A Well-to-Wheel Analysis to Estimate the Potential Environmental Impact of Converting Agricultural Tractors and Trucks to Electric in California and the United States

Conference Paper · June 2023

DOI: 10.1061/9780784484883.028

Mazen A. Eldeeb
California State University, Fresno

A Well-to-Wheel Analysis to Estimate the Potential Environmental Impact of Converting Agricultural Tractors and Trucks to Electric in California and the United States

Mazen A. Eldeeb, Ph.D.[1]; and Aly M. Tawfik, Ph.D.[2]

[1]Dept. of Mechanical Engineering, California State Univ., Fresno, Fresno, CA.
Email: meldeeb@csufresno.edu
[2]Dept. of Civil and Geomatics Engineering, California State Univ., Fresno, Fresno, CA.
Email: tawfik@csufresno.edu

ABSTRACT

There is a global belief that the electrification of our transportation systems will help make significant savings in energy use, and in greenhouse gas and air pollution emissions. Both the literature and practice are full of numerous articles and reports analyzing different aspects of benefits and costs resulting from such electrification. However, the size of the literature discussing the possible impacts of electrifying vehicles in our agricultural industry does not seem to be as abundant. This paper presents a well-to-wheel analysis that attempts to estimate greenhouse gas and air pollution impacts resulting from converting the agricultural tractors and trucks to electric. Two different models are employed in the estimations, one developed by the research team using national averages, and a second model that is developed by the California Air Resources Board (CARB). Additionally, the research team conducted field visits, recorded observations, and gathered field data for the use and performance of different diesel and electric tractors over a year at a farm in Reedley City in California. The analysis and impact estimates are developed for two geographic regions: California and the US. Results of all conducted analyses indicate significant reductions in greenhouse gas and air pollution emissions.

INTRODUCTION

Electrification of transportation systems is believed to significantly reduce the global use of fossil fuels, in addition to reducing the emissions of greenhouse gas and other pollutants. Electric vehicles (EV) already exhibit better emission intensities than their fossil counterparts even with the current carbon footprint of electricity generation, and this behavior is projected to improve in the future (Knobloch, et al. 2020).

Evidence on the positive impact of electrifying passenger cars is readily available in the literature. For example, Milev et al. estimate that expending the use of EVs in Scotland can lead to up to 33.7% reduction in carbon emissions from the electricity grid, as well as annual savings to the owner of about 69.1% in the long term (Milev, Hastings and Al-Habaibeh 2021). Another study reports an estimated immediate carbon dioxide (CO_2) emission reduction of up to 64% if the taxi fleet in Brazil is completely electrified (Teixeira and Sodré 2016).

However, similar evidence on the impact of electrification of vehicles used in the agricultural sector seems scarce in the literature. Hence, there is a need for a comparative analysis that discusses the potential financial and environmental impact of replacing conventional diesel tractors and trucks with electrical ones.

This work presents a well-to-wheel (WTW) analysis that is aimed at estimating the environmental impact of converting agricultural vehicles to electric. The WTW analysis is supported by field visits and experimental emission data collection from a local farm in Reedley, CA. Two different models are utilized for the well-to-wheel analysis. The first model is developed by the authors and is based on national averages for emissions, while the second model is based on the methodology developed by California Air Resources Board (CARB). This kind of analysis is not only an attempt to fill the aforementioned gap in the literature, it can also shed light on the environmental feasibility of such conversion. In addition, this work is intended to be an informative resource that can potentially motivate the relevant authorities around the world to provide farm owners with incentives to switch to electric engines if needed.

RESEARCH METHODOLGY

For the purposes of analysis and demonstration of the potential benefits of utilizing the advanced technology of electric tractors and trucks in agricultural application as an alternative to their diesel-powered counterparts, a multi-stage research method is employed. The research team collaborated with a manufacturer of electrical vehicles for agriculture, HummingbirdEV, which provided the novel electrical tractors and truck for the study. The team also collaborated with a local farm and fruit packing company, Moonlight, which agreed to test the electrical vehicles in their daily duties and allow the team to collect data in field.

Experiments were performed to collect emission data from diesel vehicles. Data was also collected from HummingbirdEV and Moonlight personnel regarding the specifications and performance of all involved vehicles. Finally, well-to-wheel analysis of environmental impact was performed based on all the collected data.

Experimental Setup

For diesel vehicle tailpipe emission testing purposes, two Portable Emission Measurement Systems (PEMS) are used in this work. Such devices are mounted on the diesel tractors and trucks for continuous real-time measurement and logging of tailpipe concentration of most important pollutants.

