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Identifying Practical Pathways for Electrification of Agricultural Vehicles through Techno-Economic Analysis

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Executive Summary

Almost all agricultural vehicles currently in use still rely on fossil fuels and diesel-based propulsion, one of the main sources of air pollutants. Electrification is the long-term solution to decarbonize agricultural vehicles. However, the road toward full electrification is challenging: the first generation of battery-based electric tractors has higher purchase price than diesel counterparts, requires additional investments in charging infrastructure and suffers from reduced number of working hours per charge. There is a critical need to find practical pathways for the electrification of agricultural vehicles. To address this challenge, we develop techo-economic models to evaluate the total costs of ownership (TCO) of electric tractors. We use this model to identify operating conditions under which electric tractors are more affordable than their diesel counterparts. The knowledge provided by this study can be particular useful to help farmers and the agriculture industry identify favorable use cases for the introduction of electric off-road vehicles.

1 Introduction

Off-road agricultural vehicles, such as tractors, are crucial in providing power to a wide range of farming tasks, including tillage, spraying, harvesting, etc. These offroad vehicles are a significant sources of global greenhouse gas emissions, representing almost 20% of all carbon dioxide emissions [1]. Because of the growth in the world's population, the number of agricultural tractors has been steadily increasing over the years in order to meet the higher demand for food production. Currently there are more than 4 million diesel tractors in the USA alone [2]. There is a critical need to decarbonize agriculture and promote sustainable and clean agricultural vehicles. Motivated by these environmental concerns, regulations are being introduced to accelerate the transition toward zero emission vehicles. For example, California has recently approved regulations to only allow the sale of zero emission vehicles by 2035. To meet these emerging regulations, manufacturers of off-road vehicles are considering electric drivelines. For example, recently Monarch [3] and Solectrac [4] introduced their first electric tractors in the American market. These vehicles have zero local emissions and can be directly charged from on-site renewable energy sources such as photovoltaic or bio-gas power plants, which are becoming increasingly available in today's farms.

Despite their environmental advantages, battery-based electric tractors are more costly to acquire than diesel counterparts and face significant power and energy limitations. Charging an electric tractor is also a growing concern, given the limited electric infrastructure available in rural areas. Upgrades in the local grid infrastructure might be necessary, further increasing costs. Because of such challenges, the transition from today's diesel-dominated agricultural machines to tomorrow's zero-emission tractors will be a long journey. There is an overall lack of decision tools that can support the agricultural industry to make this transition.

The main goal of this work is to develop a techno-economic tool that can help the agricultural industry understand the overall total costs of owernship (TCO) of this emerging technology. We are particularly interested in identifying operating conditions under which electric tractors provide lower TCO than their diesel counterparts. This knowledge is important because it can help farmers find uses cases where the deployment of electric tractors is technically and economically viable.

2 Method

This section summarizes the methods employed to compute the TCO of electric tractors.We will start by characterizing the mission profile of the tractor, which is uncertain and depends on the type of task and implement. To facilitate this characterization, we will use the motor load (α), defined as the ratio of the instantaneous motor power (P_m) over its nominal power (P_{nom}):

$$\alpha = P_m/P_{nom} \tag{1}$$

Figure 1a represents the cumulative distribution function (CDF) of the motor load for different farming operations. The data from the first tractor (T1) is based on orchard tasks [5], while the the other three (T2-T4) are based on row crops and dairy farms located in San Joaquin Valley (California).
One can observe that tractor T1 require relatively low motor loads (less than 20% in the majority of the time); the tractors T2-T4 have significant higher motor loads (between 40% and 60%) because they support farming tasks that require heavy engagement with the soil (e.g. tillage). The amount of working time per day (t_{day}) is another important element in the mission profile. Both the motor load and t_{day} play a significant role in the sizing of the tractor's battery, and are key variables in the TCO analysis.

