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LIMITS OF WHEEL BASED TIMBER HARVESTING IN INCLINED AREAS

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Abstract: *In times of a growing demand for forest products, timber harvesting in inclined areas becomes more important. If this has to be done with cable cranes or other specialized mountain equipment harvesting becomes expensive and is reduced to profitable stand structures. The question about the inclinational and ecological limits of wheel based, high mechanized harvesting has a lot of influence on the economical possibilities of lumbering. But the discussion about the limits is very controversial while real scientific investigations are lacking. A project about save and ecological timber harvesting in inclined areas is going to close this gap of scientific information. Drawbar pull measurements under even conditions done with a forwarder will lead to a model about the limits of wheel based forest machinery on hillside situations. The relation between slip and tractive force can be compared with the down hill slope force. An ecological limit will result from an accepted slip level while the maximum tractive forces determine the absolute limitation of wheel based machinery. The measurements are taken on two different soil types and varying soil moistures. In addition to the soil properties different configurations (tyre pressure, tracks, chains etc.) of the test machine (forwarder) will be included.*

1. Introduction

In the last few years timber mobilization became more and more a theme of interest in Germany. Wood product industries are building up new enterprise locations with increased production volume. A second growing stream in timber utilization is the energy recovery. In order to satisfy the competing demand for raw timber new ways to mobilize timber especially from smaller forest owners and from unprofitable areas have to be found. Whereas the smaller owners are more a political and organizational problem some of the unprofitable areas might be made accessible by technical solutions. Unprofitable conditions are often assumed in inclined areas were a manual timber harvesting is thought to be inescapable.

Timber harvesting under such conditions is for economical and ecological (stand stability) reasons an important operation in forest enterprises. Timber mobilization from these areas is associated with specialized working systems which are often characterized by low productivity and high ergonomic stress. In order to increase locally produced timber usage, as politically demanded (BMVEL, 2004), Germany is depending on the wood reserves in inclined areas.

Concerning the development of forest engineering to solve the occurring problems are forest experts who propagate the use of standard machines like harvesters and forwarders. Thereby limits for hillside use with different configurations (tires, tracks, chains) of the machines are mentioned, but they are not well-founded related to their terramechanic efficiency. The discussion about the limits of high mechanized harvesting is growing more and more important but is often influenced by particular circumstances.

The aim of the project is the investigation of the terramechanic effects of a well organized machine usage. Tests done by the Institute of Forest Work Science and Engineering (ifa) in Göttingen with a mobile measurement system (DREWES, 2004) will be carried out for different configurations of the undercarriage and varying soil types and moistures. With the help of a special deceleration machine the traction performance and the occurring slip for the different variants will be measured. The results will enable a definition of the limits for the different variants in order to assure a save and ecologic timber mobilization.

The aspect of an ecological harvesting is closely related to the soil properties. An inappropriate machine usage can lead to serious and irreversible soil damages (BECKER ET AL., 1989; KREMER ET AL., 2003; LI ET AL., 2007). The negative effects of driving can be splitted into soil compaction and the destruction of the topmost soil structures (RAPER, 2005). Especially the compaction by the high weight of the machinery is well investigated for agricultural and forest soils (MATTHIES AND KREMER, 1999; VOßBRINK, 2005), while the effect of driving with high slip has not been focused by forest researches yet. High slip levels while travelling lead to a destruction of the topmost soil structures which is the base for erosion (KREMER ET AL., 2007). Especially in inclined areas water erosion can lead to considerable rutting.

2. 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}**)** subsequently simplifying the formula to:

$$F_T = F_N * (\mu_{fr} - \mu_{ro}) \quad (2)$$

Under the assumption that the rolling resistance coefficient has a constant value depending on the soil the formula can be reduced to 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. This also means that high tractive forces depend on high mass weights of the machinery. 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 will 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):

$$\sigma = \left(1 - \frac{\upsilon_{ef}}{\upsilon_{th}}\right) * 100 \tag{3}$$

σ is the wheel slip (%), ν_{th} the theoretical speed (at the wheel circumference) and ν_{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:

$$F_T = F_G * \sin\alpha \tag{4}$$

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:

$$F_N * \mu_{tr} = F_G * \sin\alpha \tag{5}$$

As the Normal Component of the axle weight (F_N) changes depending on the surface inclination it can be replaced by cosine of the weight force (F_G*cosα). Reduced by the weight force of the machine which is the same for both sides of the formula, the result is as follows:

$$\mu_{tr} = \frac{FG * \sin\alpha}{FG * \cos\alpha} = \tan\alpha \tag{6}$$

From this point the maximum traction coefficient (μ_{tr}**)** 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 inducted erosion. In the agricultural sector slip values up to 25 % are accepted (SÖHNE, 1952 cf.; RENIUS, 1985). Values beyond this result in a damage of the topmost soil structures.