For measurement of tailpipe emission concentrations of gaseous pollutants, such as greenhouse gases (GHG), nitrogen oxides (NO_x) and sulfur oxides (SO_x), NOVA Plus portable emissions analyzer manufactured by MRU Instruments is used. The device, shown in Figure 1, is capable of the simultaneous measurement of the concentrations of CO_2, CO, NO_x, and SO_x among other gases at high temperatures up to 2,012°F. It can internally store up to 16,000 measurements, with the possibility of adding memory through SD cards. Using lithium-ion batteries, the device can function unplugged for up 20 hours.

Since the aforementioned device is a gaseous emissions analyzer, it does not have the ability to measure solid particle emissions. Therefore, a second device is used for the measurement of tailpipe particulate matter (PM) emissions, which is the Haz-Dust HD-7204 personal direct reading aerosol monitor manufactured by Environmental Devices Corporation (EDC), shown in Figure 1. With a minimum sampling rate of 1 second, continuous high-resolution measurement of DPM can be performed. The Haz-Dust has a PM sensing rate of 1 – 500,000 μg/m^3 and can internally store up to 43,200 data points. The device can detect PM sizes of 0.1 μm up to 100 μm. Its lithium-ion battery ensures continuous operation for up to 22 hours.

To decide the proper locations for mounting the PEMSs to the investigated diesel agricultural vehicles, the research team performed a preparatory field visit to Moonlight facilities in Reedley, CA. The visit was planned and coordinated with Moonlight personnel, who made available the three diesel tractors and the diesel truck to be tested. The tractors were not being used during that period since it was not a harvest season, which facilitated their availability for the test run. During the visit, the team planned and tested mounting and securing the PEMSs to all diesel vehicles and ensured that they remain in place while the vehicles are moving.

Figure 1. NOVA Plus gas emissions monitor (top), Haz-Dust HD-7204 PM monitor (bottom) setup on the diesel vehicles to be tested for emissions.

Benefits of conducting the test run included the: i) identification and acquisition of necessary equipment needed for securing the PEMSs, ii) identification and testing of the locations to which the PEMSs are fixed on the vehicles, iii) training of the research team members on the performance of emission data collection tasks, and iv) identification of potential problems with the physical fixing and securing of the PEMSs and also with the data recording and transfer. This led to immediate planning of ways to avoid such problems in the actual data collection sessions.

Vehicle Specification Data Collection

The research team collected two different sets of data to support the analysis. At the beginning of the project, the team collected data on the specifications, energy consumption, capital costs and operating and maintenance costs of both the diesel vehicles and their electric counterparts. This data was collected using survey forms that were filled by Moonlight personnel for diesel vehicles and HummingbirdEV personnel for electric vehicles. A summary of this data for diesel and electric vehicles is show in Tables 1 and 2, respectively.

Table 1. Specifications of the tested diesel vehicles.

Data Item	Diesel Tractor #1	Diesel Tractor #2	Diesel Tractor #3	Diesel Truck
Manufacturer	Mitsubishi	New Holland	John Deere	GM
Model	Mahindra 3016	TC30	5075E	Chevrolet Silverado 3500 HD
Year	2014	2008	2008-2017	2018
Fuel tank capacity	7.1 gal	7.1 gal	18 gal	63.5 gal
Number of cylinders	3	3	3	8
Engine capacity	1.3 L	1.5 L	2.9 L	6.6 L
Number of gears	10	12	12	9
Lift capacity	2,646 lbs	1,635 lbs	3,192 lbs	1,900 lbs
Wheelbase	66 in	63 in	80.7 in	162 in
Gross vehicle Weight	2,459 lbs	2,193 lbs	5,000 lbs	13,400 lbs
Fuel consumed / hour	94 oz	88 oz	100 oz	896 oz
Horsepower	28 hp	30 hp	75 hp	360 hp
Time on one full tank	9.5 hr	10 hr	23 hr	504 miles
Capital costs	$17,000 new, $7,000 used	$17,000 new, $7,000 used	$50,000	$55,000

Table 2. Specifications of the tested electric vehicles.

Data Item	e-Tractor #1	e-Tractor #2	e-Tractor #3	e-Truck
Manufacturer	Hummingbird	HummingBird	HummingBird	Freightliner chassis re-powered to Hummingbird unit
Model & Year	E-Trac50 2020	E-Trac50 2020	E-Trac50 2020	2011
Battery life on full charge	2 days @ 8-hr shifts/day	2 days @ 8-hr shifts/day	2 days @ 8-hr shifts/day	90 miles unladen; 75 miles to GVWR
Recharge duration	1 hr (20-80%), 2 hrs (0-100%)*	1 hr (20-80%), 2 hrs (0-100%)*	1 hr (20-80%), 2 hrs (0-100%)*	90 min (10-80%), 175 min (0-100%)[&]
Battery cost	$6,500	$6,500	$6,500	$42,000[#]
Battery capacity	24 kWh	24 kWh	24 kWh	24 kWh
Gross vehicle Weight	5,800 lbs	5,800 lbs	5,800 lbs	26,000 lbs
Charge consumed / hour	Idle: Full charge consumed in 36 hrs. With load: Depends on load.	Idle: Full charge consumed in 36 hrs. With load: Depends on load.	Idle: Full charge consumed in 36 hrs. With load: Depends on load.	Depends on load; hard to quantify
Horsepower	50 hp (can be scaled to 75 hp)	50 hp (can be scaled to 75 hp)	50 hp (can be scaled to 75 hp)	Peak: 268 hp Continuous: 160 hp
Range on single full charge	22 miles unladen	22 miles unladen	22 miles unladen	90 miles unladen; 75 miles to GVWR
Capital costs	Low volume cost: $70,000 Medium volume cost: $55,000	Low volume cost: $70,000 Medium volume cost: $55,000	Low volume cost: $70,000 Medium volume cost: $55,000	Low volume cost: $150,000 Medium volume cost: $120,000

