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Modelling of Downhill Timber Skidding: Bigger Load – Bigger Slope

Andreja Đuka, Tibor Pentek, Dubravko Horvat, Tomislav Poršinsky

Abstract

Skidder mobility during timber extraction is defined by: 1) basic dimensional features of the vehicle, 2) ability to overcome obstacles during movement, 3) traction performance and 4) environmental soundness. Traction performance depends on the ground conditions (soil bearing capacity) and the total effect of all forces on the vehicle. In downhill skidding, the skidder is under great influence of parallel component of forces, adhesion weight and longitudinal terrain slope, which combined result in negative traction force, torque and thrust force. When the horizontal component of rope force is equal to zero i.e. the moment when the weight of the load and resistance to traction are in equilibrium, the slope angle α is a function of load mass distribution factor and skidding resistance factor. This is a »turning point« that can be defined as a critical slope because the load starts to push the vehicle downhill, which results in negative horizontal component of rope force. Depending on skidder Ecotrac 120V dimensional features, centre of gravity, load mass distribution factor, skidding resistance factor of previous research, five different loads were analyzed (1 to 5 tonnes) in order to define the critical slope angle for each of them. Critical slope for downhill skidding of 1 tonne timber is on longitudinal slope of –26%, for 2 tonne timber on –30%, 3 tonne timber on –34%, 4 timber on –38% and for 5 tonne timber on –43% of terrain longitudinal slope. Even though skidding bigger load increases vehicle mobility to even greater slope angles, the most important in downhill skidding, is to avoid blocking of the wheels, which will lead to a complete vehicle slippage and the driver must be constantly aware of that fact. The general recommendation should be that skidding small loads (1 to 3 tonnes) downhill is suitable for smaller longitudinal terrain slopes (up to maximum –34%), while the heavier the load, the further down the slope the skidder can go. The load of 5 tonnes »anchors« the skidder better and therefore it can go on terrain slopes up to –43%, during which less traction force is used (torque is used for braking) and skidder pulls the load by its own weight. It can be concluded that extending the operating range of skidder onto steeper slopes with heavier loads has the potential to decrease harvesting costs and increase productivity.

Keywords: skidder, downhill timber extraction, rope force, critical slope

1. Introduction

Terrain trafficability is a terrain property that allows vehicle mobility, during which various terrain factors (slope, ground obstacles, soil bearing capacity) show their influence (Janosi and Green 1968, Eichrodt 2003, Suvinen 2006, Lubello 2008). From the standpoint of timber harvesting and forest opening, terrain slope is the most important terrain factor affecting the choice of a harvesting system. Terrain slope affects vehicle stability because all wheels (i.e. tracks) are »in conflict« with the same macro-topographic conditions. Skidder mobility is its ability to move from point A to point B while achieving its primal goal – timber transport. In timber extraction, vehicle mobility can be considered from two different aspects: 1) extraction on soils of limited bearing capacity (for example lowland forests on gley soils) and 2) extraction in hilly and mountainous forests, where slope and ground obstacles define conditions for application of specialised forestry vehicles. Many parameters define vehicle mobility during timber extraction (Šušnjar 2005, Šušnjar et al. 2010, Poršinsky et al. 2012), of which these four are the most important ones: 1) basic dimensional features of the vehicle (dimensions, turning radius, mass, centre of gravity, longitudinal and lateral angle of stability, clearance, frame and axle oscillation, unloading of the front axle, payload of rear axle, tyres load capacity), 2) the ability to overcome obstacles during movement (ground clearance and lateral vehicle stability), 3) traction performance (dependence of slip, traction power and speed to traction force and soil bearing capacity) and 4) environmental soundness (nominal ground pressure and minimal cone index).

Many scientists determined critical terrain slopes for a skidder between 30% and 50%, regardless of extraction direction (MacDonald 1999, Heinimann 1999), while others differentiate between downhill and uphill skidding. So, critical slope in downhill skidding ranges from 23% to 50% (Rowan 1977, Inoue and Tsuji 2003, Lubello 2008) and in uphill skidding from 18% to 30% (Rowan 1977, Inoue and Tsuji 2003, Lubello 2008). Some highlight the importance of load size such as Hippoliti and Piegai (2000), as quoted by Lubello (2008), who reported that an unloaded skidder can overcome the maximum gradient of 40%, but loaded only up to 20% regardless of slope direction. Eger and Kiencke (2003) reported that the effect of dynamic changes in load should be also considered as key factors that affect machine stability. Sarles and Luppold (1986) state that when skidding up the slope, for any increase in the terrain slope of 1% (above the terrain inclination of 10%), the quantity of hooked timber should be reduced by 2.5%. Other scientists emphasise the importance of secondary forest network. According to Heinimann (1999) if skidder is extracting timber on terrain slopes higher than 35%, it should move only on secondary forest road network. Hippoliti and Piegai (2000) note the possibility of skidding timber down the slope of 60%, but only in the case of well-designed and built strip roads. Importance of ground obstacles and soil bearing capacity of forest stand during timber extraction by ground based vehicles is highlighted by Kühmaier and Stampfer (2010). Tendency of anchoring vehicles for timber extraction, and thus moving critical terrain slopes to even higher extents, has become more and more popular in the past couple of years. Sauter et al. (2012) define critical terrain slope as 55% for the skidder with a crane equipped with the additional winch for anchoring the vehicle, and Cavalli (2015) surmised that wheeled machines with chains or bands might have an upper limit of 45%, integral track machines up to 60%, and that tethered machines should be able to operate up to a range of 75 to 85% terrain longitudinal slope.

