catalysts are combined with the oil / fat feedstock to produce methyl esters and glycerol. It is the fatty acid methyl esters (FAME) that are used as the biofuel commonly called biodiesel.

Even though RD and biodiesel are produced from essentially the same feedstocks, these very different production processes result in two distinctly dissimilar biomass-based diesel fuels. A number of these differences make RD a superior HDV fuel, compared to both biodiesel and fossil diesel. Most importantly from an air quality perspective, RD offers a superior criteria pollutant emissions profile compared to biodiesel (and petroleum-based diesel). Specifically, as further described below and in Section 7, RD can reduce NOx emissions, which react with volatile organic compounds to produce harmful photochemical "smog" (ozone). Also, because RD is produced through hydrotreatment, it does not contain oxygen like

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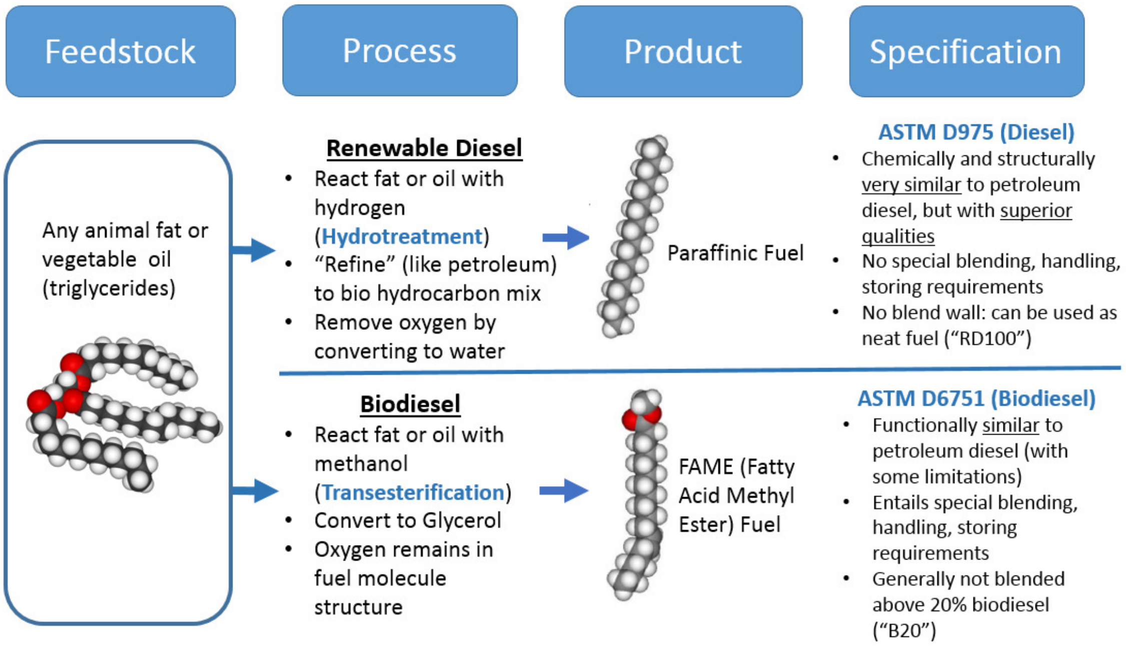
[21] It's worth noting that hydrotreatment -- the most-prevalent method to produce RD -- requires use of hydrogen. The CI value for the production pathway of that hydrogen (e.g., steam methane reformation of fossil natural gas versus a "renewable" hydrogen pathway like solar electrolysis) will impact the CI value of the RD that is produced.

biodiesel. This results in a lower cloud point for RD, which means that RD (unlike biodiesel) does not readily form waxy crystals in colder climates that impede fuel flow.[22]

From the end users perspective, perhaps the most important advantage of RD relative to biodiesel is that is has no "blend wall"; it can be used in high-level blends (including 100 percent, or RD100) in existing heavy-duty diesel engines without modification. By comparison, heavy-duty engine manufacturers limit the blend percentage of biodiesel that can be used in their engines. Most heavy-duty engine OEMs sanction biodiesel blends up to B20; this was enabled by adoption of ASTM standard D7467.[23] Typically, OEMs impose restrictions on any biodiesel blend greater than B20. If it can be demonstrated that use of a higher-level biodiesel blend causes engine damage, an OEM may void the harmed engine's warranty.

Importantly, EPA has noted that these types of "constraints" related to the distribution and use of biodiesel may lead to increased demand for RD, "which faces fewer potential constraints related to distribution and use than biodiesel."[24] (See the call-out box for additional EPA comments.)



Feedstock | Process | Product | Specification

Any animal fat or vegetable oil (triglycerides)

**Renewable Diesel**
- React fat or oil with hydrogen (**Hydrotreatment**)
- "Refine" (like petroleum) to bio hydrocarbon mix
- Remove oxygen by converting to water

Paraffinic Fuel

**ASTM D975 (Diesel)**
- Chemically and structurally very similar to petroleum diesel, but with superior qualities
- No special blending, handling, storing requirements
- No blend wall: can be used as neat fuel ("RD100")

**Biodiesel**
- React fat or oil with methanol (**Transesterification**)
- Convert to Glycerol
- Oxygen remains in fuel molecule structure

FAME (Fatty Acid Methyl Ester) Fuel

**ASTM D6751 (Biodiesel)**
- Functionally similar to petroleum diesel (with some limitations)
- Entails special blending, handling, storing requirements
- Generally not blended above 20% biodiesel ("B20")

**Source:** recreated / adapted from Renewable Energy Group, "Biomass-Based Diesel Comparison," 2017.

Figure 9. Key similarities and differences between production of RD and biodiesel

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[22] California Environmental Protection Agency, "Staff Report: Multimedia Evaluation of Renewable Diesel," prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf.

[23] DieselNet.com, "Compatibility of Biodiesel with Petroleum Diesel Engines," accessed online at https://www.dieselnet.com/tech/fuel_biodiesel_comp.php.

[24] U.S. EPA, "Renewable Fuel Standard Program: Standards for 2017 and Biomass-Based Diesel Volume for 2018," Federal Register Vol. 81, No. 238, December 12, 2016.

> *While biodiesel and renewable diesel are both diesel fuel replacements produced from the same types of feedstocks, there are significant differences in their fuel properties that result in differences in the way the two fuels are distributed and consumed. Renewable diesel is a pure hydrocarbon fuel that is nearly indistinguishable from petroleum-based diesel. As a result, it can generally use the existing distribution infrastructure for petroleum diesel and there are no significant constraints on its growth with respect to distribution capacity. Biodiesel, in contrast, is an oxygenated fuel rather than a pure hydrocarbon. It historically has not been distributed through most pipelines due to contamination concerns with jet fuel, and may require specialized storage facilities, additives, or blending with petroleum diesel to prevent the fuel from gelling in cold temperatures.*
>
> -**U.S. EPA,** https://www.gpo.gov/fdsys/pkg/FR-2016-12-12/pdf/2016-28879.pdf

## 2.3. Major Producers, Distributers and Brand Names

Various companies have trademarked names for the RD they produce or sell; some of these are summarized in Table 2. Neste (formerly Neste Oil) is the world's largest RD producer. As previously described, Neste's "NExBTL" process is capable of using 10 different feedstock to make RD.

Table 2. Examples of trademarked / registered names used for RD

| **Company (Role)** | **Name Used for RD** |
|---|---|
| Honeywell UOP (Production Process) | Green Diesel™ |
| Neste (Producer) | NExBTL® |
| Solazyme (Producer) | SoladieselRD® |
| Amyris (Producer) | Biofene® |
| Propel (Distributor) | HPR Diesel |
| Renewable Energy Group (Producer) | REG-9000™ / RHG |

While hydrotreatment of fats, oils and esters is currently the dominant method to produce RD (refer back to Figure 9), there are several other production pathways. These include 1) biomass pyrolysis, 2) catalytic upgrading of sugars, 3) biomass-to-liquid processes (Fischer-Tropsch diesel, and 4) biogas-to-liquid processes. However, most of these other processes are not yet used to produce RD on a commercial scale.[25]

## 2.4. Cost, Price and Cost Effectiveness to Reduce GHG Emissions

RD costs more to produce than conventional petroleum-based diesel. This is generally the case with renewable transportation fuels that are produced on a relatively small scale. The actual incremental cost to produce RD can vary as a function of many factors. These include feedstock type and location, capital and operational costs associated with the production process, and how far the final product must be transported to reach end-use markets. RD producers generally don't publicize their RD-specific costs or

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[25] National Renewable Energy Laboratory, "Renewable Diesel Fuel," Robert McCormick and Teresa Alleman, July 18, 2016, https://cleancities.energy.gov/files/u/news_events/document/document_url/182/McCormick___Alleman_RD_Overview_2016_07_18.pdf.

pricing[26], but a reasonable estimate (based on limited information) is that RD currently costs about 20 to 30 percent more to produce than petroleum diesel.

It appears that the costs to produce RD are dropping. Neste Corporation recently cited a "variable production cost guidance" for 2017, which seems to indicate a recent 15 percent drop in its RD-production costs (from $130 per ton to $110 per ton). Neste expects high utilization rates in 2017 for existing RD-production facilities, and expects by 2020 to increase worldwide production capacity at its existing facilities in Europe and Asia by about 15 percent. Neste is also assessing the feasibility and costs to build new production facilities in Singapore and/or the U.S.[27] Potentially, all these factors can help further reduce Neste's average production costs.

The higher cost to produce this renewable transportation fuel does not reflect RD's very significant societal benefits, especially in older diesel engines. These include improved ambient air quality, reduced toxic air contaminants (e.g., DPM), reduced GHG emissions, enhanced energy security, and other types of benefits. To help account for these market externalities, programs like the California LCFS and the Federal Renewable Fuel Standard (RFS) are essential to offset the higher costs of producing RD, and make it an affordable choice for end users as a substitute for petroleum diesel.

In particular, the LCFS program provides lucrative monetization of RD's benefits when the fuel is consumed in California HDVs. This has made it possible for California fleets to purchase RD at cost parity with -- or even cheaper than -- conventional diesel. For example, at the current LCFS credit price (April 2017) of about $87 per MTCO2e, a transit fleet using RD with a CI score of 30 (gCO2e/MJ) would create LCFS credits worth approximately $8,400 per year for each transit bus, or about $0.79 for each RD gallon consumed. If the price of LCFS credits reaches $120 per MTCO2e (as it did in Q1 2016), a bus using the same RD fuel will generate credits worth about $1.13 per RD gallon.[28]

Alone, this LCFS credit value presents a compelling case for RD producers to make and sell RD in California's multi-billion-dollar diesel market. This is just part of the story. LCFS credits for producing RD (or other low-CI fuels) can be combined with Renewable Identification Number ("RIN") values from the federal RFS, which further improves the economics of producing the fuel. RINs are the currency used for RFS2 compliance. They are generated by renewable fuel producers as market participants in RFS2 along with "obligated parties" (refiners and importers of diesel or gasoline) and other entities. RINs are used for compliance, and then retired.[29] Under this system, RD (from hydrotreatment production pathways) and biodiesel that are derived from certain feedstocks[30] can generate so-called "D4" RINs, which are

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[26] For example, Neste does not discuss cost or price in its 60-page "Neste Renewable Diesel Handbook," published in May 2016, https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel_handbook.pdf.

[27] Neste Corporation, 2016 Financial Statement, https://www.neste.com/na/en/nestes-financial-statements-release-2016.

[28] Based on information in CARB's "Draft Discussion Topics on Costs: Transit Agency Workgroup Meeting, Table 1: Potential Revenue for Transit Buses from Low Carbon Fuel Standard, January 28, 2016, https://www.arb.ca.gov/msprog/bus/wg201601cost.pdf.

[29] For details about RINs and how they are transacted, see EPA's webpage at: https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-numbers-rins-under-renewable-fuel-standard.

[30] These feedstock include soybean oil, oil from annual cover crops, oil from algae grown photosynthetically, biogenic waste oils/fats/greases, non-food grade corn oil, and camelina sativa oil. While RD mostly generates D4 RINs, some RD generates D5 RINs, as a result of being produced through co-processing with petroleum or being produced from the non-cellulosic portions of separated food waste or annual cover crops.

assigned to biomass-based diesel fuels defined to achieve a 50 percent minimum GHG reduction relative to petroleum diesel.

RD producers and their distributors generally claim most (or all) of these LCFS and RFS values. However, to make the market viable for end users, they pass some of this benefit on to HDV fleets. The result is that, in California at least, fleets are able to purchase RD at very affordable prices. Very large RD users (e.g., UPS) are probably able to purchase RD for California use at cost parity with conventional diesel fuel, or possibly cheaper. Even retail RD is being sold in California at near cost parity. For example, as of mid-2017, Propel Fuels is selling its "HPR" brand of RD98 for just a few cents more than petroleum diesel, at more than 30 retail stations in California.[31]

As further described in Section 4.2, the California Department of General Services (DGS) has issued Management Memo #MM 15-07 to establish State agency requirements for the bulk purchase of HDV transportation fuels, including RD. The DGS memo essentially provides information and mechanisms for large public fleets in California to gain access to favorable contracts for procuring RD. However, it's unclear if MM 15-07 and the DGS process helps eligible fleets obtain an additional discount for RD, beyond what private sector fleets pay for RD in bulk (e.g., United Parcel Services; see Section 4.1).

Outside California, some fleets are reportedly paying an affordable incremental amount (roughly 15 cents per gallon) for RD compared to conventional diesel.[32] However, such cases may be restricted to large-volume purchases, and/or involve negotiated agreements between providers and buyers, with sharing of RFS RIN values. Outside these parameters, the price of RD can be much higher than petroleum diesel. For example, the City of Knoxville, Tennessee recently purchased a relatively small batch of Neste's RD (7,500 gallons). The City reports it paid $2.80 per RD gallon (including transportation from Louisiana, about 700 miles). This was *83 percent higher* than the $1.53 per gallon that the City was paying for ULSD.[33]

However, Knoxville's fleet services department achieved significantly lower maintenance costs during its brief RD test, which partially offset the much-higher fuel costs. This highlights a tangible cost-related benefit that RD can provide end users. Modern on-road heavy-duty vehicles are equipped with diesel particulate filters (DPFs), which require frequent "regeneration" events (a process that uses fuel to burn-off trapped carbon that accumulates on the filter). Because RD significantly reduces engine-out emissions of PM, DPFs trap (filter) much less PM over a given operating time. The result – as reported by the City of Knoxville, the City of Oakland and other RD end users – is that HDVs with DPF systems do not require as much maintenance when using RD compared to petroleum diesel, and DPF life may be extended. End user fleets consider this to be a highly attractive attribute.[34] Additional discussion and documentation about this phenomenon are provided in Section 6.3.

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[31] Based on calls to Propel stations, April 2017.

[32] Government Fleet, "What You Need to Know about Renewable Diesel," March 2016, http://www.government-fleet.com/channel/biofuels/article/story/2016/03/what-you-need-to-know-about-renewable-diesel.aspx.

[33] The City of Knoxville Fleet Services, "Renewable Diesel Test, FY 2017," obtained by GNA through Clean Cities Coalition contacts.

[34] Personal communication to GNA from Penske Truck Leasing personnel, June 2017.

Finally, RD offers another very compelling cost-related benefit for end users. Its use requires no significant new capital investments. As noted, RD is a drop-in replacement for conventional diesel with no special fuel handling, infrastructure or training costs.

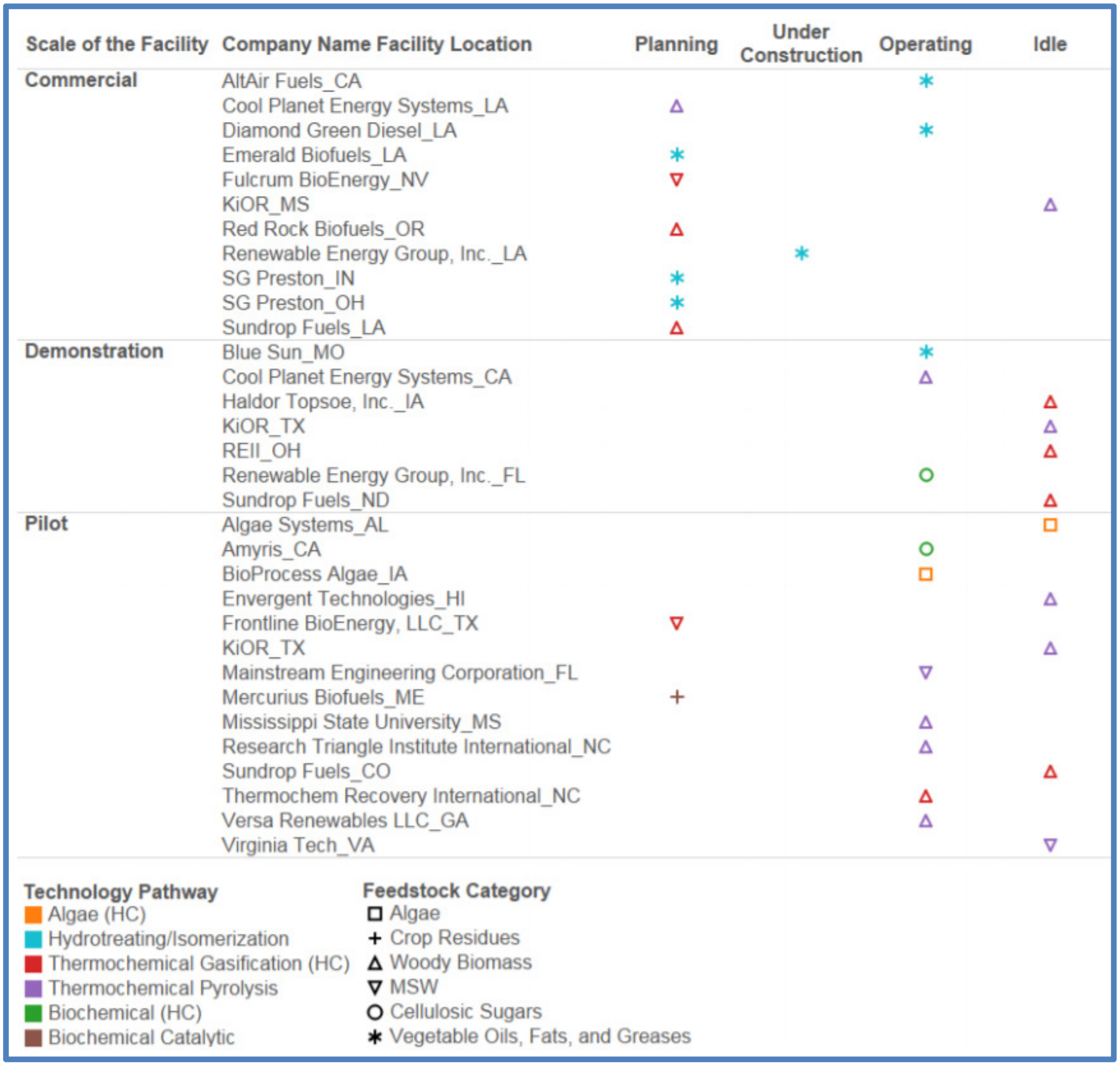
In summary, in California (and certain other parts of the U.S.), RD can provide fleets with an affordable and immediate strategy to achieve major cost-effective GHG reductions from their heavy-duty diesel vehicles and equipment. The affordability is due to availability of combinable monetary credits from California's LCFS and the federal RFS. The GHG reductions that are being achieved today in California average approximately 64 percent (on a volume-weighted basis), relative to using the baseline petroleum diesel (California ULSD). In addition to affordability of the fuel itself through available LCFS and/or RFS values, the economics of switching to RD are made compelling through at least two other attributes: 1) its use does not require significant new capital investments, and 2) it can help reduce fleet operational costs associated with maintaining proper operation of DPF systems.

It's important to note that the cost/price dynamics of using RD could change significantly, depending of the long-term viability of the LCFS and RFS programs. Section 5.2 provides a discussion about the relationship between assumed LCFS credit prices and CARB's projections for the long-term supply of RD. In the long run, the cost and price of RD will be tied to the issue of available feedstock and supply. As noted elsewhere in this report, there are significant challenges and uncertainties about RD supply that must be addressed before RD could fully replace petroleum-derived diesel as the major HDV transportation in the U.S. and/or California.

## 3. Current Production for and Consumption in Transportation Markets

### 3.1. Domestic RD Production for Transportation Use

In 2015, the National Renewable Energy Laboratory (NREL) surveyed existing or potential U.S. producers of "hydrocarbon biofuels" (essentially synonymous with RD). A key objective was to characterize the status of RD production in the U.S., as of December 2015. Survey responses were screened to ensure that respondents genuinely constituted RD producers that were actively "planning, developing, owning, or operating a pilot-, demonstration-, or commercial-scale facility in the United States." NREL obtained and validated data from 32 RD facilities using six different production pathways and six distinct feedstock types (see Figure 10).



| Scale of the Facility | Company Name Facility Location | Planning | Under Construction | Operating | Idle |
|---|---|---|---|---|---|
| **Commercial** | AltAir Fuels_CA | | | ✱ | |
| | Cool Planet Energy Systems_LA | △ | | | |
| | Diamond Green Diesel_LA | | | ✱ | |
| | Emerald Biofuels_LA | ✱ | | | |
| | Fulcrum BioEnergy_NV | ▽ | | | |
| | KiOR_MS | | | | △ |
| | Red Rock Biofuels_OR | △ | | | |
| | Renewable Energy Group, Inc._LA | | ✱ | | |
| | SG Preston_IN | ✱ | | | |
| | SG Preston_OH | ✱ | | | |
| | Sundrop Fuels_LA | △ | | | |
| **Demonstration** | Blue Sun_MO | | | ✱ | |
| | Cool Planet Energy Systems_CA | | | △ | |
| | Haldor Topsoe, Inc._IA | | | | △ |
| | KiOR_TX | | | | △ |
| | REII_OH | | | | △ |
| | Renewable Energy Group, Inc._FL | | | ○ | |
| | Sundrop Fuels_ND | | | | △ |
| **Pilot** | Algae Systems_AL | | | | □ |
| | Amyris_CA | | | ○ | |
| | BioProcess Algae_IA | | | □ | |
| | Envergent Technologies_HI | | | | △ |
| | Frontline BioEnergy, LLC_TX | ▽ | | | |
| | KiOR_TX | | | | △ |
| | Mainstream Engineering Corporation_FL | | | ▽ | |
| | Mercurius Biofuels_ME | + | | | |
| | Mississippi State University_MS | | | △ | |
| | Research Triangle Institute International_NC | | | △ | |
| | Sundrop Fuels_CO | | | | △ |
| | Thermochem Recovery International_NC | | | △ | |
| | Versa Renewables LLC_GA | | | △ | |
| | Virginia Tech_VA | | | | ▽ |

**Technology Pathway**
- 🟧 Algae (HC)
- 🟦 Hydrotreating/Isomerization
- 🟥 Thermochemical Gasification (HC)
- 🟪 Thermochemical Pyrolysis
- 🟩 Biochemical (HC)
- 🟫 Biochemical Catalytic

**Feedstock Category**
- □ Algae
- + Crop Residues
- △ Woody Biomass
- ▽ MSW
- ○ Cellulosic Sugars
- ✱ Vegetable Oils, Fats, and Greases

Figure 10. NREL's findings on status of U.S. RD production facilities at end of 2015

The NREL study found that the total installed U.S. commercial capacity for RD (as of year-end 2015) was approximately 255 million gallons per year. About two thirds of this capacity (167 million gpy) were actually operational. As the figure shows, NREL documented 12 "operating" U.S. RD-production facilities (of which two were producing RD at "commercial" scale). For the remaining 20 RD-production facilities, 10 were found to be "idle", nine were in the "planning" stage, and one was "under construction."[35]

The two largest RD-production facilities in the U.S. (at least by production capacity) are located in Louisiana. These are 1) the Diamond Green Diesel facility in Norco, with a capacity of 137 MGPY, and 2) the REG Synthetic Fuels facility in Geismar, with a capacity of 75 MGPY. Both companies have registered fuel pathway documents with CARB for the LCFS program, and appear to be supplying RD for California fleets.[36] However, the respective volumes of RD they currently provide for HDV consumption in California are not obtainable from public information. Based on high-level information, the volume of RD sent to California markets from these domestic producers appears to be (roughly) on par with the volume imported by Neste (next subsection).