[*] At 12 kW/hr charging rate. [&] At 480 V, 3 phase. [#] Including packaging, BMS, hardware and low volume

Emission Data Collection and Validation

Another set of data that is crucial for the successful completion of the analysis is the baseline emission behavior of the diesel vehicles to be replaced by electric ones. Following the preparatory field visit described earlier in this section, the research team performed two data collection field visits to Moonlight facilities. The two PEMSs were used to continuously capture and record tailpipe concentrations of pollutants such as carbon monoxide (CO), NO_x, hydrocarbons (HC), and diesel particulate matter (DPM).

The first field visit took place in February 2021. All diesel and electric tractors were off duty because no crops were being harvested at the time of the visit. Two of the diesel tractors (#1 and #2) were made available by Moonlight for testing on that day, in addition to the briefly available truck. Since the vehicles were off duty, they were tested during idle operation, and they were also driven around the facility to capture emissions in motion.

The second visit occurred in June 2021. During that second visit, only one diesel tractor was available for testing, tractor #3. At that time, the job the electric tractors were performing was moving fruit pallets from a loading dock to the packaging facility. Although diesel tractors were not typically used at Moonlight for that job, Moonlight personnel made tractor #3 available at the loading dock for the purpose of emission data collection and to serve as backup for the electric vehicles.

The collected emission data for CO, NO_x, HC and DPM during the two visits was compared to US emission standards for off-road diesel vehicles to ensure their validity and compliance with standards. For gaseous pollutants, the NOVA plus system reports the concentrations in parts per million (ppm). Therefore, emission data was converted the relevant unit of grams per kilowatt-hour of energy (g/kWh) using literature conversion factors (Pilusa, Mollagee and Muzenda 2012).

The collected emission data for CO, NO_x and HC was converted to g/kWh, averaged out for each vehicle, and then compared with the relevant US standards (Office of Transportation and Air Quality 2016, Office of Transportation and Air Quality 2016). Table 3 demonstrates the comparison between average measured concentrations of gaseous pollutants values and the relevant US standards, as well as literature emission data for similar vehicles for gaseous pollutants (Pang, et al. 2021, Hou, et al. 2019, Papadopoulos, et al. 2020, Yao, et al. 2015) and particulate matter (Fu, et al. 2013).

The results show that for all gaseous pollutant, the average measured concentrations are well below the relevant US standard. A very good agreement with literature data can be observed for NO_x and HC, and a reasonable agreement is present for CO concentrations. In all cases, the agreement of this work’s measurements with literature data is closer than that with the US standards despite that most of the available literature data for agricultural tractors are for those with rated power of 50 hp or higher.

Noteworthy is that the tailpipe concentrations of CO in the tailpipes of diesel engines are typically low since compression ignition (CI) engines usually operate fuel lean (i.e., with excess air in the fuel-air mixture) as a means for NO_x reduction. This naturally results in complete combustion of the diesel fuel, which in turn means that almost all the carbon in the fuel will have enough oxygen to be completely oxidized to CO_2. Therefore, CO emissions from CI engines are mostly non-significant (Heywood 2018). The same can be said about HC emissions whose CI engine concentrations are typically less significant than those from gasoline engines. The abundance of oxygen in lean mixtures leads to full oxidation of most of the hydrocarbon compounds that may form during the combustion process (Heywood 2018).

Table 3. Average pollutant concentration (g/kWh) vs. literature values and US standards.

Vehicle	Pollutant	Average conc.	Literature conc. #	US Standard
Diesel Tractor #1 (2014, 28 hp)	CO	0.336	1.755±1.073	5.5
	HC + NO_x	3.788	3.397±1.343	4.7
	PM	0.024	0.039	0.03
Diesel Tractor #2 (2008, 30 hp)	CO	0.430	1.638±1.001	5.5
	HC + NO_x	1.602	3.170±1.253	7.5
	PM	0.036	0.036	0.3
Diesel Tractor #3 (2008, 75 hp)	CO	0.683	0.655±0.401	5.0
	HC + NO_x	3.106	2.800	4.7
	PM	0.006	0.136	0.3
Diesel Truck (2018, 360 hp)	CO	0.067	0.049!	20.8*
	HC + NO_x	1.084	0.984±0.263!	3.2*
	PM	0.0013	0.003	0.013*

*Converted from g/bhp-hr. ! Converted from g/km. # Weighted average of idle and walking values.