Besides dimensional characteristics defined in ISO standard 13861 (2000), some authors (Bekker 1969, Janosi and Green 1968, Sever and Horvat 1985, USA Code of Federal regulations 49 CFR 523.2) give additional characteristics that allow bypassing and overriding of macro (slope) and micro (ground obstacles) terrain properties during vehicle off-road movement: 1) approach angle (the smallest angle, in a plane side view of a vehicle, formed by the level surface on which the vehicle is standing and a line tangent to the front tyre static loaded radius arc and touching the underside of the vehicle forward of the front tyre), 2) departure angle (the smallest angle, in a plane side view of a vehicle, formed by the level surface on which the vehicle is standing and a line tangent to the rear tyre static loaded radius arc and touching the underside of the vehicle rearward of the rear tyre), 3) break-over angle (means the supplement of the largest angle, in the plan side view of a vehicle that can be formed by two lines tangent to the front and rear static loaded radii arcs and intersecting at a point on the underside of the vehicle), 4) longitudinal clearance diameter (diameter of a circle that touches the inner side of the tyres from each axle and the lowest hanging point under a vehicle), 5) transverse clearance diameter (diameter of a circle that touches the inner side of the tyres and the lowest hanging point under a vehicle, usually a differential) and 6) centre of gravity position (height from ground, distance from front and rear axles), which is an important constructional parameter that influences load distribution on axles depending on terrain slope during timber extraction.

Visser and Berkett (2015) state that, according to Bell (2002), McMahon (2006) and Raymond (2010), extending the operating range of ground-based machinery onto steep slopes has the potential to decrease harvest costs and improve safety. The same authors conclude in their study of 22 machines and effect of terrain steepness during harvesting, that machines exceed slope limits commonly associated with harvesting operations, and exceed them often and for longer periods of time, which is in accordance with Visser and Stampfer (2015), who claim that today there is no guidance on slope limits, based on either science or experience. Authors conclude that many guidelines refer to manufacturer's specifications, yet few of the major forestry equipment manufacturers provide slope and/or operating limits for their purpose built machinery.

The goal of defining limiting terrain slopes for downhill timber extraction of cable skidders should be considered as guidelines for operators and planners, who can then, depending on load size and terrain