Only three of the 32 existing or planned RD production facilities surveyed by NREL are located in California. Of these, only the AltAir Fuels facility in Paramount California (current RD capacity of about 35 MGPY, with a planned increase to 150 MGPY) appears to be operational at commercial scale. AltAir's Paramount facility can produce three different renewable fuels from the same feedstock (beef tallow and vegetable oils): 1) RD, 2) renewable jet fuel, and 3) renewable gasoline (see Figure 11). Currently, most of this production is dedicated to making renewable jet fuel (for use by United Airlines), rather than to make RD for on- and off-road vehicles.


Photo courtesy of AltAir Fuels

| | |
|---|---|
| Location | Paramount, California |
| Process Technology | Catalytic Hydrotreating (Honeywell-UOP) |
| Production Capacity | 3,000 bbls/day |
| Feedstock | Inedible agricultural fats and oils |
| Products | Renewable F-76 and JP-5<br>Renewable Jet, Diesel and Gasoline |

Figure 11. AltAir Fuels renewable fuel production facility

The California Energy Commission (CEC) and CARB are prioritizing efforts to help increase in-State production of RD and other biofuels that can be used in the state's vast transportation sector. Several projects are underway to expand California's existing RD-production facilities, or build new facilities. For example, CEC recently awarded $11.2 million in funds from the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) to add approximately

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[35] National Renewable Energy Laboratory, "2015 Survey of Non-Starch Ethanol and Renewable Hydrocarbon Biofuels Producers," January 2016, http://www.nrel.gov/docs/fy16osti/65519.pdf.

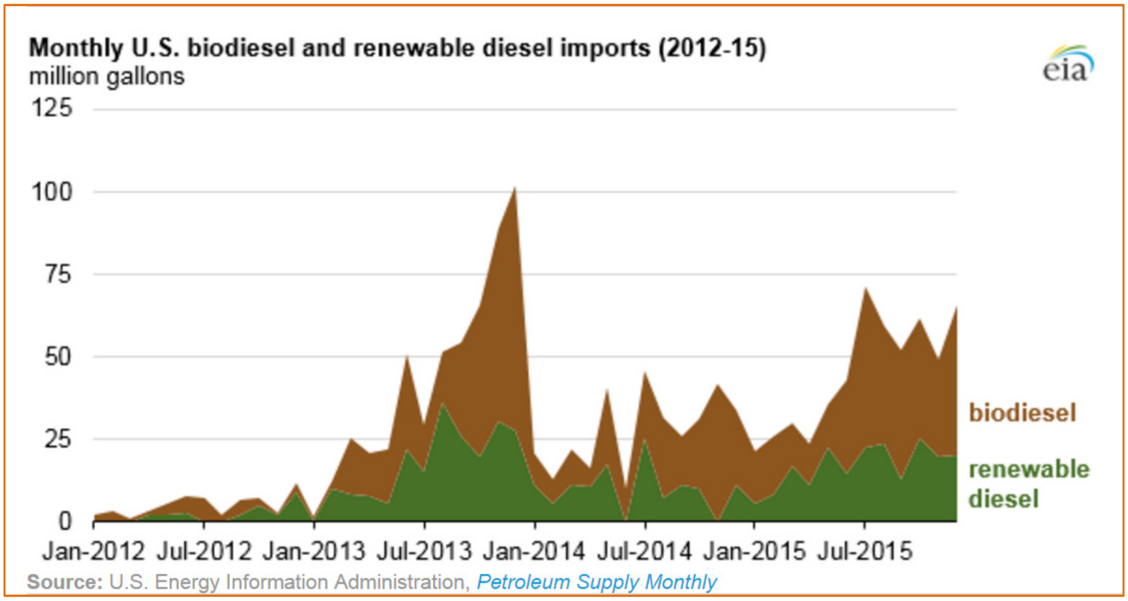
[36] California Air Resources Board, "Biomass-Based Diesel as a Transportation Fuel: Staff Discussion Paper," February 8, 2016, https://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/02102017discussionpaper_bdrd.pdf.

27 MGPY of additional RD production capacity.[37] Most or all of these efforts involve pilot-scale RD production plants; some have individual RD capacities at or below 10 MGPY.

## 3.2. International Production (Imported to U.S. for Transportation)

Despite recent significant progress to increase commercial-scale domestic RD production (including in California), the reality is that most RD consumed in the U.S. is imported from other countries. The primary importer is Neste Corporation, via its Singapore production facility. Neste is the world's leading producer of RD, with annual revenue of $12.7 billion across multiple product lines. Neste cites an annual worldwide production capacity today that exceeds 900 million RD gallons, divided between three different plants located in the Netherlands (42 percent), Singapore (42 percent) and Finland (16 percent).[38] Currently, all RD that Neste imports to the U.S. comes from its Singapore plant, and it destined for California. (Note: as this report was being finalized, Neste Oil USA reportedly delivered 20 million RD gallons to the U.S. in May 2017 alone, which represented an increase of 74 percent compared to May of 2016.[39])

The U.S. Energy Information Administration (EIA) tracks and reports imports of biodiesel and RD together. As shown in Figure 12, during the period of 2012 through 2105, the month-to-month volume of imported biodiesel was roughly three times greater than that for RD. During this time frame, monthly imports for both fuels peaked at the end of 2013, but decreased sharply in 2014. This was largely due to uncertainty surrounding the future of biofuel targets under the Renewable Fuel Standard (RFS).



Source: U.S. Energy Information Administration, *Petroleum Supply Monthly*

Figure 12. Monthly U.S. biodiesel and RD imports, 2012 through 2015

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[37] California Energy Commission, Alternative and Renewable Fuel and Vehicle Technology Program Project Funding Summary through April 15, 2015, accessed online, http://steps.ucdavis.edu/files/09-11-2015-Compendium-Narrative-updated-4.15.15.pdf.

[38] Neste Corporation, Jeremy Baines, Vice President of Sales North America, presentation at Neste Renewable Diesel Symposium, San Francisco, March 30, 2017.

[39] Oil Price Information Service, "U.S. Renewable Fuel Imports Boosted by Neste Renewable Diesel Deliveries," August 15, 2017.

However, when EPA finalized higher targets for these biomass-based diesel fuels in 2015, there was a rapid increase in U.S. imports of biodiesel and RD. For RD, 2015 imports reached 204 million gallons – an increase of 69 percent compared to 2014. All this imported RD in 2015 was sourced from Singapore (i.e., imported to the U.S. by Neste), and "entered the United States primarily through West Coast ports, likely destined for California LCFS compliance."[40]

This exemplifies just how important California LCFS credits are in providing "market pull" for RD (and other renewable fuels). There are two ways that LCFS credits are generated with RD. First, suppliers / distributers sell "neat" RD as a retail or wholesale HDV fuel. (Typically, pure RD is blended with one or two percent ULSD, to take advantage of the IRS "biodiesel blenders credit."[41]) Second, oil companies blend low levels of RD into billions of ULSD to reduce their LCFS compliance obligation. This enables them to bring down the carbon intensity of ULSD, as needed to meet the targeted LCFS reduction. Blending in RD also helps oil companies improve the quality of their ULSD, given RD's valued characteristics (e.g., a high cetane value and low aromatics content).[42]

## 3.3. Consumption in the National Transportation Sector

As shown in Figure 13, the U.S. transportation sector consumed nearly 1.9 billion gallons of biodiesel and RD combined in 2015. However, RD's share of this has ranged from only 45 million gallons (five percent) in 2012, to about 350 million gallons (20 percent) in 2015.

The 2013 ramp-up in consumption of biodiesel and RD resulted from two strong incentives in the U.S. That year, there was unprecedented high demand for non-ethanol fuels. This led to an increase in RIN prices under the federal RFS, as regulated parties sought to meet their program obligations. In combination with favorable blender tax credits, there was strong economic incentive for biodiesel and RD growth beginning in 2013, which resulted in significantly increased use for both of these substitutes for conventional diesel. Thus, RD consumption in U.S. transportation markets grew to about 350 million gallons by the end of 2015, and today (mid 2017) this has grown to roughly 400 million gallons of RD.

(Note: as this report was being finalized, Neste Oil USA reportedly delivered 20 million RD gallons to the U.S. in May 2017 alone, which represented an increase of 74 percent compared to May of 2016.[43])

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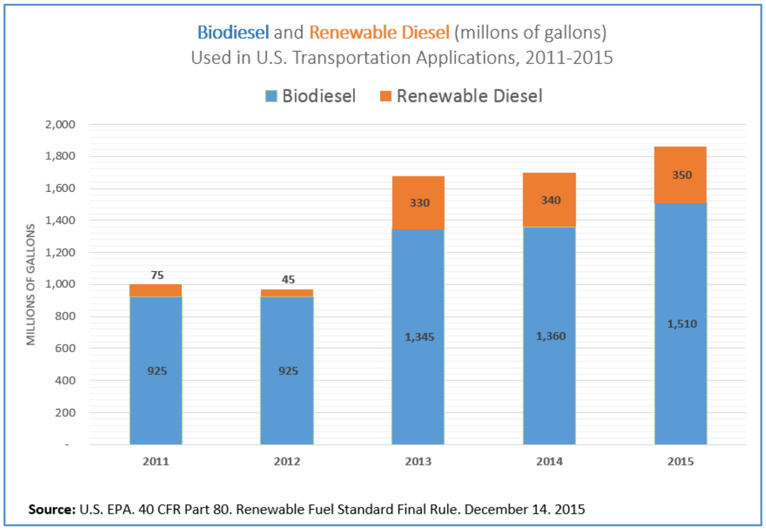
[40] U.S. Energy Information Administration, "U.S. biodiesel and renewable diesel imports increase 61% in 2015," https://www.eia.gov/todayinenergy/detail.php?id=25752.

[41] An IRS-registered biodiesel or RD blender may be eligible for a tax incentive of $1.00 for every gallon of biodiesel or RD it blends with petroleum diesel (ULSD) to produce a mixture containing at least 0.1% diesel fuel. For RD, the result is that it is actually dispensed at the pump as RD99 or RD98. See additional details at http://www.afdc.energy.gov/laws/395.

[42] Green Car Congress, "NREL/Chevron team characterizes chemical composition and properties of renewable diesels derived from FT, Hydrotreating, and fermentation of sugar;" November 21, 2012, https://www.evdriven.com/chevron/diesel/renewable/.

[43] Oil Price Information Service, "U.S. Renewable Fuel Imports Boosted by Neste Renewable Diesel Deliveries," August 15, 2017.

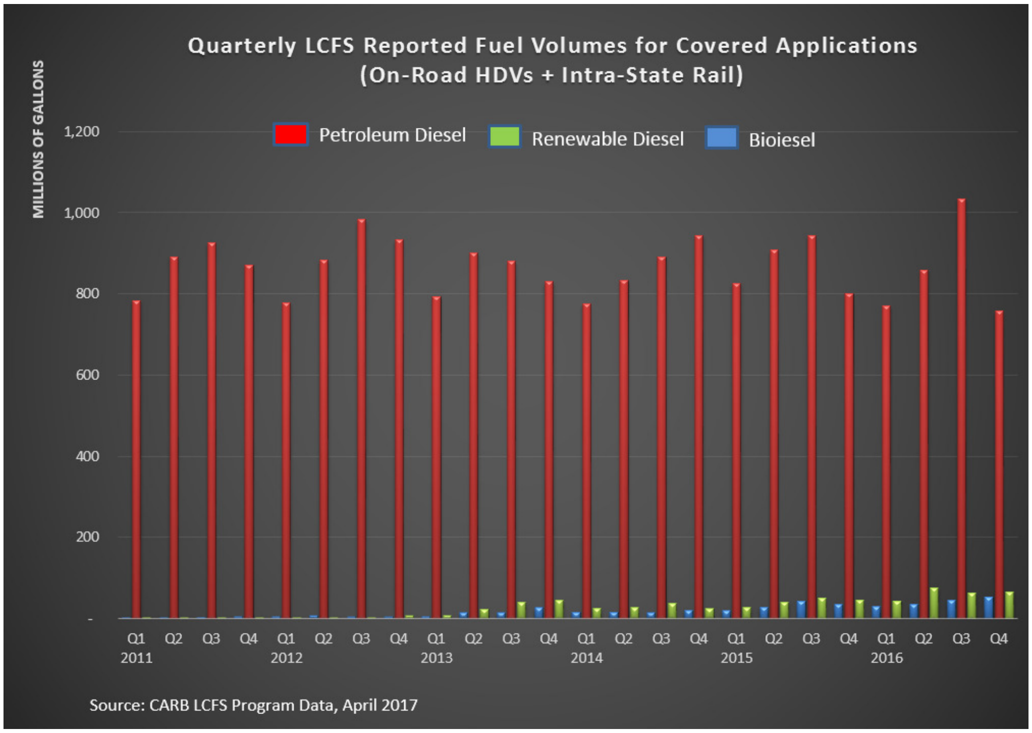


**Source:** U.S. EPA. 40 CFR Part 80. Renewable Fuel Standard Final Rule. December 14. 2015

Figure 13. Biodiesel and RD volumes consumed in U.S. transportation applications, 2011 to 2015

## 3.4. Consumption in California’s Transportation Sector

More than half of the RD consumed in America is dispensed in California. Figure 14 shows the steady growth trend for RD use in California, since inception of the LCFS program in 2011. The graph compares quarter-by-quarter LCFS volumes for petroleum diesel (red bars), RD (green bars) and biodiesel (blue



Source: CARB LCFS Program Data, April 2017

Figure 14. Quarterly volumes of RD, biodiesel and petroleum diesel sold for LCFS-covered applications

bars). As can be seen, RD has surpassed biodiesel for generating credits under the LCFS. Totaling all four quarters, more than 200 million RD gallons were consumed during 2016 in LCFS-covered applications (on-road HDVs and intra-state locomotives). Still, petroleum diesel's use in the LCFS (3.42 billion gallons in 2016) continues to dominate both RD and biodiesel use; RD use currently constitutes about 6.7 percent.

The California Energy Commission (CEC), uses somewhat different metrics to track transportation fuel consumption.[44] CEC reports that 157 million gallons of RD were consumed in California during 2015. This constituted 4.2 percent of all diesel fuels sold in California that year (totaling 3.72 billion gallons for on-road, off-road, military, agricultural, and rail applications).[45] Similar data for 2016 have not been obtained. CEC officials have indicated that as much as 350 million RD gallons were consumed in California in 2016, when considering all end uses (i.e., inclusive of those outside the LCFS program).[46]

As was described in the previous sections, almost all of the 250 million RD gallons being annually consumed within California's LCFS today are imported from abroad, or shipped by rail from other states. Neste Corporation is providing a large percentage of California's RD supply, all of which is currently imported from Singapore. Worldwide, Neste has capacity to produce 900 million RD gallons each year, although actual production may be about 90 percent of this total (~810 million RD gallons). Based on Neste's financial statements, California sales constituted about 15 percent of its 2016 worldwide RD production. Thus, it appears that Neste imported at least 122 to 135 million RD gallons into California in 2016, all of which was shipped from Singapore.

Based on this estimate for Neste's imports of RD, it appears that the other 115 to 130 million RD gallons that are now annually consumed in California under the LCFS program are being supplied from within the U.S. NREL estimated that the two major RD producers in Louisiana (Diamond Green Diesel and REG) currently have a combined operational capacity to produce at least 167 million gallons per year, so they appear to be the primary domestic suppliers of RD for California's transportation sector. Both of these companies are believed to be expanding RD production at these existing facilities, and possibly building new production plants elsewhere in the U.S.

Neste estimates that California will receive approximately 25 percent of its total worldwide RD production by the end of 2017.[47] This roughly translates to 200 to 225 million gallons per year. The company notes that it is very committed to California transportation markets for its RD product, with the state constituting a very important part of its global strategy. Neste intends to continue expanding RD distributors, provide greater RD volumes to its distributors, and generally be more aggressive with its efforts to market RD in California.[48] This strategy is clear from the RD seminars and events that Neste is

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[44] CEC reports in-State production volumes (where applicable), while CARB's reports on LCFS volumes refer to fuel sales in California. Also, there are differences in how the two State agencies report or differentiate between rail fuel usage. Generally, CEC estimates for volumes of fuels are lower than CARB estimates.

[45] California Energy Commission, "California Fuels Used in Transportation Energy Assessment Division," spreadsheet provided to GNA dated January 4, 2017.

[46] Personal communication to GNA from CEC officials, April 2017.

[47] Neste Corporation, "Neste Corporation Financial Statements Release 2016," February 7, 2017, https://www.neste.com/sites/default/files/780831.pdf.

[48] Personal communication to GNA from Tuija Kalpala, Marketing Manager, Neste US, Inc., January 10, 2017.

planning and implementing throughout California, such as the "Renewable Diesel Seminar" conducted in San Francisco in March 2017.

Neste is now evaluating the feasibility of various options to invest build new RD production capacity. Options under consideration include expanding existing Singapore production, or building new facilities in the U.S.[49] Neste has held preliminary discussions with California officials about the possibility of building such a facility in California, but it has not yet made any public announcement about such plans.

In summary, the worldwide current capacity to produce RD appears to be approximately 1.2 billion gallons per year (BGPY). Approximately 78 percent (900 MGPY) of this existing production capacity consists of Neste's three major RD-production facilities in Europe and Asia. The other 22 percent (255 MPGY) of production capacity primarily consists of two RD-production plants in Louisiana. Several pilot-scale RD production facilities are being added in California. This existing supply of RD has been sufficient to meet current demand in California (at least 250 million gallons for LCFS-covered applications, and possibly up to 350 million gallons in total). It appears that Neste (and possibly other RD suppliers) plan to significantly increase the volume of RD they will sell into California markets. In May 2017 alone, Neste Oil Use reportedly imported 20 million gallons of RD for use in California.

However, there are already indications that HDV fleets (especially outside of California) may not be able to obtain sufficient RD volumes to meet their demand. Total annual diesel consumption in California is expected to reach 4.0 billion gallons, and it appears that CARB targets a large percent to be met with RD by 2030. Section 8 discusses some of challenges and constraints (e.g., feedstock limitations) associated with RD being able to meet this major demand growth in California (and across America) over the next 10 to 15 years.

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[49] Neste Corporation, "Neste Corporation Financial Statements Release 2016," February 7, 2017, https://www.neste.com/sites/default/files/780831.pdf.

## 4. Examples of Heavy-Duty Fleets Using Renewable Diesel

RD is becoming a significant replacement for petroleum diesel across the U.S. Due to a unique combination of "carrot" and "stick" drivers toward clean low-carbon transportation fuels, California's HDV transportation sector is responsible for at least half of America's RD consumption, even though it consumes only about 10 percent of U.S. petroleum fuel. This section provides examples of the major private and public HDV fleets that have switched significant portions of their operations to consume RD instead of fossil diesel.

Some of these fleets are converting their own diesel facilities to dispense RD. Others purchase it from retail RD suppliers at public-access stations. For example, Propel Fuels now sells its "Diesel HPR" (High Performance Renewable) at more than 30 stations in northern and southern California. This RD consists of 98 percent RD (supplied by Neste, from the NEXBTL process) blended with 2 percent California ULSD.

### 4.1. Private Fleets

United Parcel Systems (UPS) appears to be the largest private fleet using RD in America today. In July 2015, UPS announced that it will buy as much as 46 million gallons of RD over the next three years. UPS has set a goal to displace 12 percent of its petroleum-based fuels with RD in its HDV fleet by 2017. The company has cited three vendors – each currently focused on a different feedstock – from which it intends to purchase this large volume of RD: 1) Neste (tallow), 2) Renewable Energy Group (other oils / fats), and 3) Solazyme (algae-derived oil). UPS executives indicate that performance of its HDV fleet will be "as good or even better" on RD compared to traditional diesel.[50] UPS has noted that monetizing RD through LCFS and RIN values enables UPS to purchase RD at a price that is "close to parity with conventional petroleum."[51]

UPS has joined with NREL to conduct a real-world operational test on six package-delivery vans and six regional tractors fueled by RD. The program is seeking to determine the fuel economy and emissions impact of RD versus conventional diesel in a controlled setting. However, program results have not yet been released.[52]

While UPS intends to be very aggressive about switching large parts of its U.S. HDV fleet from petroleum diesel to RD, the company has cited RD's limited availability as a significant constraint. In mid-2016, UPS's president stated that "The bad news (about RD) is on the supply side. We can't get enough of it."[53]

Ryder System is a trucking industry leader that provides fleet management and heavy-duty truck rental services. Ryder operates 440 diesel fueling stations nationwide, and purchases more than 275 million gallons of diesel fuel each year, some of which it sells to its trucking customers. In May 2017, Ryder began

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[50] New York Times, "UPS Agrees to Buy 46 Million Gallons of Renewable Diesel," July 29, 2015, accessed online at http://www.nytimes.com/2015/07/30/business/ups-agrees-to-buy-46-million-gallons-of-renewable-diesel.html?_r=0.

