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# Trailers with Propelled Axle

## Approaches for Solutions and Potentials

*Trailers with propelled axles have existed for a long time, but have only been used on extreme slopes for decades. Despite various disadvantages in the current systems, the propelled axle trailer is technically a meaningful concept. For this reason a trailer with a new power drive-train configuration is being introduced, which solves the known problems and offers new advantages.*

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**Keywords**

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Propelled trailers (PTs) are known from the past. They were driven by the tractor-PTO via a drive shaft as were the working parts (e.g. beater rotors). Due to different wheel sizes, it was necessary to use intermediate gear boxes in order to match tractor and trailer. To have draught at the trailer axle only above certain levels of wheel slip and to prevent the trailer from pushing the tractor, a slight after run was implemented. Similar to the problem of invariable pre run on tractor front axles [1], this leads to circulating power or kinematically incorrect circumferential speeds of wheels during curves. Forces between tractor and PT were examined in [2], where also the use of a free-wheel to avoid circulating power is proposed. Nevertheless, the intermediate gear box with usually two shiftable gears remained. Due to the limited number of steps or the missing stepless transmission respectively, it was only possible to operate in the speed-range provided by adjusting the revolutions of the engine. Going through broader speed-ranges was impossible. Additional possibilities for transmission are the infinitely variable PTO as in [3] and the ground speed PTO, both of which offer a broader speed-range. With the introduction of all-wheel-drive and rising masses of tractors, the PT vanished almost entirely. The basic concept itself remained almost unchanged over the years, full hydrostatic drive-trains are found sporadically on smaller trailers. In recent years PTs became again available in Belgium, Luxembourg and The Netherlands. Especially slurry and manure spreaders are equipped with driven axles. On the one hand these had a significant rise in load capacity for the sake of increased productivity. On the other hand these spreaders are often operated in adverse soil conditions, which sometimes leave even heavy and powerful tractors at the limits of transmissible power.

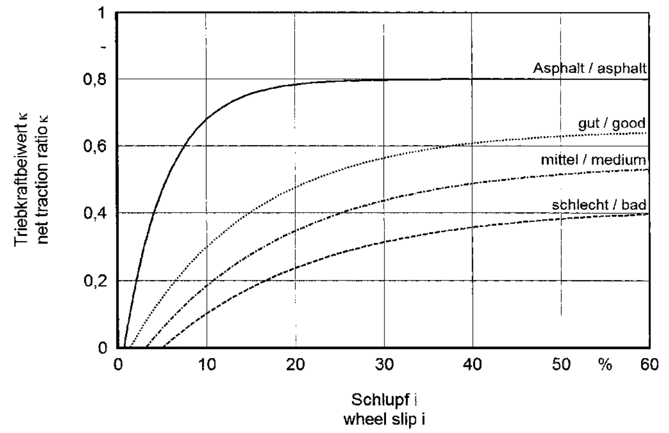


*Fig. 1: Curves of net traction coefficient vs. wheel slip contained in the model*

### Problem statement

Due to the interrelation of normal force $F_z$ and rolling resistance force $F_R$ (Eq. 1) heavy trailers demand high draught, especially in off-road conditions. Driving on slopes adds downhill force $F_H$ (Eq. 2). Like the rolling resistance, maximum draught $F_T$ of the driven wheel (Eq. 3) is connected to the normal force.

$$F_R = \rho \cdot F_Z \quad (1)$$
$$F_H = G \cdot \sin \alpha \quad (2)$$
$$F_T = \kappa \cdot F_Z \quad (3)$$

Pulling heavy trailers therefore requires the use of heavy tractors. Nevertheless, in adverse soil conditions wheel slip rises significantly, sometimes reaching 100%. If PTs are employed, lighter tractors with sufficient engine power can pull heavy trailers. Hence, a few problems are to be solved.

To operate within a broader speed-range and in order to adapt to changing conditions of tyre-ground-contact or to set the correct speeds in curves, a infinitely variable transmission (IVT) for the trailer is mandatory. Additionally, one has to consider changing axle loads during field operation due to loading and unloading of the trailer with the mentioned effects on rolling resistance and maximum possible draught.

### Concept

To fulfil the tasks as described a drive-train-configuration with the following features is proposed: the PT's drive-train is an IVT, at least two wheels are driven by individually controlled single-wheel-motors. To distribute the share of additional costs of the drive-train among different lines of production, a trailer with interchangeable superstructures should be used.

To evaluate potential benefits of such systems a MATLAB/ Simulink- model of a tractor-trailer-combination was built. Important inputs into the model are: output-torque of the single-wheel-motors, inclination of terrain, and tyre-ground-contact, the latter mainly depending on soil condition and the chosen tyre. For reasons of simplification, tyre-ground-contact is categorised into four classes: bad, medium, good and asphalt. The respective curve progressions of net traction ratio vs. wheel slip are shown in *Figure 1* [modified from 4].