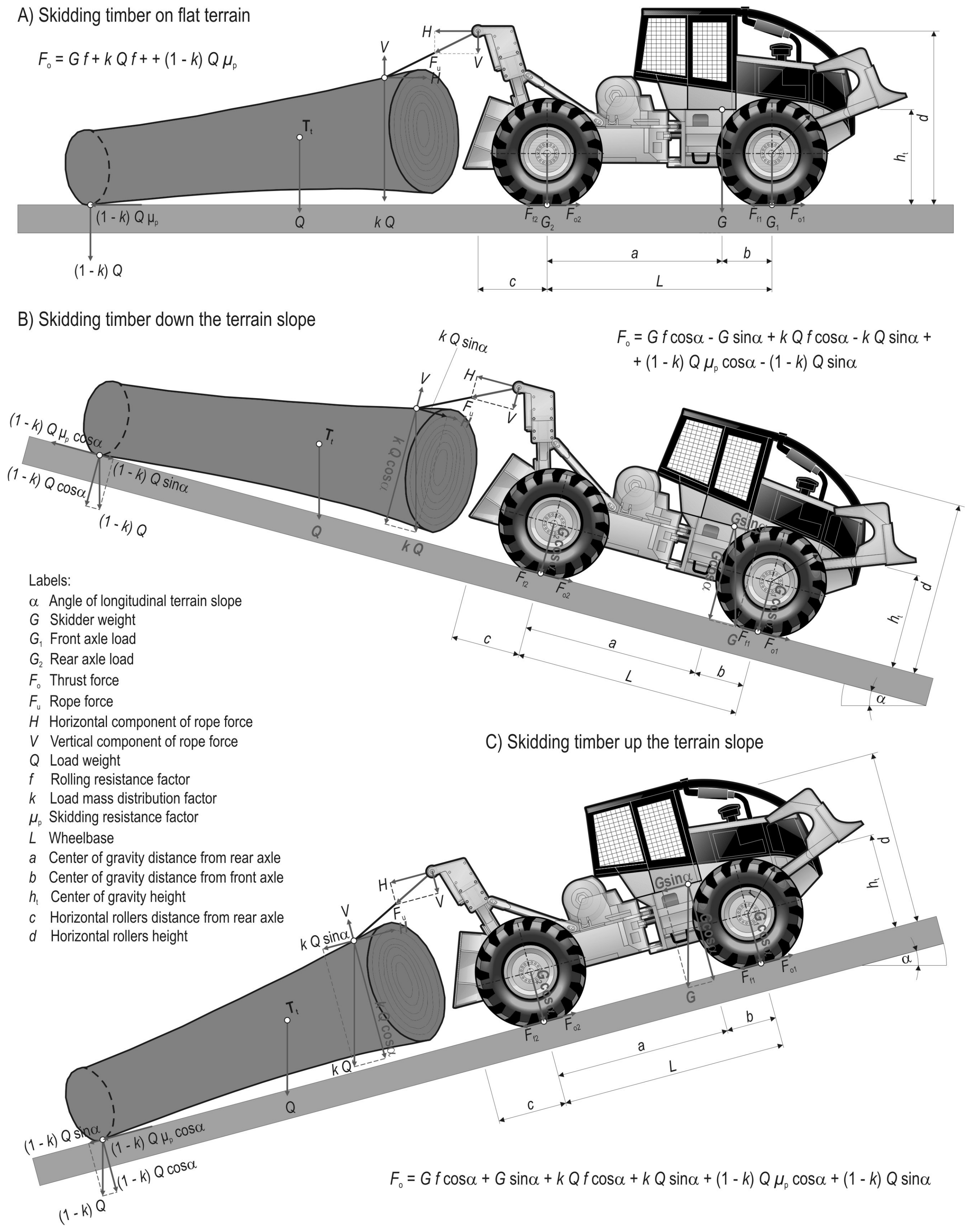


Fig. 1 Distribution of forces during timber skidding

Table 1 Equations of some parameters of downhill and uphill timber skidding

Downhill skidding	Uphill skidding
Adhesive weight $G_\mathrm{a} = G\cdot\cos\alpha + V$ (1)	
Vertical component of rope force $V = k\cdot Q\cdot\cos\alpha$ (2)	
Horizontal component of rope force	
$H = Q\cdot(1-k)\cdot\cos\alpha\cdot\mu_\mathrm{p} - Q\cdot\sin\alpha$ (3)	$H = Q\cdot(1-k)\cdot\cos\alpha\cdot\mu_\mathrm{p} + Q\cdot\sin\alpha$ (4)
Front axle load	
$G_1 = \dfrac{G\cdot\cos\alpha\cdot a + G\cdot\sin\alpha\cdot h_\mathrm{t} - H\cdot d - V\cdot c}{L}$ (5)	$G_1 = \dfrac{G\cdot\cos\alpha\cdot a - G\cdot\sin\alpha\cdot h_\mathrm{t} - H\cdot d - V\cdot c}{L}$ (6)
Rear axle load	
$G_2 = \dfrac{G\cdot\cos\alpha\cdot b - G\cdot\sin\alpha\cdot h_\mathrm{t} + H\cdot d + V\cdot(L+c)}{L}$ (7)	$G_2 = \dfrac{G\cdot\cos\alpha\cdot b + G\cdot\sin\alpha\cdot h_\mathrm{t} + H\cdot d + V\cdot(L+c)}{L}$ (8)
Drawbar pull	
$F_\mathrm{v} = H - G_\mathrm{a}\cdot\sin\alpha$ (9)	$F_\mathrm{v} = H + G_\mathrm{a}\cdot\sin\alpha$ (10)

macro characteristics (slope), define better routes for skidder off-road movement providing better control and manoeuvrability of vehicles.

2. Theoretical Approach

During skidding, timber is partially suspended on the vehicle i.e. one part of the load is lifted above ground level and hanged by rope to the rear end of the skidder, while the other part is dragged (trailed) on the ground. Since a part of the load is on ground, only a part of the load weight is actually carried by the skidder rope. While skidding, the force in the rope that carries a part of the timber weight is the so called vertical component of rope force (V), and force that must overcome tractive resistance of timber that is on the ground is called horizontal component of rope force (H). During skidding, the adhesion weight of the skidder is greater than its static weight as the rear axle of the vehicle is under additional influence of the load, while the vertical component of rope force shows its effect.

Theoretical approach to distribution of forces during skidding was established by Bennet (1962), who differentiated horizontal, vertical and frictional forces involved in timber skidding of different loads, and since then many scientists used them in their own research (Calvert and Garlicki 1967, Richardson and Cooper 1970, Hassan 1977, Perumpral et al. 1977, Sever 1980, Matthes and Watson 1981, Hassan and Sirois 1983, Hassan and Gustafson 1983, Iff et al. 1984, Horvat 1990, Sever and Horvat 1995, Šušnjar and Horvat 2006, Tomašić et al. 2007, Tomašić et al. 2009, Šušnjar et al. 2010, Poršinsky et al. 2013).

Skidding timber on flat terrain begins in the moment when thrust force (brought by transmission system to the wheels) begins to overcome resistance forces (Fig. 1A): 1) skidder rolling, 2) rolling of hooked timber and 3) friction of timber on the ground.

During skidding up the slope (Fig. 1C), load distribution becomes more complex and traction begins when thrust force overcomes resistance forces: 1) skidder rolling, 2) terrain slope, 3) rolling of hooked timber, 4) overcoming terrain slope of hooked timber, 5) friction of timber on the ground and 6) overcoming terrain slope of timber on the ground.

