Trinity Consultants

# MEMORANDUM

**To:** California Advanced Biofuels Alliance

**From:** Jon Snoeberger and Jim Lyons, Trinity Consultants

**Date:** January 31, 2022

**RE:** Review of NOx Emissions Data for NTDEs from CARB's LED Study

The California Air Recourses Board (CARB) has conducted four significant studies[1,2,3,4] intended to evaluate the impacts of the use of biodiesel and renewable diesel as well as blends of both fuels on emissions from diesel engines compared to conventional petroleum diesel sold in California. Of these studies, the first three focused primarily on what CARB refers to as "legacy" engines as opposed to "new technology diesel engines" or NTDEs which are characterized as having both selective catalytic reduction (SCR) system to control emissions of oxides of nitrogen (NOx) emissions and diesel particulate filters (DPFs) to control particulate matter (PM) emissions. The fourth and most recent study, referred to by CARB staff as the "Low Emission Diesel" or LED study included one legacy engine and two NTDEs - one intended for on-road and the other intended for non-road applications.

In releasing the results of the LED study, CARB noted that the results obtained using the legacy engine were consistent with the result of past CARB studies in that they indicate substantial reductions in emissions of PM from the use of renewable diesel and blends with biodiesel. Statistically significant reductions in NOx emissions were also observed as expected from the use of renewable diesel in the legacy engine. However, NOx emissions were observed to increase from a blend of 50% biodiesel with 50% renewable diesel.

In contrast, the results of the LED study for the two NTDEs found no discernable impact on PM emissions from the use of renewable diesel and blends of renewable diesel and biodiesel but increases in NOx emissions that were statistically significant for blends of biodiesel and renewable diesel. The finding that renewable diesel resulted in slightly higher NOx emissions from NTDEs despite the increases not being statistically significant was unexpected and generally inconsistent with the existing literature. CARB's position has been, based on its analysis of the available literature, that renewable diesel is expected to reduce NOx emissions. The increases seen from blends of biodiesel with renewable diesel, while of interest, are consistent with CARB's position that no increase in NOx emissions from the use of biodiesel is expected from NTDE's up to 20% biodiesel but could be observed at higher biodiesel blend levels.

Based on the results of the LED emissions study, CARB staff has issued a request for responses to the following questions[5]

- How do these results align with previous studies on BD and RD emissions performance in legacy engines and NTDEs? Are there additional data or testing results that CARB should be aware of to further evaluate BD and RD emissions performance?

[1] https://www.arb.ca.gov/fuels/diesel/altdiesel/20111013_carb%20final%20biodiesel%20report.pdf
[2] https://www.arb.ca.gov/fuels/diesel/altdiesel/20140630carbstudyb5_b10.pdf
[3] https://ww2.arb.ca.gov/sites/default/files/2020-03/ADF_BD_Additive_Testing_Report_March2020.pdf
[4] https://ww2.arb.ca.gov/sites/default/files/2021-12/Low_Emission_Diesel_Study_Final_Report_12-29-21.pdf
[5] https://ww2.arb.ca.gov/sites/default/files/2022-01/CARB_Notice_for_Low_Emission_Diesel_Study.pdf

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- How representative of NTDEs used in California are the engines used in this study?
- How representative are the test cycles in this study to in-use activity cycles?
- Would the addition of a low-load test cycle contribute to the accuracy of calculating in-use NOx excess emissions from NTDEs?
- How might these findings impact NOx emissions estimates from BD and RD fuel use?

At the request of the California Advanced Biofuels Alliance, Trinity has performed a technical review of CARB's emission testing studies and the technical literature in preparing responses to the above questions.

## Comparison of LED Study Results for NTDEs to Other Results

Given that only two NTDE engines were tested in the LED study, a key issue is how do the results from the LED study compare with the results of other studies. In order to address this question, Trinity first reviewed the LED study to look for comparisons of its results with other results available in the literature.

Only one reference[6] involving two NTDEs operated on chassis dynamometers over two different driving cycles is cited in the LED study. The fuels involved in the study were a conventional diesel, renewable diesel, blends of renewable diesel and conventional diesel at 20% and 50% by volume, and a blend of 20% biodiesel and conventional diesel. The authors of this study, reported "discordant" results. The authors also reported increased NOx emissions from the use of the biodiesel blend. However, the results of the study show fairly dramatic differences in the changes in NOx emissions in the two engines to the different test fuels and perhaps more importantly dramatic differences in response of NOx emissions from each engine to the driving cycle. Further, in most cases, the changes in NOx emissions resulting from the use of a different driving cycle were far larger than any of the changes in NOx emissions due to the fuels. Overall, the authors concluded that "while the NOx results did show some trends for both vehicles, they were sufficiently complex that in many cases the results were probably attributable to a combination of combustion effects, aftertreatment effects and the associated engine control strategy." The authors also state that preconditioning of the emissions control aftertreatment systems was not performed which is interpreted to mean that some or all of the fuel impacts observed could have been created by the fact that the adaptive learning occurring in the engine in response to the change in fuels was not completed and therefore the system was not stabilized. Potential for this was evidenced by the fact that the authors observed changes in engine operation during subsequent emissions tests performed over the same driving cycle. Finally, another potential cause of variability in the NOx emission results of this study cited in the LED study itself was the use of chassis dynamometers which could lead to differences in engine operation over the same driving cycle from test to test.