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; HITTENBECK 2006). A project about “save and ecological timber harvesting in inclined areas” at the Institute of Forest Work Science and Engineering (ifa) is going to prove if this theoretical considerations about slope resistance and tractive forces match with measurements.

3. Methods

The determination of traction coefficients is done by traction slip measurements carried out with a forwarder (Ponsse, model S10 Caribou) under even conditions. The resulting data are used to calculate the relationship between slip and tractive forces. This is 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 two soil types and varying soil moisture. In addition to measurements with an empty forwarder a few variants will be tested for a loaded machine as well.

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 ankers and tied to a tree. In order to reduce the forces acting on the winch the steel cable is mounted to the forwarder with a deflexion pulley, which halves the forces on the rope and leads to a doubling of the rotational speed of the winch. 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.

The deflexion pulley is connected to the experimental forwarder by a load cell (Hottinger Baldwin Measurements (HBM), model U2B). In Figure 2 can be seen how the sensor is attached to the test machine. The measuring range of the transducer is 200 kN with a precision of 0,1 % of the maximum value, the forces are measured by wheatstone bridges in resistance strain gauges.

Figure 1: Deceleration machine installed on a skidding lane

Figure 2: Force transducer and deflection pulley mounted to the test machine

As the calculation of slip depends on the difference between the wheel rotational speed (theoretical) and the velocity above ground (effective), these factors have to be measured. The speed of the wheels and the effective velocity is determined using incremental rotary encoders (Kübler, model 5800). Figure 3 shows how one of the encoders is adapted in extension of the wheel hubs in order to measure the wheel rotational speed. A second rotary encoder is implicated to a kind of tachyometer compass, where it measures the rotation of a spill drum. The spill drum is driven by a strain free nylon cord, which is tied to the deceleration machine.

Figure 3: Mounting of rotary encoders in extension of the wheel hubs

A modularly equipped measurement system MGCsplit by HBM serves as data collector for all described transducers. Different measuring amplifiers enable the physical adaptation of the sensors (rotary encoder and load cell). This allows the sensors to be synchronized with each other and to be aligned via one single communication device (model CP 42). All data from the measuring amplifiers are saved to a PCMCIA card. Afterwards the data can be fed to a computer, which transfers the specific data format to a common data set.

The tests are driven on skidding lanes under two different site conditions, which are characterized by high loess percentages. The difference between the two site types is the stone admixture. One site is characterized by pure loess while the second one has a high skeletal ratio. For the tests skidding lanes with a free length of 70 to 100 m are required. This is due to the length of the forwarder and the deceleration machine. The tests are carried out on bare soil because of the ambiguous effect of a brushwood layer (HITTENBECK, 2004; JACKE ET AL., 2004). Depending on the soil moisture the brushmat increases or decreases the available tractive forces. Before the test drive starts all soil parameters like soil type, soil moisture, humus layer and inclination of the stand are determined.

When the test procedure is started at the feedforward control the forwarder pulls out the rope from the winch against the rising resistance. The experimental drive starts with low required tractive forces which are increased by the rising of forces acting on the brake pads. This leads to higher tractive forces on the load cell and to an increase of wheel slip until it reaches 100 % (turning wheels but no motion above ground). During the tests the forwarder works in its lowest gear while the differentials are locked, so that all eight wheels turn with the same rotational speed. Depending on the length of the skidding lane this procedure is repeated until the rope on the winch is almost empty. Experience from already done test drives show that between four to ten decelerations can be arranged on one pullout of the rope. The skidding lanes are usually used up to ten times which results in about 60 recurrences per test lane.

4. Traction Performance

Due to the high measurement frequency of 10 Hz the resulting data have to be post processed. Experiences from the previous project SliFor (Slip and Tractives on Forest Conditions) by (JACKE ET AL. 2004) showed, that the data are reduced to about 40 %. Especially the longer periods between the single breakings of the test machine lead to this reduction. In addition the interpretation of the data is focused on times of increasing wheel slip values. Otherwise the effects of pulling forces and accelerational resistance would interfere with each other.