[51] UPS comments to EPA on draft 2017 RFS rulemaking, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PV0A.pdf.

[52] National Renewable Energy Laboratory, "Renewable Diesel Testing in UPS Fleet Vehicles," https://www.nrel.gov/transportation/fleettest-fuels-diesel.html.

[53] Carlton Rose, Unitied Parcel Services, keynote speech at ACT Expo, May 2016.

dispensing neat RD (imported by Neste) at its diesel fueling station in San Francisco. Ryder's RD cost is at near parity with petroleum diesel.[54]

## 4.2. California Government Agencies and Fleets

California Department of General Services (DGS) - In December 2015, the California DGS issued a Management Memo #MM 15-07 stipulating that California agencies "shall purchase state-contracted renewable diesel fuel, in lieu of conventional diesel and biodiesel fuels, when making bulk purchases of fuel for diesel powered vehicles and/or equipment." DGS issued an Information for Bid (IFB) that established a California Statewide Contract to purchase RD.

DGS uses this process to impose certain requirements on RD, by providing bid specifications and sample agreements government agencies can use. For example, RD purchased under the DGS program cannot have a CI value that exceeds 50 gCO2e/MJ. It also appears to require RD99 as the preferred blend. DGS has selected several RD vendors under its statewide contract system, but it appears likely that a large percentage of the RD will be "NexDiesel" distributed by Golden State Petroleum (supplied by Neste).[55]

In addition to state agencies, local government agencies can utilize the DGS bid specifications to ensure they purchase low-CI RD under favorable conditions and pricing. Thus, some (if not all) of the cities in California described below may be taking advantage of the DGS Statewide Contract to procure RD.

City of San Francisco - In mid-2015, the City of San Francisco announced its intentions to switch its entire municipal diesel-powered fleet from ULSD to RD by early 2016. Today, the City is operating 1,297 on-road and off-road diesel vehicles on Neste RD supplied through Golden Gate Petroleum. This includes shuttle buses serving San Francisco International Airport. In addition, 986 transit buses from the San Francisco Municipal Transportation Agency (SFMTA) are sharing the same RD supply. These buses where switched to RD from biodiesel (B20) in late 2015.

Collectively, this fleet of approximately 2,300 HDVs in San Francisco is now consuming approximately 6.0 million gallons of RD99, with all 53 of the City's diesel fueling sites dispensing RD99.[56] In addition, the City is exploring the potential to collaborate with Bay Area ferry operators to test out RD in marine vessel applications. Section 7.2 provides additional discussion about the likely air quality benefits that the City of San Francisco is realizing by using RD in its HDV fleet.

Figure 15. SMTA's underground RD tanks

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[54] Fleets and Fuels, May 19, 2017, http://www.fleetsandfuels.com/category/fuels/renewable-diesel/

[55] California Department of General Services, "Buying Green," http://www.dgs.ca.gov/buyinggreen/Goods/Transportation/Fuel.aspx.

[56] San Francisco Examiner, "City fleet to adopt use of renewable diesel fuel," July 21, 2015.

City of Oakland – Oakland began using RD in late 2015, and now fuels all of its diesel vehicles and equipment with RD. Out of the City's 1,575 unit fleet, 381 vehicles (24 percent) have been switched to RD. Annual RD consumption is currently approximately 230,000 RD gallons, or about 33 percent of the transportation fuel consumed by the City's total fleet.[57] Like the City of San Francisco, Oakland purchases Neste RD obtained through Golden Gate Petroleum. Oakland reports a very favorable experience using RD. This includes a claimed GHG-reduction benefit of 48 to 83 percent (depending on which specific feedstock Neste uses) compared to ULSD, as well as "average emission reductions" for NOx and PM of 10 percent and 30 percent, respectively (see Section 6 for further discussion). True to the nature of a drop-in diesel substitute, the City has incurred no additional costs on equipment, facilities or fuel infrastructure, and no vehicle performance issues. As with other end users, Oakland's fleet personnel have reported lower maintenance costs when using RD, associated with reduced need to perform manual / forced DPF regenerations and improvements in DPF durability.[58]

Figure 16. City of Oakland RD dispenser

One important potential new application for RD in the Oakland area relates to this ability to improve DPF performance and/or durability. A recent study conducted by the Department of Civil and Environmental Engineering at UC-Berkeley for CARB and BAAQMD[59] investigated the impacts of CARB's statewide Drayage Truck regulation on the Port of Oakland's drayage truck fleet. Through both fleet modernization and DPF retrofits, CARB's regulation has helped rapidly increase the percentage of drayage trucks equipped with DPFs, from two percent in 2009 to 99 percent in 2015. The study found that a relatively small number of Port of Oakland drayage trucks where experiencing DPF failures, resulting in excessive emissions of black carbon (BC). BC is a component of PM emissions that has a number of deleterious impacts (e.g., it's a short-lived climate pollutant); measuring BC emissions from in-use HDVs can serve as a useful surrogate for DPM emissions.

The study concluded that future efforts to reduce BC (and therefore DPM) emissions in the Port of Oakland drayage truck fleet "should aim to improve durability (and) reduce the failure rate" of DPFs on the fleet.[60] Given emerging information that appears to solidly corroborate the benefits of RD to reduce DPF failure rates and improve durability, it's reasonable to conclude that using RD in the Port of Oakland drayage fleet could provide significant benefits.

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[57] Government Fleet, "Contra Costa County Moves to Renewable Diesel," September 2016, http://www.government-fleet.com/channel/green-fleet/news/story/2016/09/contra-costa-county-moves-to-renewable-diesel.aspx.

[58] City of Oakland, "Renewable Diesel Use in the City of Oakland, CA," Richard Battersby, presentation at Neste Renewable Diesel Symposium, San Francisco, 2017.

[59] C. Preble, R Harley and T. Kirchstetter, UC-Berkeley, "Effects of Exhaust After-Treatment and Fleet Modernizing on Port of Oakland Truck Emissions Following Complete Implementation of California's Drayage Truck Regulation," Draft Final Report, prepared for CARB and BAAQMD, November 2016.

[60] Ibid.

The City of San Diego – San Diego is transitioning its entire fleet of 1,125 diesel vehicles over to use RD imported by Neste Corporation and distributed by the SoCo Group. This includes approximately 900 medium- and heavy-duty on-road vehicles, and 192 off-road vehicles.[61]

Contra Costa County – This Bay Area county has switched from biodiesel to RD (RD99) to fuel many of its heavy-duty diesel vehicles, including more than 220 diesel-powered municipal public works trucks, specialty vehicles, and equipment. The RD distributor is believed to be Golden Gate Petroleum.[62]

City of Walnut Creek – Walnut Creek was one of the first municipalities to switch its City-owned HDVs over to RD. Today, the City operates at least 60 HDVs on RD that include dump trucks, tractors, mowers and street sweepers.[63]

City of Carlsbad – Carlsbad is using RD (imported by Neste and distributed by Propel) to power "a range of Fire Department and Public Works heavy-duty vehicles including fire trucks, dump trucks and vacuum trucks serving the community."[64]

## 4.3. Government Agencies in Other States

The Oregon Department of Energy (ODoE) - ODoE is working with public entities across the state to "tap into the emerging renewable diesel market." ODoE helps public HDV fleets by offering RD expertise; this includes advice about RD production pathways to avoid, due to potential negative environmental impacts (e.g., deforestation). Oregon cities and organizations that are have switched to RD, or are considering switching, include the Eugene Water & Electric Board (EWEB) and the City of Portland.[65] Under ODoE's guidance, EWEB switched its fleet to RD from biodiesel, and now uses about 6,100 gallons of RD per month. Similar to fleet managers at the City of Oakland and the City of Knoxville (below), Eugene's fleet manager has noted that the use of RD results in less-frequent (or even non-existent) need for DPFs on their HDVs to undergo forced regeneration (by manual cleaning).[66]

The City of Knoxville Fleet Services – Knoxville recently tested the impacts of using RD in five medium-duty trucks. The City reported a very positive overall experience using RD, although the test period only lasted two months. As described in Section 2, Knoxville paid a high price for RD relative to what it pays for ULSD, but this was in a small batch and apparently without benefit of fuel subsidy for RD's low-carbon / renewable attributes. Section 6.3 provides discussion about how Knoxville's controlled RD test has

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[61] Government Fleet, "San Diego Adopts Renewable Diesel," November 2016, http://www.government-fleet.com/channel/green-fleet/news/story/2016/11/san-diego-adopts-renewable-diesel.aspx.

[62] Government Fleet, "Oakland Moves to Renewable Diesel for City Fleet," October 2016, http://www.government-fleet.com/news/story/2015/10/third-calif-fleet-switches-to-renewable-diesel.aspx.

[63] Fleets & Fuels, California Embraces Renewable Diesel," September 11, 2015.

[64] "Renewable Diesel to Power City of Carlsbad's Fleet in California," Neste press release, July 11, 2016.

[65] Biodiesel Magazine, "Oregon Pushes Renewable Diesel Use," by Ron Kotrba, January 13, 2016, http://www.biodieselmagazine.com/blog/article/2016/01/oregon-pushes-renewable-diesel-use http://ngtnews.com/eugene-water-electric-board-touts-switch-to-renewable-diesel/?utm_medium=email&utm_source=LNH+01-19-2016&utm_campaign=NGT+Latest+News+Headlines

[66] NGTNews, "Eugene Water & Electric Board Touts Switch to Renewable Diesel," January 18, 2016, https://ngtnews.com/eugene-water-electric-board-touts-switch-to-renewable-diesel.

provided some of the best documentation to date that RD's much-lower engine-out PM emissions can significantly reduce operational costs associated with DPFs.

City of Seattle Fleet - Seattle will be initiating a pilot demonstration of RD blended with biodiesel in its truck fleet, beginning in late 2017. The blend to be tested will be 80 percent RD and 20 percent biodiesel.[67]

New York Department of Sanitation – NYC Sanitation accounts for 80 percent of the City government's diesel consumption. As part of NYC's "Clean Fleet" initiative, NYC Sanitation has aggressively switched to biodiesel blends (B5 and B20) to operate all its HDVs. NYC Sanitation operates an underground biodiesel storage system with a capacity of 680,000 gallons, and it consumes up to 850,000 gallons of B20 each month in non-winter months. The City purchases its biodiesel from Renewable Energy Group, which also has capability to produce RD at its Louisiana facility. NYC Sanitation reports being satisfied with using biodiesel.[68]

New York City's Clean Fleet initiative also includes aggressive targets for RD to displace petroleum diesel. In fact, NYC Sanitation seeks to transition at least one third of its diesel fleet to RD as soon as possible. However, NYC Sanitation has stated that RD "is not currently distributed in the northeast United States." Apparently, it has only been able to purchase RD in a very small volume for laboratory testing purposes.[69] The agency states that if RD supply were to become abundant, the City of New York would likely switch all its diesel vehicles to RD. Notably, "a transition of this magnitude would likely require large-scale changes to the City's fuel procurement arrangements," regardless of whether the RD is sourced from other regions (e.g., the two Louisiana RD producers), or an RD producer develops local production capacity.[70]

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[67] City of Seattle, "Renewable Diesel," presentation by Andrea Pratt, Green Fleet Program Manager, April 2017.

[68] Renewable Energy Group, "New York City is Ahead of the Curve," http://www.nyc.gov/html/dcas/downloads/pdf/fleet/NYC_case_study_renewable_energy_group_2.pdf.

[69] Successful Dealer, "NYC Sanitation Fleet to Test Renewable Diesel, July 26, 2016, http://www.successfuldealer.com/nyc-sanitation-fleet-to-test-renewable-diesel/.

[70] The City of New York, "NYC Clean Fleet," December 2015, http://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/NYC%20Clean%20Fleet.pdf.

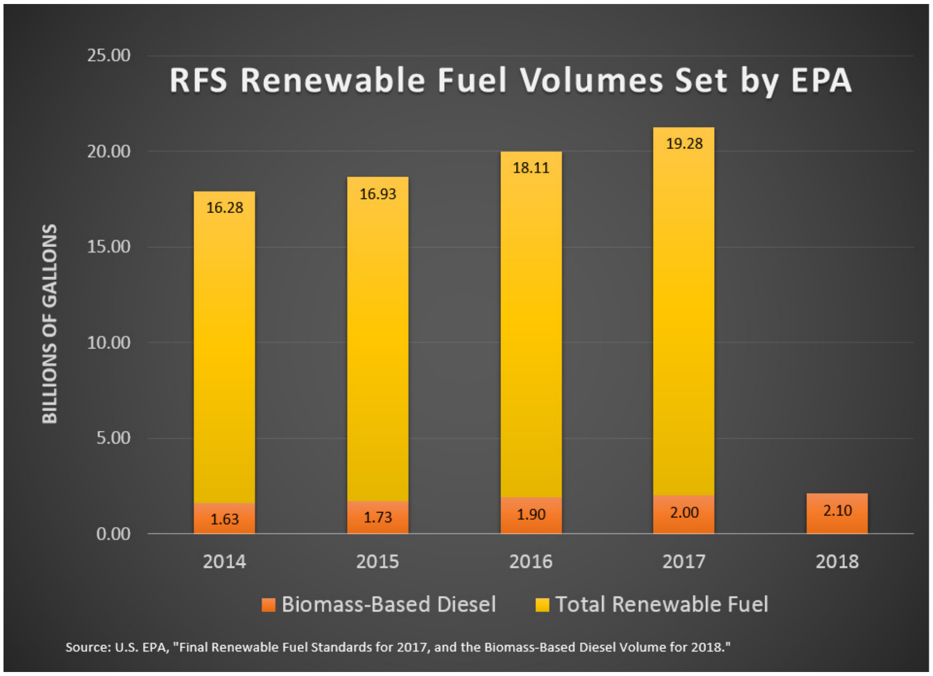
## 5. Drivers and Projections for Expanded RD Supply and Demand in Transportation

### 5.1. Federal Requirements / Incentives and Projections

Under the federal RFS, EPA is required to set standards for using renewable fuel to replace or reduce consumption of petroleum-based fuels (transportation fuel, heating oil or jet fuel). The latest version (RFS2) calls for consumption of 36 billion gallons of renewable fuels by 2022. Much of that volume must be met with so-called "D5 advanced biofuels" derived from renewable biomass and providing at least a 50 percent lifecycle GHG reduction compared to petroleum fuels. Either RD or biodiesel – also called biomass-based diesel (BBD) fuels – can be used to meet this requirement.

Recently, EPA set finalized volume requirements that apply under the RFS program in calendar year 2017. EPA set requirements specifically for BBD (RD and biodiesel), as well as cellulosic biofuel (required to achieved a 60 percent GHG reduction) and total renewable fuel. In the case of BBD only, EPA also finalized the volume requirement for 2018. As shown in Figure 17, EPA has set a goal of 2.0 billion gallons of BBD in 2017, increasing to 2.1 billion gallons in 2018. EPA does not separate out the respective targeted roles for RD and biodiesel in meeting this 2.1 billion gallon target. One major RD producer estimated that in 2017, RD will comprise up to 20 percent (about 540 million gallons) of the BBD obligations met in 2017.[71]

In general, RD producers have commented that EPA should increase its requirement beyond 2.1 billion BBD gallons in 2018. They specifically cite good potential to increase the RD portion of BBD volumes. For example, Neste commented to EPA that "there is sufficient support" to require 2.5 billion gallons of BBD



Source: U.S. EPA, "Final Renewable Fuel Standards for 2017, and the Biomass-Based Diesel Volume for 2018."

Figure 17. Most recent fuel volume requirements set by EPA under RFS2 for biomass-based diesel

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[71] Darling Ingredients, comments to EPA on RFS standards for 2017, November 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PV0A.pdf.

in 2018, and noted that EPA "failed to fully account for the impact of renewable diesel" relative to biodiesel in setting its 2018 BBD standard. Darling Ingredients (feedstock supplier to, and partner with RD producer Diamond Green Diesel) noted that RD is contributing an "increasing portion" of BBD production relative to biodiesel. Darling requested EPA to increase the BBD volume in 2018 up to 2.335 BGY, while noting that 235 MGY of additional RD production capacity was coming online in California and Louisiana. Other existing or potential RD producers offered similar comments.[72]

In responding to these comments, EPA agreed that RD will likely surpass biodiesel as the major BBD fuel, because it does not have significant distribution-related limitations. Specifically, EPA cited RD's advantage over biodiesel for having no blend wall, which creates "significant opportunities to expand" RD use in the U.S. However, EPA also cited a key barrier for RD: its "limited production capacity . . . in the United States and abroad."[73] Further discussion about this barrier is provided in Section 8.

## 5.2. California Requirements / Incentives and Projections

### Proposed New LCFS Target for Carbon Intensity Reduction

California's unique LCFS program is a pillar of the State's aggressive efforts to reduce GHG emissions in accordance with various goals and targets. The LCFS is intended to spur innovation in transportation fuels, reduce California's dependence on petroleum, and achieve collateral benefits such as improved ambient air quality. Using full fuel cycle, or "well-to-wheels" (WTW) analysis, CARB developed the LCFS to achieve a 10 percent reduction in WTW GHG emissions from the transportation fuel mix by 2020. This existing 10 percent target has been a strong driving force towards the fact that California today consumes approximately 250 MGPY of RD within LCFS-covered markets.

Under its 2017 Climate Change Scoping Plan Update, CARB seeks new strategies to ensure the State can achieve 2030 GHG reduction targets. This includes extending the LCFS beyond 2020 and increasing its target for reducing carbon intensity of the transportation fuel mix from 10 percent to 18 percent. CARB has modeled the estimated RD volumes that may be needed in California if this new LCFS "18% Scenario" is adopted. As can be seen from the light purple shading in Figure 18, approximately 1.4 billion gallons per year of RD will be needed by 2030 to meet the targeted overall 18 percent reduction in carbon intensity. Although much of this RD would likely need to be imported, a new 18 percent target (if adopted) will strongly incentivize expanded production of RD in California.

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[72] Neste Oil and Darling Ingredients, separate comments to EPA on RFS standards for 2017, November 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PV0A.pdf.

[73] U.S. EPA, response to comments from United States Canola Association on RFS standards for 2017, November 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PV0A.pdf.

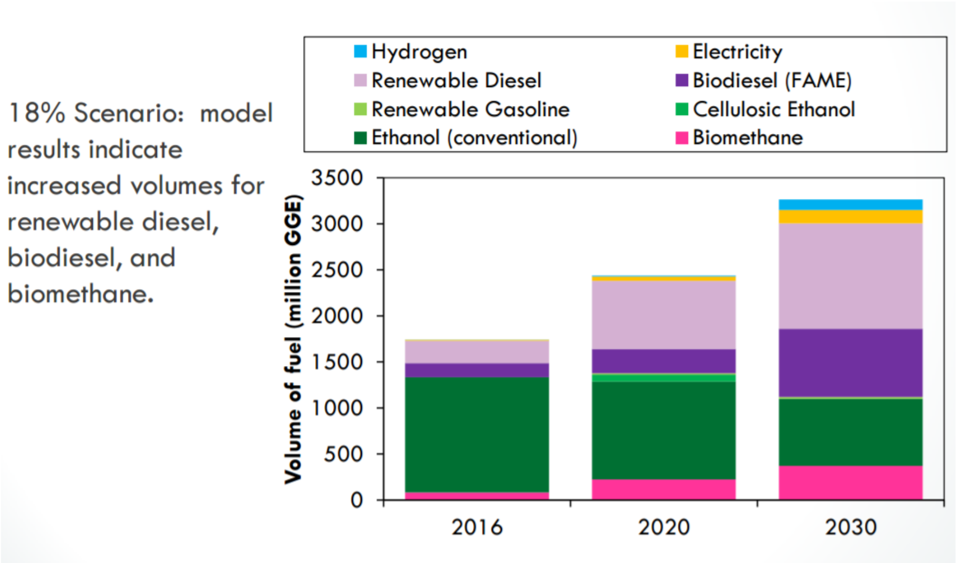
18% Scenario: model results indicate increased volumes for renewable diesel, biodiesel, and biomethane.

Figure 18. CARB's "18% Scenario" for the LCFS (approximately 1.4 billion RD gallons by 2030)

Oregon has adopted a Clean Fuels Program similar to the LCFS, with the goal to reduce the carbon intensity of transportation fuels used in Oregon by 10 percent over the next 10 years. The Oregon Department of Energy has indicated that RD will likely play a significant role in helping the state reach that goal. This will create further demand for domestic RD production, possibly in new facilities in California that could supply both the California and Oregon low-carbon fuel markets.

### State Implementation Plan, Mobile Source Strategy and Low-Emission Diesel Requirement

CARB's 2016 Mobile Source Strategy (MSS) is California's comprehensive plan to simultaneously reduce criteria pollutant and emissions from mobile sources, as needed to meet the State's critical air quality and climate goals in 2023 and 2030. The MSS states that HDVs powered by internal combustion engines (ICEs) achieving very-low NOx levels (0.02 g/bhp-hr, or lower) are "the most viable approach" to meet California's mid- and longer-term air quality goals. In devising the MSS, CARB assumed that California will need more than 430,000 of these low-NOx HDVs in the South Coast Air Basin alone by 2031. To simultaneously meet GHG and petroleum-use-reduction targets, at least half of the fuel demand for these trucks will need to be met with renewable fuel.[74] Notably, heavy-duty engines fueled by natural gas are the only ICE technology that has been certified to meet a NOx level of 0.02 g/bhp-hr, which is unofficially referred to as "near-zero-emission" technology. In particular, CARB expects that heavy-duty NGVs fueled by renewable natural gas (RNG) will play a significant role in meeting State goals for near-zero-emission HDVs using renewable fuel. CARB expects that the majority of the other low-NOx HDVs will be powered by advanced diesel engines fueled by RD; however, this assumes that heavy-duty diesel engines will be able to achieve NOx levels of 0.02 g/bhp-hr (see Section 6.6). Heavy-duty propane engines (already certified by CARB to 0.05 g/bhp-hr, and expected to soon achieve 0.02 levels) could also play a role in this mix. However, it will have to be demonstrated that renewable propane – which is a byproduct of the RD production process – can be incorporated into the LCFS program and emerge as a major transportation fuel.

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[74] California Air Resources Board, "Mobile Source Strategy," May 2016, https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdf.

