DETERMINING THE PERFORMANCE AND THE ENVIRONMENTAL IMPACT OF FOREST MACHINES – CLASSIFICATION NUMBERS AND PERFORMANCE DIAGRAMS

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Abstract: *The testing of forest machines has to provide the user with viable information on a wide range of aspects so that they will be able to make a well based decision about buying the right equipment and using it for the correct range of application. The KWF approach to give this information is based on two types of examination, a test of the machinery in the forest by forest engineers and the assessment of the machine by mechanical engineers by direct measurements and by evaluating the documentation of the machine.*

In order to summarize the great amount of information provided and to yield comparable results, it was tried to apply methodologies from commercial goods logistics and from benchmarking military vehicles for the use with forest machines. The main field of application of this method are the loading capacity of forwarders, soil strain, cross-country-mobility and the performance of forest machines with load.

To do this, KWF has developed a load distribution diagram for the assessment of forwarders and benchmark tests for the evaluation of the soil strain and the cross-country-mobility of wheel driven forest machines. This diagram was used to calculate the carrying capacity for various assortments thus enabling KWF to rank different cargo holds according to their suitability for given machines. Furthermore performance diagrams for various types of forest machines are being developed at present which will help to estimate what load at what speed a machine may be able to move. The assessment of the impact on the soil of different machines was the aim of a complex rating based on 6 factors regarded as the most important ones ruling the impact of driven wheels onto the soils. This rating made it possible to compare various vehicles and rank them according to their impact onto the soil.

The aim of this methodology is that users and buyers of forest machines will have reproducible and comparable technical information on the capabilities of the machines they are considering, this information being highly aggregated, and in a form that it yields to all users instant evidence on the performance and thus on the range of application for this special machine. Furthermore the methods may be used to determine critical values for the use of the machines and may serve as a basis for modelling their performance.

1 Load distribution diagram for forwarders

In order to evaluate the quality of a forwarder, criteria had to be identified which can serve as benchmarks. Furthermore it became necessary to judge the loading capacity of forwarders for various assortments. A promising approach seemed to be the load distribution diagrams developed for commercial goods vehicles.

1.1 Basics and diagram

Loading of commercials goods vehicles is done as a matter of routine by using load distribution plans (Lieber and Woda, 1992). These plans show for given positions of the centre of gravity the possible load. Loading according to this theory is limited by 4 borderlines:

1. The loading capacity of the machine is limited
2. The maximum load on the front axle must not be exceeded
3. The maximum load on the rear axle must not be exceeded
4. A minimum load should remain on the front axle to ensure steering; on the road a minimum of 20 % of the total machine weight has to remain on the front axle, for offroad use 10 % are regarded as sufficient

Heavy goods vehicles are built in a way that it is not possible to place the complete payload on one axle. Thus the payload must be distributed between the axles of the vehicle. Technical mechanics allow the calculation of the axle load. Using the formulas given in Lieber and Woda (1992), the following typical diagram can be obtained (Figure 1).