Trinity also performed a general internet literature search and a search specific to the Society of Automotive Engineers technical literature in an effort to identify additional studies focused on the impact of renewable and biodiesel fuels and blends on emissions from NTDEs. Unfortunately, these searches identified a limited number of additional studies.

One study identified was published by National Renewal Energy Laboratory (NREL)[7] and involved measurements of NOx emissions from heavy-duty trucks equipped with 2015 model-year PACCAR MX-13

[6] Karavalakis, G., et. al., "Emissions and Fuel Eoconomy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends", SAE Technical Paper Series, Paper 2016-01-0876.
[7] https://www.nrel.gov/docs/fy18osti/68896.pdf

NTDEs equipped with SCR which were operated on conventional and renewable diesel fuels. NOx emissions from the vehicles were measured using chassis dynamometer testing. The results were again discordant as any impact of fuel effects appeared to be confounded by changes in NOx emissions due to test to test variability. In addition, the impacts of vehicle operation over different cycles on NOx emissions was at least as great if not more so than any of the observed differences due to the use of the different test fuels.

Another study[8] involving a non-road NTDE found little impact of B20 on both engine out and tail-pipe out NOx emissions as well as SCR catalyst conversion efficiency while noting increases in NOx emissions and a decrease in SCR catalyst efficiency with B100. The authors also noted that they expected the exact chemical composition of the biodiesel used as well as the chemistry of the SCR system being used to impact the results. Further, given that the principal effect was reported to be due to the ratio of $NO_2$ to NOx over the SCR catalyst, the implication is that overall design of an NTDE emission control system is important given that some system components function to increase the fraction of $NO_2$ present in the exhaust.

Overall, there appears to be no data suggesting that the use renewable diesel increases NOx emissions from NTDEs and there appears to be no data regarding the emissions impacts of renewable/biodiesel blends on NOx emissions from NTDEs beyond that generated by the LED study. Further, it is clear that there are other factors including operating cycle which seem to have greater impacts than fuel composition on actual NOx emission levels for NTDEs.

## Representativeness of the NTDEs Used in the LED Study

As noted in Table 3-5 of the LED study report, the two NTDE engines were reported to be a 2018 model-year Caterpillar non-road engine (engine family JPKXL07.0BN1) and a 2019 model-year Cummins on-road engine (engine family KCEXH0912XAW). The emission standards and the certification emission levels of these engine families are not presented in the LED study report.

A review of CARB's website[9] shows that the "Caterpillar" engine is in fact manufactured by Perkins and certified to a 0.30 g/bhp-hr standard with certification emissions of 0.20 g/bhp-hr. The Cummins engine[10] was certified to a 0.20 g/bhp-hr standard and had certification test emissions of 0.12 and 0.16 g/bhp-hr over the FTP and RMC cycles, respectively. Little description for the choice of the test engines is provided in the LED study report other than the fact that the engines have high sales in California. The LED report presents no detailed description of either engine's emission control system properties (e.g. catalyst layout, catalyst volumes, SCR catalyst chemistry, etc.) or the model-year in which these engine families were first certified[11] which would be important to help determine how advanced the emission control systems actually are. Further, there is no discussion of how the engines and emission control systems are calibrated to accommodate changes in fuel properties which is particularly important for the biodiesel blends.

Based on the above, it is difficult to judge how representative the two NTDE test engines are of the entire population of NTDEs currently operating in California (both older and newer engine and emission control system

[8] McWilliam, L., and Zimmermann, A., "Emissions and Performance Implications of Biodiesel Use in and SCR-equipped Caterpillar C6.6" Society of Automotive Engineers Technical Paper Series, Paper 2010-01-2157.

