Low Overhead Simulation Method for Farm Vehicles

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***Abstract*—**Agricultural tractors form a subset of off-highway vehicles that are typically powered by diesel engines, although their operational duty cycles may in some ways be poorly suited to diesel power. The simulation methods used in this research analyze opportunities for efficiency improvements based on typical farming duty cycles. Diesel power is prevalent because the fuel is economical, portable and widely available, whereas gasoline engines incur higher running costs, and battery-electric powertrains are not suitable for all applications. Diesel engines are most efficient when operating at high power demand. Some agricultural tasks are very well suited to this efficiency characteristic, but others are not. Periods of idling, for example, are very inefficient in their use of fuel, and the same is true when the engine is working but using only a small fraction of its maximum power. At the other extreme, the maximum power capacity of an engine may be required only for infrequent operations, and where it is required, it may be only for very short durations. Yet the highest power requirement determines the size of the engine, and the choice of a larger engine brings associated penalties in the forms of cost, weight and package, not to mention increased fuel wastage when idling. This paper presents accessible methods for exploring the benefits of alternative powertrain designs, with specific examples using battery energy storage, for the benefit of specialist original equipment manufacturers (OEMs) who may be considering such improvements, but do not maintain a large simulation staff or the overhead of expensive software packages. These methods are also of interest for higher-volume producers in the early phases of planning future products, when reductions in time, cost and resources are welcome.

***Keywords*—**Farming, simulation, hybridization, fuel efficiency.

I. Introduction

THE selection of a powertrain architecture for an off-road vehicle (or other powered implement) is an optimization problem with many adjustable variables, and all the more so, now that technologies such as hybridization components have become available for a wide range of applications. A large OEM can justify maintaining an engineering group with simulation expertise, and a suite of software tools, adding up to a significant overhead cost, in order to optimize designs for mass production. A smaller manufacturer may have to make do with a small team and minimal simulation tools, because the product, while profitable, is specialized and produced in smaller volumes. Yet the smaller manufacturer can still find benefits in using custom architectures, on the basis of approximate analysis tools that are affordable and easy to learn. Even the larger manufacturer can benefit from less accurate tools and methods that are quick and low-effort to apply, when in the early phases of selecting architectures for further study. Further incentives to look beyond conventional solutions include rising energy costs and new environmental considerations, so that any manufacturer of off-road vehicles may want to explore enhancements to its portfolio of legacy technologies, but be unwilling to invest in significant engineering costs to do so. A common problem in this genre is the question of whether hybridization, in the form of electrical traction systems, may be a beneficial addition to an internal combustion engine, for a specific – and perhaps under-analyzed – commercial application. This paper presents an analysis of three farming tractors of ascending size, performing common farming tasks such as harrowing and seed drilling, to determine whether a conventional diesel engine is still the best choice, or whether hybridization could improve the total ownership and running cost over a period of 10 years, and if so, with what architecture. The purpose of the paper is not to settle this question for a specific application, but rather to demonstrate how an OEM might go about such an analysis task without incurring excessive engineering cost and time.

II. Application Data

A. Use Case

This analysis uses a set of time-series measured data, for three Fendt diesel tractors, taken from Götz et al. (2025), *Agricultural Load Cycles: Tractor Mission Profiles from Recorded GNSS and CAN Bus Data* [1], funded by the German Federal Ministry of Education and Research. The authors have published papers analyzing the full electrification of five such tractors, for example one [2] where driveline configurations for hypothetical fully-electric versions are compared. Several farming tasks are included, such as seeding, harrowing and spraying, and multiple data channels are recorded at a frequency of 10 Hz, including engine speed and load. This method of data capture is very useful for those considering alternative power sources, as the diesel engine may be substituted by any hypothetical combination of other hardware, to deliver the same shaft power by other means. The five tractors in the study, of which three are used here, were measured over a 1-year period, as they performed over 1200 hours of typical farming tasks.

Fig. 1 shows a plot of power versus time for the smallest tractor, the Fendt 211, performing one of the analyzed tasks, power harrowing. A pattern can be seen which is probably the processing of rows in a field, with a turnaround at each end where less power is required.

