

INCLINATION LIMITS FOR HIGH MECHANIZED HARVESTING

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Abstract: *Forestry operates between a growing demand for timber products and increasing ecological requirements. Especially harvesting operations in inclined areas cope with these sometimes competing aims: On the one hand larger resources and therefore utilization potential but on the other hand an ecosystem which is particularly sensitive to unadjusted harvesting operations. Mobility of soil linked machinery in inclined areas is bonded to erosion by (wheel) slip. Therefore an ecological timber harvesting with high mechanized machines has to observe a limitation of slip.*

Drawbar pull measurements with a forwarder determine the traction performance. The resulting relation between wheel slip and traction can be compared with the downhill slope force acting on the machine. The traction performance allows to define a model with an ecological limit based on an accepted wheel slip level and an absolute limit for operations with traction support winches (based on the maximum traction force). Tests were performed on a typical soil for low mountain range in Germany at varying soil moisture. In addition to the soil properties different configurations (e.g. tire pressure, tracks, chains, tire type) of the test machine (forwarder) were included. Subsequent to the traction measurements the model was verified by test drives under inclined conditions. The prognosis of the model was the traffic ability (inclination) with a maximum of 25 % wheel slip. Over 80 % of the test drives were assessed correctly in advance.

The economic utilization of wood resources in inclined areas often depends on the application of high mechanized harvesting. An inappropriate machine usage can lead to serious damages and consequently traffic ability is ruined by a few passes. Utilized for a well organized harvesting operation the model leads to safe and ecological timber harvesting operations in inclined areas and therefore to an increased timber mobilization from these areas.

1. Introduction

Timber as a regrowing resource is getting more and more popular for material use as well as for energetic usage. In order to meet the demands it is important to make previously unused wood potentials accessible for the timber market. One interesting block are the incompletely utilized resources in inclined regions. Problems arise in these areas by the topographic limitations of high mechanized timber harvesting. Apart from economical problems there are great uncertainties about the terramechanic limits in inclination for the adoption of high mechanized harvesting machines.

Limitations occur from the stability of the machines as well as from the damages done to the soils. In inclined areas the later often result from driving with high slip. Results from agricultural research (Söhne, 1952) indicate that with increasing slip the risk of serious harm that is done to the soil gets bigger. For the present question of how far high mechanized harvesting machines can be used in inclined areas the acceptable limit for wheel slip was set to 25 %. Higher wheelspin leads to a complete shearing-off of the topmost soil structures. Loose soil material gets washed away with the next intense rain. In order to reduce this additional strain objective limits for harvesting operations with land-based machinery are important.

On the basis of traction measurements under level conditions an inclination limitation model for a forwarder was developed. Considerations about the downhill slope forces acting on the machines show a direct correlation between the inclination and the traction coefficient, which describes the relation between drawbar pull and machine weight. Linear regressions of traction coefficient and wheel slip lead to a good description of traction abilities and can be faced with the downhill slope force.

Trials were conducted on typical loess soils of the uplands in southern Lower Saxony. Traction measurements identified the soil water content and the skeletal admixtures as the main soil parameters that effect the climbing ability of the forwarder. While the variation of tires and tire inflation pressure showed little influence an obvious advancement in traction performance was achieved by mounting wheel tracks and chains. All these factors were used to calculate a prognosis about the trafficable inclinations with regard to soil protection and a second (maximum) limitation with regard to stability against an uncontrolled gliding.

The calculated ecological limits as well as the test drives under inclined conditions point out that land-based high mechanized timber harvesting is limited in uplands. In order to protect the soil from erosion and for the safety of the machine operators it is recommended to use traction aids (tracks and chains) early enough. If the soils bearing capacity is assured tracks and chains allow an ecological passing of forest soils even at higher water contents up to inclinations of 35 %. Inclinations higher than that can be traveled only at good conditions (dry soil) or with the additional aid of a traction support winch.

Theoretical Considerations

Every offroad machinery has to produce a tractive force which allows to move in the field. The tractive force (F_T) of machines is described by the general tractive force equation (e.g. Jacke, 1999):

$$F_T = F_N * (\mu_{st} + \mu_{sl} + \mu_{fo} - \mu_{ro}) \quad (1)$$

containing the following variables:

- F_T = Tractive Force
- F_N = Normal Component of the axle weight
- μ_{st} = Static Friction Coefficient
- μ_{sl} = Sliding Friction Coefficient
- μ_{fo} = Form Closure Coefficient
- μ_{ro} = Rolling Resistance Coefficient

The coefficients which exert a positive influence on tractive force are generally summarized as the “frictional connection coefficient” (μ_{fr}). Under the assumption that the rolling resistance coefficient has a constant value depending on the soil the formula can be reduced by the “traction coefficient” (μ_{tr}). This traction coefficient combines frictional connection (μ_{fr}) and rolling resistance (μ_{ro}). Therefore the tractive force is derived by the traction coefficient and the weight on the driven wheels. The traction coefficient of a machine varies depending on the variation of final drive. Tracks, wheel chains and a reduced tire pressure lead to higher tractive forces (Vechinski et al., 1999; Sommer et al., 2001; Weise, 2002; Hittenbeck, 2006) and were also be tested for their influence.