[9] https://ww2.arb.ca.gov/sites/default/files/classic/msprog/nvepb/executive_orders/EO%20Files/OFCI/2018/PERK/ofci_u-r-022-0212__date--20171227__year--2018__mfrcarb--perk__ver--orig__uid--10-9626__itr--1__fam--jpkxl07.0bn1.pdf

[10] https://ww2.arb.ca.gov/sites/default/files/classic/msprog/nvepb/executive_orders/EO%20Files/MDE-HDE/2019/CUMM%20-%20CUMX/cummins_hhdd_a-021-0690__date--20181213__year--2019__mfrcarb--cumm__ver--orig__uid--7-3763__itr--1__fam--kcexh0912xaw_14d9_0d20-0d01.pdf

[11] Provided that there are no changes in engine's design and emission control system, a given engine's certification can be carried over for a number of years without any need for new emissions testing. Therefore, the design of an emissions control system on a 2018 or 2019 model-year could in fact be several years old.

designs). It should also be noted that only one engine of each type was tested. Without data from a second engine the issue of engine to engine emission variability within a given engine family cannot be addressed. This means that the representativeness of the test engines responses to changes in fuel might not be representative of the average response of engines from the same engine family. Most studies focused on the determination of fuel impacts on emissions generally account for this by testing at least two vehicles/engines. Finally, despite the fact that manufacturers are required to meet the same emission standards that apply during certification, the design and operation of their engines and emission control systems can differ substantially. Therefore, the representativeness of the Cummins and Caterpillar (Perkins) NTDEs with respect to other manufacturer's products is also not clear.

It should also be noted that the NTDE test engines from the LED study cannot be extrapolated to future diesel engines that will operate in California. CARB has recently adopted more stringent emission standards for on-road heavy-duty diesel engines[12] that are expected to affect emission control system designs on engines sold in California as early as the 2024 model-year. CARB has documented in detail a number of potential changes in emission control system design that may be required to comply with the new more stringent emission standards.[13] CARB is also considering the imposition of similar more stringent standards on off-road engines that will likely result in substantial changes in engine and emission control system design that are expected to apply beginning in the 2028 to 2029 model-year time frame.[14]

## Impact of Test Cycles on the Results of the LED Study

As noted above, CARB asks two questions related to engine testing cycles, one about the representativeness of the cycles to in-use operation and the other regarding the import of adding a low-load test cycle with respect to the calculation of "excess emissions" from NTDEs. Beginning with the first question, as indicated in the LED study report both the on- and non-road NTDEs were tested on an engine dynamometer using the test procedures required for new engine certification. The operating cycles that are part of those test procedures were developed by U.S. EPA and CARB and were intended to be representative of in-use engine operation.

Turning to the second question, it is clear that emissions from NTDEs can vary substantially depending on driving or operating cycles and that NOx emissions can increase when vehicles operate under low speed/low load conditions where exhaust temperatures may drop below those required for high SCR conversion efficiencies. Understanding of this phenomena is not new however as CARB has published studies documenting exhaust temperatures of various types of in-use heavy-duty on-road vehicles[15] as well as the emissions impacts of different operating cycles on NTDEs of different model-years produced by different manufacturers at different vehicle mileages.[16] In response, CARB has already adopted a low load emission test procedure and emissions standards for on-road NTDEs that will apply beginning with the 2024 model-year[12] and has proposed to adopt a similar cycle and standards for non-road NDTEs that will apply beginning with the 2028 or 2029 model-year.[14] In addition, CARB has both accounted for increased NOx emissions from existing on-road NTDEs and the impacts of the new low load testing requirements in its EMFAC emissions inventory model.[17,18]

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[12] https://ww2.arb.ca.gov/rulemaking/2020/hdomnibuslownox
[13] https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/hdomnibuslownox/appi.pdf
[14] https://ww2.arb.ca.gov/sites/default/files/classic//msprog/tier5/off_road_tier_5_rulemaking_overview.pdf
[15] For example, https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/13-301.pdf
[16] For example, Misra, C., et. al, of the California Air Resources Board, "Evaluating In-Use SCR Performance: Older vs. Late MY Engines" Presented at the 26th CRC Real World Emissions Workshop, Newport Beach, CA, March 12 - 16, 2016
[17] https://ww3.arb.ca.gov/msei/downloads/emfac2017-volume-iii-technical-documentation.pdf
[18] https://ww2.arb.ca.gov/sites/default/files/2021-08/emfac2021_technical_documentation_april2021.pdf

Given the above, it is not clear why CARB staff is asking these questions with regard to the LED study other than perhaps to solicit comments recognizing that the magnitude of the reported increases in NOx emissions observed from the blends of renewable diesel and biodiesel observed were much smaller than the magnitude of the increases in NOx emissions that occur as the result of low speed and low load operation of vehicles equipped with NTDEs. Alternatively, the questions could be directed at the potential NOx emissions impacts of the LED study test fuels on NOx emissions from NDTEs while they are operating under low speed, low load conditions. Examination of Figures 4.3 and 4.5 as well as Tables 4-4 and 4-7 of the LED study could be interpreted as suggesting that because of the increases in engine out NOx emissions observed with the blends of renewable diesel and biodiesel increases in NOx emissions would be expected under low speed, low load operation when SCR efficiency drops. However, that interpretation would not be correct unless engine out NOx emissions data were available from the test engines using the different test fuels under low speed, low load operation. Further reinforcing the need for actual engine out data is the observation that the impacts of biodiesel use on engine out NOx emissions are expected to be much smaller at low load conditions than under higher load conditions.[19,20]

## Import of the Findings from the LED Study

The final question asked by CARB staff relates to the import of the LED study results on estimates of emission impacts due to the use of renewable diesel and biodiesel use in NTDEs. As discussed in detail above, there are a number of issues with the LED study that need to be considered in applying its results. Additional issues related to the import of the findings from the LED study are summarized here.