Fig. 2 shows a similar plot for tractor Fendt 314, and here it can be seen that the pattern is different (seed drilling) and the power requirement is higher. It is probable that the operator set the speed and gearing to maximize the speed of operation, utilizing as much of the available maximum power as possible;

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this tractor is rated at 112 kW, whereas the 211 has a power rating of 77 kW, but did not use all of it in Fig. 1.

Fig. 3 shows a similar plot for the Fendt 724, and here we see a power usage up to around 200 kW, whereas the tractor's power is rated at 240 kW. Of course, there may be an exact gear ratio at which the maximum power could be utilized for maximum speed but which lies in between the available gears, or perhaps the maximum power was not used for some other reason. However, it can be seen that the 724 performed work at a rate that the 314 could not, perhaps by selecting a larger implement, and likewise the 314's work could not have been performed at that speed by the 211.

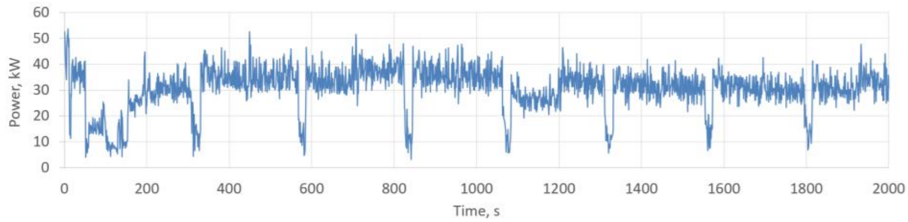

Fig. 1 Power (kW) versus time (s) for Fendt 211, power harrowing

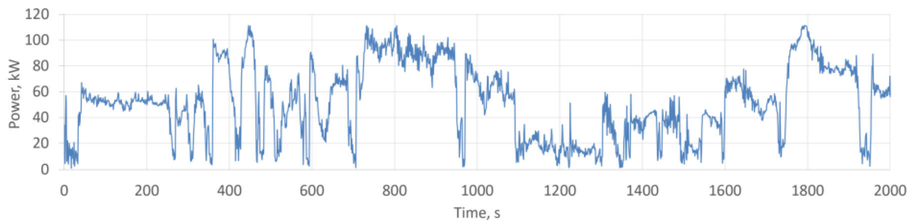

Fig. 2 Power (kW) versus time (s) for Fendt 314, seed drilling

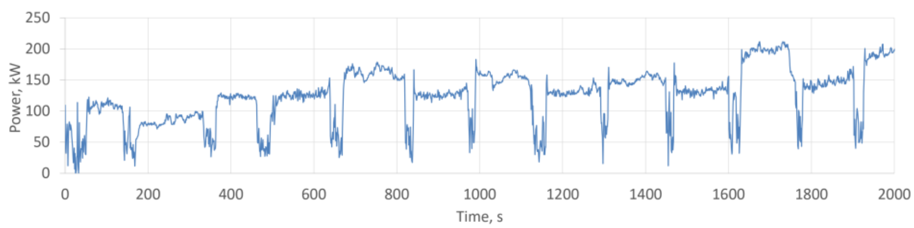

Fig. 3 Power (kW) versus time (s) for Fendt 724, ploughing

B. Tractor Specifications

The tractors used in the study were Fendt models 211, 314 (Fig. 4) and 724. Each tractor was a standard model fitted with a diesel engine, but our analysis considered alternative, hypothetical combinations of diesel engines with electric motors.

Fig. 4 A Fendt 314 tractor

C. Data Access and Software

The simulation methods presented in this paper were chosen specifically for their ease of use and affordability. The raw data for the study were downloaded without charge via Zenodo [4].

The simulation software was "ePop Cloud", a tool under development at ZeBeyond Ltd for public release in the near future, as a simplified version of the full "ePop Pro" product already in commercial use. EPop Cloud is being developed in order to fill a perceived gap in the availability of low-overhead, and low-effort, analysis solutions. The only other tool required was Microsoft Excel, to prepare the input data for ePop Cloud. In this case a Python program was also used in a Linux server environment to sort through the unusually large amount of available data, identify the required channels and to reduce the 10 Hz sample rate to a more manageable 1 Hz frequency, but for other data sets, nothing more than Excel would normally be required. These points are mentioned to emphasize the ease with which this method can be applied, without the need for intensive training in simulation methods. In particular, conventional simulation methods require laborious gathering of input data (like engine maps) which are not freely available, whereas this method uses generic scalable component models requiring minimal input.