While skidding timber down the slope (Fig. 1B), thrust force overcomes the same resistance as for skidding timber up the slope, only resultants of the three forces of resistance (terrain slope, overcoming terrain slope of hooked timber, overcoming terrain slope of timber on the ground) are now in the opposite direction, i.e. direction of the vehicle movement.

Since skidder movement dynamics is considerably different depending on extraction direction, forces distribution and relating equations are presented in Table 1 for: adhesive weight, vertical component of rope force, horizontal component of rope force, front axle load, rear axle load and drawbar pull (traction force).

Load mass distribution factor (*k*) shows how much load mass is lifted from the ground (hooked on the rope) and how much is pulled on the ground surface (Eq. 11). If the load mass distribution factor is 0.5, this means that the same part of the timber mass is hooked by rope as it is pulled on the ground. Authors (Sever 1980, Hassan and Gustafson 1983, Hassan and Sirois 1983, Iff et al. 1984, Horvat 1987, Šušnjar 2005, Tomašić 2007, Poršinsky et al. 2012) reported that the nature of loading and load mass distribution factor depend on these variables: tree diameter and slenderness ratio, number of trees per load, height of suspended butt above ground, tree form (method of timber processing), timber orientation (thinner or thicker end is above ground). If the load increases, the portion of its weight supported by the ground increases at higher percentage. This increase is also attributed to the butt height above ground, which tends to decrease as the number of trees in the load increases. Tree weight on ground contact length decreases and load mass distribution factor increases with the increase in tree semi-suspension height above ground. Load mass distribution factor is unaffected by tree length of up to 20 m.

$$k=\frac{V}{Q\cdot\cos\alpha} \qquad (11)$$

Skidding resistance occurs due to the effect of load weight pulled on the ground and skidding resistance factor – μ_p (Hassan 1977, Perumpral et al. 1977, Sever 1980, Hassan and Gustafson 1983, Hassan and Sirois 1983, Samset 1985, Šušnjar 2005, Tomašić 2007). Samset (1975) according to Megille (1954) stated that skidding resistance factor depends on soil type and moisture level, and Samset (1975) according to Dahl (1973) claimed that it also depends on orientation of suspended timber (thinner or thicker end is above ground) and on timber processing method (full-tree, half-tree, etc.). The horizontal component of rope force overcomes the skidding resistance between the load and forest soil and according to known values of force, weight, load mass distribution factor and terrain slope, skidding resistance factor can be determined (Eq. 12).

$$\mu_\mathrm{p}=\frac{H\pm Q\cdot\sin\alpha}{Q\cdot(1-k)\cdot\cos\alpha} \qquad (12)$$

In exploring skidder traction features during skidding down the slope, Šušnjar et al. (2010) give some limitations identified through two »turning points« of terrain slope.

The first »turning point« is determined by the angle of inclination of the terrain in which vehicle no longer achieves positive traction and breaking force i.e. thrust force is equal to zero (Eq. 13).

$$\mathrm{tg}\alpha=\frac{G\cdot f+Q\cdot k\cdot f+(1-k)\cdot Q\cdot\mu_\mathrm{p}}{G+Q} \qquad (13)$$

The second »turning point« is determined by the angle of terrain inclination in which hooked timber starts to push the skidder down the slope (Eq. 14), which occurs at the time when the horizontal component of the rope force in the rope is equal to zero ($H=0$), or when the weight of the load ($Q\sin\alpha$) and traction resistance are in balance.

$$\mathrm{tg}\alpha=(1-k)\cdot\mu_\mathrm{p} \qquad (14)$$

3. Materials and Methods

Valid model of skidder–terrain interaction will permit forestry researchers to study and analyse many issues and problems related to skidder performance under a wide range of conditions (different loads, various terrain characteristics, etc.). This way, skidder optimisation and improvement of its operational parameters can be expected. Significance of skidders parameters that affect its off-road performance can be identified without expensive field testing. The results will not only help forestry planners in better forest management, but also practitioners in real-life situations of a skidder off-road locomotion.

Analysis was done based on skidder Ecotrac 120V dimensions and centre of gravity (Šušnjar 2005), dependence of skidder Ecotrac 120V load mass distribution factor and skidding resistance factor to affecting parameters (Poršinsky et al. 2012), load distribution during timber extraction on different terrain slopes and five different loads (from 1 to 5 tonnes). Load mass distribution factor (Eq. 15) is a function of (statistically and inversely correlated) load mass, load weight, number of logs per load, load volume. Skidding resistance factor (Eq. 16) is a function (statistically and inversely correlated) of terrain slope and direction of timber extraction i.e. uphill or downhill skidding.