To help ensure that sufficient volumes of renewable fuels for heavy-duty ICE vehicles will be available, CARB's MSS includes a proposed "Low-Emission Diesel" (LED) regulation. This draft rule calls for 50 percent of the State's current diesel demand to be replaced with renewable "LED" fuels by 2030. Potential LED fuels include RD, RNG and biodiesel, but all must meet common requirements that include having 1) a low carbon intensity rating (30 to 60 gCO2e/MJ, depending on feedstock type); 2) an aromatics content less than 1 percent, and 3) a sulfur content at (or near) zero ppm. CARB currently anticipates adopting the LED rule by 2020. The specific target is to initially require LED fuel use in certain HDV sectors in the South Coast Air Basin, as part of the overall strategy to meet daunting deadlines in 2023 and 2030 to attain NAAQS for ozone. The air quality implications of the LED regulation (and RD's expected role) for the SCAB are discussed in Section 7.1.

Notably, if CARB's proposed LED regulation is adopted and implemented, it will likely require "rethinking" by sister agency DGS about the decree in MM 15-07 that all State agencies must purchase RD for diesel powered vehicles and equipment. Presumably, DGS will need to align with CARB on where limited supplies of RD are most needed, to meet state air quality and climate change objectives.

CARB identified RD as the "potentially most readily available" LED fuel for the 2030 timeframe. (It can be argued that RNG falls in the same category; LCFS records indicate California fleets consumed 87 million DGE in 2016). To assess how much RD supply will potentially be available to meet California's transportation needs by 2030, CARB conducted a "top-down" analysis with "conservative assumptions." This resulted in the estimate that approximately 2.4 billion gallons per year of RD will be available to the State by 2030. CARB assumes that various feedstock types and RD-production technologies (hydrotreatment, pyrolysis, etc.) will be utilized. It further assumes that California will have access to 100 percent of the RD produced in State, 20 percent produced in the rest of the U.S., and 1 percent produced worldwide.[75] CARB found that the total supply of LED fuel available in California by 2030 could realistically be 2.6 billion gallons (of which 2.4 billion gallons, or 92 percent, will apparently be RD). The overarching conclusion was that this volume "exceeds the approximately 1.6 billion gallons of Low-Emission Diesel required to meet the 50 percent petroleum displacement goal by 2030."[76]

### California's Biofuel Supply Module (BFSM)

The BFSM is a complex spreadsheet developed by CARB to help predict future availability of low carbon fuels in California. It relies on transportation energy demand inputs to calculate the type and quantity of transportation biofuels that may be cost-effective compared to fossil fuels, given a set of assumptions about biofuel subsidies, LCFS prices, carbon prices and the cost of delivered biofuels. A key objective of the BFSM is to quantify and "inform" the potential biofuel supply needed to achieve California's comprehensive GHG-reduction strategy. Among the many goals is to better characterize "how prices and policies impact long-run LCFS targets" and identify focus areas that will need extra policy support.

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[75] California Air Resources Board, "Workshop on Mobile Source Strategy Discussion Draft," staff presentation, October 16, 2015, https://www.arb.ca.gov/planning/sip/2016sip/wkshp_presentation.pdf.

[76] California Air Resources Board, "Response to Comments on the Draft Environmental Analysis for the Proposed 2016 State Strategy for the State Implementation Plan," released March 10, 2017, https://www.arb.ca.gov/planning/sip/2016sip/2016statesip_RTC.pdf.

The BFSM models a range of factors, including biofuel supply, demand, pricing, and incentive and subsidy amounts, to determine supply. In particular, a fundamental assumption of the BFSM is that "price incentives motivate the necessary commitment of capital to encourage low carbon fuel production," and thus will impact future fuel volume curves for any given type of biofuel.[77]

Figure 19 shows how the BFSM projects volumes of RD as a transportation fuel that will be used to generate LCFS credits, from 2015 and 2050.[78] The three curves assume credit prices of $0 per $MTCO_2e$ (i.e., tantamount to no LCFS program), $80 per $MTCO_2e$, and $200 per MTCO2e (i.e., CARB's current cap on LCFS credit prices). Each curve starts at an annual RD volume of 159 million DGE, reflecting the actual volume of RD that generated LCFS credits in 2015.

These three different curves help provide the following outlook for RD, as a function of LCFS credit price:

- The **green** curve reflects the highest-price scenario for LCFS credits, at $200 per $MTCO_2e$. Under this scenario, the BFSM projects that **1.635 billion DGE** of RD will generate LCFS credits in 2024; this will increase up to **2.312 billion DGE** of RD by 2050.

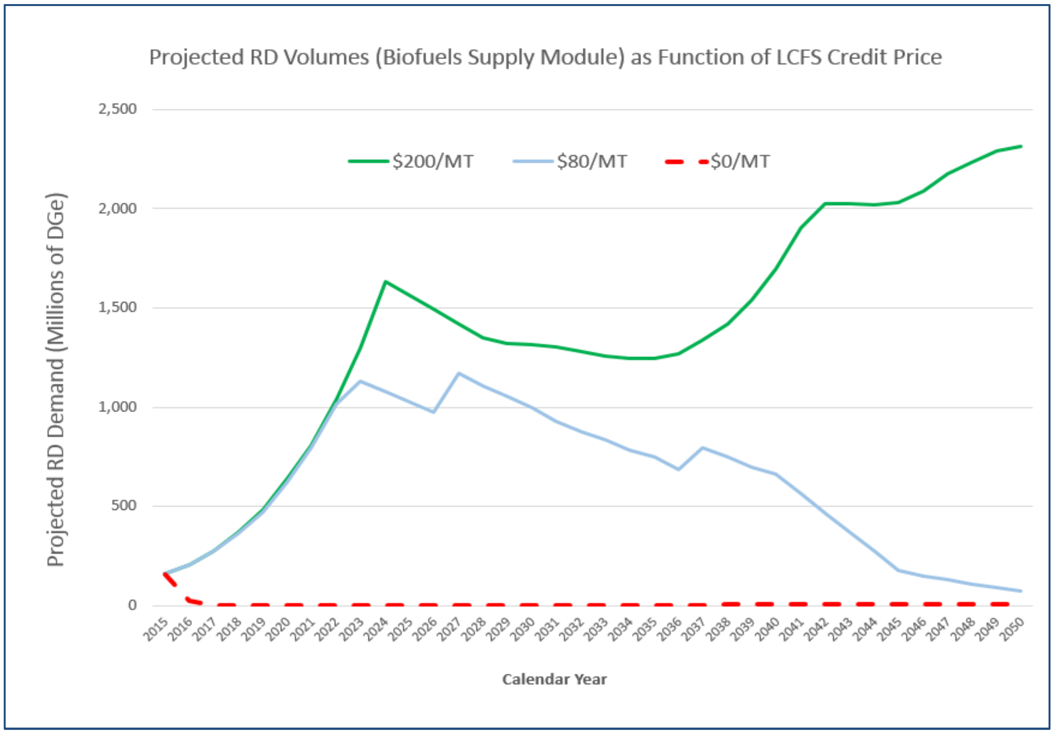

Figure 19. Projected volumes of RD generating LCFS credits as a function of credit price

- Under the **blue** curve scenario ($80 per $MTCO_2e$), the BFSM projects that RD volumes in the LCFS will peak at **1.173 billion DGE in 2027**, and then gradually decline down to just **76 million DGE** in 2050.

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[77] California Air Resources Board, "Biofuel Supply Module: Technical Documentation for Version 0.91 Beta," Released January 19, 2017, https://www.arb.ca.gov/cc/scopingplan/bfsm_tech_doc.pdf.

[78] See CARB's "Mobile Source Strategy," May 2016, https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdf.

- Under the **red** (dotted) curve scenario (\$0 per $MTCO_2e$), it can be seen that the BFSM essentially projects a rapid and sustained decline to **zero DGE** of RD to be transacted through the California LCFS. Presumably, this is projected because under this scenario, there are no monetary incentives to offset the higher costs of producing RD. It's unclear what assumptions are made here about RD use under the proposed LED rule.

This helps convey the clear importance that monetization programs like California's LCFS play to drive demand for RD and other renewable transportation fuels in California. The \$0 per $MTCO_2e$ scenario presents a stark illustration that RD subsidization is critical unless and until it can achieve cost parity with diesel.

However, this scenario does not necessarily project that RD would cease to be a major transportation fuel in California in the absence of any LCFS credit value. As described above, in addition to "carrot" drivers for RD, there are "stick" drivers. CARB has made it clear that 1) diesel-fueled heavy-duty internal combustion engines will continue to dominate California's goods movement sector at least until 2030, 2) these engines will require using renewable fuel (RD) to achieve the State's GHG reduction goals, and 3) it intends to adopt a LED rule that will likely be a major impetus for expanded use of RD.

# 6. Implications of RD Use on Exhaust Emissions from Diesel Engines

## 6.1. Introduction

RD producers, suppliers and end-user fleets have made various claims about the ability of RD to reduce exhaust emissions from heavy-duty diesel vehicles and equipment. Often, these claims cite CARB as the source. They tend to make a blanket statement that neat RD provides compelling tailpipe emissions reductions relative to conventional (petroleum) diesel. A typical example is the following statement made by one RD distributer in California:

> *"(RD) reduces NOx emissions by 14%, PM by 34%, and CO by 13% compared to petroleum diesel."*[79]

Statements such as this are partially accurate, but they leave out an important caveat. The reality based on a significant body of emerging data is that RD's criteria-pollutant-reduction and other air quality benefits strongly depend on key use parameters; these include (but are not limited to) the following inter-related factors:

- Engine age and application
- The duty cycle over which the engine is operated
- The type of emissions control technology utilized by the diesel engine (if any)

CARB and other air quality regulators have been cautious about making definitive statements about the exhaust emission implications of using RD instead of petroleum diesel. This is partly because, until recently, there has been a very limited body of credible test data, especially regarding how RD impacts tailpipe emissions from the newest diesel engines and vehicles. In 2015, CARB issued the following summary about RD's effects on exhaust emissions:

> *"In general . . . .most emissions from renewable diesel are reduced (relative to) diesel fuel meeting ARB motor vehicle fuel specifications (CARB diesel), including particulate matter (PM), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO2), total hydrocarbons (THC), and most toxic species."*[80]

Fortunately, recent emissions testing programs are helping to better characterize how RD affects tailpipe emissions. This includes quantification of how RD impacts emissions from today's modern diesel-fueled HDVs, which employ selective catalytic reduction (SCR) to reduce NOx, and DPFs to reduce PM. To expand the body of knowledge, CARB has been performing in-house emissions testing involving RD-fueled engines, while also contracting with academic institutions like the University of California-Riverside (UCR). These test programs have included chassis dynamometer testing of on-road HDVs, as well as engine dynamometer testing of on- and off-road engines. Various test engines, vehicle types, emission control technologies, test cycles and RD blends have been included in the test matrices. Beyond these CARB-led

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[79] Propel Fuels, http://dieselhpr.com/learn-more.

[80] California Environmental Protection Agency, "Staff Report: Multimedia Evaluation of Renewable Diesel," prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf.

efforts, other emissions testing programs have been conducted in the U.S. and abroad, to more fully assess RD-related emissions.

A major emerging development is that the California Energy Commission (CEC) has joined with SCAQMD, CARB, and Southern California Gas Company to design a new study on the in-use emissions performance of HDVs using a variety of engine-fuel platforms, including current-technology diesel engines fueled by RD. This study will start in 2017 and is expected to run through 2019. In-use emissions testing will be conducted on a large sample of HDVs by the University of California and West Virginia University. Additional details are provided in Section 6.6.

Based on the relatively limited test data that have been collected to date, on both older and newer diesel HDVs (all Classes and categories), it is clear that RD's effects on diesel engine emissions (especially NOx) are complex and inconclusive. The growing body of data indicate that RD's tailpipe emission-reduction benefits can be quite significant for diesel engines that are not equipped with SCR systems and DPFs (older on-road HDVs, and most types of heavy-duty off-road vehicles and equipment). However, as further discussed, the picture is much less clear about how RD affects emissions from diesel HDVs with engines that use SCR and/or DPF systems.

Table 3 lists some of the key emissions studies that have helped better understand the current pollutant-specific knowledge about how RD impacts tailpipe emissions from both older and newer heavy-duty diesel engines. These five studies, which are each assigned a "Source #" in the table, are further discussed below to summarize what is currently known, unknown or poorly defined about the impacts of RD on exhaust emissions.

Table 3. Summary of key emissions studies involving HDVs and engines using RD

| Source # | Testing Institution(s) | Title / Main Topic | Study Year | Types of Test Diesel Vehicles / Engines |
|---|---|---|---|---|
| **1** | UCR CE-CERT,<br>UC Davis,<br>Arizona State | CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California - "Biodiesel Characterization and NOx Mitigation Study" | 2011 | 2006 Cummins ISM (10.8L)<br>2007 MBE 4000 (12.8L)<br>1998 Kubota V2203-DIB (2.2L)<br>2009 John Deere 4045HF285 (4.5L) |
| **2** | UCR CE-CERT | CRC Project No. AVFL – 17b: Biodiesel and Renewable Diesel Characterization and Testing in Modern LD Diesel Passenger Cars and Trucks | 2014 | 5 LD passenger cars<br>3 LD trucks |
| **3** | CARB | Impact of biodiesel and renewable diesel on emissions of regulated pollutants and greenhouse gases on a 2000 heavy duty diesel truck | 2015 | MY2000 HD Truck with CAT C15 engine |
| **4** | UCR CE-CERT,<br>Neste Corporation | Emissions and Fuel Economy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends | 2016 | 2014 Cummins ISX15<br>2010 Cummins ISB6.7 |
| **5** | VTT Finland | Alternative Fuels with Heavy-Duty Engines and Vehicles | 2009 | Engines: 2006 Cummins ISB (4.5L), 2005 Scania DT 12 11 420 (11.7L), 2008 Sisudiesel 74 CTA-4V (7.4L)<br>Vehicles: 2006 Volvo B7RLE/680 bus, 2005 Scania K230 UB4x2LB bus, 2008 Scania K9 UB-B bus, 2007 IVECO CITELIS LINE bus, 2008 MAN CNG LION's CITY bus |

## 6.2. Oxides of Nitrogen (NOx) Emissions

Summary of Results - As can be seen in Table 4 below, the effects of RD on NOx emissions show a dependence on the types of aftertreatment employed and the drive cycles over which the engine/vehicle is tested. Diesel engines that do not employ SCR generally show a reduction in NOx emissions of 3 to 18 percent for neat RD (typically RD98 to RD100), depending on the specific vehicle/engine and test type conducted. The exception to this trend was the 2005 Scania DT 12-liter truck engine (Source 5), which exhibited a 5 percent increase in NOx emissions when fueled by RD100.

The effects on NOx emissions from using RD in SCR-equipped engines are less clear, partly due to the paucity of credible studies on this subject. For the few studies that do exist involving RD use in modern SCR-equipped engines, researchers have observed inconsistent results on NOx emission levels, even within a given study. For example, UCR's CE-CERT's 2016 study on 2010-technology heavy-duty on-road engines (Source 4) tested two RD-fueled trucks powered by modern SCR-equipped engines; a 2010 Cummins ISB 6.7 and a 2014 Cummins ISX 15. The smaller 6.7L engine demonstrated NOx decreases over the UDDS test cycle for RD50 and RD100 levels, but small NOx increases over the HHDDT transient test cycle. Conversely, the larger 15L engine showed substantial NOx increases at RD50 and RD100 levels over the UDDS test cycle, but small decreases over the HHDDT cycle. The researchers noted that the majority of NOx emissions measured during the tests over the UDDS cycle were associated with low exhaust temperatures. Specifically, below 250°C, the urea-dosing system did not inject urea, causing the SCR system to be largely inactive. Hence, the differences in NOx emissions in these tests may have been dominated by the performance of the emissions controls, masking any fuel-related effects.

Other studies also suggest that SCR system performance masks RD's potential effects on NOx emissions. The Coordinating Research Council AVFL 17-b study of light-duty diesel vehicles (Source 2) noted no discernable trend in NOx emissions associated with using an RD20 blend. It concluded that "any combustion process-related impacts on NOx emissions were likely overshadowed by the significant reductions from the advanced NOx aftertreatment controls leading to a lack of any significant differences in NOx emissions between fuels." Similarly, the results of the VTT study for the 2007 Iveco transit bus with SCR (Source 5) demonstrated a 22 percent NOx reduction when using RD100, but noted a significant increase in urea-injection rates with RD (12 to 16 percent), which could have been a significant contributor to these reductions.

This basic finding – that RD reduces NOx emissions when used in non-SCR engines as a replacement for petroleum diesel, but insufficient information exists about SCR engines – was essentially confirmed in CARB's 2015 "multimedia" report about RD. Testing cited in that report suggested that RD can provide reduced NOx emissions across a broad range of engine sizes and duty cycles, for any HDV or diesel engine that does not use SCR for NOx control.[81]

Further Discussion on Mechanisms for RD's Effects on NOx - In the 2016 UCR study done in conjunction with RD producer Neste Corporation (Source #4), the UCR research team proposed potential mechanisms

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[81] California Environmental Protection Agency, "Staff Report: Multimedia Evaluation of Renewable Diesel," prepared by the Multimedia Working Group, May 2015, http://www.arb.ca.gov/fuels/diesel/altdiesel/20150521RD_StaffReport.pdf.

for the measured decreases and increases in NOx emissions (relative to ULSD), with and without SCR aftertreatment. Lower NOx emissions observed on RD-fueled HDVs without SCR might be attributable to the lower adiabatic flame temperatures typically generated by fuels like RD with lower hydrogen-to-carbon ratios. RD's absence of aromatic hydrocarbons with high H/C ratios could result in lower adiabatic flame temperatures, reducing NOx formation in the cylinder. However, the higher NOx emissions observed in some test cycles may be one effect of RD's much higher cetane value, which promotes less delay at the onset of combustion. This may effectively advance the ignition timing, which leads to higher peak cylinder pressures and localized temperatures. This increases NOx formation. If the diesel engine could be optimized to take advantage of RD's higher cetane rating, this condition would likely be avoided or mitigated. Neste has been working with engineering firm FEV to look at possible benefits of optimizing diesel engines around RD's combustion characteristics. The key complication associated with this strategy is that heavy-duty engines must currently be geared around the dominant diesel fuel (ULSD), which has a much lower cetane rating than RD (see Section 6.7).

Another positive factor for reducing NOx formation in diesel engines may involve RD's lower volumetric energy density compared to ULSD (ranging from 3 to 5 percent lower). Modern diesel engines employ fuel injection maps that associate engine load and speed with fuel injection timing, which is based on the energy density of ULSD. When the engine is fueled by RD (or RD blends), the corresponding reduced energy density may cause the engine to operate at a different map point than would be observed for ULSD at the same throttle position. One potential manifestation would be a proportional under-fueling of the engine; this would lead to lower engine temperatures, resulting in reduced in-cylinder NOx formation.

However, for HDVs with SCR, these lower engine temperatures can also result in reduced exhaust temperatures that potential deactivate the SCR system, resulting in increased tailpipe NOx emissions under some operating conditions. Conversely, one researcher has suggested that the lower volumetric energy density of RD requires longer injector-on times than ULSD, at the same engine load. This lengthens the effective combustion time, despite the more rapid onset of combustion due to the higher cetane number, resulting in lower peak cylinder temperatures and reduced NOx formation.

Implications to Air Quality Strategies - While the specific mechanisms for RD's variable effects on NOx emissions remain unclear, the preponderance of experimental results indicate that RD consistently reduces NOx emissions from non-SCR equipped engines. However, the NOx benefits of RD in SCR-equipped engines remain unclear, and may be small relative to the effects of the aftertreatment system in any case. These conclusions are consistent with the assumptions used by CARB in its Mobile Source Strategy and associated Low-Emission Diesel (LED) Requirement. Under the LED requirement, CARB assumes that LED fuels (most of which would be RD) will reduce NOx emissions by 9 to 18 percent in non-SCR engines, but CARB assumes no NOx reductions in SCR-equipped engines.[82] Given that much of the on-road heavy duty fleet in California will be required to meet US EPA 2010 emissions levels by 2023 and that this will predominantly be achieved through the use of SCR-equipped engines, the greatest opportunity for NOx reductions from RD appears to lie in its use to fuel off-road HDVs and equipment that do not utilize SCR aftertreatment (i.e., the majority of diesel engines in this sector). This is fully consistent

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[82] https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdf

with the projections made by CARB for RD's use and NOx-reduction benefits under the State Implementation Strategy (as further described elsewhere).

Clearly, significant uncertainties exist about the specific mechanisms that dictate the effect of RD on NOx emissions from diesel HDVs/engines equipped with SCR systems. Given the major role that RD is expected to play in California by 2030 – especially in the South Coast Air Basin, which will serve as a test-bed for roll-out of RD as a means to reduce NOx and PM from diesel engines – there appears to be strong need to conduct additional emissions testing programs and research. This topic is further discussed in Section 6.6.

Table 4. Summary of NOx Emissions Results from Tests Conducted on HDVs Fueled by RD

| MY/Make/Model | NOx Emission Controls (+ Other) | Test Type | Results | Source |
|---|---|---|---|---|
| 2000 Caterpillar C15 | EGR | Chassis Dyno | Trend of decreasing NOx emissions with higher RD blend levels. 10-12% NOx reduction at RD50 and RD100 levels over UDDS. No statistically significant reductions over 50 MPH cruise cycle. | 1 |
| 2000 Caterpillar C15 | EGR | Chassis Dyno | Trend of decreasing NOx emissions with higher RD blend levels. ~7% reduction in NOx at RD100 level on UDDS test cycle. No statistically significant reductions over 50 MPH cruise cycle. | 3 |
| 2005 Scania DT 12 | EGR (+ DOC) | Engine Dyno | 5% NOx increase at RD100 level over Braunschweig (European) test cycle. | 5 |
| 2006 Volvo B7RLE/680 | SCR | Chassis Dyno | 5% NOx reduction with RD100 | 5 |
| 2005 Scania K230 UB4x2LB | EGR (+ DOC) | Chassis Dyno | 9% NOx reduction with RD100 | 5 |
| 2008 Scania K9 UB-B | EGR | Chassis Dyno | 4% NOx reduction with RD100 | 5 |
| 2007 Iveco Citelis Line | SCR (+CRT) | Chassis Dyno | 22% NOx reduction with RD100. Reductions were accompanied by a 12-16% increase in urea injection. | 5 |
| 2006 Cummins ISM | EGR | Engine Dyno | Trend of decreasing NOx emissions with higher RD blend levels. 3-18% NOx reduction at RD20 to RD100s over UDDS, FTP, and 50 MPH cruise tests. | 1 |
| Eight various 2012-2014 cars and trucks certified to Tier 2 Bin5 | SCR (+DPF/ DOC) | Chassis Dyno | No discernable trend in NOx emissions at RD20 blend levels. Fuel effects likely overshadowed by influence of SCR system | 2 |
| 2010 Cummins ISB 6.7 | SCR (+DPF/ DOC) | Chassis Dyno | 13% decrease at RD50, and 9% decrease at RD100 over UDDS cycle. Non-significant increases in NOx over HHDDT Transient cycle. | 4 |
| 2014 Cummins ISX 15 | SCR (+DPF/ DOC) | Chassis Dyno | 24% increase at RD50, and 21% increase at RD100 over UDDS cycle. Non-significant decreases in NOx over HHDDT Transient cycle. | 4 |

## 6.3. Particulate Matter (PM) Emissions and Associated Maintenance Cost Benefits

Summary of Results - Trends in PM emissions are similar to those observed with NOx emissions, with regard to the impact of advanced emissions controls. As can be seen from Table 5, engines not equipped with DPF technology exhibited major reductions in PM emissions when operating on RD blends. For pure RD (RD100), PM reductions for non-DPF engines ranged from 22 percent to 43 percent. In engines utilizing a DPF for PM control (and SCR for NOx control), the impacts of RD on PM emissions were inconclusive. Only one of the three studies showed PM reductions from RD-fueled engines that were equipped with DPF technology, and those results showed test-cycle dependency. Two of three reviewed studies found statistically significant increases in PM emissions when using RD. These studies did not differential between "passive" and "active" DPFs, but it not appear to be an important distinction is the context of tailpipe PM emissions.