III. Calculations

The raw data included multiple channels logged from the engine management systems at 10 Hz, but for this purpose, the channels used were Time_(s), "EngSpeed_(RPM)", "ActualEngPercentTorque_(%)", "EngFuelRate_(L/h)" and "EngReferenceTorque_[Nm]". The two torque parameters were multiplied together to obtain engine torque in Nm. Engine power was calculated from torque and engine speed, and brake specific fuel consumption from power and fuel flow rate. The fuel flow parameters were captured for illustrative purposes, but the only data input required for ePoP Cloud was a time series of Time (s) and Engine Power (kW), easily prepared from the downloaded data using Microsoft Excel. It may be noted that the time constants of the data logging methods were probably not well enough aligned to ensure complete accuracy of a point-by-point fuel consumption calculation, but they were considered acceptable for this broad level of analysis, which did not use the fuel data from the tests. When logging engine management system data, engine RPM is generally accurate (if transient phenomena are not of interest) but torque, being based on inferred-torque calculations, is generally less accurate than e.g., dynamometer test data. However, they are appropriate for analyses of this type, and for this purpose.

IV. Simulation

Previous published research on the electrification of agricultural tractors has generally made use of sophisticated simulation packages, either commercially available at significant cost, or even requiring in-house development for the task [3], [5]. A highly resource-intensive approach is appropriate when applied to academic research or commercial applications with high-volume potential, but may not be accessible for more specialized niche applications. For example, the 211 tractor in this dataset is described as a specialized tractor for orchard spraying [2], and although Fendt tractors are clearly based on high-volume platforms, this illustrates the need for customized vehicles in niche applications that may comprise a smaller market. Some tasks do require resource-intensive software tools (high in both software costs and setup effort), for example detailed investigations of efficiency losses in drivetrain components [6], but this paper deals with general questions of architectural design, normally performed at an earlier stage in a product development cycle [7], [8].

The ePop Cloud simulation tool is cloud-based, so it makes minimal demands on the computer equipment of the user. The analysis process is quick to learn, and is done in three steps; Application, Configuration and Results. The Application stage, in this case, consisted simply of importing the time-series of Time (s) and Engine Power (kW), mentioned above, after editing each series to represent a single 8-hour shift, and interpreting its total duration by specifying that the time series should be repeated 5 times per 40-hour week, for the purpose of cost calculation. The 1-day shift length is important as it defines the daily frequency of charging between shifts. The Configuration phase consisted of selecting components and architectures from a database within the software. Here it is possible to specify a pure-ICE (Internal Combustion Engine) configuration, for example, or pure-electric, or a hybrid combination of both. Components such as engine types, motor types, battery or ultracapacitor types, inverter types etc. may also be selected, or the program will configure all these automatically if desired. The key here is the order of entry, which must begin with Application, i.e. the time-series of power required for the task. The user can also add another time-series, for example for electrical accessory loads, climate control or power-takeoff, to be handled in parallel with the main actuation work. Given the Application data, and some decisions about architecture, the program then automatically sizes the components to match the required output.