Figure 4 demonstrates an example of how the scatter plots look like after the reduction. On the ordinate the traction coefficient is displayed depending on the measured wheel slip in percent. The traction coefficient indicates how much of the machines mass weight can be turned to tractive force. In order to calculate the traction coefficient the measured tractive forces were divided by the specific normal force of the machine. This includes the mass differences between the variants (tracks, chains and payload). The examination of the traction coefficient has the advantage that differences in weight do not affect a comparison between two or more variants.

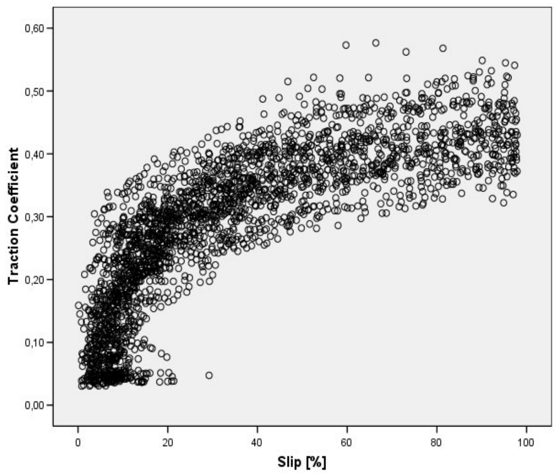

Figure 4: Scatter plot for tires with an inflation pressure of 2,7 bar

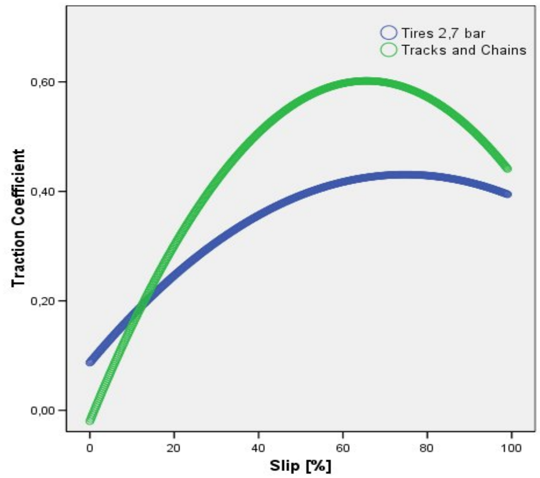

Figure 5: Regression curves for the variants tires vs. tracks and chains

Since the scatter plots for the different variants are identical in their universal outline to Figure 4, the presentation of preliminary results is reduced to linear regressions. Due to the experiences from the project SliFor a quadratic regression served to explain the relationship between the traction coefficient and the measured wheel slip (JACKE ET AL., 2004; HITTENBECK, 2004; HITTENBECK, 2006). Other regression types up to nonlinear models were tested but did not result in a better fitting.

Figure 5 demonstrates the regression curves for the variants regular tire pressure (2,7 bar) and tracks combined with chains on a test area near Göttingen at soil moistures between 20 and 30 %. It can be seen that the differences between the two variants are rather pronounced. As expected the lower values for the traction coefficient are registered for tires with the "regular" tire pressure. Tracks and chains interlock better with the topsoil (WIPPERMANN, 2000) and therefore lead to the expected and measured higher traction coefficient values (VECHINSKI ET AL., 1999). Especially the tracks increase the tractive performance (BLEY, 2002), which is due to the larger contact area and the traction studs mounted to the cross members.

5. Traction and Slopes

As the differences in traction performance between the two variants are obvious, the forecasted abilities in

Table 1: Climbing ability and slip for three variants depending on soil type and soil moisture

Variant	Soil Type	Average Soil Moisture [%]	Max. Inclination	Slip at max. Inclination [%]	Inclination at 20 % Slip	Inclination at 30 % Slip
Tires (2,7 bar)	Loess without stone admixture	27,0	43 %	74,8	25 %	31 %
Tracks and Chains	Loess without stone admixture	20,5	60 %	65,6	30 %	42 %

inclined areas do as well. In Table 1 the limits for the variants and conditions are displayed. The presented values are based on the respected regression curves. A comparison between tires and tracks combined with chains demonstrates the advantages in traction and therefore mobility under sloped situations. For both variants the soil type and moistures are given as well as the estimated maximum inclination, the occurring slip at the maximum and inclinations for two different slip levels, which are 20 % and 30 %.
Compared for the conditions found near Göttingen, the prognosis for the maximum climbing ability differs by 18 % between tires inflated to 2,7 bar and the combination of tracks and one pair of chains. Equipped with tires the maximum inclination is predicted with 43 % while for tracks and chains up to 60 % inclination are within reach. The maximum inclination is of high relevance, because it can be seen as the point where the machine is at least able to stand without sliding downhill. This is *the* important point in two different situations, first for a machine driving downhill and second for machines which have a traction supporting winch. In case of a rope crack or other difficulties it would be most likely that the machine would not slid uncontrollably. Apart from the risk for the machine and the operator this are inclinations where every movement would lead to serious damages of the topmost soil structures.

