Visions on electric drive components for implements and trailers

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1. Introduction

As opposed to on-highway vehicles agricultural tractors are designed to provide high tractive power in often fairly poor tractive conditions. In addition to this, tractors with implements can often not use the combined weight for creating traction, which can lead to tractors losing their mobility in the field.

Many particular solutions on tractors and tractor/implement combinations are on the market that improve tractive performance and mitigate the effects of lacking tractive power from the tractor to the implement.

On the other hand, a trend towards electrification can be observed in agricultural machinery systems. Developments of integrated generator systems for tractors and even electrical power-split continuously variable transmission (eCVT) provide electrical power that can be utilized for propulsion of the tractor, but also the process and traction drives of the implements.

As a result above, all types of trailers will benefit from electric traction drives, almost regardless of the tractor size that is used by this type of applications. Another important target group of implements is represented by heavy, pull-type primary and secondary tillage equipment with/without combined seeders and planters when hitched to the tractor by a kind of drawbar with little or even no load transfer to the tractor.

These developments increase system efficiency, promote the flexible controllability and manoeuvrability of electrified axle- and wheel drive concepts. The functional integration of the electrified drivetrain (eCVT) and the electrical implement drive (ePTO) create various advantages for the overall system tractor/implement.

According to ZF, the market requires a modular system for multi-axle drives (eTrac). We conducted a survey of market and application demands in order to develop here the best solution within a possible technical kit. This was done in combination of the synthesis and analysis of various drivetrain systems.

A modular system for different application will significantly increase volume and reduce systems costs which are one of the major challenges of drivetrain/system electrification.

2. Motivation

It is with confidence that we can describe the tractor as the fundamental agricultural machine which can carry out almost all agricultural work in conjunction with attached or trailing implements [1].

If we take a look at the technical development of tractors, in particular the increase in their tractive force and their implements, we can see the constant need to increase productivity by providing more tractive power. **Figure 1** shows the simplified evolutionary development of tractors with a focus on increasing tractive performance.

The most important step in the evolution of the tractor with the most significant increase in tractive force, apart from the rollout of low-pressure pneumatic tires, is likely the development of an all-wheel drive that can be switched on and off on demand. The principle idea behind the four-wheel drive is, to use the entire tractor weight, to create traction and to improve the overall tractive efficiency [2]. However, on all-wheel drive tractors with tires of the same size, the front axle wheels compact the soil more than those of standard tractors with tire sizes that differ. The resulting reduction in overall rolling resistance results in better power transmission from the rear wheels.

In the course of further tractor development, tractive performance was more and more increased. Unfortunately due to physical limitations and sometimes legal restrictions tire sizes and hence tire footprints did not grow with engine power at the extent as they should. What has been earliest derived analytically by [2] and later on been proven in [3] by statistic evaluations, is that tire sizes and hence tire footprint should over-proportionally increase with tractor power and weight, in order to keep the footprint area per kW of power at a constant level.

Furthermore, in an attempt to reduce fuel consumption, strong and successful measures have been taken by the tractor industry to increase power density and reduce the specific tractor weight in kg/kW [4]. As a consequence, the high-hp tractors that typically do the heavy field work lose their tractive capabilities by design if not other measures like e.g. ballasting are applied to compensate for this.

In order to work in a manner that protects the soil, rubber tracks are increasingly used today. The larger contact area not only increases the tractive force but also reduces the soil pressure. However, rubber track drives also have disadvantages such as high costs and reduced comfort, in particular the base weight of track tractors is significantly higher and there is no possibility to reduce the weight if not needed.

With the vehicle sizes being achieved today, technical, physical and agronomic limits are increasingly being reached. The focus here is particularly on power transmission between tire and soil, the associated slip limits, and dynamic and static soil stress (soil compaction and rollover frequency). A further increase of tractive performance can only be achieved with the involvement of implements. As mentioned in the beginning, various drive axle systems in mechanical or hydraulic designs are available on the market today. Electrification of the tractor and electric PTO (ePTO) now offer the option of an electrified drive axle or drive wheel on the implement.

3. Electric Implement Traction Drive: System Considerations

3.1. Electric Power Generation

During the past ten years different solutions for providing electric power to the implement have been presented to the market. PTO generator modules have been proposed and - due to their flexibility - are widely considered to be a bridging solution as long as electric implement drives are not very common. Prototype solutions of integrated generators **Figure 2** were shown by ZF [8] and Fendt [9], a series production version was available for sale on JD 6RE tractors [10] for a limited period of time. Recent announcements to the market are favouring technical solutions based on stepless transmissions that replace the hydrostatic variator by electric machines taking advantage of the fact that the electric machines can at the same time be used as a variator for the transmission but also for providing electric power to the implement [11, 7] **Figure 2.**

From an implement perspective the electric traction drive system needs to be designed to work with either an AC or a DC voltage interface on the tractor. For the DC voltage interface on the tractor the implement traction drive unit needs to have an inverter on board and hence preferably also the control responsibility is on the implement.