Discussion on Mechanisms for RD's Effects on PM – The favorable qualities and combustion characteristics of RD (e.g., high cetane value, very low aromatics content) help RD combust more completely than petroleum diesel. This is responsible for the very significant reduction in engine-out PM emissions (CARB staff cite 29 percent, typically). However, for DPF-equipped diesel engines, RD appears to provide minimal incremental PM-reduction benefit, relative to using baseline ULSD.

A useful way to think about this is that DPFs filter PM from HDV exhaust streams with fixed efficiency, regardless of PM composition and mass concentrations at the filer inlet. Figure 20 helps illustrate the implications, and provide perspective. Consider as the baseline case a DPF-equipped HDV fueled by ULSD: the DPF is at least 90 percent efficient at reducing PM emissions from engine to tailpipe. Now, assume the engine is fueled by RD, resulting in a 30 percent reduction of engine-out PM before reaching the DPF inlet. The DPF provides an additional 90 percent reduction. The total PM reductions from engine to tailpipe would increase from 90.0 percent for the baseline case (ULSD + DPF), to 93.7 percent for the test case (RD + DPF). This represents a 3.7 percent improvement in overall PM-reduction efficiency compared to the baseline case.

While this incremental PM reduction at the tailpipe is *not insignificant*, it can be hard to even measure, and therefore quantify the real value. Modern diesel engines emit PM at levels near (or below) the detection limits of exhaust analyzers used in engine certification testing (some HDV engines now certify at 0.00 g/bhp-hr PM). Therefore, any actual changes in PM emissions from RD in a DPF-equipped engine could occur below the sensitivity of the analyzers, or be masked by test-to-test variability. This makes it hard to accurately assess and quantify RD's added PM reduction benefits on modern engines.

One important question is whether or not RD helps make diesel exhaust less toxic (with or without a DPF). This is a complex subject involving particle size and number, plus other factors that define diesel PM toxicity. There are some indications that RD may reduce the overall toxicity of diesel PM, but it appears that more testing and data are needed before drawing firm conclusions.[83]

Table 5. Summary of PM Emissions Results from Tests Conducted on HDVs Fueled by RD

| MY/Make/Model | PM Emission Controls (+ Other) | Test Type | Results (vs ULSD/EN590 Diesel) | Source |
|---|---|---|---|---|
| 2000 Caterpillar C15 | None (+EGR) | Chassis Dyno | Trend of decreasing PM emissions with higher RD blend levels. 26-33% PM reduction at RD50 and RD100 over UDDS. 22% reduction at RD100 level over 50 MPH cruise cycle. | 1 |
| 2000 Caterpillar C15 | None (+EGR) | Chassis Dyno | Trend of decreasing PM emissions with higher RD blend levels. 21-29% PM reduction at RD50 and RD100 over UDDS and 18-25% reductions over the 50 MPH cruise cycle. | 3 |
| 2005 Scania DT 12 | DOC (+EGR) | Engine Dyno | 17% PM reduction at RD30 blend level and 44% reduction at RD100 over Braunschweig test cycle without DOC. With DOC, PM reductions were 40% at RD100. | 5 |
| 2006 Volvo B7RLE/680 | None (+SCR) | Chassis Dyno | 30% PM reduction with RD100 | 5 |
| 2005 Scania K230 UB4x2LB | DOC (+EGR) | Chassis Dyno | 46% PM reduction with RD100 | 5 |
| 2008 Scania K9 UB-B | None (+EGR) | Chassis Dyno | 43% PM reduction with RD100 | 5 |
| 2007 Iveco Citelis Line | CRT (+SCR) | Chassis Dyno | 19% PM reduction with RD100 | 5 |
| 2006 Cummins ISM | None (+EGR) | Engine Dyno | Trend of decreasing PM emissions with higher RD blend levels. 12-34% PM reduction at RD50 and RD100 over UDDS, FTP, and 50 MPH cruise cycles | 1 |
| Eight various 2012-2014 cars and trucks certified to Tier 2 Bin5 | DPF / DOC (+SCR) | Chassis Dyno | No statistically significant changes in PM observed. Fuel effects likely overshadowed by high efficiency of PM filters. | 2 |
| 2010 Cummins ISB 6.7 | DPF / DOC (+SCR) | Chassis Dyno | Increases in PM emissions over the UDDS cycle and decreases in emissions over the HHDDT Transient cycle. | 4 |
| 2014 Cummins ISX 15 | DPF / DOC (+SCR) | Chassis Dyno | Substantial increases in PM emissions over both the UDDS and HHDDT Transient cycles. | 4 |

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[83] Personal communication from CARB staff to GNA, April 2017.

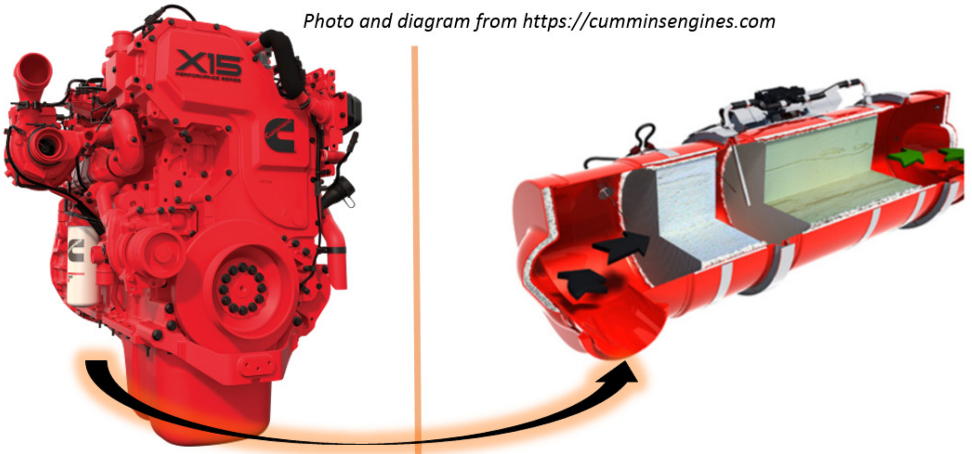

Photo and diagram from https://cumminsengines.com

| | | | |
|---|---|---|---|
| **ULSD + DPF Case:** | Engine-out PM from Cummins X15 diesel engine using ULSD = 10 mass units | 10 mass units of PM enter Cummins Particulate Filter; DPF reduces this by 90% = **1.00 mass units emitted at tailpipe** | **PM reduction from engine to tailpipe = 90.0%** |
| **RD + DPF Case:** | Engine-out PM from Cummins X15 diesel engine using RD = 7 mass units | 7 mass units of PM enter Cummins Particulate Filter; DPF reduces this by 90% = **0.63 mass units emitted at tailpipe** | **PM reduction from engine to tailpipe = 93.7%** |

Figure 20. Illustration of incremental PM-reduction benefits from RD in DPF-equipped diesel engines

RD's Beneficial Impacts on DPF Performance and Operational Costs – Preliminary information indicates that there is a very significant *cost-related* advantage of using RD in DPF-equipped vehicles. Multiple RD end users, HDV OEMs, and academic researchers have noted that RD-fueled HDVs can entail lower operational costs associated with maintaining proper operation of their passive and/or active[84] DPF systems. These claims have largely been anecdotal, although the authors were able to obtain one report (further described below) that corroborate this phenomenon with field data.

There is solid engineering basis to explain this claimed RD benefit. The much lower mass (~29 percent) of engine-out PM emissions when using RD significantly slows the rate at which PM accumulates in the DPF. Fleets using RD are reporting that this reduces the frequency needed for the filter to be "regenerated," which is the process that prevents the filter holes to become plugged and dysfunctional. For example, the Cummins Particulate Filter shown above consists of a diesel oxidation catalyst at the inlet (to reduce carbon monoxide and hydrocarbon emissions), followed by the PM filter itself. As the HDV is operated, trapped DPM accumulates on the filter, which must be oxidized (regenerated) into a gaseous state so it can flow out of the DPF. This regeneration process can be continual and "passive" as long as the HDV's operating conditions maintain sufficient exhaust temperatures.

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[84] There has been no information disseminated by end users about whether this observed phenomenon has helped improve DPF performance and/or DPF life for passive DPF systems, which are primarily found in retrofitted (non-OEM) systems used to comply with CARB's Truck and Bus regulation. In contrast to higher temperature active regeneration, passive regeneration uses normal exhaust temperatures and nitrogen dioxide (NO2) as the catalyst to oxidize PM in the DPF. It's likely that passive DPF systems also benefit from RD's reduction of engine-out PM emissions.

However, an "active" regeneration process is periodically required for vehicles that do not regularly achieve sufficient exhaust temperatures to initiate passive regeneration. Under optimal conditions, this process is automatically handled by the HDV's exhaust system, with little or no operator action required. Typically, the active regeneration process injects a small amount of fuel upstream of the DPF, which raises exhaust gas temperatures high enough to oxidize the trapped PM and burn it off the filter.[85] However, in some cases that can be routinely encountered by HDVs under certain duty cycles, an active DPF regeneration must be "forced" by the fleet operator. This requires taking the vehicle temporarily out of service, bringing it into a repair shop, and using special equipment to complete the forced regeneration.

CARB effectively corroborates how RD helps improve DPF performance and longevity by noting that a diesel engine that produces more soot (especially those that are poorly maintained) leads to filter plugging and or "more frequent cleanings." This can prevent the DPF from performing at its design level for PM filtration (approximately 90 percent). Thus, CARB cautions, "reducing soot from your engine reduces filter plugging and cleaning," Reducing engine-out soot is exactly the effect that RD provides when it is used in any diesel engine as a substitute for fossil diesel.

Based on end-user testimonials, it appears that RD's ability to reduce engine-out PM (by roughly 30 percent) is paying major dividends, by improving the performance and life of DPFs (both passive and active types). For example, end users are indicating that RD is helping to reduce, or possibly eliminate, the frequency of "forced" DPF regeneration events for original equipment active DPFs (which became essentially standard equipment with 2007 and newer HDVs). This significantly reduces operational costs.

While there is little hard quantitative data about this phenomenon, many fleets (as well as OEMs and RD suppliers) have touted this benefit. Perhaps the best documentation comes from the City of Knoxville (TN) Fleet Services. After obtaining 7,500 gallons of Neste RD from Louisiana, the City conducted a controlled test of using RD on five medium-duty trucks ranging from MY 2009 (DPF systems) to MY 2016 (DPF + SCR). The City's use of these trucks frequently does not enable their exhaust systems to reach optimal operating temperatures. The City reported that these engines had to undergo "excessive" forced DPF regenerations (once per week) when using petroleum diesel, requiring use of a special diagnostics tool in the repair shop. Over time, these excessive generation events led to extreme heat exposure on the vehicle exhaust systems, causing some DOCs and DPFs on City trucks to be damaged. The City also reported that:

> *The excessive regeneration (when using petroleum diesel) has promoted oil dilution, which causes premature bearing wear. It also caused excessive cylinder temperature which, over time, has caused the cylinder rings to become brittle and break. In 2016, the City fleet lost 5 engines due to these issues.*

By comparison, Knoxville reported no such problems with excessive DPF regeneration or wear during the course of its eight-week test on five HDVs using RD.[86] "Not a single test truck came into the shop for a forced regen during the two months of testing." By contrast, the City reported having to perform forced DPF regenerations on two of the test trucks within two weeks of switching them back to operate on ULSD.

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[85] Cummins Engine Company, "Cummins Particulate Filter: Meeting Low Emissions with the Right Technology, https://cumminsengines.com/cummins-particulate-filter.

[86] The City does not indicate what percentage of RD was purchased and used in the demonstration, but it was likely RD98 or higher.

Overall, the City reported a very positive experience using RD, with "no adverse side effects noticed, no reportable issues with performance of the vehicles, nor any fuel system related issues." The purchased RD proved to be completely miscible with the City's existing diesel storage and dispensing systems, corroborating its "drop-in" status. The City cited the "down sides" of RD to be its higher cost and limited availability, but noted that increased demand in that area of the country could help improve both issues.[87]

In sum, diesel engines without DPF systems -- such as those commonly used in pre-2007 trucks, and for most off-road applications -- are likely to exhibit very significant PM reductions when fueled by RD, owing to their higher baseline PM emission rates. However, for DPF-equipped HDVs and engines, the real-world impacts of RD on PM emissions appear to be negligible, or poorly understood. That said, RD can still provide a significant, tangible benefit for fleets with DPF-equipped HDVs. End users and RD stakeholders report that RD can improve DPF performance and decrease associated life-cycle costs, by significantly reducing the mass of PM emissions that flow into the DPF system for collection and oxidation. This valuable benefit is just beginning to be carefully documented and quantified (to the authors' knowledge).

## 6.4. Carbon Monoxide (CO) and Hydrocarbon (HC) Emissions

As summarized in Tables 6 and 7, respectively, tests show that emissions of carbon monoxide (CO) and total hydrocarbons (THC) generally decrease with increasing blends of RD. However, CO emissions can exhibit major swings that seem to be related to test cycle and percentage of RD blended with ULSD.

The 2014 UCR study (Source 2) noted that CO and THC reductions were most significant in DOC-equipped engines during cold starts. This is attributed to the fact that the catalyst is deactivated at the low exhaust temperatures present during cold starts. Hot starts and running emissions tests showed much reduced affects from RD content in the fuel. Other testing on a 2014 Cummins ISX engine showed no clear trend in CO emissions as a function of RD blend level over the UDDS or HHDDT Transient cycles (Source 4). For that same test program, both the 2014 Cummins ISX and 2010 Cummins ISB engines exhibited very low or negative CO emissions, suggesting that the efficiency of the DOC/DPF aftertreatment system was masking any effects from the RD content.

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[87] The City of Knoxville Fleet Services, "Renewable Diesel Test, FY 2017," obtained by GNA through Clean Cities Coalition contacts.

Table 6. Summary of CO Emissions Results from Tests Conducted on HDVs Fueled by RD

| MY/Make/Model | Emissions Controls | Test Type | Results | Source |
|---|---|---|---|---|
| 2000 Caterpillar C15 | EGR | Chassis Dyno | Trend of decreasing CO emissions w/ higher RD blend levels. 9-15% CO reduction at RD50 and RD100 over UDDS. 12-21% reduction at RD50 and RD100 over 50 MPH cruise cycle. | 1 |
| 2000 Caterpillar C15 | EGR | Chassis Dyno | Trend of decreasing CO emissions w/ high RD blend levels. 15% CO reduction over UDDS, 19% reduction over 50 MPH cruise cycle at RD100. | 3 |
| 2005 Scania DT 12 | EGR, DOC | Engine Dyno | 12% CO reduction at R30 blend level and 24% reduction at RD100 over Braunschweig test cycle without DOC. With DOC, CO increased approximately 9% at RD100. | 5 |
| 2006 Volvo B7RLE/680 | SCR | Chassis Dyno | 5% CO reduction with RD100 | 5 |
| 2005 Scania K230 UB4x2LB | EGR + DOC | Chassis Dyno | 78% CO reduction with RD100 | 5 |
| 2008 Scania K9 UB-B | EGR | Chassis Dyno | 42% CO reduction with RD100 | 5 |
| 2007 Iveco Citelis Line | CRT, SCR | Chassis Dyno | 13% CO reduction with RD100 | 5 |
| 2006 Cummins ISM | EGR | Engine Dyno | Trend of decreasing CO emissions with higher RD blend levels. 16-33% PM reduction at RD20 to RD100 over UDDS. 4-12% reductions at R20 to RD100 over FTP, and 3% increase in emissions at RD100 over 50 MPH cruise cycle. | 1 |
| Eight various 2012-2014 cars and trucks certified to Tier 2 Bin5 | DPF, SCR, DOC | Chassis Dyno | Approximately 5% CO reduction with RD20 blend with Federal ULSD. | 2 |
| 2010 Cummins ISB 6.7 | DPF, SCR, DOC | Chassis Dyno | Most tests showed emissions levels below the detection limit and no real fuel effects observed. 163% increase in CO emissions at R20 blend level over the UDDS. | 4 |
| 2014 Cummins ISX 15 | DPF, SCR, DOC | Chassis Dyno | 84% increase in CO emissions at R20 blend and 98% reduction at RD50 blend over UDDS. 42-116% CO reductions for R20 to R100 over the HHDDT Transient cycle. | 4 |

Table 7. Summary of HC Emissions Results from Tests Conducted on HDVs Fueled by RD

| MY/Make/Model | Emissions Controls | Test Type | Results | Source |
|---|---|---|---|---|
| 2000 Caterpillar C15 | EGR | Chassis Dyno | Trend of decreasing THC emissions with higher RD blend levels. 22% THC reduction at RD100 over UDDS. No statistically significant reductions in THC over 50 MPH cruise cycle. | 1 |
| 2000 Caterpillar C15 | EGR | Chassis Dyno | Trend of decreasing THC emissions with higher RD blend levels. 20% and 23% THC reductions over UDDS at RD50 and RD100, respectively. No statistically significant reductions over 50 MPH cruise cycle. | 3 |
| 2005 Scania DT 12 | EGR, DOC | Engine Dyno | 20% THC reduction at R30 blend level and 35% reduction at RD100 over Braunschweig test cycle without DOC. With DOC, THC emissions were below detection limits for all fuels, including ULSD and RD. | 5 |
| 2006 Volvo B7RLE/680 | SCR | Chassis Dyno | 61% THC reduction with RD100 | 5 |
| 2005 Scania K230 UB4x2LB | EGR + DOC | Chassis Dyno | 65% THC reduction with RD100 | 5 |
| 2008 Scania K9 UB-B | EGR | Chassis Dyno | 24% THC reduction with RD100 | 5 |
| 2007 Iveco Citelis Line | CRT, SCR | Chassis Dyno | 100% THC reduction with RD100 | 5 |
| 2006 Cummins ISM | EGR | Engine Dyno | 3% to 12% reduction in THC emissions over UDDS cycle for RD20 to RD100. No statistically significant changes over FTP and 50 MPH cruise tests. Use of "winter blend" may have reduced apparent THC reductions as a "summer blend" showed THC reductions in prior tests. | 1 |
| Eight various 2012-2014 cars and trucks certified to Tier 2 Bin5 | DPF, SCR, DOC | Chassis Dyno | Approximately 24% NHMC reduction with RD20 blended with Federal ULSD. (Similar reductions if blended with CARB ULSD.) | 2 |
| 2010 Cummins ISB 6.7 | DPF, SCR, DOC | Chassis Dyno | All tests showed emissions levels below the detection limit and no real fuel effects observed due to the efficiency of the DOC. | 4 |
| 2014 Cummins ISX 15 | DPF, SCR, DOC | Chassis Dyno | 49% reduction in THC emissions at RD50 blend over UDDS. No statistically significant effects at RD20 or RD100 blends. 74% and 62% THC reductions for RD50 and RD100, respectively, over HHDDT Transient cycle. | 4 |

## 6.5. $CO_2$ Emissions and Fuel Economy

Across all reviewed studies, neat RD and RD blends resulted in decreased tailpipe $CO_2$ emissions. However, RD also resulted in decreased volumetric fuel economy. The reviewed studies reported that decreases for both tailpipe $CO_2$ emissions and fuel economy were in the range of 3 to 5 percent.

These laboratory test findings are consistent with RD's fuel properties compared to ULSD. Due to its paraffinic nature, neat RD has lower carbon-specific and volumetric energy densities than Federal or California ULSD. Table 8 summarizes these differences, as reported for the emissions testing carried out by UCR in 2014 (Source 2). The RD measured (for this program) had a carbon-specific energy density that was 4 to 5 percent higher than CA and Federal ULSD, respectively. This is a positive attribute; it means RD has more energy per pound of fuel-borne carbon, resulting in lower tailpipe $CO_2$ emissions. However, the tested RD also had a lower volumetric energy density than CA and Federal ULSD, by 5 to 6 percent, respectively. It is this RD attribute that translates to slightly reduced fuel economy of RD-fueled vehicles (miles per gallon) or engines (operating time per gallon).

It has been reported that some RD end users (existing and potential) have expressed concern that RD's lower volumetric energy content significantly reduces HDV fuel economy, which increases fuel costs relative to using ULSD, and/or decreases vehicle range. However, this appears to be a relatively minor concern rather than a significant barrier to RD's wide-scale use to replace ULSD.