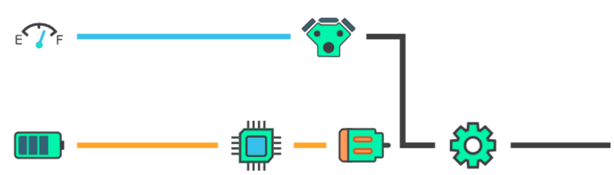

Fig. 5 Powertrain A: Parallel Hybrid, non plug-in

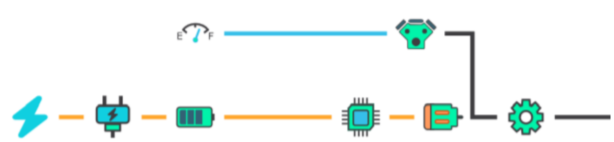

Fig. 6 Powertrain B: Parallel Hybrid, plug-in

The program used two architectures, but each one can be "swept" from 0% electrification, i.e. purely ICE, to 100% electrification, i.e. purely electric, or any proportion in between. Fig. 5 shows the architecture for a Parallel hybrid (where the engine drives the tractor directly, and a motor supplements the power) without the ability to recharge from an electricity supply, i.e. non-plug-in. Fig. 6 shows an alternative configuration where charging is enabled, i.e. it is plug-in.

Two kinds of comparison are presented by ePop Cloud. The first is to compare two architectures, A and B, which may be manually or automatically configured. An architecture in this sense is a combination of components, such as e-motor, inverter, ICE, and/or hydraulic drive, arranged in a structure such as parallel (ICE and electric drivetrain acting in parallel on the application) or series (ICE drives generator, and motor drives application). The second kind of comparison is the degree of electrification, which is swept by automatically sizing the electrification components progressively larger and the ICE smaller, or vice versa, to simulate a hypothetical selection of components.

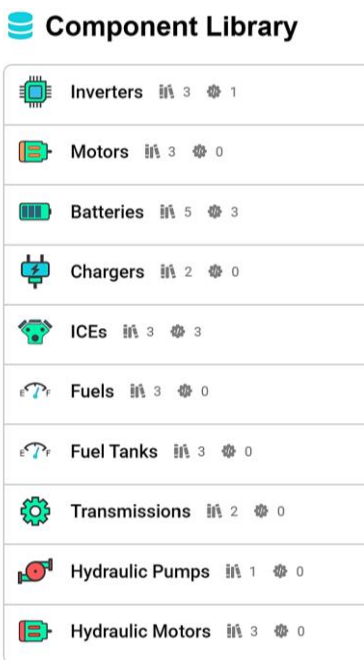

Fig. 7 The component library in ePop Cloud

TABLE I
COMPONENT LIBRARY PARAMETERS

Engine	Cost $/kW	Density kW/L	Density kW/kg	BSFC Kg/kWh	Efficiency %
Diesel	145	0.95	0.25	0.3	28
Gasoline	115	1.25	0.4	0.3	26
Hydrogen	160	0.7	0.7	0.107	50
Custom	-	-	-	-	-

Fig. 7 and Table I show the component library in ePop Cloud. There are drop-down menus for components including batteries, chargers and ICE's, with different options under each one. All the specifications are scalable (e.g. engine cost is in $/kW rather than $) and the actual size of the engine is not yet set, so automatic adjustment takes place when the program changes the size of the engine. The same is true of the other components. The user may select the generic diesel engine, for example, or it is also possible to add a new engine with custom properties that are user-defined. It is also possible to limit the engine size (kW) within bounds, to force a certain engine size. In this case, the program was allowed to size all the components without constraint, except for maximum size limits for the batteries.

V. RESULTS

A. Engine Sizing

The program selected an engine for each of the three use cases (from tractors 211, 314 and 724) as shown in Table II.

TABLE II
ENGINE SELECTION

Test Vehicle	Dutycycle Max Observed Power, kW	Engine Selected by ePop Cloud, kW	Test Vehicle Engine Rating, kW
Fendt 211	55	70	77
Fendt 314	110	118	112
Fendt 724	205	230	240

The first column of Table II shows the highest observed power in the "Application" load cycle loaded by the user. The second shows the engine power selected by ePop Cloud to accommodate this duty cycle, and the third shows the maximum rated power of the vehicle used in the test. In each case, the program selected an engine with a margin of power greater than that seen in the use case. It is also possible for the user to set minimum and maximum power limits on the engine, as described in the previous section. If at any time the Application were changed, for example by substituting a different duty cycle, then the engine size would be automatically adjusted to suit.