The curve progressions for the net traction ratio κ can be calculated according to [5] by Eq. 4. The corresponding parameters a, b, and c can be found in *Table 1*.

$$\kappa = a + b \cdot e^{c \cdot i} \quad (4)$$

With improved soil condition the rolling resistance coefficient ρ is decreasing. For the sake of simplification it is assumed as constant for each single axle with a decrease of the coefficient from front to rear axles due to the so called multi-pass-effect. Changes in rolling resistance induced by changing axle loads which are a result of varying draught are taken into consideration.

For a given tyre-soil-contact the model calculates the effects on tractor wheel slip for switching all-wheel-drive and PT-drive on and off as well as altering the PT motors' output torque. All this is done for different inclinations.

### Results

The basis for the following results is a 6.3 to. tractor with a 22 to. tandem axle trailer, the two front wheels of the trailer are driven. The trailer is hitched at drawbar height to the unballasted tractor with all-wheel-drive on. *Figure 2* shows results of the model calculation for single-wheel-motor torques from 0 to 160 Nm and inclinations ranging from 0 to 10% with bad tyre-ground-contact conditions. To transfer the circumferential force, the net traction ratio of the trailer wheels should not be higher than 0.2 (this is the case under approximately 110 Nm). For the sake of soil conservation wheel slip shall not exceed 20%. This leads to a straight line at 110 Nm (change of normal force due to inclination and thus reduced maximum draught in this case neglected) and one at 20% wheel slip. These lines (together with the x-axis) form a target triangle for the operational torque-range of the PT-drive.

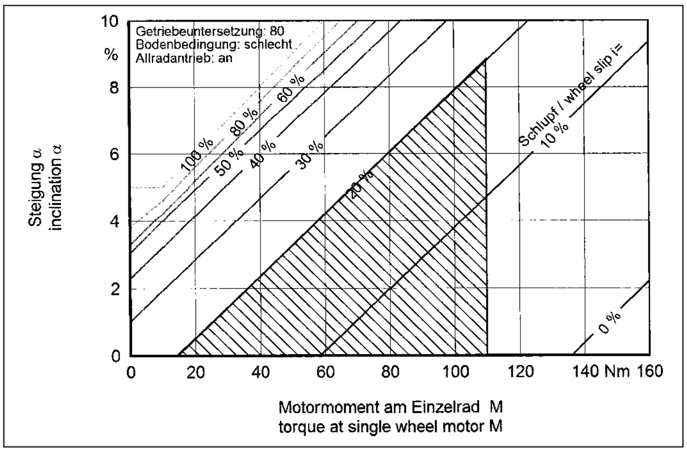


*Fig. 2: Iso-slip-lines for set torque and inclinations*

Having a look at wheel slip on a 5% slope one can asses a decrease from 100% to about 17% by an input of 80 Nm at each wheel drive. For a desired travel speed of 5 km/h this results in roughly 28 kW of required power, which lies within the limits of good hydraulic systems of tractors of the desired weight class. It has to be stated, however, that a PT-drive with a maximum power like this is only suitable as a supportive drive for field operations.

### Summary and perspective

A number of advantages can be achieved with a PT, which has an IVT. Depending on the circumstances, wheel slip can be reduced significantly. Additionally, a lighter tractor can pull heavy trailers. Compared to a larger tractor it is more manoeuvrable and contributes to soil conservation. Moreover, the larger tractor can be utilised in other applications (e.g. in tillage) and the utilisation of the smaller tractor is increasing. Safety and comfort can be raised by incorporating a control to diminish dynamic oscillation of wheel loads and hitch shocks. A single-wheel-drive adds additional advantages by rendering lateral dynamics control possible. Such drive-trains do not need differentials neither.

As a matter of principle drive-train- and undercarriage-efficiency of both tractor and trailer must be taken into consideration in order to decide the optimum distribution of available power to the respective drives. Drive-train-efficiency is crucial. Provided that more electrical power will be installed in future tractors, electric drives present a viable alternative for this application. Electric drives would offer the known advantages compared to hydraulic drives but overload capacity might be the most advantageous. Furthermore, they provide the possibility of electric braking and associated with it deceleration management- so called anti-jack-knifing. Extra costs of such a system finally have to be justifiable through improved efficiencies, operational advantages, and increased comfort.

| soil condition | a | b | c | equivalent to |
|---|---|---|---|---|
| bad | 0.4164 | -0.5504 | -0.056 | harvested beet field (humid) |
| medium | 0.55 | -0.66 | -0.059 | harvested silage maize field (humid) |
| good | 0.6499 | -0.7119 | -0.0707 | stubble field (dry) |
| asphalt | 0.8 | -0.909 | -0.2015 | street |

*Table 1: Parameters describing tyre-ground-contact*

## Literature


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