3.2 Electric Implement Traction Drives versus Hydrostatic and Mechanical Solutions

Implement traction drive solutions can be mechanical, hydrostatic or electrical, **Figure 3**. The advantages of mechanical drives are clearly in the area of superior efficiencies and high transmittable power (with little change efforts on the tractor). However, the opportunities in terms of control and regulation (power on demand) and flexibility in the arrangement of the drives are limited. The latter are clear strengths of hydrostatic drives, but with weaknesses in efficiency. With knowledge of its fundamental advantages, the electric implement traction drive appears to be an interesting alternative, as it combines the advantages of mechanical and hydrostatic drives. It offers a clear advantage over other concepts – such as mechanical ground-speed PTOs and hydrostatic drives – especially with regard to controllability as depending on the power requirement.

The electric traction drive on the implement and an intelligent traction management system on the tractor enable a system that is very flexible in its use. If necessary, additional traction can be provided by the implement and engine output can be increased by activating the tractor’s power boost without overloading the tractor driveline. The service weight of the tractor can be kept low here and excessive ballasting can be dispensed with, which contributes to less rolling resistance, soil protection and increases the possible payload during transport.

3.3. Traction Management and Control

Besides the physical configuration of the combined tractor / implement traction drive system, the traction on the implement needs to be controlled and optimized with respect to the tractor. Thinking about the tractor trailer combination, the task of controlling the axle drive on the trailer can be rather demanding and even safety-relevant; clear overall responsibility in such applications is key and mandatory.

As on the tractor the engine power is managed and distributed to the different consumers following sophisticated control strategies and since the tractive performance of the tractor is managed by controlling different submodules like the 4WD clutch, the differential locks in front and rear axle, 3-point hitch (tire pressure regulation in future etc.), it appears reasonable that the optimization of the entire tractive performance of tractor & implement is governed by the tractor.

3.4. Systems Architecture

The integration of electric traction drives of a tractor/implement combination requires collaboration across companies' borders. Tractor, implement manufacturer and component industry need to work together closely starting from the definition of the system architecture over design, validation and during the entire life cycle of the product/system. This is mainly due to the fact that implements of various manufacturers are requested to match different tractor brands and models. An example of the share of tasks for a particular combination of a tractor and an electric trailer axle is shown in **Figure 4**. Collaboration is also requested by the fact that tractor and implement generate a traction system that share new interfaces like electric power transfer, cooling, operative data exchange for the traction management etc.. A successful example of such partnering is described in [12].

4. Market and Application Requirements

As a conclusion of the above, two groups of implements can be identified for supporting tractive performance of the tractor by means of electric drive solutions:

- Preferred implements for electric traction drives are all types of trailers, almost regardless of the size of tractor that is used for this type of applications.
- Another important target group of implements is represented by heavy, pull-type primary and secondary tillage equipment with/without combined seeders or planters when hitched to the tractor by a kind of drawbar with little or even no load transfer to the tractor.

In the following, the key parameters for the development of electric traction drive solutions on the implement are briefly described using bullet points:

- **Tractive force**: High tractive force and starting torques from standstill or specific tractive forces over a wide speed range (0–60 km/h) are required for various agricultural applications.

- Tractive force support in **reverse driving direction**: Tractive force support in reverse driving direction is particularly advantageous for all trailer applications in field use, in harvesting operations or particularly driving situations e.g. on the silage pit.

- **Wheel and axle load**: Various applications lead to various wheel load requirements in the field. Legal requirements must also be taken into account. In some applications wheel loads change over time which needs to be considered for the traction control strategy and even in the design/layout of the electric components.

- **Effective rolling radius**: Rollers for soil tillage with 500 mm diameters over rubber tracked undercarriages through to transport tires with 1,075 mm span a large range of rolling radii to be taken into consideration.

- **Vehicle and work speed**: A speed range of 0–60 km/h has been established for agricultural tractors. However, tractive force support is often not required for the entire speed range. A range of 0–20 km/h has emerged especially for field work.

- **Installation space**: Likely the most important requirements for a traction drive are today's installation space requirements for implements. Primary target is, to integrate the electric wheel drive unit into the existing installation space, even though from field testing with early prototypes it becomes apparent, that modifications on the implement architecture would sometimes be beneficial for exploiting the full potential of electric traction drives.