If the accessible slope is limited by an ecologically accepted slip level of for instance 30 % the maximum inclinations are reduced to 31 % for tires and 42 % for tracks and chains. The difference of 11 % in this example demonstrates that a well planned harvesting operation in inclined areas can be done with wheel based machines without the risk of increased erosion.

In order to validate those predictions test drives in inclined areas were driven without the deceleration machine. Under soil conditions comparable to flat test areas the machine drove up a steady slope while the wheel slip was measured. Measurements with the tire variant were accomplished on a slope of 33 % at an average soil moisture of 28,8 %. The measured slip values were mainly located between 10 % to 50 % and leaded to an average slip level of 29 %. The rather wide range of values is due to the conditions found on the inclination. Roots and smaller changes in slope have a considerable influence on the tractive abilities and therefore lead to the high variation of the measured slip values. Especially when the inclination is close to the limit little changes in the soil surface have a lot of influence. Roots of a few centimeters height can become a real barrier whereas they act as a support when they interlock with the tire studs.

6. Discussion

The already conducted tests show that the presented measurement system is able to record the traction performance of off road vehicles under forest conditions. In addition to the test carried out on bare soil and on a brushwood layer in a former project (JACKE ET AL., 2004; HITTENBECK, 2004) the influence of tracks and chains on the traction abilities of a forest machine is investigated. Regarding the exemplary presented regression curves the traction coefficient of tracks in combination with chains is about 40 % higher than for tires with the regular inflation pressure. As an effect of the higher traction coefficient and therefore of the increased climbing ability tracks and chains can be recommended for steeper terrain. But it has to taken into consideration that this just regards the damages caused by higher slip and not the damages which result from tracks and chains. A study conducted by (SCHARDT ET AL, 2007) shows the structural destructions of roots by the studs of the tracks. Compared to tracks tires caused more damages to the bark of the roots.

Working at the limits of traffic ability of the machine 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 posses tiltable driver seats. This results in ergonomic stress (LAMBERT AND HOWARD, 1990 cf.; HEINIMANN, 1999) for the operator which often results in tensions of the neck muscles. 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.

7. Conclusion

At present forestry in Germany is confronted with an increasing demand for timber products, especially for material and energetic utilization. Therefore it is getting more interesting to mobilize the wood in steep terrain as well. But inclined areas are often considered to be unprofitable for timber harvesting but this is just half the truth. Areas which are accessible by wheel based machines without serious damage to the soil and without increased risk for the operator can be harvested economically justifiable.

The presented project deals with the determination of limits for wheel based harvesting in inclined areas. Traction tests carried out with a precise measurement system under flat conditions lead to the relationship between the traction coefficient of a machine and the ecologically undesired wheel slip. Mathematical logic shows a close relation between the measured traction curves and the downhill slope force acting on the machine when driving uphill. As these forces have to be at least equal it is possible to make predictions about the occurring slip at certain inclination angles. Exemplary results for tires on loess soil show an agreement of measured and predicted values.

Further tests with different configurations of the machine and varying soil conditions will provide an overview of the climbing abilities of a wheel based forwarder. Utilized for a well organized harvesting operation the results can lead to a save and ecological timber harvesting in inclined areas and therefore to an increase of timber mobilization from Middle European forests.

8. References

Becker, G.; Hofmann, R.; Roeder, A.; Eisenbarth, E.; Hanewinkel, M. (1989): Bodenschäden durch Forstmaschinen auf Tonstandorten. –Entstehung, Messung, Begrenzung-. Forst und Holz, Jg. 44, 19/1989 Alfeld, p. 507-512.

Bley, D. (2002): Sind Traktionshilfsmittel immer nötig? Zugkrafterhöhung nur mit Absenkung des Reifeninnendruckes. In: Forsttechnische Informationen, H. 1+2, S. 14–16.

Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft (BMVEL) (Hg.) (2004): Zur Zukunft des Waldes. Berlin.

Drewes, D. (2004): Zugkraft- und Schlupfmessungen an Forstmaschinen. Hottinger HOTLine (1): 16-17, Darmstadt

Heinimann, H. (1999): Ground-based Harvesting Technologies for Steep Slopes. In: Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symbosium, Jg. 1999.