When higher tractive forces are required the relevance of the sliding friction coefficient (μ_{sl}) is increasing, which is always combined with an increase of slip at the wheels. The wheel slip (or the travel reduction ratio) is derived from a difference between (theoretic) speed of the wheel at the circumference and the traveled velocity above ground (effective speed). Depending on the required tractive forces and the ground conditions slip varies between zero (both velocities are equal) and 100 % (wheels are turning while the machine stands still). Wheel slip is calculated by the following formula (e.g. Zoz and Grisso, 2003):

$$\sigma = \left(1 - \frac{v_{ef}}{v_{th}}\right) * 100 \quad (2)$$

σ is the wheel slip (%), v_{th} the theoretical speed (at the wheel circumference) and v_{ef} the effective velocity above ground. Slip can also be calculated by the traveled distances, but this would mean to divide them into shorter sections to be accurate enough.

Driving on slopes requires higher tractive forces which are closely related to the occurring higher slip. As high slip courses rutting soils under hillside conditions are more exposed to erosion than soils on flat land. In order to protect these sensitive soils there have to be valid information about the required tractive forces and therefore the occurring slip. The required tractive forces can be estimated by the downhill slope force (F_T) which is derived from the product of weight of the loaded vehicle (F_G) and the sine value of the inclination angle (Höpke et al., 2000; Jacke and Drewes, 2004) following the equation:

$$F_T = F_G * \sin \alpha \quad (3)$$

With increasing inclination angle the downhill slope force and therefore the required tractive force increases until the forces are equal and no further movement is possible. Expressed in a formula this leads to:

$$F_N * \mu_{tr} = F_G * \sin \alpha \quad (4)$$

The forces used on the both sides of the formula are different. In order to solve the equation the axial or normal force of the machine (F_N) has to be expressed as a function of weight force (F_G) and the inclination angle.

$$F_N = F_G * \cos \alpha \quad (5)$$

Inserted into formula (4) this leads to:

$$(F_G * \cos \alpha) * \mu_{tr} = F_G * \sin \alpha \quad (6)$$

Reduced by the normal force of the machine (which is know the same for both sides of the formula) and the cosine value of the inclination angle, the result is as follows:

$$\mu_{tr} = \tan \alpha \quad (7)$$

From this point the traction coefficient (μ_{tr} , measured under level conditions) leads to the slope which is barely accessible. The tangent value of the inclination can easily be transformed to slope inclination given in percent by multiplying with 100. As the traction coefficient is closely related to the wheel slip it is possible to predict the occurring slip values. The other way around makes it possible to define an acceptable slip level and to see which slopes can be worked without slip induced erosion. In the agricultural sector slip values up to 25 % are accepted (Söhne, 1952).

Values for the traction coefficient (μ_{tr}) for different soil properties and machine variants can be derived from traction measurements as they are shown at Jacke et al. (2004), Hittenbeck (2004) or Hittenbeck (2009).

Methods

The determination of traction coefficients was done by traction slip measurements carried out with a forwarder (Ponsse, model S10 Caribou) under level conditions. This was done for different variants

which result from different setups of the final drive (worn tires, new tires, reduced tire pressure, tracks and chains) as well as different soil types and varying soil moisture. In addition to measurements with an empty forwarder a few variants were tested for a loaded machine as well (Hittenbeck, 2009).

A special deceleration machine was constructed for the traction tests. The machine bases on a winch which is linked to a breaking system from a heavy truck. Both are mounted to a platform in order to be able to install the machine on skidding lanes. Figure 1 shows the deceleration machine fastened with ground anchors and tied to a tree. The deceleration of the forwarder is controlled by a feedforward control. The forces acting on the brake disc are increased until the forwarder is not able to pull out the rope any more. Afterwards the pressure on the brake is reduced until the machine is able to drive without interference. This proceeds until the feedforward control is switched off.



Figure 1. Deceleration machine installed on a skidding lane

During the trials the tractive forces of the forwarder as well as the speed of wheels and above ground were measured on the forwarder. Forces result from a load cell (Hottinger Baldwin Measurements (HBM), model U2B). The speed of the wheels and the effective velocity is determined using incremental rotary encoders (Kübler, model 5800). A modularly equipped measurement system MGCsplit by HBM serves as data collector for all applied transducers.