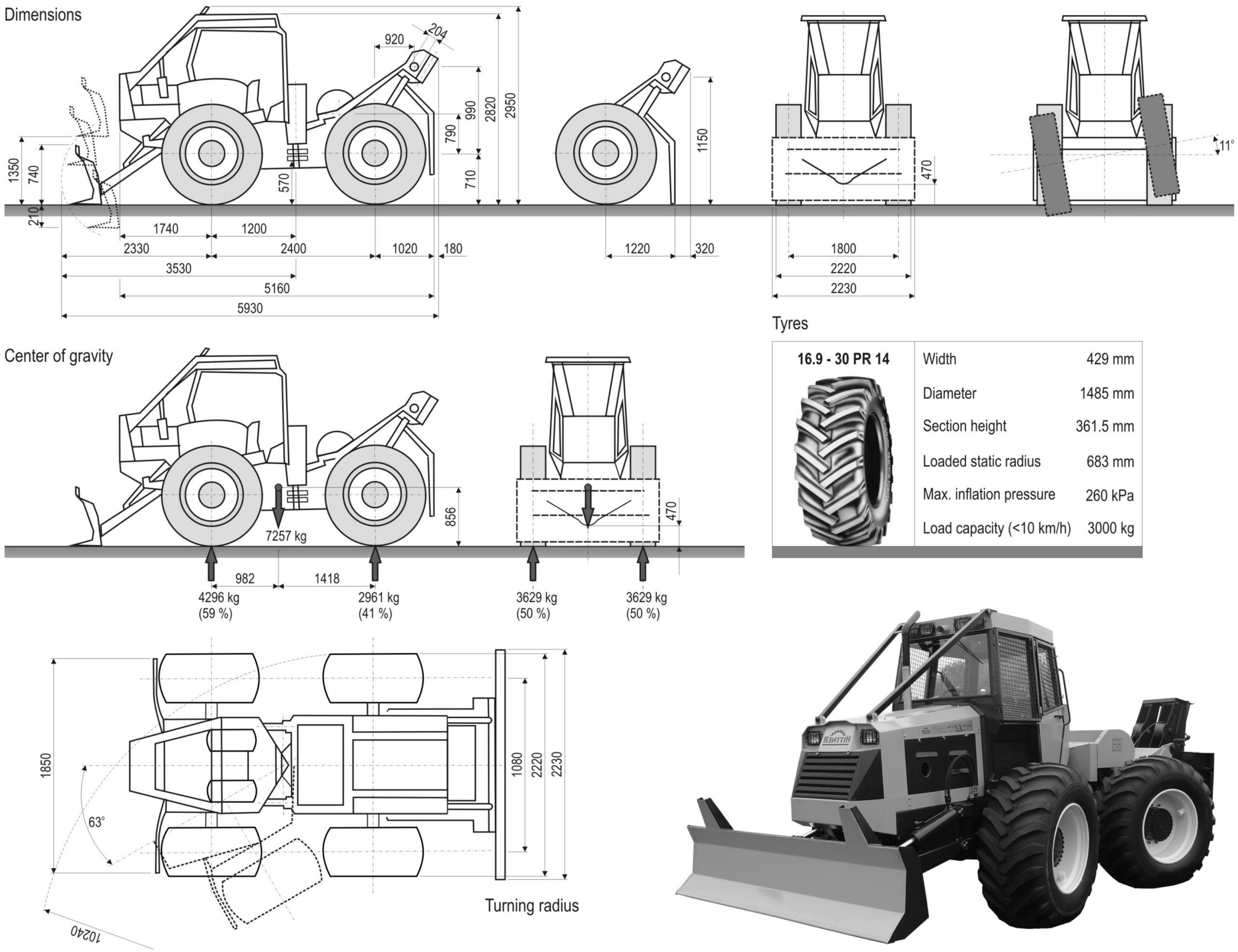
$$k=0.62017-0.0476\cdot Q \qquad (15)$$

$$\mu_\mathrm{p}=0.50529-0.042\cdot\alpha \qquad (16)$$

Where:

Q – Load mass, t

α – Longitudinal terrain slope,% (+, – indicate direction of skidding)



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	Width	429 mm
	Diameter	1485 mm
	Section height	361.5 mm
	Loaded static radius	683 mm
	Max. inflation pressure	260 kPa
	Load capacity (<10 km/h)	3000 kg