For the on-road NTDE, it should be noted that the testing generated a number of "outliers" which were reported but eliminated from the comparative data summaries presented in the LED study report. The rational for the outliers was that the engine was that the "engine appeared to be running in a slightly different operating mode compared to the other tests." Although not discussed in the report, it appears based on the data presented in Appendix G-3 that most of the outliers occurred during the first test following a fuel change. Although not analyzed in detail in the report, there appears to be a downward trend in the emissions test data obtained using a given fuel from the first test to the last test performed on a given day. This suggests that the preconditioning described in Section 3.4.2 of the report may not have been adequate to stabilize the system. To the extent that adaptive learning was occurring over the course of testing, it would call into question the veracity of the test results.

The above notwithstanding, the emissions data sans the outlier data points summarized in the LED study report show that on average the on-road NTDE engine complied with the 0.2 g/bhp-hr certification NOx emission standard over both the FTP and RMC cycles regardless of the test fuel being used. Further, the efficiency of the SCR system over the RMC cycle was not affected by the type of test fuel being used. Finally, the observed emissions on all test fuels were in the range of those reported from the certification engine which as noted above were 0.12 g/bhp-hr over the FTP and 0.16 g/bhp-hr over the RMC. Therefore, there is no evidence of excess emissions from the on-road NTDE as NOx emissions on all test fuels remained below the emissions standard.

Turning to the non-road NTDE it is interesting to note that while there was no discussion or outlier analysis performed, the NOx emissions results of the last four tests using the R565/B35 blend over the NRTC that were apparently performed on April 19, 2021, as reported in Appendix G-5, are substantially higher than the

[19] Sze, C., et. al, "Impact of Test Cycle and Biodiesel Concentration on Emissions" SAE Technical Paper Series, Paper 2007-01-4040,

[20] Chen, P. and Ma, Y., "Mdoel Predicive NOx Emission Control for a Biodiesel Engine Coupled with a Urea-based Selective Catalytic Reduction System, SAE Technical Paper Series, Paper 2019-01-0734.

first two tests apparently performed that day and all of the tests that were apparently performed on May 9, 2021. There are also differences in the $CO_2$ data for these tests which again suggest that some type of different engine operation may have been occurring. Obviously, elimination of these data points would have substantially reduced the average NOx emission result for this fuel as the resulting average for the NTRC is 0.27 g/bhp-hr compared to the value of 0.34 g/bhp-hr reported in Table 4-5 of the LED study result.

A similar issue can be seen in the NTRC data for the tests performed using the R50/B50 blend that were apparently conducted on April 20, 2021, and May 8, 2021, as shown in Appendix G-5 as well as in the data from the C1 cycle testing performed on different days that is presented in Appendix G-6. Here elimination of results for the first day of testing would reduce the average NRTC NOx emissions on the R50/B50 blend from 0.45 g/bhp-hr to 0.36 g/bhp-hr. The potential for these differences in the data where different engine operating modes may have occurred to be statistically significant or impact on the statistical significance of the comparisons of NOx emissions between different test fuels was not analyzed here.

As noted above the NOx certification emission standard for the Perkins off-road NTDE was 0.30 g/bhp-hr and the emission level of the certification test engine was 0.20 g/bhp-hr. The observed test results indicate that the engine would comply with the certification standards using renewable diesel as well as the R65/B35 blend if the outlying high emission test results discussed above were eliminated. Further, NOx emissions from all test fuels over the C1 cycle were very low. Only the emissions data from operation on R50/B50 suggest that emissions may have been above the certification emission standard.

Overall, it is unclear how the data from the LED study can be used, if at all, to estimate the impacts of the use of renewable diesel and biodiesel in California on NOx emissions. It is also noted that the development of emissions test data suitable for use in separating the effect of fuel composition and fuel properties on emissions is usually performed using statistically driven parametric experimental designs and data analysis methods like those employed in the Auto/Oil study[21] and similar fuels testing programs. This type of design was not used in the development of the LED study and leads to many of the concerns with the results expressed above.

[21] Painter, L.J., and Rutherford, J.A., "Statistical Deisgn and Analysis Methods for the Auto/Oil Air Quality Research Program", Society of Automotive Engineers Technical Paper Serices, Paper No. 920319.