The tests are driven on skidding lanes under different site conditions, which are characterized by high loess percentages. The main (apart from soil moisture) difference between the site types is the stone admixture. The tests are carried out on bare soil because of the ambiguous effect of a brushwood layer (Hittenbeck, 2004; Jacke et al., 2004). Before the test drive starts all soil parameters like soil type, soil moisture, humus layer and inclination of the stand are determined.

The resulting relations between wheel slip and traction coefficient for the different test variants were used to calculate a model for the accessible inclinations. First aim is the (ecologically justifiable) inclination at a maximum of 25 % slip. Second is the (theoretical) inclination resulting from the maximum values for the traction coefficient which assures a safety against uncontrolled slipping. The ecologically limited inclinations were validated by test trials under inclined conditions near the models assumptions.

Results

Also over 20 different (possible) influence factors were surveyed at the trials the linear regression models (using the stepwise modus) spotted out only a few relevant variables. The greatest influence on traction and therefore mobility in inclined conditions results from the mounting of traction aids. For the test these

were tracks and wheel chains. On the soil side the soil water content and skeletal ratio of the soils dominated the traction abilities. Based on these main influence factors the limitation model for high mechanized harvesting with wheel carriages was calculated. The resulting limits for soil without stone admixture as well as for soils with higher skeletal ratios above 7 % are displayed in table 1.

Table 1. Inclination limits for high mechanized harvesting with wheel based machinery depending on soil conditions and configuration of the machines (Hittenbeck, 2009)

Soil-Water-Content (skeletal ratio) (%)	Wheels		with Tracks and Chains	
	<i>inclination limit (ecological) (%)</i>	<i>inclination limit (max.) (%)</i>	<i>inclination limit (ecological) (%)</i>	<i>inclination limit (max.) (%)</i>
25 (0 %)	34	50	48	70
30 (0 %)	30	48	43	67
35 (0 %)	26	45	39	64
40 (0 %)	21	42	35	61
45 (0 %)	17	39	31	58
25 (over 7 %)	46	60	60	79
30 (over 7 %)	42	57	56	76
35 (over 7 %)	38	54	52	73
40 (over 7 %)	34	51	47	71
45 (over 7 %)	30	48	43	68

The validation tests for the ecological limits revealed that for over 80 % of these tests the prognosis (trafficable with a maximum of 25 % slip or not) matched the reality. The maximum inclinations of the model were not tested for reliability. But the validation test stated out already that the maximum inclinations from the model are not trafficable by driving uphill. Anyway this was not expect, but the resulting values might be use full for the question of limitations for machinery with traction support winches. These machines should only be used in areas where they can stand (in case of rope cracks) without sliding.

Conclusion

For rather unfavorable soil conditions (skeletal free, 40 % soil water content) the presented inclination model results in an ecologically trafficable inclination of at least 20 %. Under the same conditions a machine equipped with tracks and chains is able to climb inclinations up to 35 %. For both examples however it has to be noticed that the bearing capacity of the soil is already reduced. Considerable soil compaction effects could be expected. Especially in inclined areas machine traffic is reduced to dry and capable of bearing weather conditions in order to reduce the risks for the soil and therefore the long-term traffic ability.

Harvesting operations in a terrain with more than 20 % inclination should therefore early enough be supported by tractions aids (tracks and/ or chains). This improvement of soil protection (vgl. Kremer et al., 2007) and safety for the operator is bought by the damages done to the root system of the trees at the skidding lane edge (Schardt et al., 2007) and an increase of machine weights (Jacke, 2007). In addition there are different types of tracks which are optimized for special operation conditions and therefore differ in there ground pressure and traction abilities. Even if under good conditions inclinations well above 40 % seem trafficable with tracks and chains the additional safety of a traction support winch is already recommended in these areas. Thereby the machine is backed by a robe which is synchronized with the traction drive (Nick, 2005; Mühlhausen, 2005; Stuhlmann und Findeisen, 2009). Apart from the additional safety it comes to much lower (wheel) slip values and therefore soil erosion damages. But it

has to be kept in mind, that traction support winches are optimized for a small range of inclinations (Amelang, 2009)

Working at the limits of traffic ability of the machines is not just a matter of soil protection and timber mobilization but also stress for the operator. Most of the machines used in steeper terrain are not equipped with tilt facilities which allow a relaxed positioning of the operator. Harvesters are often provided with tiltable cabins but there are very few forwarders which possess tiltable driver seats. This results in ergonomic stress (Lambert and Howard, 1990 cf. Heinemann, 1999) for the operator. Apart from the physical strains there are psychic stresses which refer to increased risks and higher requests for the operation because of the reduced handling opportunities. In order to ease the harvesting and forwarding operations in steep terrain the machines which are regularly used for inclined areas should be equipped with tiltable cabins or driver seats and cranes. This would reduce the physical strains for the operator and in case of a tiltable boom will decrease the damages to the residual trees.

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