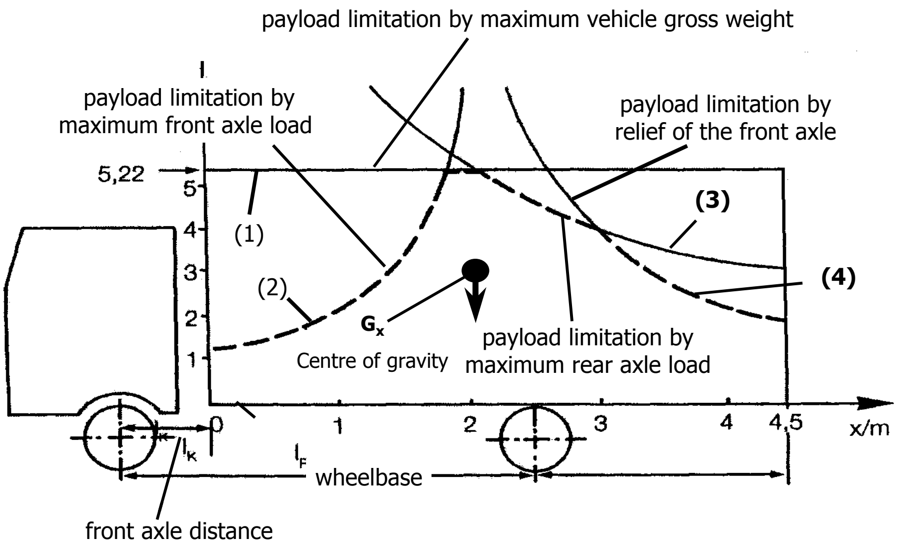

Figure 1: Load distribution diagram for commercial goods vehicles

Figure 1 shows the relevant geometry of the vehicle and the limits to the load by the 4 limitations given above. The effect of the limitations 2 to 4 is that there is actually only a rather small space in the vehicle for the position of the centre of gravity of the load so that the complete payload can be used. While in commercial goods vehicles stowage is to a certain degree variable, especially when packaged goods are transported, the load in forwarders cannot be varied very much as the cargo hold has to be filled from the front end to the rear. This fact however makes it possible to use a simplified load model which helps to judge the design and the dimensioning of a forwarder. For this load model it was assumed that the whole cross section of the loading space is filled with wood and that the centre of gravity is situated at half of the length of the log, while certain corrections are made for the fact that logs have to be piled up with some amount of interspace. The load can be represented by a straight line whose inclination is a function of the dimensions of the cargo hold. The problem of the load model is that it gives the total weight of the wood payload as a function of its overall length while the load distribution model needs the position of the centre of gravity. But this can be solved by an easy coordinate transformation. With this transformation all lengths in the load distribution diagram for the forwarder are given in assortment lengths so that all necessary information is available in an easily understandable way.

An example for a complete diagram is given in Figure 2. Together with the diagram characteristic numbers are calculated which supports the results of the diagram. The most important data obtained are the total possible load the resulting axle loads, and the capacity use of the machine for softwood and hardwood.

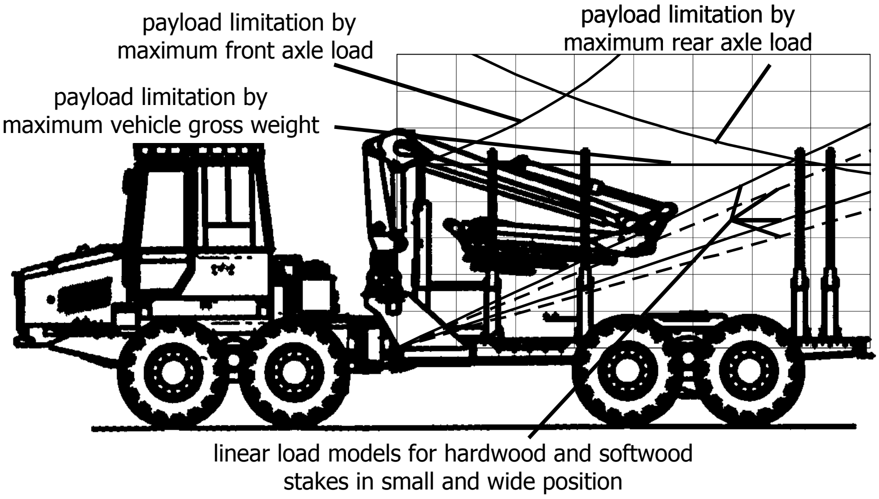

Figure 2: Load distribution diagram for a forwarder together with linear load model for softwood and hardwood

Furthermore the diagram shows which assortment length must be chosen to achieve full use of capacity and how far the load is sticking out of the cargo hold, what is the limiting factor to the load (in most cases it is the maximum possible load or load on the rear axle; it may happen that the front axle is unloaded too much and in rare cases the front axle is overloaded) and what lengths of wood can reasonably be stored in the cargo hold.

Thus relevant information on the design of the machine is available to the user and the manufacturer while testing and comparing forwarders are put on scientifically sound base yielding valid information and reproducible comparison of different machines based on technical data obtained during the test of the machine.

1.2 Evaluation of the hold

In order to judge the differences between the distribution diagrams of different forwarders it is necessary find objective parameters for the evaluation. Important for the practical value of a forwarder are the gradients of the lines representing the load, because they show how fast the forwarder will reach his maximum load. For example there are forwarders, with narrow cargo areas, which cannot obtain their loading capacity with softwood of conventional length. For wood-lengths of 2, 3, 4, 5 and 6 metres the obtainable payload, as a proportion of the loading capacity of the machine, is rated with one point for every ten percent difference. The same is done for combinations of short length wood (2+2, 2+3, 3+3, 2+4), provided that the design of the cargo area allows to load them.