- **System costs**: The system costs determined within the market study are allocated to the specific assemblies of the wheel drive by means of a value analysis of the individual systems. This ensures that the total costs are adhered to.

5. Electric Implement Traction Drive: Solution Finding

From the market analysis above it can be concluded that the greatest possible market coverage and market penetration can only be achieved with a flexible construction kit system.

For most of agricultural trailers an electric axle drive is considered the most favourable solution in terms of efforts and system costs. In a combination with a transfer gear box its flexibility can be extended towards a multi-axle drive solution with optional range gear shift, inter-axle differential incl. differential lock mechanisms **Figure 5**.

But still there are some agricultural trailer architectures in the market that provide no space for an axle drive unit but need single wheel drive solutions. This is also required for the large group of all other agricultural implements with high tractive power requirements e.g. for primary & secondary tillage and planting which distinguish themselves by their heterogeneous architecture. Making use of the implement weight for traction needs to consider various implement architectures from one single wheel to multiple single wheels and to even compactor rollers that carry the weight during work, **Figure 6**.

It is challenging, to find the best compromise between mechanical effort (gear set) and the size and complexity of the installed power (electrical motor). Here it is necessary to pay particular attention to the appropriate interplay of electric motor and mechanical transmission ratio. For cost reasons, it is desirable to implement the construction kit with as little variance in the electric motor as possible, which requires a mechanical transmission ratio range that is as flexible as possible. High-speed electric motors with high power density are able to demonstrate their strengths here. To take full advantage of the high power density, external cooling (using water or oil) is required. In order to be able take into consideration the most varied tractive force requirements and the most varied tire sizes, it is necessary to cover a wide range of transmission ratios.

With computer-aided synthesis [5], it is now possible to systematically search for power-split, nested gear set structures. In addition, a partially automated evaluation method is used to compare a large number of systems at an early stage of concept development and analysis [6].

The wide array of applications entails different requirements with regard to work and transport speeds. In most cases, the traction wheel is also used for transport trips, so that different separating elements are required in order to meet the speed requirements. Excess rotation speed and the associated mechanical damage would be the result. A market survey shows the necessary differentiation of the separating elements into three design variants.

The simplest variant is to dispense with a separating element, which is the case with lifted implements or drive wheels. If traction support is required only in one direction of travel, a simple mechanical freewheel can be used. This is the case in particular with tillage operations such as ploughing or cultivating. Controllable separating elements are important when traction support is required in both directions of travel. As an example, the use of trailers in road transport, field transport or silage can be mentioned here.

The possibility of an integrated brake system on the drive wheel must also be guaranteed due to various technical and legal requirements to which the tractor-implement combination is subject. In general, a distinction can be made here between drum brakes and wet multi-disk brakes. The brake actuators must be designed for mechanical (e.g., via Bowden cable), hydraulic or pneumatic actuation depending on the available infrastructure on the tractor and/or implement.

The following **Figure 7** shows how the different requirements from the applications described above can be transformed into a flexible construction kit for an electric single wheel drive unit with a still reasonable complexity.

6. Summary

Looking at the future of agricultural equipment technology, the use of electric power for the optimization and automation of work processes and for improving tractive performance of tractor/implement combinations is generally expected on the market.

Using the weight of implements for creating traction is seen as the logical next steps to improve tractive performance of particularly high hp tractors. Different solutions are proposed and are under development, in order to provide electric power by the tractor, which is mandatory for successfully implementing electric traction drives on implements. Agricultural trailers and heavy primary and secondary tillage equipment are the most favourable groups of implements for electric traction drives that have proven in field test to significantly increase tractor productivity e.g. see [12].

In order to be able to meet a wide range of application requirements in the market, a flexible portfolio of electric axle drive and wheel hub drive units is necessary. A modular structure of this product portfolio is essential for managing complexity and system costs. Tractor, implement and component manufacturers need to work together closely over the entire product lifecycle in order to fully exploit the potentials of electric traction drive solutions on tractor/implements combinations.