An overall good agreement is also observed between measured PM concentration and literature PM emission factors for most vehicles. PM values for tractor #3 were significantly below those recorded for the other 2 tractors. Noteworthy is that tractor #3 measurements occurred during the second visit in late spring, while the measurements for the other 2 tractors were taken in winter, as mentioned earlier. The ambient temperature difference between the two days was 42°F, which explains the difference in PM emissions, as they generally increase exponentially with decreasing atmospheric temperature (Nam, et al. 2010). The truck is observed to have average PM levels that are significantly below the standard. In this context, it is important to point out that for heavy duty highway vehicles, the standards only depend on model year, not rated power. Therefore, it is expected that the PM mass/kWh is relatively low for the truck since its horsepower is one order of magnitude higher than the other tested vehicles.

From the above, it can be concluded that the measured data for CO, NO_x, HC, and PM for all tested diesel vehicles are within the expected and regulated ranges for their respective classes, and in an overall good agreement with literature data. Therefore, this agreement supports the validity of the measured concentrations and therefore the subsequent analysis.

Well-to-Wheel Analysis Methods

The well-to-wheel (WTW) energy consumption refers to the total indirect energy consumption of a vehicle that includes the energy needed for fuel extraction, refinery, transportation, and pumping. It can be broken down into well-to-tank (WTT) energy, referring to the energy needed to produce fuel and deliver it to vehicle (or equivalently, deliver it to power plant and produce electricity to power electric vehicle), and tank-to-wheel (TTW) energy, which is the energy released from burning fuel in the tank, or its equivalent value for electric vehicles.

Two WTW analysis approaches are employed in this work. The first approach developed by the research team uses the overall WTW energy consumption as provided in literature for various vehicle types based on the type of fuel used, including diesel vehicles and battery-electric vehicles (BEV) (Kromer 2007). The reported WTW footprint of electric vehicles reflects the US average grid mix reported by Kromer, where 52% of electricity was produced from coal, 20% from nuclear energy, 16% from natural gas, 10% from renewables, and about 3% from petroleum. The footprint would be much greater if a larger proportion of electricity is produced from coal, and vice versa (Kromer 2007). The analysis includes WTW GHG emissions (Kromer 2007), particulate matter emissions (OECD 2020), in addition to pollutants such as CO, NO_x, SO_x and volatile organic compounds (VOC) (Liu, et al. 2020). Data for pollutants other than GHG is reported in the literature for various classes of passenger vehicles (OECD 2020, Liu, et al. 2020). This data is used because of the lack of literature footprint data for electric agricultural machinery. In all cases, data for the vehicle classes closest in weight to the vehicles used in the project are chosen. Like with energy consumption data, the emission data also reflects the US power grid proportional distribution of energy sources.

The second approach used in this work is the methodology reported by California Air Resources Board (CARB) to determine emission reductions and cost-effectiveness of the conversion from conventional transportation technology to any form of advance technology vehicles (ATV), including electric vehicles (California Air Resources Board 2020). The methodology involves following a set of steps and formulas to estimate the potential savings in energy use and pollutant emissions (California Air Resources Board 2020). The approach starts with calculating the annual energy use of the diesel and electric vehicles as follows:

$$Fuel\ Usage\ \left(\frac{gal}{year}\right) = \left(\frac{gal}{hour}\right) \times \left(\frac{hours}{day}\right) \times \left(\frac{days}{year}\right)$$

$$ATV\ Fuel\ Usage\ \left(\frac{kWh}{year}\right) = Baseline\ fuel\ usage \times ED_{diesel} \times \left(\frac{1}{ED_{electricity}}\right) \times \left(\frac{1}{EER}\right)$$

where ED is the energy density and EER is the energy economy ratio. Then, the GHG emission factor (EF) for each diesel and electric vehicle is estimated from the fuel usage as follows:

$$GHG\ EF\ \left(\frac{tons\ CO2e}{year}\right) = CI \times fuel\ energy\ density \times fuel\ usage \times \frac{1\ ton\ CO2e}{1{,}000{,}000\ grams}$$

The potential reduction in GHG emissions resulting from replacing electric vehicles with electric ones is calculated using the following formula:

$$ATV\ GHG\ ER_{annual}\ \left(\frac{tons\ CO2e}{year}\right) = GHG\ EF_{base} - GHG\ EF_{ATV}$$