On the other hand there is a risk to exceed the maximum load as long as there is not any device to help avoiding this, like scales or markings. In case of that risk there is a deduction of points for the possible overload mass calculated in the same way as just described, regardless of the achieved points for the obtainable payload if it is possible to load the assortments mentioned above. If a forwarder has an adjustable cargo hold always the best case is calculated. The principle of the evaluation method is shown in Figure 3.

Often the maximum permitted axle load is exceeded while the loading capacity of the machine is not yet fully used, especially when long wood (5 or 6 metres) is transported. Then the reference value is the line describing the maximum permitted load on the rear axle and not any more the line of the total loading capacity as shown in Figure 3.

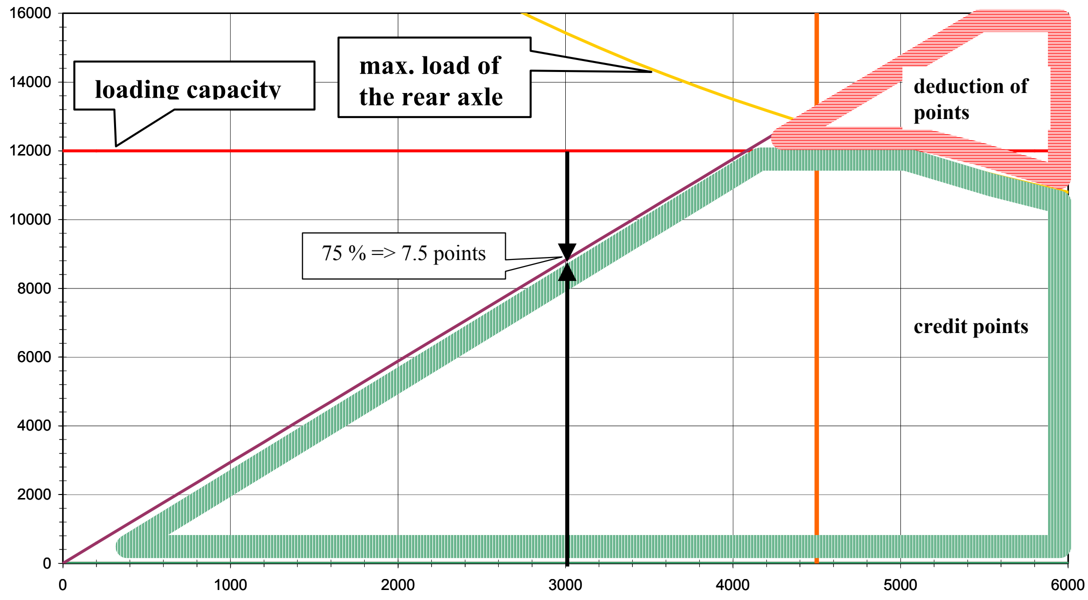

Figure 3: Evaluation of the cargo hold

2 Impact on soil by forest machines

While for many years the assessment of the environmental impact was based on the mean contact pressure (Abeels, 1999), this being regarded as a good measure of the charge to the soil, recent findings (Renius, 1985; Sommer and Lebert, 2003; Weissbach, 2003) made it necessary to change the approach. While tyre width had started to play a major role in the discussion, scientific research showed this parameter alone was not able to explain soil compaction sufficiently. As scientists and testing experience had identified 6 major impact factors on the soil, KWF chose to put them together in a weighted form for a multivariable approach. This was done using a point system. As it is known that tyre inflation pressure is of major importance, this factor was given the greatest influence. Other factors were given importance according to the testing experience and, where available, to scientific findings. The main factors and their respective weighting were:

- tyre inflation pressure / equipment for tyre inflation pressure adjustment (50 %)
- wheel load (20 %)
- power transmission (continuous transmission or gear-change-gearbox) (10 %)
- tyre width (5 %)
- tyre diameter (5 %)
- water in the tyres (10 %)

The factors are measured during the KWF performance test for the individual machines. According to the results points are allocated and added up for an overall rating. The complete system is given in Table 1. In case it is not clear which wheel to use, the most adverse conditions arising have to be chosen. In the case of forwarders this is generally a wheel of the rear axle at full load; the load data being calculated by the load distribution scheme just described. For Harvesters the wheel with the greatest wheel load is chosen when the boom is fully extended and turned sideways in a way that the relevant single wheel load is maximised.