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FIGURES

Figure 1 – Improving tractor tractive performance: the path from two-wheel drive over front-wheel assist/ four-wheel drive, tracks instead of tires through to the system concept of the electric implement traction assist

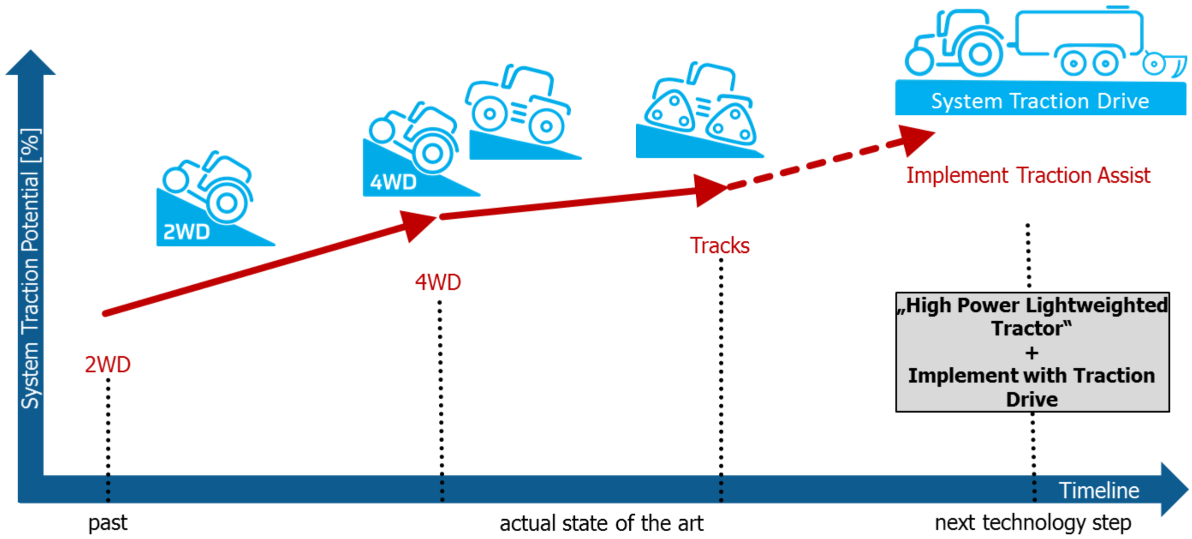
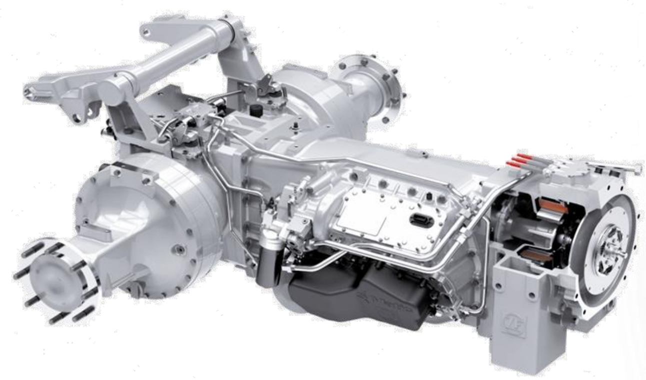
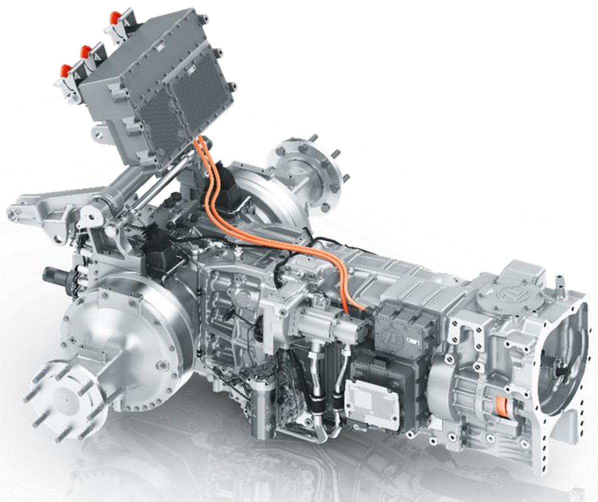


Figure 2 – Two highly integrated technical solutions to generate electric power on the tractor for use on an implement: integrated electric generator module ZF-TERRA+ (left) and electric powersplit CVT ZF-eTERRAMATIC (right) (Sources: ZF)



Hydrostatic powersplit transmission with integrated electric generator module (Source: ZF 2008 [8])



Electric powersplit transmission with functional integration of ePTO (Source: ZF 2019 [7])

Figure 3 – Pros and cons of mechanical, hydrostatic and electrical implement traction drive technologies

	Mechanic	Hydraulic	Electric
Efficiency	++	-	+
Flexibility	-	+	+
Controllability / Power on Demand	-	+	++
Transmittable power	++	+	++
Effort on tractor architecture	+	+	-

Figure 4 – Electric system architecturing and integration need collaboration across companies' borders over the entire product (=system) lifecycle (Example)