Fig. 2 Technical data of Ecotrac 120V skidder

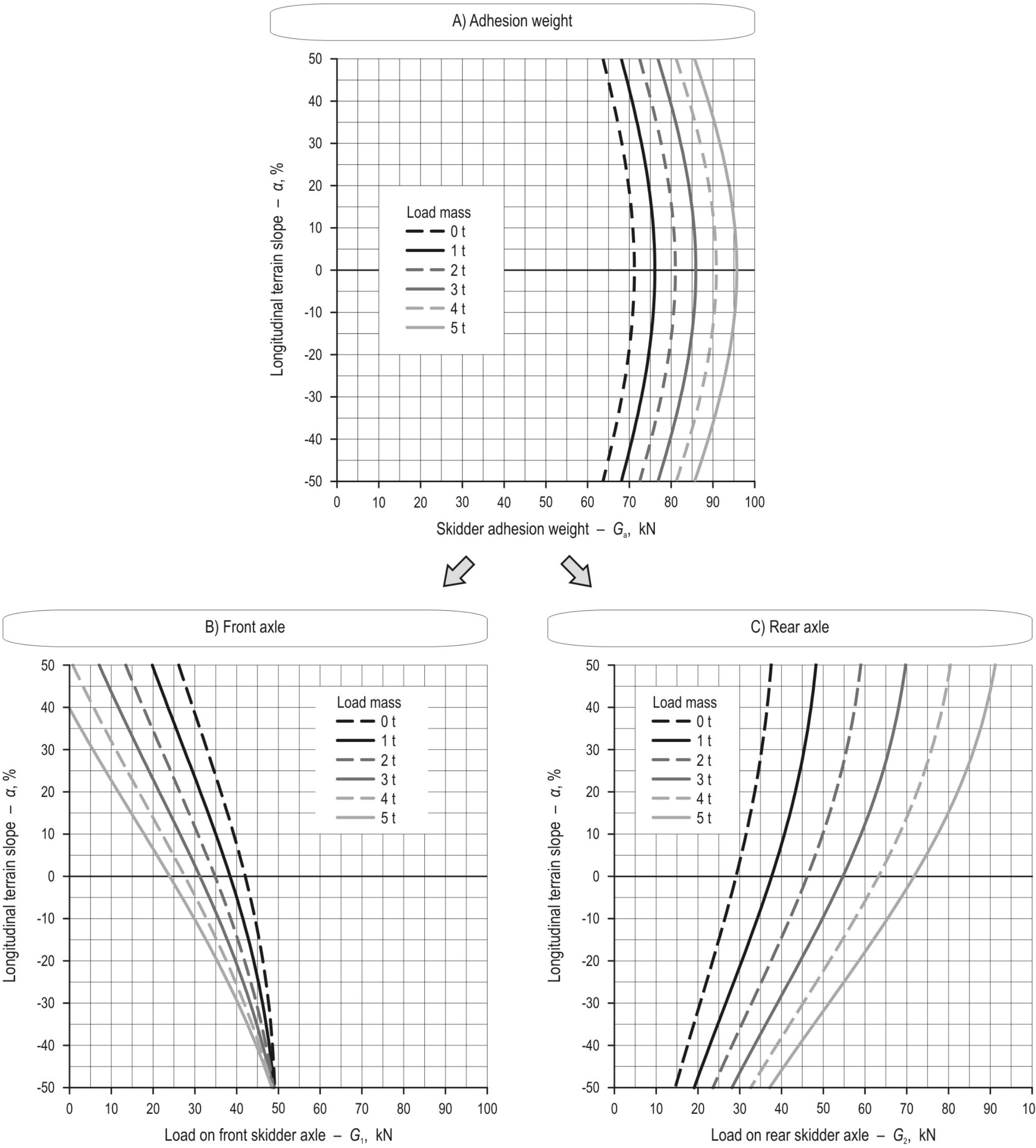


Fig. 3 Slope and load influence on skidder adhesion weight and its distribution on both axles

Load distribution was determined by calculation and analyses of the following parameters: 1) adhesion weight (Eq. 1), 2) vertical component of rope force (Eq. 2), 3) horizontal component of rope force (Eq. 3), 4) load distribution on front axle (Eq. 5), 5) load distribution on rear axle (Eq. 7), 6) angle of terrain inclination in which hooked timber starts to push the skidder down the slope (Eq. 14), and 7) traction force (Eq. 9).

Skidder Ecotrac 120V is a four-wheeled (4×4) articulated forestry vehicle, equipped with a hydraulic forest winch Hittner 2×80, of the nominal tractive force of 80kN. It is driven by a 6 cylinder diesel DEUTZ engine with the nominal power of 84 kW at 2300 min^{-1} and maximum torque of 400 Nm at 1500 min^{-1}. Basic technical data of Ecotrac 120V skidder is given in Fig. 2.

4. Results and Discussion

Skidder traction performance and force distribution during timber extraction depends on gained forces on wheels and forces resisting them, where adhesion weight is a very important parameter. It actually represents the sum of vertical loads on driving wheels during skidding (Fig. 3A). Adhesion weight depends on skidder weight (*G*), longitudinal terrain slope (α) and the size of the vertical rope force component (*V*), which is directly influenced by load weight (*Q*). Adhesion weight is different than empty skidder weight (*G*) because skidder rear axle is additionally loaded with the full amount of the vertical rope force component (*V*) that is dispersed to rear wheels through horizontal rollers of the winch.