Table 1: Assessment of the soil impact of wheeled machines in the KWF performance test

Valuation method soil impact	(maximum 200 points)		
Criteria 1 **Tyre inflation pressure [kPa]**		**Criteria 2** **Wheel load [kN]**	
Weighting coefficient: 10	Points	Weighting coefficient: 4	Points
p<= 100	10	F<=10	10
100<p<=125	9	10<F<=20	9
125<p<=150	8	20<F<=30	8
150<p<=175	7	30<F<=40	7
175<p<=200	6	40<F<=50	6
200<p<=225	5	50<F<=60	5
225<p<=250	4	60<F<=70	4
250<p<=275	3	70<F<=80	3
275<p<=300	2	80<F<=90	2
300<p<=350	1	90<F<=100	1
p>350	0	F>100	0
Criteria 3 **Power transmission**		**Criteria 4** **Tyre width [mm]**	
Weighting coefficient: 2	Points	Weighting coefficient: 1	Points
continuous	10	b>=800	10
power shift transmission	5	760<=b<800	9
manual gearbox & hydrodynamic clutch	3	720<=b<760	8
manual gearbox	0	670<=b<720	7
		630<=b<670	6
		580<=b<630	5
		640<=b<580	4
		490<=b<540	3
		450<=b<490	2
		400<=b<450	1
		b<400	0
Criteria 5 **Tyre diameter [mm]**		**Criteria 6** **Water ballast**	
Weighting coefficient: 1	Points	Weighting coefficient: 2	Points
d>=1900	10	no	10
1800<=d<1900	9	yes	0
1700<=d<1800	8		
1600<=d<1700	7		
1500<=d<1600	6		
1400<=d<1500	5		
1300<=d<1400	4		
1200<=d<1300	3		
1100<=d<1200	2		
1000<=d<1100	1		
d<1000	0		

ad 1:
an extra 20 points are given to vehicles with tyre inflation pressure regulation system

ad 2:
For harvesters the maximum load that will be measured when the boom is fully extended and turned sideways, must be utilized. For forwarders the maximum calculated load on the rear axle is relevant. For skidders the calculated maximum load on the rear axle with logs will be considered while for skidder-forwarder combinations values will be calculated for the skidder and the forwarder function separately

Results from tested machines are given in Figure 4. As it can be seen, the model differentiates quite well between the machines so that comparisons can be made with profit. One result is that the best ratings were reached by the comparatively lightweight skidders which are often fitted with large tyres at low tyre pressure for good traction. The worst results were scored by the harvesters, which is mainly due to the high tyre inflation pressures prescribed by the manufacturers. Forwarders are rated generally better as manufacturers are aware of the impact and the problems of the high masses and tend to equip these machines with generous tyres permitting reduced inflation pressures.

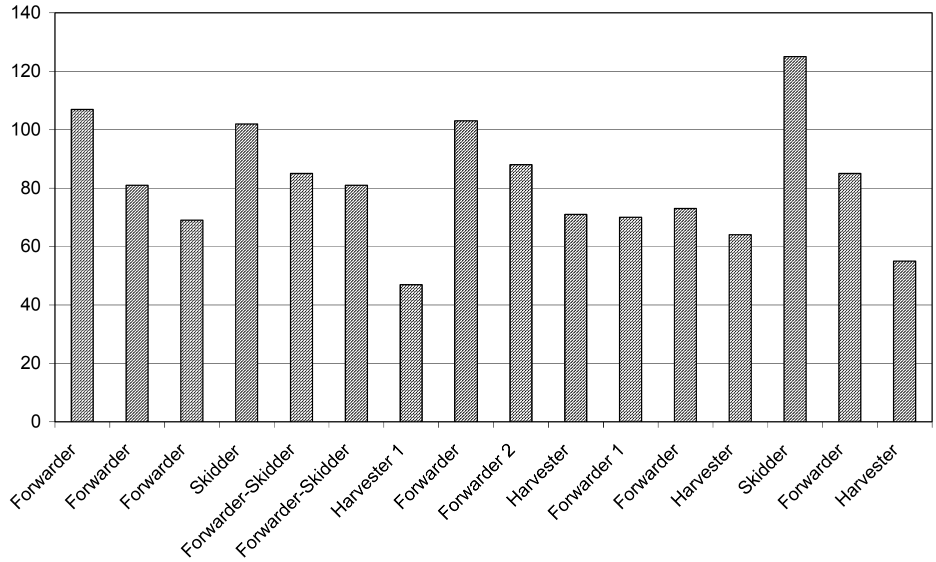

Figure 4: Resulting soil protection points from the KWF soil impact assessment of tested machines