B. Comparing Architectures and Degrees of Electrification

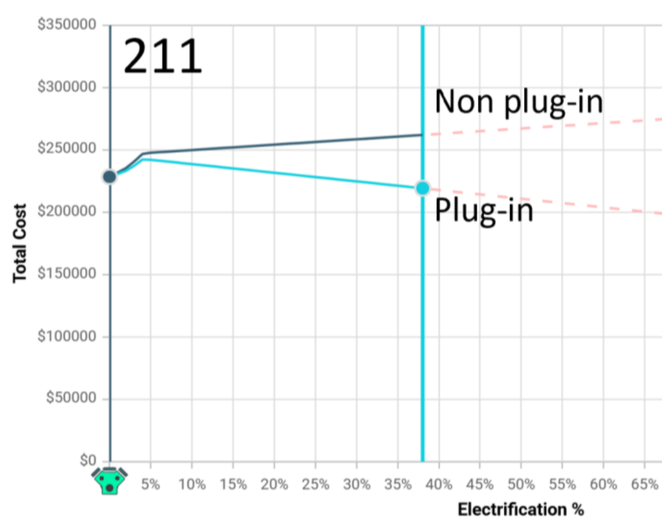

Fig. 8 10-year cost of ownership, versus electrification (211)

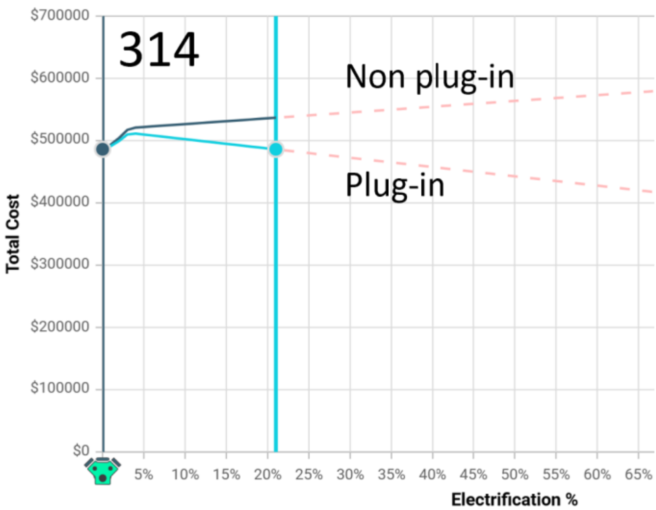

Fig. 9 10-year cost of ownership, versus electrification (314)

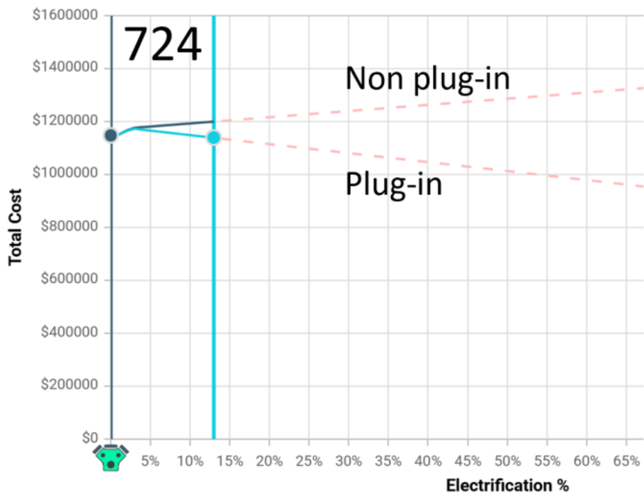

Fig. 10 10-year cost of ownership, versus electrification (724)

Figs. 8-10 show the effect on TCO (total cost of ownership, over 10 years) of increasing "degree of electrification" for each tractor, for two powertrain configurations, A and B (non plug-in and plug-in respectively). The left end of the graphs represents a pure-ICE configuration, and the right end (100%, not shown) represents a pure-electric configuration. There is a third point arising close to the left end, where two lines meet, and this represents the introduction of the electric hardware, which brings a step change. The program could presumably be improved by showing a similar step near the right hand end, where the ICE disappears, but instead it is considered as a vanishingly small component, which of course is unrealistic. However, the graphs serve to show a general result which is of interest.