Table 8. Comparison of RD100's carbon content and energy density to ULSD

| | | **Federal ULSD** | **CA ULSD** | **RD100** |
|---|---|---|---|---|
| **Carbon Content Comparison** | | | | |
| Carbon Content by Mass | % C | 86.75% | 86.55% | 85.07% |
| Mass-Specific Energy Density | BTU/lb | 18,417 | 18,590 | 18,964 |
| Carbon-Specific Energy Density | BTU/lb C | 21,230 | 21,479 | 22,292 |
| RD100 **Carbon-Specific Energy Density** Change vs Federal ULSD | | - | - | +5.0% |
| RD100 **Carbon-Specific Energy Density** Change vs CA ULSD | | - | - | +3.8% |
| **Volumetric Energy Density Comparison** | | | | |
| Density | lb/gal | 7.10 | 6.93 | 6.47 |
| Volumetric Energy Density | BTU/gal | 130,695 | 128,785 | 122,785 |
| RD100 **Volumetric Energy Change** vs Federal ULSD | | - | - | -6.1% |
| RD100 **Volumetric Energy Change** vs CA ULSD | | - | - | -4.7% |
| *Fuel properties as reported by Karavalakis 2014 (Source #2). Some RD properties (e.g., Volumetric Energy Density) may vary batch to batch, depending on feedstock, production process, and if any ULSD is blended.* | | | | |

## 6.6. The Need for Additional RD Emissions Testing and Research

As noted, the current scientific body of data and information about RD's effects on 2010-compliant on-road engines is relatively limited. Given the projected volumes of RD that are likely to be consumed in California by 2030 and beyond, there is clear need to develop a more-robust body of test data and literature. This is needed to fully assess RD's impacts on NOx and PM emissions from modern diesel vehicles (on- and off-road). Future testing should include a broad range of test cycles, particularly those that result in lower exhaust temperatures and reduce the effectiveness of SCR aftertreatment systems.

Fortunately, the California Energy Commission has joined with SCAQMD, CARB, and Southern California Gas Company to design such a new study, for implementation starting in 2017. The project team is retaining the services of UCR/CE-CERT and West Virginia University (WVU) to conduct emissions testing on a large sample of in-use HDVs. The two universities will conduct in-use emissions testing, characterize fuel usage profiles, develop new or improved test cycles, and assess the impact of both fuel type and emissions control technology on HDV fuel consumption and in-use emissions. All test vehicles will have gross vehicle weight ratings of at least 14,000 lb.

As shown in Table 9, the proposed project will involve up to 200 on-road heavy-duty vehicles used in goods movement, local delivery, refuse, transit bus, and school bus applications. At least six different fuel-technology platforms will be tested, including HDVs powered by internal combustion engines fueled by RD and equipped with SCR-DPF systems. The engines will be categorized into six groups including natural gas engines certified at or below 0.2 g/bhp-hr NOx, engines certified at or below 0.02 g/bhp-hr NOx, diesel engines certified at or below 0.2 g/bhp-hr NOx, diesel engines without selective catalytic reduction, dual fuel engines and alternative fuel engines (hybrid and fully electric technology).[88]

Table 9. Preliminary test matrix for 2017 in-use HDV testing program

| Test Vehicle Type | Number of Test Vehicles | Test Fuels |
|---|---|---|
| Class 7 and 8 Tractors | 100 | ULSD, **RD**, natural gas, renewable natural gas, hybrid electric, battery electric |
| Deliver Trucks | 40 | |
| Refuse Trucks | 30 | |
| School and Transit Buses | 30 | |
| **TOTAL** | **200** | |

## 6.7. RD's Potential Role to Help Diesel Engines Achieve a Near-Zero NOx Level

As described, CARB has adopted various interrelated regulations and strategies designed to sharply reduce both NOx and GHG emissions by 2030. It appears possible (if not likely) that sales in California of new HDVs powered by ICE technology will not be allowed by 2024 unless they emit at (or below) the near-zero-NOx level of 0.02 g/bhp-hr and use renewable fuels to minimize life-cycle GHG emissions. To date, heavy-duty spark-ignited natural gas engines fueled by RNG provide the only certified, commercially available combination that meet both parts of this tandem requirement. At least one medium-duty propane engine appears to be on the verge of being certified at the near-zero-NOx level, although renewable propane does not yet exist as a commercial transportation fuel.

As described in this paper, RD is already commercially available for use in diesel engines. It offers certified pathways in California and Oregon with carbon intensity values that are 30 to 90 percent below petroleum diesel. Thus, RD is doing its share on the GHG-reduction side to ensure that diesel engines can provide the necessary environmental performance likely to be needed to perpetuate California sales well into the

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[88] South Coast Air Quality Management District, "Near-Zero Heavy-Duty Engines and In-Use Emissions Testing Program Update," presentation to Clean Fuels Advisory Group, September 1, 2016, http://www.aqmd.gov/docs/default-source/technology-research/clean-fuels-program/clean-fuels-program-advisory-group---september-1-2016/near_zero_hd_engine_update_aoshinuga.pdf?sfvrsn=11.

21st century. However, it remains to be seen if/when – and at what cost – OEMs will be able to develop and certify heavy-duty diesel engine technology at the near-zero-NOx level of 0.02 g/bhp-hr. One of the major challenges is that ultra-low-NOx diesel engines also need to meet federal requirements for tailpipe GHG emissions. There are significant NOx-GHG tradeoffs to overcome as OEMs seek to achieve the 0.02 g/bhp-hr NOx level and federal GHG requirements. Encouragingly, major government-industry efforts led by CARB, CEC and SCAQMD are underway by to develop advanced ultra-low-NOx diesel engines, and important progress is being realized. However, there is no consensus among officials at these agencies that heavy-duty diesel engines will certify at the near-zero-NOx level in the foreseeable future.

This raises the question about what role, if any, RD can play in helping OEMs manage NOx-GHG tradeoffs and develop and certify new heavy-duty diesel engines that meet near-zero-NOx levels and very low tailpipe GHG levels. As described, RD offers beneficial combustion characteristics compared to petroleum-based ULSD. These include:

- A higher cetane value (35 to 40 percent), which can potentially help improve combustion and resolve NOx-PM tradeoffs
- A near-zero sulfur content, which can provide better catalyst performance and durability
- A lower carbon content by weight, which can help reduce tailpipe $CO_2$ emissions

In theory, at least, it appears that OEMs could optimize their heavy-duty engine development efforts around these beneficial qualities of RD (especially its higher cetane value), to help achieve near-NOx levels while also meeting GHG emission limits. On the light-duty diesel vehicle side, Neste commissioned a recent European study by FEV (a leading emissions engineering company) to assess if “optimizing engine control parameters” in a diesel passenger car around RD’s favorable combustion characteristics could improve performance and emissions. Neste reports that FEV documented significant improvements for both emissions and engine efficiency. However, it appears FEV only measured engine-out emissions (i.e., upstream of the test vehicle’s aftertreatment systems for NOx and PM),[89] and it’s already documented that RD reduces engine-out NOx and PM emissions. Thus, it’s unclear if this Neste-commissioned FEV study sheds any additional light about the potential to optimize heavy-duty engines around RD’s combustion characteristics to achieve the near-zero-NOx level of 0.02 g/bhp-hr, while also meeting GHG emission limits.

The authors of this white paper discussed this issue independently with a heavy-duty engine OEM, CARB staff, academic researchers and other industry stakeholders. The basic finding is that heavy-duty OEMs do not have the resources or motivation to optimize their engines around alternative diesel fuels like RD. OEMs need their engines to work well for the properties of standard diesel fuel (federal or California ULSD), which have a much lower cetane rating (as low as 40, but typically in the 50s). For now at least, RD is intended to be a drop-in fuel that can be combusted by any diesel engine, in varying mixes with ULSD. As of mid-2017, no sensor exists that would make it practical for heavy-duty engines to identify RD’s much higher cetane value, and then shift the engine map mode to optimize operation and emissions

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[89] Neste Corporation, “Optimizing engine for renewable diesel reduces fuel consumption and emissions,” press release, May 17, 2017, https://www.neste.com/en/optimizing-engine-renewable-diesel-reduces-fuel-consumption-and-emissions.

around that property. OEMs must be focused on ensuring that their engines operate optimally on the existing fuel pool, within the limits of commonly encountered variance in specifications.

While it's true that RD can help engines reduce tailpipe GHG emissions because it has a 2 to 4 percent lower carbon content by weight, this does not necessarily help OEMs manage NOx-GHG tradeoffs in the certification process. Unless they were to certify their engines on RD (which would not happen in the current fuel market), OEMs would not be able to take credit for RD's tailpipe $CO_2$-reduction benefits under EPA's "Phase 2" GHG rulemaking. This further points out the challenges of relying heavily on fuel-based strategies to achieve near-zero-NOx levels in diesel engines.

Finally, heavy-duty engine OEMs don't have clear motivation to commit major resources towards achieving the very low NOx level of 0.02 g/bhp-hr. No such standard exists, except as a voluntary certification level under CARB's optional low-NOx standard. Presumably, if CARB and/or EPA adopt a future mandatory NOx standard of 0.02 g/bhp-hr, OEMs will evaluate all available practicable means to achieve that standard. This would likely include further assessing the role that RD could play, if it becomes a widely available replacement for ULSD.

## 6.8. Summary and Assessment

The above test results and findings lead to the general conclusion that RD provides significant NOx and PM exhaust emission reductions from heavy-duty engines and vehicles that are not equipped with state-of-the-art emissions controls. CARB applies this finding in its Mobile Source Strategy, by assuming that RD will reduce NOx by 13 percent and PM by 29 percent (on average) from non-SCR/non-DPF off-road vehicles and equipment.[90] CARB estimates that statewide, 8.0 tons per day of NOx and 1.0 tons per day of PM2.5 will be reduced from off-road diesel engines by 2031 through application of its proposed LED regulation.[91] RD is expected to be the leading LED fuel used under this regulation. It appears that any NOx and PM emission reductions from RD use in the off-road sector can and will be used as SIP credits, i.e., to officially meet California's requirements towards attaining and/or maintaining NAAQS.

However, for RD's use in modern diesel engines that incorporate SCR and DPF technology, it appears prudent to assume that emissions benefits will be insignificant or nonexistent. In particular, it appears that the NOx emission impacts of RD in SCR-equipped heavy-duty vehicles and engines remain unresolved, with insufficient data to definitively conclude that RD provides NOx-related benefits or dis-benefits. The only two studies to date (UCR Sources 2 and 4) that evaluated RD use in EPA 2010-complant engines (those with SCR) suggest that RD's NOx emission implications in such engines may be masked by other factors (such as the selected test cycle) that determine the SCR system's NOx-conversion efficiency. They generally support a preliminary conclusion that RD itself has no significant impact on NOx emissions from modern SCR-equipped HDVs, except to the possible extent that the fuel changes the engine map in a way that impedes SCR performance and could actually increase NOx emissions.

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[90] California Air Resources Board, "Workshop on Mobile Source Strategy Discussion Draft," staff presentation, October 16, 2015, https://www.arb.ca.gov/planning/sip/2016sip/wkshp_presentation.pdf.

[91] California Air Resources Board, "Mobile Source Strategy," May 2016, see Table 4: Statewide Expected Emissions Reductions, https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdfSip.

Therefore, at least until further information and data are available, California's air quality management districts should be very conservative when estimating the potential NOx-reduction benefits associated with using RD in the on-road heavy-duty diesel vehicle sector. This is consistent with CARB's assumptions for the emissions impacts of using RD as modeled for California's Mobile Source Strategy and State Implementation Plan.

However, heavy-duty off-road vehicles and engines, which are much less likely to use SCR-DPF exhaust aftertreatment systems, can provide very significant NOx and PM reduction benefits when using RD. The consistent trends of emissions benefits for non-SCR/DPF on-road HDVs (across a wide range of engine displacements, emissions standards, and test cycles) suggest that most off-road engines will demonstrate similar benefits when using RD. ARB recognizes this potential in its documents such as the MSS, Multimedia Assessment on RD, and efforts to quantify the criteria pollutant reduction benefits of the draft LED regulation. Because the LED regulation falls within CARB's MSS and SIP, NOx and PM reduction benefits from RD will be "SIP creditable," in terms of progress and attainment plans that must be submitted by individual air districts. As with on-road vehicles and engines, ARB assumes no NOx benefits when RD is used in SCR-equipped off-road engines.

Little is currently documented about RD's potential role to help diesel engines achieve the near-zero-NOx level of 0.02 g/bhp-hr, which has already been achieved by advanced natural gas and propane engines (with or without renewable fuel). Theoretically, RD's superior fuel qualities over ULSD -- especially its very high cetane rating -- could help heavy-duty engine OEMs manage NOx-GHG tradeoffs, and develop advanced diesel engine technology capable of being certified at the near-zero-NOx level of 0.02 g/bhp-hr. The difficulty of such a strategy is that ULSD, with a much lower cetane value, is the dominant fuel around which OEMs must optimize and certify their engines. Moreover, there appears to be no obvious current motivation for OEMs to focus their diesel engine development efforts on near-zero-NOx levels, and/or employ emissions strategies around RD's beneficial qualities. That could change, if 1) CARB or EPA adopt a mandatory 0.02 g/bhp-hr NOx standard, and/or 2) RD becomes a mainstream, widely available alternative to petroleum diesel in a major transportation market like California.

# 7. Potential Implications to Air Quality in California Air Basins

## 7.1. South Coast Air Quality Management District

Ambient Air Quality Status and Air Quality Management Plan for NAAQS Attainment

The South Coast Air Basin (SCAB) is categorized as an "extreme" nonattainment area for the federal 8-hour ozone NAAQS. Through its 2016 Air Quality Management Plan (AQMP), SCAQMD demonstrates how it will achieve ozone NAAQS attainment in the SCAB by 2023 for the 1997 8-hour ozone standard, and by 2031 for the 2008 8-hour ozone standard. The 2016 AQMP also demonstrates how the region will achieve, as expeditiously as possible, the 2012 annual $PM_{2.5}$ NAAQS.

As indicated in Figure 21, to achieve these milestones, SCAB NOx emissions must be reduced 45 percent (relative to the baseline) by 2023, and 55 percent by 2031.

Mobile source categories are the predominant source of SCAB NOx emissions, which are the main precursor to ozone formation. In the SCAB, about 28 percent (144 tpd) of total NOx emissions comes from heavy-duty diesel trucks. Off-road equipment (73 tpd) and ships / commercial boats (47 tpd) are the next-largest NOx emitters. These same three categories – which are powered almost exclusively by heavy-duty compression-ignition engines – also emit large quantities of $PM_{2.5}$ in the SCAB.

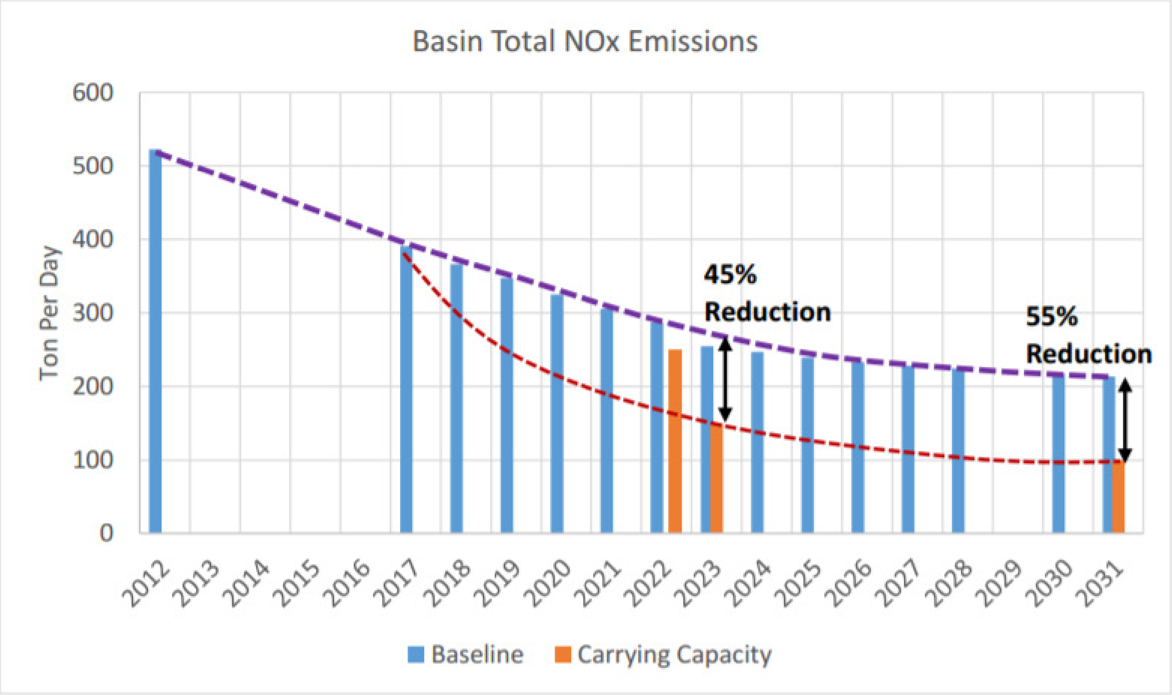

Figure 21. SCAB total NOx emissions with baseline and ozone carrying capacity (SCAQMD)

In total, mobile sources contribute about 88 percent of the SCAB's total NOx emissions. SCAQMD has limited authority to regulate mobile sources, so it works closely with CARB, EPA and other government agencies to systematically reduce transportation-related NOx emissions. As recognized in the 2016 AQMP, "a coordinated suite of measure concepts" are being applied by CARB, EPA and SCAQMD to reduce NOx from mobile sources, with a focus on heavy-duty vehicles, off-road equipment, and high-horsepower applications like marine vessels and locomotives that are primarily regulated by federal and international sources.

A key need identified by SCAQMD in its 2016 AQMP is to rapidly transition the SCAB's on-road HDV fleet to near-zero-emission and zero-emission fuel-technology platforms. In mid-2016, SCAQMD joined with BAAQMD and 17 other local and state air quality agencies across the nation to petition EPA to adopt a more-stringent nationwide on-road heavy-duty engine NOx standard. These petitions call for a NOx standard of 0.02 g/bhp-hr, or 90 percent lower than the existing federal standard. It was recommended that the regulation be implemented by January 2022, or if not feasible by January 2024, with a phase-in starting in January 1, 2022. A national standard is estimated to result in NOx emission reductions from this source category from 70 to 90 percent in 14 to 25 years, respectively.

In responding to the these petitions in late 2016, EPA acknowledged the need to continue reducing NOx emissions from new heavy-duty on-road HDVs. EPA noted that sufficient technical progress has been made to significantly reduce NOx emissions beyond the existing (2010) federal standards. Consequently, EPA stated intent to work closely with CARB and consider issuing a Notice of Proposed Rulemaking for a potential near-zero-NOx standard that could take effect by the 2024 model year. This timing would align with key milestones imposed under EPA's heavy-duty Phase 2 GHG program.[92]

In addition to pushing for this near-zero-NOx federal standard, SCAQMD's 2016 AQMP identifies several other policy objectives that can help the SCAB meet air quality goals while minimizing adverse impacts to the regional economy. Examples related to expanded use of RD in the SCAB include, but are not limited to, the following:

- Eliminate reliance on future technologies (the so-called "black box" provision of the Clean Air Act) to the maximum extent possible, by providing specific control measures that rely on commercially available fuels and technologies with quantifiable emission reductions and associated costs.
- Calculate and take credit for co-benefits from other "parallel and complementary" planning efforts, such as other local, state and federal efforts that are addressing GHG reductions, improved energy efficiency, and lower-emission transportation technologies.
- Invest in strategies and technologies meeting multiple objectives regarding air quality, climate change, air toxics exposure, energy, and transportation. Prioritize strategies that meet fast approaching deadlines and assist EJ impacted areas.

### Existing and Potential Future Role of Renewable Diesel in the SCAB

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[92] U.S. Environmental Protection Agency, "Petitions for Revised NOx Standards for On-Highway Heavy-Duty Engines and Trucks, https://www.epa.gov/regulations-emissions-vehicles-and-engines/petitions-revised-nox-standards-highway-heavy-duty.

It's likely that a large portion of the 250 million RD gallons being used today in California's transportation sector are being dispensed and/or consumed in the SCAB. The largest users of RD are probably goods movement HDV fleets. For example, UPS fuels and domiciles a large HDV fleet in the SCAB, and uses this area as a test bed for the many types of alternative fuels and technologies it is demonstrating. In addition, it's likely that State fleets such as Caltrans, as well as local municipalities, are operating significant numbers of HDVs on RD in the SCAB.

However, in terms of private and public fleets in California that have publicly declared making a switch to RD, more are located in Northern California and San Diego County. The fact that fleets in the SCAB are less visible as RD users may be attributable to SCAQMD's "1190 fleet rules," which SCAQMD adopted to gradually shift public and certain private fleets away from diesel fuel, towards clean-burning alternative fuels (primarily natural gas). Adopted in 2000 and 2001, SCAQMD initially developed these fleet rules to address findings made in its original Multiple Air Toxics Exposure Study (MATES) study, which found that excess cancer risks in the SCAB associated with breathing polluted ambient air in southern California was 1400 in one million. The excess cancer risk was primarily driven (75 percent) by ambient levels of diesel exhaust. To reduce human exposure to diesel exhaust, SCAQMD's Governing Board adopted the Source Specific (Regulation XI) series of Fleet Rules. These "1190 fleet rules" essentially preclude routine use of diesel (whether fossil or renewable) in a wide array of HDV uses and applications, including transit buses, public fleets, refuse collection vehicles, school buses and street sweepers.[93]

SCAQMD's 2016 AQMP does not specifically discuss replacing RD for conventional diesel fuel in the SCAB as an emissions-reduction strategy. However, the AQMP does include discussion about CARB's potential Low-Emission Diesel (LED) regulation, as one means to reduce HDV emissions from the portion fleet that will continue to be powered by ICE engines. Recognizing the SCAB's key role as a test-bed for CARB's LED requirement, the AQMP states that "the magnitude of needed NOx reductions" in the SCAB "and the large volumes of Low-Emission Diesel needed for full statewide implementation" require that CARB's proposed LED measure "be phased-in with a gradual implementation strategy that starts in the Basin, and subsequently expands Statewide."

CARB has noted that the specific emissions reductions that the LED rule can potentially deliver in the SCAB (or other California air basins) will be determined by a combination of factors. These include 1) the ultimate level of penetration for HDVs using the various types of LED fuels, and 2) the relative composition of "legacy" and newer fleet vehicles. As previously noted, CARB assumes that RD will constitute most of the LED fuel used to implement its LED rule, and most of the NOx and PM reduction benefits from its LED rule will be realized from "older diesel vehicles and off-road equipment."[94] Neither agency estimates the number of diesel HDVs or equipment that will contribute to such reductions. Roughly, it appears that there are approximately 7.2 million off-road vehicles and equipment operating in the SCAB today.[95]

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[93] Input for this paragraph comes from 1) South Coast Air Quality Management District, "Fleet Rules, http://www.aqmd.gov/home/regulations/fleet-rules; and 2) personal communications to GNA from SCAQMD staff, August 2017.

[94] California Air Resources Board, "Mobile Source Strategy, Appendix A: Economic Impact Analysis, May 2016, https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc_appA.pdf.

[95] South Coast Air Quality Management District, "Off-Road Equipment: 2016 White Paper," October 2015, Table 2, http://www.aqmd.gov/docs/default-source/Agendas/aqmp/white-paper-working-groups/wp-offroad-final.pdf?sfvrsn=2.