Hittenbeck, J. (2004): Zugkraft- und Schlupfmessung an einem Forwarder (unter besonderer Berücksichtigung von Aspekten der Bodenverträglichkeit in Fichtendurchforstungen). Masterarbeit am Institut für Forstliche Arbeitswissenschaften und Verfahrenstechnologie der Georg-August Universität Göttingen, 68 p.

Hittenbeck, J. (2006): Tractive Forces, Slip and Slopes. In: ISTRO (Hg.): Proceedings of Istro 17 "Sustainabiltiy - its Impact on Soil Management and Enviroment, S. 16–26.

Jacke, H. (1999): Öko-Controlling im Maschineneinsatz – oder. wie man die Leistung steigert ohne der Umwelt zu schaden. Forsttechnische Informationen, 5+6/99, Groß-Umstadt, p. 41-44.

Jacke, H.; Drewes, D. (2004): Kräfte, Schlupf und Neigungen – ein Beitrag zur Terramechanik forstlicher Arbeitsmaschinen. Forst und Holz, Jg. 59, (6): p. 259-262, Hannover.

Jacke, H.; Drewes, D.; Hittenbeck, H. (2004): Zugkraftentwicklung auf reisigbewehrten Rückegassen und gewachsenem Boden bei variierendem Reifeninnendrucken. ifa-Mitteilungen Reihe A, Heft 1, Göttingen.

Kremer, J.; Schardt, M.; Borchert, H.; Matthies, D.; Ganter, C. (2007): Bogiebänder im Direktvergleich mit Reifen. In: Forst und Technik, H. 1, S. 6–11.

Kremer, J.; Matthies, D.; Wolf, B.; Ohrner, G.; Uhl, E. (2003): Bodenstrukturveränderungen und Wurzelverletzungen. Rad- gegen Raupenfahrwerk bei der Holzernte. In: AFZ - Der Wald, H. 17, S. 847–850.

Lambert, M. B.; Howard, J. O. (1990): Cost and productivity of new technology for harvesting and in-woods processing small-diameter trees. Pacific Nortwest Research Station. (Research Paper PNW-RP-430).

Li, Q.; Ayers, P. D.; Anderson, A. B. (2007): Prediction of impacts of wheeled vehicles on terrain. In: Journal of Terramechanics, Jg. 44, S. 205–215.

Matthies, D.; Kremer, J. (1999): Bodenmechanische und bodenphysikalische Ergebnisse im Rahmen des "Informationssystems zum bodenverträglichen Forstmaschineneinsatz. In: Forsttechnische Informationen, H. 5+6, S. 34f.

Raper, R. L. (2005): Agricultural traffic impacts on soil. In: Journal of Terramechanics, H. 42, S. 259–280.

Renius, K.-T. (1985): Traktoren (Technik und ihre Anwendung). 10 Auflage, München, Frankfurt, Münster, 191 p.

Schardt, M.; Kremer, J.; Borchert, H.; Matthies, D. (2007): Wurzelschutz beim Einsatz von Forwardern. In: Forst und Technik, H. 2, S. 6–11.

Söhne, W. (1952): Die Kraftübertragung zwischen Schlepperreifen und Ackerboden. In: Grundlagen der Landtechnik, H. 3, S. 75–87.

Sommer, C.; Walter, K.; Lebert, M.; Jaklinski, L.; Jasinski, B. (2001): Effiziente und bodenschonende Triebkraftübertragung vom Reifen auf den Boden, Landtechnik 5/2001, p. 316-317.

Team of Authors (2002): Nutzfahrzeugtechnik. Herausgeber: Hoepke, 2. Auflage, Braunschweig und Wiesbaden.

Vechinski, C. R.; Johnson, C. E.; Raper, R. L.; McDonald, T. P. (1999): Forestry Tire Tractive Performance: New, Worn, and with Chains. In: Applied Engineering in Agriculture, Jg. 35, S. 263–266.

Voßbrink, J. (2005): Bodenspannungen und Deformationen in Waldböden durch Ernteverfahren. In: Dissertation.

Weise, G. (2002): Einfluss des Reifeninnendrucks auf die Zugkraftübertragung. Der richtige Reifeninnendruck bringt ökologische und ökonomische Vorteile, Forsttechnische Informationen 9/2002 Groß-Umstadt, p. 110-111.

Wippermann, D. (2000): Einsatz von Raupenbändern bei Forstmaschinen. In: Forst und Technik, H. 9, S. 4–6.

Zoz, Frank M.; Grisso, Robert D. (2003): Traction and Tractor Performance. ASAE. St Joseph. (ASAE Distinguished Lecture Series).