For pollutants other than GHG, referred to as criteria pollutants, the annual emissions (AE) are estimated based on hours of operation using the following formula:

$$AE_{criteria} = EF \times usage \times horsepower \times load\ factor \times \left(\frac{1\ ton}{907{,}200\ g}\right)$$

The annual emission reductions in each of the criteria pollutants is calculated as the difference between the annual emissions from a diesel vehicle and those from the replacement electric vehicle that typically has zero emissions of criteria pollutants.

$$Criteria\ ER = AE_{diesel} - AE_{electric}$$

Finally, the individual reductions in criteria pollutants can be combined into a weighted emission reduction (WER) as follows:

$$WER = [NOx\ reductions\ + ROG\ reductions\ + (20 \times NOx\ reductions\ )] \left(\frac{tons}{year}\right)$$

RESULTS AND DISCUSSION

WTW Analysis using Research Team's Methodology

The WTW analysis using the first methodology starts with literature values for the energy usage for diesel and electric agricultural vehicles (Kromer 2007). For electric vehicles, the energy usage in kWh/mile is converted to gallon of diesel equivalent per mile using the diesel gallon equivalent (DGE) for electricity, which is 137 MJ/gal (38.1 kWh/gal) (U.S. Department of Energy 2014). The WTW energy usage for both classes of vehicles is shown in Table 4.

Table 4. WTW Energy Consumption (Kromer 2007).

Value	**Diesel**	**EV**
WTT energy consumption	0.0023 gal/mile	0.0146 gal-eq/mile
TTW energy consumption	0.0169 gal/mile	0.0063 gal-eq/mile
WTW energy consumption	**0.0192 gal/mile**	**0.0209 gal-eq/mile**

The WTW emission analysis for GHG, CO, NO_x, SO_x PM, and VOC is presented for both classes of vehicles in Table 5 (OECD 2020, Liu, et al. 2020, Kromer 2007). The results show that converting from diesel agricultural vehicles to electric vehicles can potentially result in savings in all kinds of pollutant emissions, except for SO_x as it is mainly produced at the power plants during electricity generation. The most significant savings are observed to be those of NO_x emissions, which can be reduced by about 78% following the conversion to electric vehicles. Similar reductions are observed for VOC and CO, with emission reductions of 72.2% and 71.3%, respectively. For these pollutants, it is observed that most emissions occur during the combustion of diesel in the engines of conventional vehicles, while the WTT emissions are similar for diesel and electric vehicles. This explains the significant emission reductions, as the TTW element is eliminated in electric vehicles. On the other hand, one can observe that GHG does not exhibit the same level of emission reduction with savings of 9%, since both the fuel burning in the power plants for EVs and in the engine for diesel vehicles result in similar amounts of GHG emissions.

WTW Analysis using CARB's Methodology

The second approach this work employs for WTW analysis is based on CARB's methodology, presented earlier in the "Research Methodology" section. All the calculations assume an average of 8 working hours per day and 260 working days per year for the tractors, for an annual usage of 2080 hours/year. Since the truck does not operate on a continuous basis like the tractors, the fuel usage data was collected in the field during the team's emission data collection visits. The worst-case scenario is used, where the diesel truck used 90 gallons of diesel in the week of the first visit. As Table 1 shows that the truck uses 7 gallons per hour, it can be estimated that it is used for 668.6 hours/year. Other data used in the calculations is also shown in Table 1, including the horsepower of all vehicles and the fuel usage of diesel tractors.

Table 5. WTW Pollutant Emissions (OECD 2020, Liu, et al. 2020, Kromer 2007).

Value	Diesel	EV	WTW Savings
WTT GHG emissions	27.8 gCO2/mile	186 gCO2-eq/mile	
TTW GHG emissions	176.7 gCO2/mile	0 gCO2-eq/mile	
WTW GHG emissions	**204.5 gCO2/mile**	**186.0 gCO2-eq/mile**	**18.5 gCO2-eq/mile**
WTT PM2.5 emissions	0.0315 g/mile	0.0326 g/mile	
TTW PM2.5 emissions	0.0068 g/mile	0 g/mile	
WTW PM2.5 emissions	**0.0382 g/mile**	**0.0326 g/mile**	**0.0056 g/mile**
WTT PM10 emissions	0.0650 g/mile	0.0326 g/mile	
TTW PM10 emissions	0.0087 g/mile	0 g/mile	
WTW PM10 emissions	**0.0737 g/mile**	**0.0615 g/mile**	**0.0122 g/mile**
WTT NOx emissions	0.24 g/mile	0.26 g/mile	
TTW NOx emissions	0.94 g/mile	0 g/mile	
WTW NOx emissions	**1.18 g/mile**	**0.26 g/mile**	**0.92 g/mile**
WTT CO emissions	0.116 g/mile	0.14 g/mile	
TTW CO emissions	0.372 g/mile	0 g/mile	
WTW CO emissions	**0.488 g/mile**	**0.14 g/mile**	**0.348 g/mile**
WTT VOC emissions	0.069 g/mile	0.045 g/mile	
TTW VOC emissions	0.093 g/mile	0 g/mile	
WTW VOC emissions	**0.162 g/mile**	**0.045 g/mile**	**0.117 g/mile**
WTT SOx emissions	0.095 g/mile	0.650 g/mile	
TTW SOx emissions	0 g/mile	0 g/mile	
WTW SOx emissions	**0.095 g/mile**	**0.650 g/mile**	**-0.555 g/mile**