First, we see that moving from the 211 case to 314 to 724 incurs rapidly ascending amounts of total cost. This does not arise from the increasing specifications of the tractor models themselves, which are invisible to ePop Cloud, but from the increasing workload in the three duty cycles. It will be seen in Table III that this cost is mostly due to fuel or electricity costs over 10 years, rather than the capital cost of the powertrain (but note that the program does not consider the cost of the non-powertrain parts of the vehicle).

Secondly, we see that all three models show some "impossible" configurations, indicated by the dotted lines. These are invalid because they break an artificial rule that was added manually, keeping the weight of the batteries to no more than 25% of the approximate original weight of each tractor. The program does not compensate the load cycle for increased vehicle weight, although this would be required in a more detailed analysis. However, it does highlight the general point that it is not practical to add battery weight to a tractor without any limitation.

Thirdly, we see that the plug-in hybrid delivers reduced cost over 10 years (where feasible), indicating that a pure electric solution would in theory save cost over 10 years (assuming that charging obstacles and battery weight could be overcome), and intermediate levels of electrification can bring benefits, at least for the smaller models. The user may reflect at this point that the assumption of an 8-hour work shift without recharging is the driver for the battery weight, and investigate whether intermediate recharging, perhaps with a very fast charger, could be considered.

Fourthly, we see that the non-plug-in hybrid brings only increased costs, for all three use cases. There are surely some use cases where it would reduce cost, transferring engine operation from low-efficiency to high-efficiency operating points, but the use cases from these three tractors show no benefit.

Finally, we see that all three tractors show similar proportional cost reductions from electrification with a given percentage of electrification provided charging is available, which may reduce to a simple comparison of electricity versus diesel energy costs, as the energy costs overwhelm the capital costs over 10 years in these cases.

TABLE III
ELECTRIFICATION EFFECTS ON COSTS AND SPECIFICATIONS

	211I	211e	314I	314e	724I	724e
Fuel, $000	217	135	467	369	1,113	970
Electricity, $000		39		46		70
EMotor, kW		70		118		230
Inverter, kW		72		123		240
ICE, kW	70	18	118	50	230	133
Charger, kW		32		38		57
Battery, kWh		137		163		245
Fuel Tank, L	88	55	190	150	454	395

Table III compares the sizing and costs associated with Powertrain B (i.e. with charging) of each tractor, in pure ICE form (e.g. "211I") and in hybrid form (e.g. "211e"). In each case, the "e" version represents the best feasible solution, and in all cases, it is truncated at a partial electrification percentage at the end of the solid line in Figs. 8-10, where it transitions to a dotted line. From this table we note:

1. The energy costs in Table III dominate the 10-year total cost values of approximately $225k, $490k and $1,160k seen in Figs. 8-10, suggesting that these vehicles in these

applications could justify additional investment in powertrain technologies for fuel saving.

2. The battery limitation, at 25% of vehicle weight, appears to constrain the electrification potential more as the vehicle power increases, stopping at 38% in Fig. 8, 22% in Fig. 9, and 13% in Fig. 10. In fact, the 724 shows so little benefit that electrification is probably not worthwhile.
3. With 8 hours of charging assumed overnight, the charger requirement for the 314 is 38 kW, and several such chargers would doubtless incur some new infrastructure for the electricity supply of a farm, but this could be reduced, as up to 16 hours may be available between day shifts.

VI. Conclusion

This research produced some interesting and non-obvious conclusions about the effects of hybridization on a range of diesel tractors, when simulated with real measured data from typical farming tasks. The results showed declining benefits of plug-in hybridization as tractor size increased, and the negative effects of attempting mild hybridization (i.e. without recharging) at any size. However, the main intention of this work was to demonstrate a democratized, easily accessible method for making approximate analyses of powertrains for off-highway vehicles. The method involved standard PC tools such as Microsoft Excel and Microsoft Word, with the sole addition of "ePop Cloud", a software tool under development at ZeBeyond, which proved very quick to learn and set up. It is to be hoped that smaller OEMs, who cannot maintain a full engineering and simulation staff, may be able to use such approaches to evaluate novel design concepts for low-volume applications, or for larger applications in the early stages of planning.

Acknowledgment

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