This represents a very large number of in-use off-road HDVs and equipment, most of which are powered by diesel engines. However, CARB's estimated NOx reductions from potentially operating a large portion of these HDVs and equipment on RD appears to be relatively small. As estimated by CARB and acknowledged in SCAQMD's 2016 AQMP, CARB's LED requirement will reduce NOx emissions in the SCAB by 0.3 tpd. This is about 1.4 percent of the total NOx reductions that CARB-enforced State SIP measures will obtain from off-road equipment in the SCAB by 2023.[96] Reductions of $PM_{2.5}$ from use of RD in the SCAB under CARB's LED regulation will also be relatively small on a tonnage basis, but it's important to acknowledge that the overall toxicity of the PM that will be emitted is likely to be significantly reduced.[97]

It's not clear at this early stage how approximately one billion RD gallons targeted for sale in the SCAB by 2030 under CARB's potential LED regulation will be distributed and dispensed in a way that ensures most of the fuel will be combusted in off-road vehicles. As the LED regulation notes, RD use in this sector will generally produce the greatest NOx and PM reductions, because off-road engines are generally not equipped with SCR and DPF technology for NOx and PM control, respectively. But, it is clear that any RD that does get dispensed into on-road diesel HDVs will be assumed to provide no significant NOx- or PM-reduction benefits.

One important RD-related consideration for SCAQMD (and other air districts) relates to its potential use under "indirect source" and/or facility cap regulations. California Health and Safety Code Section 40716 states that air districts can "adopt and implement regulations to reduce or mitigate emissions from indirect and area-wide sources of air pollution". An indirect source refers to any building, structure, installation, etc. that "attracts mobile source activity" and results in any emissions of regulated pollutants. According to SCAQMD, "examples of indirect sources include residential housing, entertainment centers, shopping malls, historical tourist attractions, amusement parks, parking lots, commercial office facilities, airports, ports, warehouse/distribution centers, schools, etc." Reducing emissions from new indirect sources could entail regulations, incentives, and hybrids of the two. One potential approach is to implement facility limits (caps) oriented around total emissions, cancer risk, or emissions per unit of activity.[98]

SCAQMD has previously adopted indirect source regulations, and is actively assessing potential future regulations focused on mobile source activity centers like marine ports, warehouse distribution centers, and airports. Presumably, part of a new regulation could involve requirements and/or incentives for diesel engines to switch to RD if they are operated in association with a given indirect source. This could make a compelling and cost-effective indirect source rule, if SCAQMD could obtain average NOx and/or PM reductions of 13 and 29 percent, respectively.

However, to be effective, the rule would have to focus RD use on diesel-engines that are not equipped with advanced emission control systems (SCR for NOx, DPFs for PM). Examples might include commercial

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[96] South Coast Air Quality Management District, "Final 2016 Air Quality Management Plan," Table 4-5, March 2017, http://www.aqmd.gov/home/library/clean-air-plans/air-quality-mgt-plan/final-2016-aqmp

[97] Personal communication from CARB staff to GNA, April 6, 2017.

[98] South Coast Air Quality Management District, "Discussion on Facility Cap Concepts and Indirect Source Review," Governing Board Retreat, May 7, 2015, http://www.aqmd.gov/docs/default-source/default-document-library/governing-board/2015-board-retreat-agenda-item-6.pdf?sfvrsn=4.

harbor craft (such as tugboats or crew boats) and cargo handling equipment. Notably, this would be a shorter-term strategy. Its efficacy would depend, in part, on 1) whether the focus is on RD use in legacy (in-use) or new HDVs and diesel engines, and 2) the degree to which near-zero-emission or zero-emission technologies are commercially available.

For air districts like SCAQMD to consider using RD as a potential indirect source strategy, it seems essential that any resulting NOx and/or PM reductions would to "SIP creditable." Based on preliminary input received from CARB staff on this issue, use of RD in off-road vehicles (not equipped with SCR-DPF technology) would in fact qualify for SIP credits. This seems to be corroborated by CARB's inclusion in the SIP of its draft LED Regulation, which specifically targets NOx and PM reductions by using RD in such off-road equipment.[99]

## 7.2. Bay Area Air Quality Management District

### Ambient Air Quality Status and Air Quality Management Plan for NAAQS Attainment

The greater San Francisco Bay Area experiences relatively good air quality compared to most other large urban areas in California. This is largely due to its close proximity to the Pacific Ocean, and the area's prevailing wind patterns. Still, the Bay Area does not yet fully attain state and national ozone standards -- even as the BAAQMD has led significant progress over several decades to reduce ozone precursor emissions. Similarly, the average cancer risk from toxic air contaminants (TACs) has been greatly reduced in the Bay Area, but localized exposure to TACs remains unacceptably high, especially for people in disadvantaged communities that are disproportionately impacted.

In April 2017, BAAQMD approved its 2017 Clean Air Plan.[100] The Plan's overarching objective is to "lead the (Bay Area) to a post-carbon economy, to continue progress toward attaining all State and federal air quality standards, and to eliminate health risk disparities from exposure to air pollution among Bay Area communities." The Plan includes a comprehensive strategy of 85 proposed control measures to simultaneously reduce ozone and fine particle pollution, reduce air toxics, and meet the State's long-range GHG reduction targets. It lays out a "bold vision" for the Bay Area in 2050 that includes a transportation system "based on EVs and renewable diesel." Priorities for the Plan include reducing criteria pollutants and toxic air contaminants from all sources (including diesel PM from on- and off-road equipment), decreasing fossil fuel combustion, and increasing renewable energy (including development of local production capacity).[101]

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[99] Personal communication to GNA from Alexander Mitchell, CARB, August 2017.

[100] Bay Area Air Quality Management District, "Final 2017 Clean Air Plan, adopted April 19, 2017, http://www.baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf?la=en.

[101] Bay Area Air Quality Management Plan, "Draft 2017 Clean Air Plan: Spare the Air, Cool the Climate;" presentation to Board of Directors by Henry Hilken, Director of Planning and Climate Protection, March 1, 2017, http://www.baaqmd.gov/~/media/files/board-of-directors/2017/bod_presentations_030117-pdf.pdf?la=en.

As is the case in the SCAB, DPM from HDVs continues to represent the leading airborne cancer risk in the Bay Area. When TAC emissions are weighted based upon their cancer risk, mobile sources of diesel emissions account for most of the cancer risk associated with TACs in the Bay Area. On-road mobile sources and construction equipment together account for 60 percent of the total cancer-risk weighted emissions (see Figure 22). In sum, while DPM emissions have declined substantially over the past 15 to 20 years as a result of CARB regulations and BAAQMD programs to reduce emissions from diesel engines, this ubiquitous pollutant still "greatly dominates the cancer risk from TACs."[102]

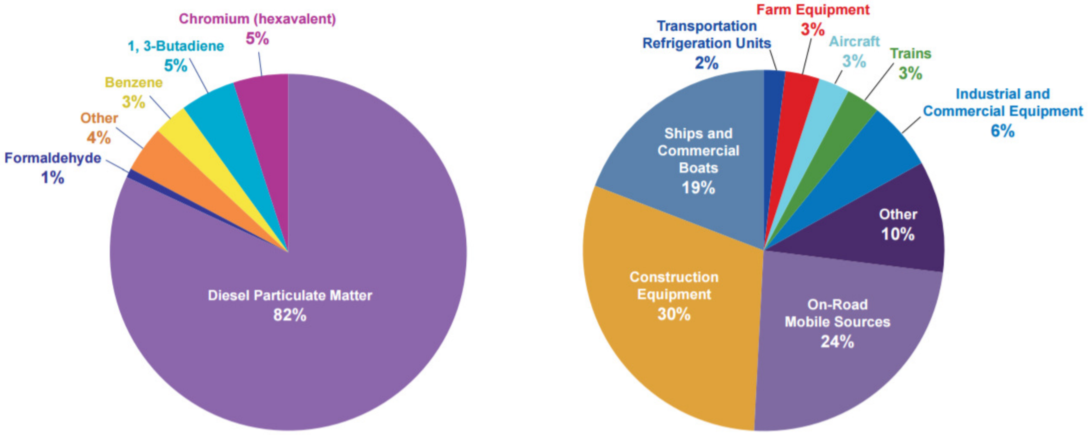

Figure 22. Bay Area cancer-risk weighted emission estimates by TAC type (L) and source category, 2015

BAAQMD also seeks to reduce black carbon (BC) emissions in the Bay Area. In addition to being a component of PM that harms public health, BC is a Short-Lived Climate Pollutant (SLCP), which means it is an especially impactful GHG targeted by CARB for major statewide reductions as soon as possible. Diesel engines and wood burning devices (fireplaces and stoves) are the leading sources of BC in the Bay Area. While local BC emissions have been cut by more than 50 percent since 1990, they are "projected to increase beyond 2020 in the absence of additional control measures, as Bay Area population increases and the number of diesel engines in service grows."

In sum, BAAQMD seeks to implement a wide array of control measures, regulations and policies under the Bay Area's 2017 Clean Air Plan. The Plan specifically calls out large-scale use of RD as part of its "bold vision" to achieve ambient air quality and climate change goals. Some of the specific goals that potentially involve expanded RD use include:

- Prioritize reducing particulate matter (including DPM in the Bay Area's most diesel-impacted areas), by reducing diesel engine emissions (SS32, TR18 and TR19)
- Enact measures to replace diesel-powered vehicles with zero emission HDVs powered by clean electricity or other renewable fuels

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[102] Bay Area Air Quality Management District, "Final 2017 Clean Air Plan, adopted April 19, 2017.

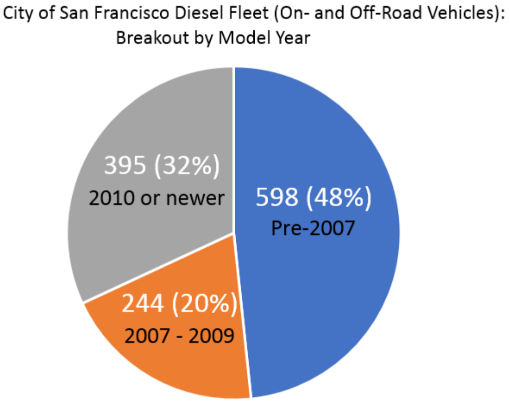
- Replace diesel-fueled equipment (e.g., pumps, tractors, trucks) with cleaner and more efficient alternatives, such as electricity and biofuels
- Rely on State and federal regulations for to reduce NOx and DPM emissions form off-road diesel construction equipment
- Continue to work with Bay Area ports and the neighboring communities to reduce emissions from the freight sector, including heavy-duty trucks, ships and locomotives.
- Promote the use of advanced technology, zero- or near-zero emission vehicles in all vehicle types and applications.

Existing and Potential Future Role of Renewable Diesel

The Bay Area is already serving as a national test-bed for RD use in HDVs. As previously summarized, several Bay Area cities are now operating large numbers of HDVs on RD, including San Francisco, Oakland, and Walnut Creek.

Notably, San Francisco appears to be using the largest RD volumes, by a significant margin. The City is already using RD in a wide array of on- and off-road HDVs, and is also exploring the potential for ferry operators to benefit from switching to RD. A closer look at the City of San Francisco's existing RD use in on-road HDVs helps shed light on the GHG and criteria pollutant reductions that may be typical when a large city fleet transitions from ULSD to RD.

The City provided high-level fleet data to the authors of this report. San Francisco's municipal fleet currently consists of 1,234 on- and off-road diesel-powered vehicles. This includes 658 on-road medium- and heavy-duty trucks, 46 buses (non-transit), and 128 off-road "heavy" pieces of diesel equipment. On-road vehicles comprise 73 percent of the fleet. In addition, SFMTA is operating 986 transit buses on RD, using the same supply as the City fleet.



**Source:** City of San Francisco, April 2017

Figure 23. Breakout by age: City of SF's diesel fleet

The average age in the City's diesel fleet is approximately 13 years. This means that a many of the vehicles and equipment are not likely to be <u>factory-equipped</u> with state-of-the-art emissions control systems for NOx and PM. In fact, as Figure 23 shows, 598 (48 percent) of the City's diesel vehicles/equipment are pre-2007 model year. (This figure excludes SFMTA's transit buses.) In other words – regardless of whether they are on- or off-road -- at least 598 diesel-powered vehicles and equipment in the City's 1,237 unit fleet are not be equipped with factory SCR-DPF systems for NOx and PM control. Notably, most (if not all) of the City's on-road diesel vehicles have been retrofitted with aftermarket DPFs to control PM emissions as required under CARB's "Truck and Bus" Regulation.[103] However, it appears likely that at least 75 percent of the City's diesel fleet does not have SCR for NOx control.

San Francisco has been using RD in this entire diesel-powered municipal fleet for several years. Most of the City's RD supply is made by Neste in Singapore from tallow feedstock. Additionally, some the City's RD comes from Diamond Green Diesel in Louisiana, also from tallow feedstock. The average CI value of the City's RD supply is estimated to be approximately 30 gCO2e/MJ.[104] The City's diesel fleet of 1,234 vehicles / equipment, combined with SFMTA's 986 transit buses, collectively consume 6 million RD gallons per year. By using neat RD (probably RD99) instead of ULSD, the City is reducing GHG emissions from this entire fleet by approximately 67 percent. Unlike criteria pollutant benefits, these GHG reductions are based on RD's "upstream" benefits (i.e., those associated with processes to extract feedstock, produce RD, and transport it for end use). The same 67 percent GHG reduction (for this particular RD supply, relative to ULSD) accrues regardless of what vehicle/equipment type uses the fuel.

It is a more-complex process to accurately calculate the criteria pollutant benefits that the City is achieving by switching this fleet from ULSD to RD. All reductions in NOx and/or PM are assumed to occur at the tailpipe. (A "full-fuel-cycle" assessment would be even more complex, and is generally not performed for criteria pollutant benefits.) As described in this report, such reductions (if any) will be dependent on vehicle age, duty cycle and other factors. Broadly speaking and in rough terms, it can be reasonably assumed that the City of San Francisco is reducing NOx by 13 percent and PM by 29 percent for every vehicle it operates on neat RD (instead of ULSD) *as long as the HDV is not equipped with SCR and DPF technology*. Notably, few remaining on-road HDVs in the City's fleet are likely to NOT be equipped with DPFs, since CARB's Truck and Bus regulation required DPF retrofits by 2015. Thus, criteria pollutant benefits associated with using RD in the City's diesel fleet most involve NOx reductions.

As a simplistic example to estimate part of the NOx-reduction benefits, consider the City's fleet of 653 medium- and heavy-duty diesel trucks (53 percent of the total diesel fleet). Of these, 443 are 2009 model year or older; therefore, they are not equipped with SCR systems to reduce NOx. By using RD in those 443 medium- and heavy-duty trucks, it can be assumed that the City is achieving a NOx-reduction benefit of approximately 13 percent compared to using the baseline ULSD.

Using CARB's 2014 EMFAC data for Bay Area "public trucks"[105] and applying the assumed 13 percent NOx reduction that RD delivers in non SCR HDVs, it is estimated using RD in these 443 older medium- and heavy-duty trucks reduces seven NOx from the City's HDV fleet by about 7 to 8 tons per year.

This magnitude of NOx reduction is significant, and it definitely helps BAAQMD get closer to achieving ozone attainment. However, this is relatively small in relation to the major NOx reductions (measured in tons per day) needed to restore healthful air quality in California's nonattainment areas for ozone and/or

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[103] CARB's Truck and Bus Regulation applies to in-use on-road heavy-duty diesel vehicles, and requires those that operate in California to be "upgraded" with DPFs to reduce PM. Effectively, starting in January 2015 most in-use on-road diesel HDVs were required to receive DPF retrofits.

[104] Personal communication to GNA from Zac Thompson, San Francisco Department of the Environment, June 16, 2017.

[105] CARB EMFAC 2014, emissions factors for 2009 MY public trucks used in the BAAQMD.

PM2.5. Still, these NOx reductions – as well as whatever PM reductions are also achieved – are quite significant as "collateral benefits" that RD can offer throughout California. Reducing any amount of PM emitted from diesel HDVs directly mitigates street-level exposure to cancer-causing DPM, which is a very important public health benefit, especially in the downtown areas of cities like San Francisco that routinely experience very large pedestrian traffic. According to CARB, DPM represents about 70 percent of the total known cancer risk related to air toxics in California, and "elevated DPM levels are mainly an urban problem." [106]

A key caveat for these criteria-pollutant benefits of RD is that the City's older trucks have limited remaining useful life. Over the next five years, they will likely be replaced with new diesel trucks equipped with SCR-DPF emissions control systems, or possibly with 1) near-zero-NOx natural gas engines fueled with RNG, or 2) zero-emission battery electric trucks. Thus, these NOx and PM benefits are short lived. As described in Section 7, CARB assumes there are no criteria pollutant reduction benefits when using RD in HDVs that have SCR systems and/or DPFs. However, the NOx and PM reduction benefits will continue to be available for most off-road vehicles and equipment for many years.

Putting all this together, the City of San Francisco's switch to RD for its diesel fleet is paying very important dividends. The City is simultaneously achieving major GHG reductions, as part of its own climate action plan and California's overall efforts to address climate change. The City is also helping to attain / maintain ozone and $PM_{2.5}$ standards, and reducing human exposure to carcinogenic, toxic air contaminants like DPM. This is all being accomplished with very little incremental capital investments over the baseline choice of using ULSD. In fact, for the City's diesel vehicles that are equipped with DPF systems (which will continue to grow), it is likely already realizing important costs savings related to reduced DPF maintenance and improved durability. This appears to be a compelling benefit.

As long as Bay Area end users such as San Francisco, Oakland, Walnut Creek and UPS can obtain RD at (or near) cost parity with ULSD – i.e., LCFS and RFS credits continue to be available –fleets are likely to continue shifting their ULSD operations over to RD. However, long-term RD supply may be a limiting factor. As discussed in the next section, there are significant challenges associated with expanding RD supply, even in California with attractive economics for both producers and end users. Moreover, the long-term supply of RD that will be available for California HDV's and equipment appears to be largely targeted for use in the SCAB, under CARB's draft Low-Emission Diesel regulation.

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[106] California Air Resources Board, "Estimated Health Effects of DPM in California, https://www.arb.ca.gov/research/diesel/diesel-health.htm.

# 8. Challenges and Barriers to Wider Use of RD in California

It's clear that both CARB and EPA acknowledge RD's advantages and benefits as a heavy-duty transportation fuel, compared to both petroleum diesel and biodiesel. Both agencies favor significant expanded use of RD in America's transportation sector. Annual demand for RD by 2030 in California alone could reach nearly two billion gallons, which is roughly an order of magnitude greater than the current supply available to the state. To achieve this magnitude of RD supply in California within next 15 years, significant challenges and barriers must be addressed and overcome. Some of these key challenges are briefly discussed in this section; a comprehensive assessment is beyond the scope of this report.

## 8.1. Limited Feedstock Availability and/or Competing Feedstock Uses

As EPA, CARB and other stakeholders have noted, the key limitation to expand national RD use is its "limited production capacity . . . in the United States and abroad."[107] There are several factors that currently play roles to limit RD's growth potential, particularly as a major replacement for ULSD in diesel engines that power California's high-impact goods movement system. These include limited domestic feedstock availability; competition for the same feedstock to produce biodiesel or other renewable hydrocarbon fuels (e.g., jet fuel); low production and import capacity; and some constraints on the ability to distribute, sell, and use increasing RD volumes. As EPA recently noted, the recent strong growth of RD's supply for use in the U.S. transportation sector "is not without limit in the near term." [108]

Environmental organizations have expressed concerns that domestic production of biofuels like RD are inadequate to meet growing demand. For example, projections made for the Union of Concerned Scientists and the International Council on Clean Transportation in mid-2015 indicated that the U.S. does not have adequate domestic feedstock supplies to meet current biofuel needs. The U.S. already overly relies on imported feedstocks to meet biofuel demand, and increased mandates (i.e., RFS2's latest call for at least 2.1 billion gallons of RD and biodiesel, combined) will cause the U.S. to increase its reliability on imported biofuel like RD. [109] The specific concern is that imported RD is more likely to be produced through non-sustainable and/or environmentally damaging feedstock and processing. These stakeholders noted that EPA's new RFS standards for advanced biofuels would likely result in RD (and biodiesel) producers "turning to greater use of palm oil as a substitute" feedstock (see next subsection).[110]

CARB has specifically commented on the availability of tallow (from animal rendering), which is currently the leading feedstock for RD sold in California (and the U.S.). Part of CARB's concern has been that there are competing uses for tallow, including for biodiesel production, that may cut significantly into its availability to produce RD. CARB summed the issue up that "additional availability of tallow feedstocks

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[107] U.S. EPA, response to comments from United States Canola Association on RFS standards for 2017, November 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PV0A.pdf.

[108] U.S. EPA, response to comments on RFS standards for 2017, November 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PV0A.pdf.

[109] "Projections of U.S. Production of Biodiesel Feedstock," Wade Brorsen (Oklahoma State University), report prepared for Union of Concerned Scientists and the International Council on Clean Transportation, July 2015, http://www.ucsusa.org/sites/default/files/attach/2015/07/Brorsen-RFS-Biodiesel-Feedstock-Analysis.pdf.

[110] U.S. EPA, response to comments on RFS standards for 2017, November 2016.

are not certain, as most of the U.S. supply of tallow may not be available to RD production, and international tallow is already being drawn to the U.S. in large amounts." The National Renderers Association has also acknowledged that tallow used to make RD can face periodic supply and demand issues and in the U.S.[111] However, one strength of RD is that is can be made from a wide diversity of fatty acid feedstocks. In the long-term, it appears that CARB expects soy oil to become the dominant RD feedstock in California, [112] although currently soy-based RD appears to play no role for RD that is generating credits under the LCFS.

Neste, the world's largest RD producer, has pointed out some of the key constraints it faces in expanding RD production. These include ongoing volatility in vegetable oil markets, which has prompted the company to further explore using "lower quality waste and residue feedstock" in production facilities such as Rotterdam. Neste notes that a number of factors are expected to continue causing market volatility in feedstock prices, which can have negative impact on the profitability of producing RD.[113] To address this, Neste continues to expand its "raw material portfolio" for producing RD, with short-term focus on waste animal fats (e.g., sheep tallow), waste oils (e.g., used cooking oil), and other "residue and side streams." In addition to a broad feedstock portfolio, Neste is pursuing multiple RD production pathways, with long-term focus on three different pathway types: 1) biological, 2) thermos-catalytic, and 3) photosynthesis.