Energy densities used in the calculations for both diesel and electricity are reported by CARB as 134.47 MJ/gal and 3.6 MJ/kWh, respectively. The calculations also use the carbon intensity values reported by CARB for both diesel and electric vehicles, which are 100.45 gCO_2e/MJ and 82.92 gCO_2e/MJ, respectively. CARB also reports an energy economy ratio for electric vehicles of 5.0. (California Air Resources Board 2020).

Factors that are needed for criteria pollutant emission estimations include load factors and criteria pollutant emission factors. For the tractors, a load factor of 0.7 is used while a load factor of 0.38 is used for the truck based on CARB’s recommendations (California Air Resources Board 2017). The emission factors used for diesel vehicles in the calculations are 0.26, 0.05, 0.009 g/bhp-hr for NO_x, relative organic gas (ROG) and PM10, respectively (California Air Resources Board 2020). For electric vehicles, an emission factor of zero is used for all criterial pollutants (California Air Resources Board 2011), which therefore leads to zero annual emissions.

Based on the previous assumptions and the aforementioned formulas, WTW analysis is performed, and the results are presented below. Table 6 shows annual energy usage and emission estimates for diesel vehicles, while Table 7 shows those of electric vehicles.

Table 6. WTW estimates for diesel vehicles using CARB's method.

Value	Diesel Tractor #1	Diesel Tractor #2	Diesel Tractor #3	Diesel Truck
Fuel usage (gal/year)	1527.5	1430	1625	4680
GHG EF (tons CO_2e/year)	20.633	19.316	21.950	63.215
AE of NO_x (tons NO_x/year)	0.0117	0.0125	0.0313	0.0262
AE of ROG (tons ROG/year)	0.0022	0.0024	0.0060	0.0050
AE of PM10 (tons ROG/year)	0.0004	0.0004	0.0011	0.0009

Table 7. WTW estimates for electric vehicles using CARB's method.

Value	eTractor #1	eTractor #2	eTractor #3	eTruck
ATV Fuel usage (kWh/year)	10682.9	10682.9	10682.9	34962.2
GHG EF (tons CO_2e/year)	3.189	3.189	3.189	10.437

Table 8 summarizes the savings in GHG emissions and criteria pollutant emissions as a result of replacing each diesel vehicle with its electric equivalent. The reduction in GHG and criteria pollutants is the difference between the annual emissions between each diesel vehicle and its electric replacement. The table shows that converting the small diesel tractors (~30 hp) could save around 17 metric tons CO2e per year and around 0.0225 tons per year of criteria pollutants. Converting the larger diesel tractor (~70 hp) could save around 19 metric tons CO2e per year and around 0.06 tons per year of criteria surplus pollutants. Converting the diesel truck could save around 53 metric tons CO2e per year around 0.05 tons per year of criteria pollutants. The WTW GHG emission reductions are observed to be between 83.4-85.4%.

Table 8. Estimated emission reductions (tons/year) using CARB's method.

Value	GHG reduction	NO_x reduction	ROG reduction	PM10 reduction	WER
Diesel tractor #1 → eTractor #1	17.444	0.0117	0.0022	0.0004	0.0219
Diesel tractor #2 → eTractor #2	16.127	0.0125	0.0024	0.0004	0.0229
Diesel tractor #3 → eTractor #3	18.761	0.0313	0.0060	0.0011	0.0593
Diesel truck → eTruck	52.778	0.0262	0.0050	0.0009	0.0492

Broader Impact Analysis

This analysis attempts to estimate plausible broader impacts from adoption of electric tractors in the agricultural sector, both in the state and nationwide. It particularly focuses on possible savings in greenhouse gas and air pollution emissions using the footprint values computed based on the WTW analysis presented earlier. In addition, the computed benefits are based on the existing and expected growth in numbers of diesel and gasoline tractors in the agricultural industry.