2.1 Electric Tractor Sizing

When acquiring an electric tractor, three key components need to be selected: i) the nominal power of the motor (P_{nom}); ii) the battery size (E_{bat}) and iii) the charging power (P_{ch}) for recharging the batteries. In this work, we assume that P_{nom} is defined by the farmer taking into account existing motor-sizing methods, which match the motor power with the needs of the implemented attached to the tractor (see [6]). To select E_{bat}, we assume that the tractor is designed to operate with a nominal motor load α^* and nominal daily working time (t^*_{day}). The asterisk denotes a design specification. Assuming a single charge per day, the battery energy needs can be approximated as:

$$E_{bat}(\alpha^*, t^*_{day}) \approx P_{nom}\alpha^* t^*_{day}/(\eta_{motor}\eta_{bat}\gamma_{bat}) \tag{2}$$

where η_{motor} is the driveline efficiency of the electric tractor (which accounts for losses in the motor and inverter) , η_{bat} the battery efficiency, and γ_{bat} is the usable energy in the battery (often 80% to prevent accelerated degradation [7]).
To design P_{ch}, it is assumed that the tractor battery is charged overnight with a maximum charging time t^*_{ch}. Under this assumption, the charging power is given as:

$$P_{ch}(t^*_{ch}) \approx \eta_{bat}E_{bat}(\alpha^*, t^*_{day})/(\eta_{ch}t^*_{ch}) \tag{3}$$

where η_{ch} is the energy efficiency of the charger.

2.2 Techno-economic Analysis

To quantify economic advantages of electric tractors, we use the TCO of the tractor as the main evaluation metric. The TCO is computed as a summation of multiple costs factors:

$$TCO^j = C^j_{veh} + C^j_{infra} + C^j_{energy} + C^j_{other} \tag{4}$$

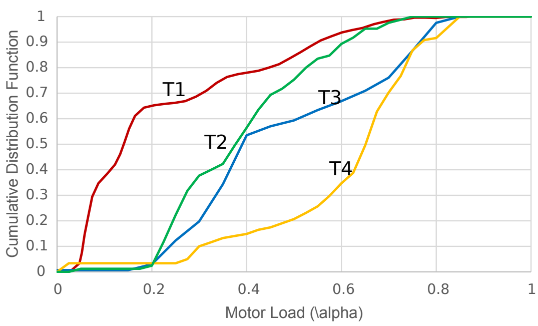
where the superindex $j \in \{d, e\}$ denotes the type of drivetrain (d= diesel, e=eletric) and

- C_{veh} is the tractor purchase cost, which includes all the purchase costs associated with the tractor components, taxes and financing.
- C_{infra} is the infrastructure cost for acquisition of the battery charger and upgrades to the electrical infrastructure of the farm. The latter cost might be particularly relevant in farms located in remote areas, with poor connection to the electric grid which might need upgrade of the transformer, trenching, cabling, conduits, etc [6].

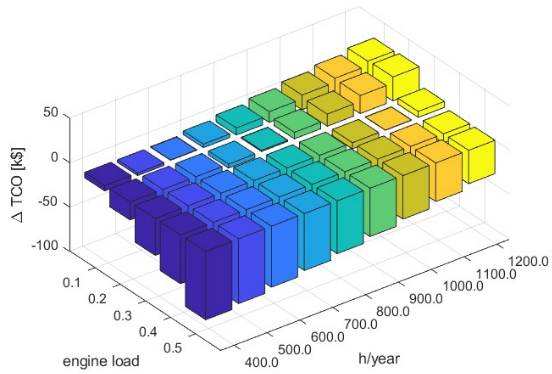
- C_{energy} represent the energy costs due to fuel consumption in the diesel driveline and electricity costs to recharge the tractor battery in the electric driveline. We used the forecasts from U.S. Energy Information Administration [8] for predicting the energy costs over the tractor's lifetime.
- C_{other}: the other costs include housing, insurance, lubricants, maintenance and repairs (M&R), and mid-life costs:

3 Preliminary Results

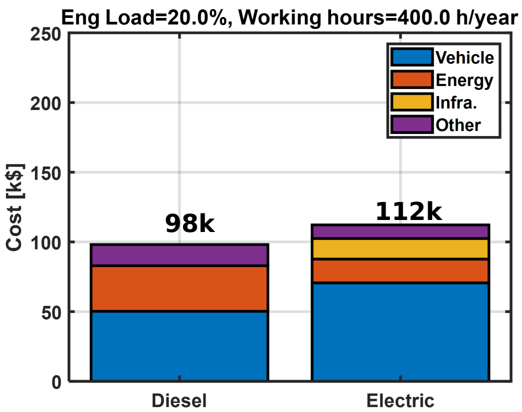
This section presents and discusses the techno-economic results of electric tractors. As a starting point, we consider a fixed nominal tractor power of $P_{nom} = 70$hp, daily operation time $t^*_{day} = 8$h/day and lifetime $n_{year} = 15$years. We investigate the impact of several factors in the TCO of electric and diesel drivelines, including nominal engine load (α^*) and working hours per year as (T_{year}).



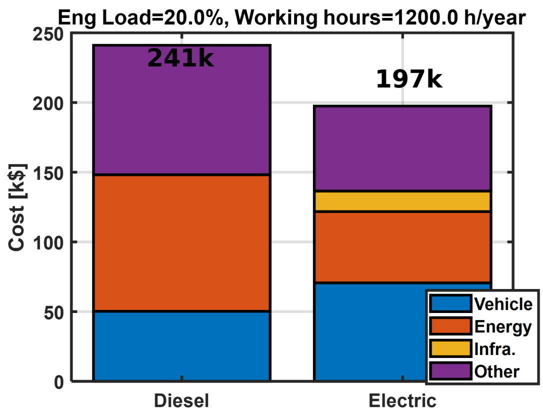
(a) mission profiles of tractors



(b) TCO difference between electric and diesel ($\Delta TCO = TCO^d - TCO^e$)



(c) TCO for light yearly usage



(d) TCO for high yearly usage

Figure 1: Total costs of ownership for diesel and electric tractors.

Figure 1a depicts the difference in total cost of ownership between diesel and electric drivelines as function of α^* and T_{year}:

$$\Delta TCO = TCO^d - TCO^e \tag{5}$$

Positive ΔTCO means that the electric option is more affordable than diesel over the tractor's lifetime, while negative ΔTCO implies cost benefits for the diesel driveline. The results reveal two main trends: i) as the annual working time increases, ΔTCO raises and the economics become more attractive for electric tractors; ii) similarly, lighter motor loads also lead to higher ΔTCO and favor electric drivelines. To understand the reason behind this trend, it is useful to perform a cost breakdown of the tractor.

Figure 1b shows this cost breakdown for a first use case with low motor loads ($\alpha^* = 0.2$) and $400h$/year of working time. In this operating mode, the initial acquisition cost of the electric tractor represents a significant portion of the overall costs; we can also observe that the (electrical) energy costs are significantly lower than the diesel fuel costs, but they are not enough to offset the high initial acquisition costs of the electric tractor. The TCO of the electric tractor is 14% higher than the diesel counterpart in this first use case.
Figure 1b shows the cost breakdown for a second use case with high yearly usage (1200h/year). In this case, the fuel costs represent the dominant factor in the TCO of the diesel tractor. These large costs are enough to offset the extra purchase price of the electric tractor and its charging infrastructure. As a result, the TCO of electric tractor is 18% more affordable than diesel for this second operating mode.
We expect these results to be useful for engineers, policy makers and farmers who are currently planning electrification of farming fleets and need practical techno-economic tools to guide their future investements.

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Presenter Biography

Dilawer Ali is a Ph.D. student in the Mechanical Engineering Department at the University of California, Merced, where he is currently conducting research on the electrification of agricultural vehicles. Dilawer's research focuses on developing techno-economic models to evaluate the total cost of ownership of electric tractors. Through his work, Dilawer aims to help agricultural communities make informed decisions about the adoption of electric tractors, which can have significant environmental and economic benefits. Dilawer is passionate about the intersection of engineering and sustainability, and he hopes to continue working in this field after completing his Ph.D.