## 8.2. Non-Sustainable and/or Controversial Feedstock

Concerns about the use of non-sustainable, environmentally damaging feedstock to produce RD are closely related to potential RD shortages in America to meet growing demand. In particular, the use of palm oil to produce RD (or other biofuels) is controversial. Palm oil, which is now the world's most common vegetable oil,[114] is made from the fruit of the African oil palm tree. This species can be grown successfully in any humid tropical climate, and it is widely cultivated in places like Malaysia and Indonesia. In addition to being a feedstock to make RD and biodiesel, palm oil is used to make a wide range of food products, soaps, cosmetics and pharmaceuticals.

While palm oil creates significant commercial value, its harvesting processes are associated with numerous negative impacts, and it is a controversial biofuel feedstock. Organizations such as the Union of Concerned Scientists (UCS) and the International Council on Clean Transportation (ICCT) have cited commercial palm oil cultivating and harvesting as a major cause of deforestation in sensitive tropical and subtropical parts of the world, where the oil palm tree thrives. This has resulted in strong environmental damage and biodiversity reduction, especially in Indonesia and Malaysia. For example, UCS cites the "huge source of global warming emissions" associated with the process to drain and burn carbon-rich peatland swamps during the palm oil cultivation process. In addition to the carbon that is released, peatland burning releases criteria pollutants and toxic air contaminants. UCS indicates that palm oil production

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[111] "Market Report," Kent Swisher, Vice President, International Programs, National Renderers Association, Render Magazine, April 2015, https://d10k7k7mywg42z.cloudfront.net/assets/55281d9ec0d6715235004d2e/MarketReport2014.pdf.

[112] California Air Resources Board, "Biomass-Based Diesel as a Transportation Fuel: Staff Discussion Paper," February 8, 2016, https://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/02102017discussionpaper_bdrd.pdf.

[113] Neste Corporation, 2016 Financial Statement, https://www.neste.com/na/en/nestes-financial-statements-release-2016.

[114] Union of Concerned Scientists, "Palm Oil," http://www.ucsusa.org/global_warming/solutions/stop-deforestation#.WUBk2lXytEY.

also takes a very large toll on biodiversity, with vulnerable species that include orangutans, tigers, rhinoceros, and elephants. Additionally, UCS and other organizations cite palm oil production as being responsible for human rights violations in parts of the world like Indonesia and Malaysia, with the hardest impact being on poor indigenous peoples and rural communities.[115]

As the world's leading RD producer, Neste is at the forefront of this need to avoid producing RD from palm oil or other controversial feedstock. According to Neste, 79 percent of its worldwide RD production comes from waste and residue streams (i.e., not plants like the African palm tree). Some portion of the remaining 21 percent (unknown to the authors) is currently produced from palm oil feedstock. However, it appears that no significant portion of the RD that Neste imports to the U.S. (most of which goes to California) is derived from palm oil. Neste is reportedly working hard to completely eliminate use of palm oil as an RD feedstock.

Data from the LCFS seem to corroborate that RD from palm oil is not being consumed in California today. LCFS statistics indicate that 97 percent of 2016 RD-related credits were based on fuel "derived from wastes and residues rather than conventional crop-based fuel credit generation." Records indicate that RD from "other feedstock" generated a small portion of LCFS credits in 2016. However, there are no pathways for palm-based RD that are certified in the current LCFS pathways. The same is true in neighboring Oregon, which has its own low-carbon fuel program. In the absence of important credit revenue streams like the LCFS, this makes it further unlikely that any significant volume of palm-based RD is being distributed in California or Oregon.

It's not hard to see why the LCFS has no RD pathway based on palm oil. Due to the above-described indirect land use impacts, RD produced from palm oil can actually have a higher carbon-intensity rating than petroleum diesel. Outside of the influence of the California and Oregon low-carbon-fuel programs, there may be greater likelihood that RD made from palm oil could be sold. In Washington State, where interest in RD is beginning to blossom, the Western Washington Clean Cities Coalition (WWCCC) now advises potential RD users to avoid fuel made from palm oil. WWCCC notes that palm oil can have higher GHG impacts than the federal ULSD it would replace, in addition to its strong association with tropical deforestation in Southeast Asia. Thus, WWCCC cautions HDV fleets to "be wary of palm-based fuel" and purchase "domestically-produced fuel derived from used cooking oil, plants or tallow."[116]

## 8.3. Unknowns or Uncertainties on Engine Impact

Acceptance of RD by major American heavy-duty diesel engine and vehicle manufacturers continues to grow. It does not appear that there are any "show stoppers" for wide-scale use of neat RD in virtually any type of diesel engine or application. However, there are some unknowns and uncertainties, and certain

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[115] Union of Concerned Scientists, "Palm Oil," http://www.ucsusa.org/global-warming/stop-deforestation/drivers-of-deforestation-2016-palm-oil#.WUWOclXytEY.

[116] Western Washington Clean Cities Coalition, "4 Things You Should Know About Renewable Diesel," http://wwcleancities.org/4-things-you-should-know-about-renewable-diesel/.

engine OEMs like Cummins have not yet fully endorsed RD in all their North American engine offerings. Biofuel experts at the National Renewable Energy Laboratory (NREL) have noted the following engine- and vehicle-related challenges about RD's potential to become a major HDV fuel in America:[117]

- Possible issues for "elastomer swell" on fuel wetted parts
- Lubricity must be addressed with additives – similar to conventional ULSD
- Little data exists about impacts on diesel engines equipped with modern emissions control systems

It's important to note that documented use of RD in high-horsepower off-road diesel engines has been nearly non-existent, at least in North America. While there does not seem to be special reason for concern, RD's specific impacts when used in large-bore medium- or slow-speed engines that power locomotives and marine vessels are not well known. This is likely to cause caution on the part of marine vessel and locomotive fleets to make the switch, even when told that RD can be trusted as a "drop-in" replacement for petroleum fuel. For example, the City of San Francisco has been in discussions with Bay Area ferry line operators about switching ferry boats from ULSD to RD, as one contribution to meeting San Francisco's GHG-reduction goals. The ferry operators have cited preliminary concerns about negative impacts on the diesel engines that power these vessels.

### 8.4. Market and Regulatory Uncertainty

The major challenge to unlock the full potential of RD as a major transportation fuel is the higher cost to produce it, which is closely related to feedstock type and availability. Until RD can be produced with cost parity to petroleum diesel, it will be important to sustain the monetized value brought to RD transactions by California's LCFS and the federal RFS. Prices / values for RINs and LCFS credits are determined by regulations and market forces, both of which are subject to unforeseen changes. All of this creates market uncertainty, which makes it more difficult to attract investors for RD-production projects. Clearly, due to policy-related uncertainties about the California LCFS and federal RFS2, there are no guarantees about the longevity of their associated monetary incentives for RD production and use.

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[117] National Renewable Energy Laboratory, "Renewable Diesel Fuel," Robert McCormick and Teresa Alleman, July 18, 2016, https://cleancities.energy.gov/files/u/news_events/document/document_url/182/McCormick___Alleman_RD_Overview_2016_07_18.pdf.

# 9. Conclusions and Recommendations

## 9.1. Conclusions

Renewable diesel (RD) is doing its part to help ensure that heavy-duty vehicles (HDVs) with diesel engines can achieve the level of environmental performance needed to perpetuate their sales well into the 21st century. Any on-road HDV fuel-engine platform that will be sold in California beyond the 2030 timeframe will likely be required by the California Air Resources Board (CARB) to 1) achieve (at a minimum) near-zero-emissions of key air pollutants (especially oxides of nitrogen, or "NOx"), and 2) use a low-carbon-intensity renewable fuel. Although not all RD feedstock and production pathways offer reduced carbon intensity, RD used in California's transportation sector achieves a volume-weighted carbon intensity rating that is about 66 percent lower than petroleum diesel (ultra-low sulfur diesel, or ULSD). This "drop-in" replacement for ULSD is already delivering major greenhouse gas (GHG) reductions, with RD consumption in California's transportation sector now exceeding *a quarter of a billion gallons per year*.

Thus – provided RD is made from environmentally benign feedstocks (as discussed in this report) – the fuel-related need for the diesel engine's future is being fully achieved today.

However, such "upstream" GHG reductions are only part of the benefits needed from heavy-duty diesel engines for California to meet its aggressive air quality and climate change goals. As CARB has clearly indicated, any on-road HDV fuel-engine platform that will be sold in California beyond the 2030 timeframe will need to 1) achieve (at a minimum) *near-zero-emissions* of criteria pollutants (especially the ozone-precursor NOx), and 2) use a low-carbon-intensity renewable fuel. With RD already meeting the fuel-side of this requirement, it appears that the long-term future of heavy-duty diesel engines in California rests on the ability for the engine technology itself – possibly in combination with a hybrid-electric drivetrain – to achieve near-zero-emissions status. This is generally defined to be a NOx certification level at or below 0.02 g/bhp-hr, which has already been achieved by commercially available heavy-duty natural gas engine technology. When fueled with widely available renewable natural gas, near-zero-NOx heavy-duty natural gas engines are also delivering deep GHG reductions.

Notwithstanding these challenges for diesel engines to compete into the future as very-low-emitting technology, RD is enabling a "better side" of diesel technology, by delivering immediate and compelling societal benefits. Switching from petroleum-based ULSD to RD is already providing major reductions in GHG emissions – along with significant collateral benefits to improve ambient air quality – in numerous California cities that include San Francisco, Oakland, San Diego and Los Angeles.

This emergence of RD as the most-promising clean, renewable compression-ignition fuel has occurred because it offers significant advantages over both ULSD and biodiesel fuel. RD is very similar to petroleum-derived ULSD in physical and chemical characteristics. As such, it can be directly used in existing diesel-powered vehicles, while requiring no engine or fuel infrastructure modifications – even when used in its "neat" form (RD100). While not yet universally accepted by heavy-duty engine OEMs and their trade organization (EMA), there appear to be no technical "show stoppers" for RD to be widely substituted for ULSD as the main fuel for on- and off-road HDVs. It has a high cetane number and other beneficial qualities for compression-ignition engines, which enable RD to help reduce "engine-out" emissions of criteria pollutants and GHGs, while providing near-equivalent vehicle performance and fuel efficiency. RD can be produced from a wide array of renewable feedstocks using existing oil refinery capacity; thus, extensive new production facilities will not be required for expanded RD use.

It is clear that the growing number of major fleets in California that already use RD are quite favorable about their experience. They note that RD provides a major and immediate strategy for their HDV fleet to achieve major GHG reductions, with no significant new capital expenditures associated with specialized vehicles or fuel storage and dispensing infrastructure. Although RD costs significantly more to produce, these fleets are able to acquire it in California at roughly the same price as ULSD. Moreover, they are finding that RD can provide reduced operational costs when used on-road HDVs (and some off-road equipment) that are equipped with DPFs. This is because RD's improved combustion reduces engine-out emissions of DPM, which must be trapped by the DPF and burned off in a process that can be costly and reduce DPF life. Although more needs to be documented about this phenomenon, engineering judgement suggests that both "active" and "passive" DPF systems significantly benefit from using RD.

For all these attributes, it is not uncommon to hear end users refer to RD as a "wonder fuel." Clearly, it can offer important benefits for end users, and society as a whole – especially with regard to the long-term GHG reductions RD provides. However, RD does not constitute a <u>widely impactful or sustainable strategy</u> to improve ambient air quality in California (or the broader U.S.). Its ability to help reduce smog-precursor emissions and toxic air contaminants is limited by the breadth of mobile source applications for which it can provide such benefits, and the time frame over which they can be derived. This is because (based on limited but robust test data) RD does not significantly reduce NOx and PM emissions from diesel engines that are equipped with state-of-the-art emission control systems.

In sum, the compelling GHG-reduction benefits of RD can be realized over the longer-term – across all diesel engine applications. RD's benefits to improve ambient air quality are also significant and cost effective, but they will become negligible over time. Across America, RD can serve as a drop-in replacement for ULSD in the millions of "legacy" (in-use) on-road HDVs and off-road vehicles that are <u>not equipped</u> with advanced aftertreatment systems. Specifically, when RD fuels diesel engines that don't use selective catalytic reduction (SCR) technology to control NOx, it appears to reduce NOx emissions on average by about 13 percent. When RD fuels diesel engines that don't use diesel DPF technology to control PM, it appears to reduce PM emissions on average by about 29 percent.

This will likely prove to be the most important air quality benefit of RD in California, especially in the South Coast Air Basin (the greater Los Angeles area). As described in this White Paper, CARB's proposed "Low-Emission Diesel" (LED) regulation seeks to direct more than a billion gallons of RD per year specifically to fuel heavy-duty off-road vehicles operating in the SCAB, to help reduce their NOx, PM and GHG emissions. CARB has noted that the specific emissions reductions that the LED rule can potentially deliver in the SCAB (or other California air basins) will be determined by a combination of factors. These include 1) the ultimate level of penetration for HDVs using the various types of LED fuels, and 2) the relative composition of "legacy" and newer fleet vehicles. CARB assumes that RD will constitute most of the LED fuel used to implement its LED rule, and that NOx and PM reduction benefits that will result from its use will primarily be realized "in older diesel vehicles and off-road equipment."

Statewide, CARB estimates that 8.0 tons per day of NOx and 1.0 tons per day of $PM_{2.5}$ will be reduced from off-road diesel engines by 2031 through application of its proposed LED regulation. It appears that any NOx and PM emission reductions from RD use in the off-road sector will be used as SIP credits, i.e., to officially meet California's requirements towards attaining and/or maintaining NAAQS.

In the SCAB where CARB's LED regulation will initially focus on increased use of RD, there are approximately 7.2 million in-use off-road HDVs and equipment, most of which are powered by diesel engines. As in the Statewide case, the estimated NOx reductions from potentially operating a large portion on RD appears to be relatively small – approximately 0.3 tpd (1.4 percent) of the total NOx reductions that CARB-enforced State SIP measures will obtain from off-road equipment in the SCAB by 2023. Reductions of $PM_{2.5}$ from use of RD in the SCAB under CARB's LED regulation will also be relatively small on a tonnage basis. However, it's important to acknowledge that any reductions in ground-level emissions of DPM can provide important human health benefits, and the overall toxicity of the PM emitted by HDVs using RD is likely to be significantly reduced. As such, expanded RD use in the SCAB strongly reinforces SCAQMD's long and successful history (e.g., its landmark Fleet Rules) of reducing human exposure to cancer-causing DPM emissions.

In the Bay Area, which has served as an initial test bed for the use of RD in HDVs, cities like San Francisco and Oakland are achieving very significant GHG reductions by substituting RD for conventional petroleum-derived ULSD. For example, San Francisco is consuming approximately six million gallons of RD, to fuel its fleet of approximately 2,300 HDVs with RD that is available at all 53 of the City's diesel fuel stations. In addition, the City is exploring the potential to collaborate with Bay Area ferry operators to test out RD in marine vessel applications. Oakland now fuels all of its diesel vehicles and equipment with RD, with annual consumption of approximately 230,000 RD gallons (about one third of the transportation fuel consumed by the City's total fleet). Both cities are getting compelling GHG-reduction benefits from RD use, while also getting important "collateral" benefits in the form of reduced NOx and PM reductions that contribute to progress in attaining or maintaining health-based NAAQS. One potential application of RD worth further exploration would be to see if its use could help the Port of Oakland drayage truck fleet improve durability and reduce the failure rate of DPFs in the fleet.

In sum, the GHG reductions associated with RD use in California are major, compelling and will last as long as RD replaces petroleum-derived fuel to power the State's large heavy-duty transportation sector. Collateral reductions in NOx, PM and toxic air contaminants will also be important for their contributions to improve ambient air quality, especially in the SCAB. Gradually (over decades), all in-use diesel engines in the SCAB and throughout California will incorporate advanced emission controls like SCR and DPFs. This will phase out any benefits RD can contribute to reduce NOx and PM emissions in California. At the same time, near-zero-emission and zero-emission technologies will more deeply penetrate into the transportation sector, replacing diesel engines.

It is clear that more studies are needed to better characterize the complex dynamics of how using RD in HDVs impacts NOx and PM emissions. A good start is the new program now being planned by CEC, SCAQMD and other entities, where a large number of in-use HDVs will be emissions tested on a variety of fuels, including RD and baseline ULSD.

There is sufficient volume of RD being imported into California today to meet growing demand. However, ability to meet future demand is less certain. Today, at least 60 percent of the estimated 400 million gallons per year of RD consumed in America is being used to fuel HDVs in California. Most of this RD is being imported into California by ship from Asia, with smaller volumes delivered by rail from domestic producers in Louisiana. Over the next decade, RD demand in California is expected to grow by (roughly) an order of magnitude. Specifically, if adopted as expected, CARB's LED rule will help create RD demand in California by 2030 that may approach two billion gallons per year. In preliminary assessments, CARB has identified multiple feasible pathways that can technically and economically meet such demand. CARB estimates that 2.6 billion gallons of RD supply for California will be possible by 2030. Relatedly, CARB's biofuels supply module (see Section 5.2) projects in-State demand for RD if the Low Carbon Fuel Standard (LCFS) carbon intensity reduction target is increased from 10 to 18 percent. Under this "18 percent scenario," the maximum RD demand that CARB projects is 2.312 billion gallons by 2050, but this assumes that LCFS credits reach their maximum value of $200 per MT of CO2e. The projected RD demand dwindles all the way down to 76 million gallons by 2050 if LCFS credits sell for $80, which is only about 10 percent less than the mid-2017 value.

Notably, these types of estimates by CARB about future demand and supply of RD are intentionally designed to provide reasonable scenarios, but they are not meant to make hard projections.

It's clear that California's LCFS (and a similar program in Oregon) provide strong incentive for the production and use of low-carbon transportation fuels like RD. However, outside these markets, it can be very hard to obtain RD. National demand for RD appears to already be outstripping supply, especially in the eastern U.S. where some major HDV fleets like UPS and the NYC Department of Sanitation have not been able to purchase enough RD. When it is obtainable, RD can cost as much more than petroleum diesel, especially when purchased in small volumes. This can make RD unaffordable to corporations and government fleets as a GHG-reduction strategy.

As with other renewable fuels, supply availability is the most-significant constraint for expanding RD use into HDV transportation markets. In addition to availability of monetary mechanisms to offset higher production costs, RD supply will be linked to feedstock issues and competition from other markets. Unlike biodiesel, the RD refining process can be controlled to produce different renewable products; these include jet fuel and bio-based chemicals such as naphtha. This makes it more likely that there will be competition from biofuel markets other than on-road HDVs, some of which may be more profitable. Further, in the event that other regions (states or nations) adopt aggressive programs to incentivize low carbon fuels, the ability to deliver RD into these markets may significantly change its supply chain dynamics for California.

In sum, the challenges that make the RD-supply picture uncertain include 1) the relatively small capacity of current domestic RD production (particularly in California, the greatest RD market); 2) competing uses for RD's major feedstocks, and 3) concerns about non-sustainable and/or environmentally harmful feedstocks. Importantly, RD and biodiesel share the same feedstock, and EPA considers both to be biomass-based diesel fuels. Taking the various factors into account about supply constraints, EPA has set a goal under the RFS for 2.0 billion gallons of BBD to be produced in 2017, and increasing to 2.1 billion gallons in 2018. This includes both RD and biodiesel, and based on fuel producer estimates, only about 26 percent of this will be RD.

Barring a major change with the LCFS and RFS programs, California districts like SCAQMD and BAAQMD will experience increasing use of RD, well beyond the estimated quarter-billion gallons that are currently being consumed under LCFS-covered transportation applications. This fuel will continue to be used in a wide array of heavy-duty diesel engines for both on- and off-road applications. However, it appears that a shift may occur over the next decade, especially if there are constraints on RD supply. In effect, the San Francisco Bay Area along with San Diego County seem to be leading the way today as national testbeds for early RD consumption, with the primary focus (to date) being on-road HDVs. However, it appears that over the coming decade, CARB's draft LED rule will shift RD's focus to the SCAB. This will essentially be a larger-scale test-bed of RD's use that is primarily dedicated to the SCAB's heavy-duty off-road vehicles and equipment.

## 9.2. Recommendations

This report summarizes the significant near-to-mid-term societal benefits that can be realized through expanded use of RD in California. It highlights the key challenges and barriers that should be addressed to realize such potential. The following provides recommended actions towards that end.

### Conduct trials of RD in high-horsepower off-road applications and select on-road applications

It is recommended that air districts consider funding trials of RD in high-horsepower off-road applications such as marine vessels and locomotives. Documented use of RD in high-horsepower off-road diesel engines has been nearly non-existent, at least in North America. While there does not seem to be special reason for concern, RD's specific impacts when used in large-bore medium- or slow-speed engines that power locomotives and marine vessels are not well known. This is likely to cause caution on the part of marine vessel and locomotive fleets to make the switch, even when told that RD can be trusted as a "drop-in" replacement for petroleum fuel. Trial tests and demonstrations should be conducted that include operating RD in a mix of older and newer units with varying types of emissions control systems, and emissions testing by an appropriate entity such as UCR CE-CERT. In particular, the SCAQMD could work with railroads and other local stakeholders (e.g., the San Pedro Bay Ports) to conduct such a trial on one or more locomotives. The BAAQMD could work with ferry operators serving the San Francisco Bay to test RD in one or more ferry vessels.

Additionally, the BAAQMD may want to work with stakeholders associated with the Port of Oakland drayage truck fleet (e.g., licensed motor carriers, port authorities) to sponsor a controlled test to use RD in the fleet, specifically to determine if it can help improve DPF performance and durability.

### Conduct further emissions studies on the impacts of RD on diesel engines with state-of-the-art emissions controls

It is recommended that CARB continues to work with air districts, academic institutions, the heavy-duty engine industry, and possibly RD producers / suppliers to conduct focused emissions testing programs designed to better characterize the impacts of RD on heavy-duty diesel engines with advanced emissions controls. Such studies are needed to better understand RD's criteria pollutant benefits (and possible disbenefits) when used in both on- and off-road HDV applications. One focus could be on better characterizing impacts RD may have on off-cycle conditions for SCR-equipped engines, where in-use diesel engines have sometimes exhibited high NOx levels due to SCR systems failing to reach operating temperature. Given the shifting focus targeted under CARB's draft LED rule, it may be especially important to better understand how RD impacts NOx emissions in high-horsepower, high-fuel-use off-road applications such as commercial harborcraft and ferries, which may or may not include SCR systems.

### Conduct a focused assessment in California of the supply and demand for RD as a heavy-duty transportation fuel

It is recommended that CARB and CEC take the lead to further study the potential future supply and demand dynamics for RD as a major transportation fuel in California.

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