Murphy et al. indicate that there were "approximately 4.2 million tractors on farms and ranches across the United States" in 2010 (Murphy, et al. 2010). This value is also corroborated by the World Bank data, which indicate that the number of agricultural tractors in the USA grew from 245 per sq-km of arable land in 1988 to 271 per sq-km of arable land in 2007, with a rate of

0.55% per year (The World Bank 2007). It also indicates that that total number of tractors in the USA in 2007 was around 4.3 million tractors. Similarly, the California Air Resources Board indicates that there are “140,000 pieces of off-road, diesel-fueled, mobile agricultural equipment” in California (California Air Resources Board 2020).

In 2019, the agricultural tractors market share by engine power in the US was dominated by low power tractors (similar to diesel tractors #1 and #2 in this work), with engine power < 40 hp. The market share of those tractors was around 65%. The second group, tractors with engine power between 40 to 100 hp (similar to diesel tractor #3 in this work) had market share of around 25%. Last, tractors with engine power greater than 100 hp had market share of around 10% (Grand View Research 2020).

Estimating broader impact values for agricultural tractors’ emissions across the state or the nation depends on numerous factors. For example, it depends on the size and type of farm, crops in the farm, types of jobs required by the tractors, water availability, climate, economic factors, and numerous other factors. Accordingly, national usage averages are adopted in the analysis. It appears that on average, an agricultural tractor may work about 250 hours per year, and have an average operating speed (i.e., total distance covered divided by total number of engine hours) of about 15 mph. However, these values can vary dramatically, depending on some of the numerous factors mentioned above.

Therefore, given the vast possible variability of agricultural tractors job tasks and conditions, and to account for some of this variability, three different scenarios are adopted in the analysis: a pessimistic view, a neutral view, and an optimistic view. The neutral view was computed as the difference between electric and diesel emissions, while the optimistic view assumed an additional 25% of improved performance, and the pessimistic view assumed only 75% performance of the neutral view.

Estimated well-to-wheel state and national savings under the three mentioned scenarios are listed in Table 9. The estimates indicate significant savings across the state and the nation in all emission criteria, except SO_x, which is produced at the power plants as mentioned earlier.

Table 9. Estimated Well-to-Wheel Annual Savings in Emission Tons (assuming Conversion of All < 40 hp Agricultural Tractors to Electric).

Scenario / Criteria	State			National		
	Pessimistic	Neutral	Optimistic	Pessimistic	Neutral	Optimistic
WTW GHG savings	5219.3	6959.0	8698.8	156578.1	208770.8	260963.5
WTW $PM_{2.5}$ savings	1.6	2.1	2.6	47.4	63.2	79.0
WTW PM_{10} savings	3.4	4.6	5.7	103.3	137.7	172.1
WTW NO_x savings	259.6	346.1	432.6	7786.6	10382.1	12977.6
WTW CO savings	98.2	130.9	163.6	2945.4	3927.1	4908.9
WTW VOC savings	33.0	44.0	55.0	990.3	1320.3	1650.4
WTW SO_x savings	-156.6	-208.8	-261.0	-4697.3	-6263.1	-7828.9

CONCLUSION

This work presented the expected impact on emissions reductions and cost effectiveness from converting the vehicles studies in this study (3 diesel tractors and truck) into electric, based on two methods. The report computed the emissions for GHGs and other criteria pollutants for each of the 4 diesel vehicles that were part of this project, as well as the electric tractors and electric truck developed for this project. Subsequently, the impacts of the developed electric vehicles on emission reductions were computed by contrasting the values computed for the diesel and electric vehicles.

The study started by presenting estimates for the energy demands of the diesel and electric tractors and truck, and the well-to-wheel greenhouse gas and air pollution emission estimates for both types of agricultural vehicles using an approach developed by the research team, in addition to a second approach developed by CARB.

Then, the broader impact of converting agricultural tractors to electric was estimated. Given the variability in tractor operations because of numerous factors, such as the size and type of farms, crops in the farms, types of jobs required by the tractors, and numerous other factors, national usage averages were researched and adopted in the broader impact analysis. Nonetheless, given that these national averages can vary dramatically depending on some of the factors mentioned in addition to both place and time, three simple scenarios were considered: neutral, optimistic, and pessimistic scenarios.

It is noteworthy that all emissions estimates are based on the well-to-wheel estimates. Results of the two approaches adopted indicated significant savings in all investigated emissions criteria, except SO_x, at both the state and national levels.

REFERENCES

California Air Resources Board. 2020. “Appendix D: Methodology for Determining Emission Reductions and Cost-Effectiveness.” September 2. https://ww2.arb.ca.gov/sites/default/files/2020-09/fy1920_ccssolicitation_appd_qm.pdf.

California Air Resources Board. 2017. “Appendix D: Tables for Emission Reduction and Cost-Effectiveness Calculations.” June 20. https://ww3.arb.ca.gov/msprog/moyer/guidelines/2017gl/2017_gl_appendix_d.pdf.