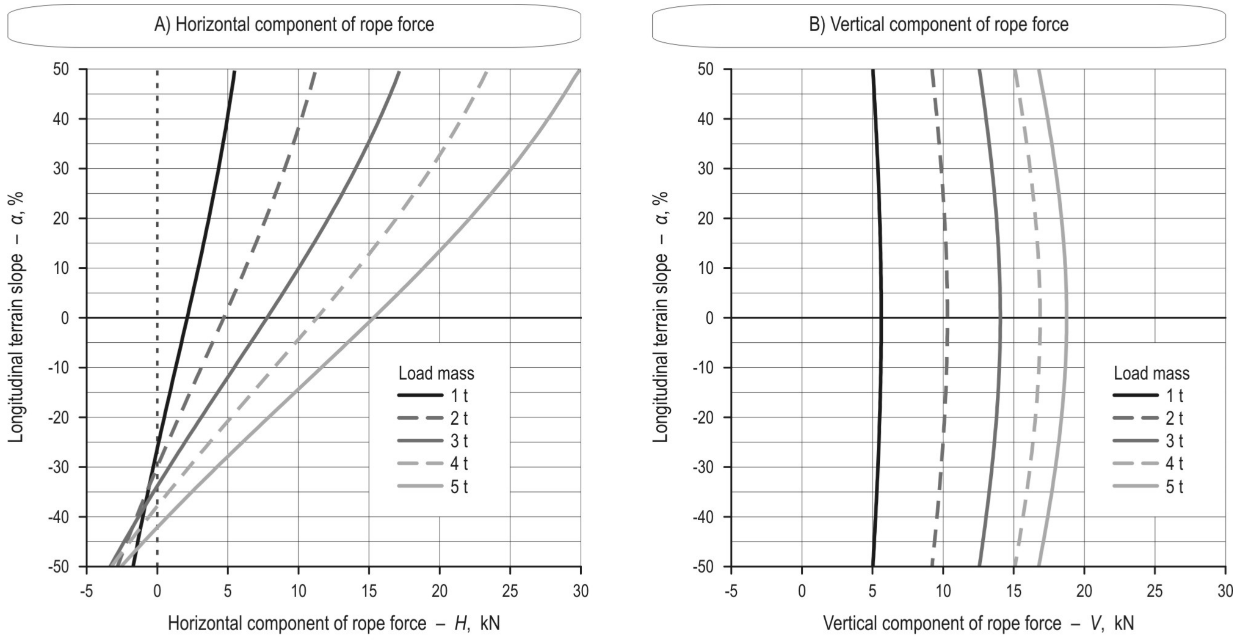
Results of modelling load distribution on skidder axles, on the example of skidder Ecotrac 120V, pointed out that load distribution varies due to the amount (mass) of hooked timber, timber extraction direction (uphill or downhill) and due to longitudinal terrain slope (Fig. 3B and 3C).

By increasing longitudinal terrain slope and load mass during uphill timber skidding, there is an increase of load on rear skidder axle due to the growth of the horizontal component of skidder weight ($G \sin \alpha$), which acts against the direction of vehicle movement, and due to the growth of the horizontal component of rope force (*H*).

Axle load distribution of the skidder, during uphill timber extraction, is related to many criteria (limits) derived from previous research: 1) Unloading of the front axle (Weise and Nick 2003), where at least 10% of the total dynamic load should remain on the front axle ($G_1 > 0.1\ G_a$) to retain control; 2) Overloading of the rear axle (Horvat 1990), whereby the load of the skidder rear axle must not exceed the total weight of the skidder ($G_2 < G$); 3) Longitudinal skidder stability (Sever 1980), which is defined as the minimum ratio of load on front and rear axles ($G_1 : G_2 > 1 : 3.5$), after which longitudinal stability of the vehicle becomes an issue; 4) Permitted tyres load capacity, with regard to the air pressure recommended by the manufacturer (Đuka 2014).

In downhill skidding, the load is transferred from the rear to the front axle of a skidder. Increasing terrain slope leads to the growth of load on the skidder front axle due to an increase in the horizontal component of skidder weight ($G \sin \alpha$), which acts in the direction of skidder movement. Increasing the quantity (mass) of hooked timber in downhill skidding will lead to the reduction of the load on the front skidder axle, because of the increase of the vertical component of rope force (*V*).

It is hard to understand the dynamics of load distribution on skidder axles regarding weight (mass) of hooked timber, direction of skidding (uphill/downhill) and slope inclination (Fig. 3B and 3C) without knowing the effect of rope force i.e. its vertical component (*V*) that carries the hooked load, and its horizontal



Limitation to skidder Ecotrac 120V mobilty :
- - - - Angle after which load starts to push the vehicle down the slope (*H* = 0)

Fig. 4 Load and slope influence on horizontal and vertical components of rope force

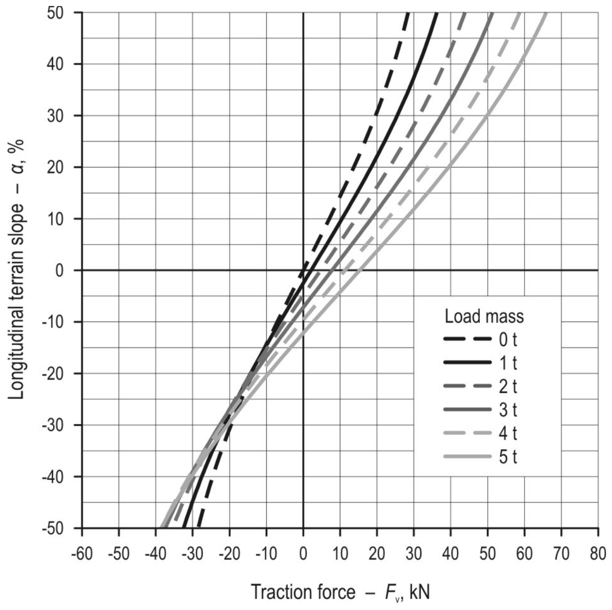


Fig. 5 Load and slope influence on traction force

component (H) which overcomes tractive resistance of the load on the ground. The analysis of horizontal and vertical components of rope force according to longitudinal terrain slope, skidding direction and load mass is shown in Fig. 4.