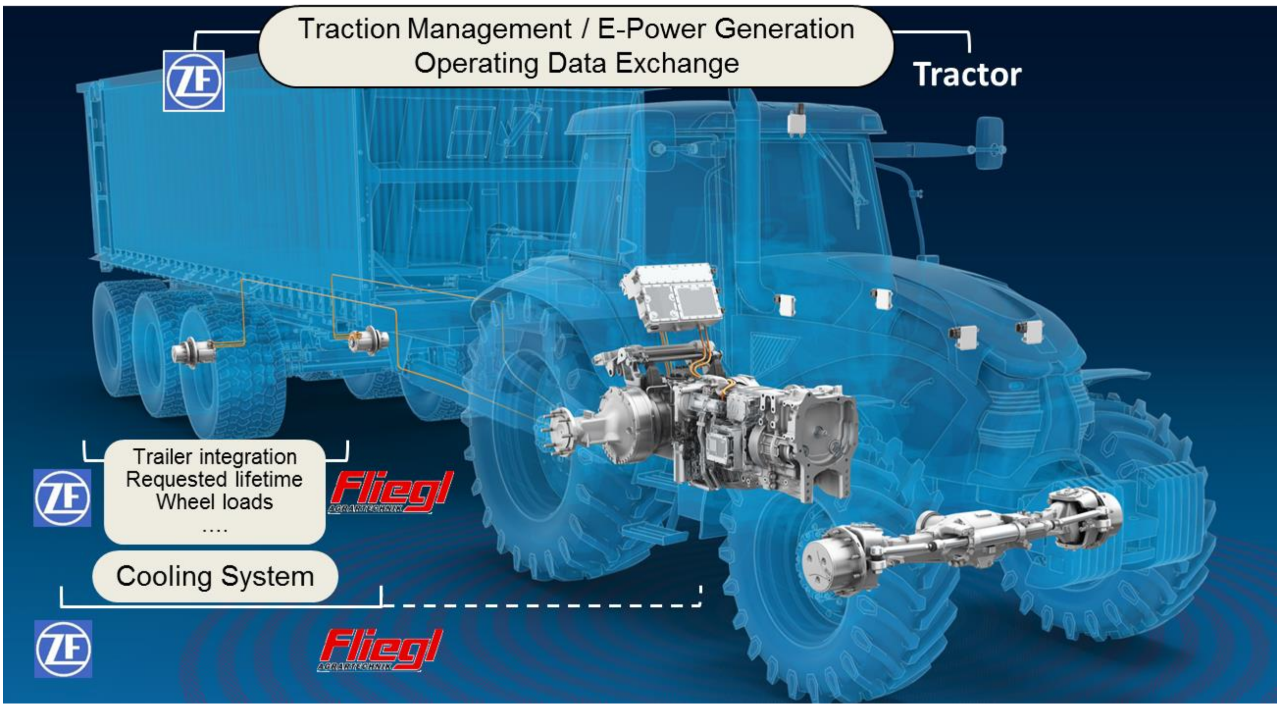


Figure 5 – Electric axle drive solution incl. an optional transfer gearbox, preferable for use with agricultural trailers.

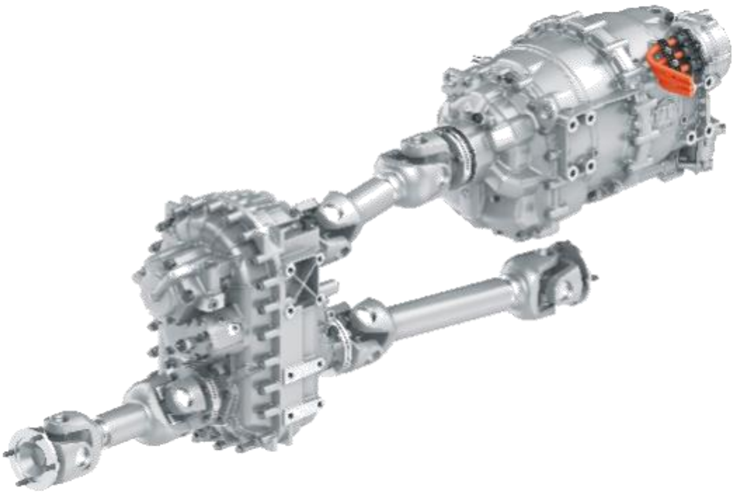


Figure 6 – Examples of implement architectures that require electric wheel hub drive units

Source: Pöttinger, Amazonen Werke, John Deere

Figure 7 – ZF electric wheel hub drive unit with features and functions derived from scanning various applications and implement requirements