California Air Resources Board. 2011. “Frequently Asked Questions: Regulation for In-Use Off-Road Diesel-Fueled Fleets (Off-Road Regulation).” May. https://ww2.arb.ca.gov/sites/default/files/classic/msprog/ordiesel/faq/emissionfactorsfaq.pdf.

California Air Resources Board. 2020. In-Use Off-Road Mobile Agricultural Equipment. California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/mobile-agricultural-equipment.

Fu, M., Y. Ding, H. Yin, Z. Ji, Y. Ge, and B. Liang. 2013. “Characteristics of agricultural tractors emissions under real-world operating cycle.” *Trans. Chin. Soc. Agric. Eng.* 29 (6): 42-48.

Grand View Research. 2020. Agricultural Tractor Market Size, Global Industry Report, 2020-2027. www.grandviewresearch.com.

Heywood, J. B. 2018. *Internal Combustion Engine Fundamentals*. New York, NY: McGraw-Hill Education.

Hou, X., J. Tian, C. Song, J. Wang, J. Zhao, and X. Zhang. 2019. “Emission inventory research of typical agricultural machinery in Beijing, China.” *Atmos. Environ.* 216: 116903.

Knobloch, F., S. V. Hanssen, A. Lam, H. Pollitt, P. Salas, U. Chewpreecha, M. A. J. Huijbregts, and J.-F. Mercure. 2020. “Net emission reductions from electric cars and heat pumps in 59 world regions over time.” *Nat. Sustain* 3: 437-447.

Kromer, M. A. 2007. *Electric powertrains: opportunities and challenges in the US light-duty vehicle fleet.* PhD Dissertation, Massachusetts Institute of Technology.

Liu, X., A. Elgowainy, R. Vijayagopal, and M. Wang. 2020. "Well-to-Wheels Analysis of Zero-Emission Plug-In Battery Electric Vehicle Technology for Medium- and Heavy-Duty Trucks." *Environ. Sci. Technol.* 55 (1): 538-546.
Milev, G., A. Hastings, and A. Al-Habaibeh. 2021. "The environmental and financial implications of expanding the use of electric cars - A Case study of Scotland." *Energy Built Environ.* 2 (2): 204-213.
Murphy, D. J., J. Myers, E. A. McKenzie Jr., R. Cavaletto, J. May, and J. Sorensen. 2010. "Tractors and Rollover Protection in the United States." *J. Agromedicine* 15 (3): 249-263.
Nam, E., S. Kishan, R. W. Baldauf, C. R. Fulper, M. Sabisch, and J. Warila. 2010. "Temperature Effects on Particulate Matter Emissions from Light-Duty, Gasoline-Powered Motor Vehicles." *Environ. Sci. Technol.* 44 (12): 4672-4677.
OECD. 2020. *Non-exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge.* Paris: OECD Publishing.
Office of Transportation and Air Quality. 2016. *Heavy-Duty Highway Compression-Ignition Engines and Urban Buses: Exhaust Emission Standards.* Washington, D.C.: United States Environmental Protection Agency.
Office of Transportation and Air Quality. 2016. *Nonroad Compression-Ignition Engines: Exhaust Emission Standards.* Washington, D.C.: United State Environmental Protection Agency.
Pang, K., K. Zhang, S. Ma, and X. Meng. 2021. "Quantification of emission variability for off-road equipment in China based on real-world measurements." *Front. Environ. Sci. Eng.* 16 (2): 24.
Papadopoulos, G., L. Ntziachristos, C. Tziourtzioumis, C. Keramydas, T.-S. Lo, K.-L. Ng, H.-L. A. Wong, and C. K.-L. Wong. 2020. "Real-world gaseous and particulate emissions from Euro IV to VI medium duty diesel trucks." *Sci. Total Environ.* 731: 139137.
Pilusa, T. J., M. M. Mollagee, and E. Muzenda. 2012. "Reduction of Vehicle Exhaust Emissions from Diesel Engines Using the Whale Concept Filter." *Aerosol Air Qual. Res.* 12 (5): 994-1006.
Teixeira, A. C. R., and J. R. Sodré. 2016. "Simulation of the impacts on carbon dioxide emissions from replacement of a conventional Brazilian taxi fleet by electric vehicles." *Energy* 115 (3): 1617-1622.
The World Bank. 2007. Agricultural machinery, tractors per 100 sq. km of arable land. World Bank Group. https://data.worldbank.org/indicator/AG.LND.TRAC.ZS?view=chart.
US DOE. 2014. "Alternative Fuels Data Center - Fuel Properties Comparison." October 29. http://large.stanford.edu/courses/2016/ph240/kountz2/docs/fuel_comparison_chart.pdf.
Yao, Z., B. Wu, Y. Wu, X. Cao, and X. Jiang. 2015. "Comparison of NOx emissions from China III and China IV in-use diesel trucks based on on-road measurements." *Atmos. Environ.* 123 (A): 1-8.