During downhill extraction of timber, the horizontal component of rope force (Fig. 4A) decreases with the increase of terrain slope and load mass, while the vertical component of rope force (Fig. 4B) increases only by increase of load mass i.e. slightly decreases with the increase of terrain slope (due to reduction of the load that is hooked by winch rope and increase of the load of timber on the ground). During downhill skidding, the horizontal component of rope force is greater than the vertical component of rope force for load mass of 1 t and terrain slope higher than 45%, for load mass of 2 t and terrain slope higher than 36%, for load mass of 3 t and terrain slope higher than 27%, for load mass of 4 t and terrain slope higher than 19%, for load mass of 5 t and terrain slope higher than 10%.

Throughout downhill skidding, the horizontal component of rope force decreases with the increase of terrain slope and with the reduction of load, by which the vertical component of rope force is always greater than the horizontal component (Fig. 4). The horizontal component of rope force decreases during downhill skidding because load tends to get closer to rear end of the skidder, which makes the vertical component of rope force more important because it holds the load above the ground. Therefore, the horizontal component of rope force is smaller because less load weight is pulled on the ground.

An important criteria in downhill skidding is terrain slope inclination (α) when the load starts to push the skidder i.e. the moment when the horizontal component of rope force is zero (H=0). When the load pushes the vehicle down the slope, due to the constant thrust of the timber at the back end of a skidder, it can be concluded that, in due time, such performance will result in fatigue of the material and early damage to the vehicle (according to FAO operating hours for wheeled skidder it is between 8,000 and 12,000 depending on operation conditions). It will also have negative influence on psycho-physical state of the driver (as conformed in patent EP2711226 A1 (Eskilsons 2014), in the vehicle-driver interactions, it is essential that the vehicle carries out the driver's commands in the manner believed to be desired by the driver). The turning point when skidding is no longer recommended for skidding loads up to 1 t is on terrain with longitudinal slope of –26%, for skidding loads up to 2 t on terrain with longitudinal slope of –30%, for skidding loads up to 3 t on terrain with longitudinal slope of –34%, for skidding loads up to 4 t on terrain with longitudinal slope of –38% and for skidding loads up to 5 t on terrain with longitudinal slope of –43%.

In uphill skidding, traction force needs to overcome the resistance of the load on the ground (H), but also the resistance of the horizontal component of skidder weight ($G \sin \alpha$), which pulls the vehicle in the opposite direction. With the growth of the inclination angle, traction force grows with the increase of load weight, due to an increase of the horizontal component of rope force (traction resistance) and the weight of the skidder that needs to overcome traction force (Fig. 5).

In downhill skidding, the horizontal component of the skidder weight ($G \sin \alpha$) acts in the direction of the skidder and due to its action the skidder overcomes traction resistance of the load on the ground (H), which causes the appearance of negative traction force (Fig. 5) i.e. appearance of braking force.

Results of modelling load distribution on skidder front and rear axles, horizontal and vertical components of rope force, based on dimension characteristics of skidder Ecotrac 120V (centre of gravity), knowing load distribution and skidder resistance factors, considering different quantity (mass) of hooked timber, extraction direction (uphill and downhill extraction) and longitudinal terrain slope, are in accordance with previous research that were based on field testing (Šušnjar 2005, Šušnjar and Horvat 2006, Tomašić 2007, Tomašić et al. 2007, Tomašić et al. 2009, Šušnjar et al. 2010).

5. Conclusions

It can be stated that during downhill skidding no real traction force can be achieved (torque is used for braking), because the skidder pulls the load by its own weight, and also the transfer of power from the motor to the wheels is used for braking due to the large impact of parallel component of the skidder weight.

Even though skidding is possible on even greater slope angles than stated above, the most important in downhill skidding is to avoid blocking of the wheels, which will lead to a complete vehicle slippage. When the load pushes the vehicle down the slope, due to the constant thrust of the timber at the back end of a skidder, it can be concluded that, in due time, such performance will result in fatigue of the material and early damage to the vehicle as well as in negative influence on the driver.

The general recommendation should be that skidding small loads (1 to 3 tonne) downhill is suitable for smaller longitudinal terrain slopes (up to maximum –34%), while the heavier the load, the further down the slope skidder can go. The load of 5 tonnes »anchors« the skidder better and, therefore, it can go on terrain slopes up to –43%, during which less traction force is used (torque is used for braking) and skidder pulls the load by its own weight.

It can be concluded that extending the operating range of skidder onto steeper slopes with heavier loads has the potential to decrease harvesting costs and increase productivity.

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Authors' address:

Andreja Đuka, PhD.
e-mail: aduka@sumfak.hr
Prof. Tibor Pentek, PhD.
e-mail: tpentek@sumfak.hr
Prof. Dubravko Horvat, PhD.
e-mail: dhorvat@sumfak.hr
Prof. Tomislav Poršinsky, PhD.*
e-mail: tporsinsky@sumfak.hr
Department of Forest Engineering, Faculty of Forestry
University of Zagreb
Svetošimunska 25
10002 Zagreb
CROATIA

* Corresponding author

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