3 Cross-country mobility

An other important question in machine testing was finding a measure for the cross country mobility. For many years ground clearance had been used. While this dimension of a vehicle is of major importance (being of consequence while overcoming the impediments of the micro relief), it is not sufficient to fully describe all relevant aspects of cross country mobility. If we regard a typical terrain classification model (Owende et al., 2001), it accounts for the steepness of the terrain (I), the micro relief (II) and the firmness of the soil (III). Therefore an approach to describe cross country mobility should try to take account of all these aspects and valuate all important aspects of the machine. KWF has adapted a model used by the military (Schulze, 1988) for the use in forest machines. 4 relevant factors are put together to one group and 4 groups are formed that way. For each factor a standard value is set and if this value is met by the machine, a preset value is allocated to this factor of the machine. If all factors fulfil the set requirements, the sum for the group will be 1. If the machine performs worse than the set standard, reductions of the value are made, if it performs better, the set assessment value is augmented in some cases.

As the idea of the model is that the groups describe functional units of the vehicle, the total coefficient of cross country mobility is calculated by multiplying the 4 group sums together. This mathematical operation has the effect that the coefficient of cross country mobility cannot be better than the worst of the groups. The complete model is shown in Table 2. At the factors it is indicated which terrain parameters are covered by the respective group.

Table 2: Model for the cross-country mobility

Factor	Unit	Basis criteria for vehicles with gross-weight ranging between		
	t	< 7,5	7,5 - 12	>12
Vehicle design and power train				
Power-weight ratio (I)	kW/t	7		
Power transmission (I, II)		continuous		
Differential locks (I)		all axles longitudinal and transversal		
Steering system (I, II)		articulated steering		
SOIL CONTACT				
Wheel load when driving (III)	t	4,5		
Tyre inflation pressure (III)	kPa	200		
Rolling resistance (III)		uniform wheel gauge at all axles		
Tyre pressure regulation (III)		tire inflation adjustment system required		
CLEARANCE DESIGN				
Ground clearance (II)	mm	650		
Curved ground clearance (radius) (II)	m	2,8		
Ramp angle front (II)	°	40		
Ramp angle rear (II)	°	40		
OBSTACLE OVERCOMING				
Climbing power (I)	°	40		
Climbing ability (theoretical) (II)	mm	700		
Wheel lift (II)	mm	300	350	450
Turning circle (II)	m	12		

The actual grading if differences from the desired values occur are given in Table 3.

Table 3: Evaluation of the criteria from Table 2

FACTOR	Weighting	Rating
Vehicle design and power train		
Power-weight ratio (I)	0,25	+/- 0,05 for every 10 % difference from the reference value
Power transmission (I, II)	0,30	power shift transmission 0,25, manual gearbox with converter 0,20, manual gearbox 0,15
Differential locks (I)	0,30	longitudinal locking only 0,25, 1 axle without lock 0,20; 0,15 more than 1 axle without lock
Steering system (I, II)	0,15	Ackermann steering 0,10, multiple steering 0,20
SOIL CONTACT		
Wheel load when driving (III)	0,30	+/- 0,025 for every 10 % difference from the reference value; -0,05 for every axle not driven of for twin tyres
Tyre inflation pressure (III)	0,35	- 0,05 for every 50 kPa over the reference value
Rolling resistance (III)	0,20	0,15 if the wheel gauge is not uniform at all axles
Tyre pressure regulation (III)	0,15	0,10 if no regulation system is available
CLEARANCE DESIGN		
Ground clearance (II)	0,35	+/- 0,05 for every 10 % difference from the reference value
Curved ground clearance (radius) (II)	0,25	- 0,05 for every 10 % difference from the reference value
Ramp angle front (II)	0,20	- 0,05 for every 10 % difference from the reference value
Ramp angle rear (II)	0,20	- 0,05 for every 10 % difference from the reference value
OBSTACLE OVERCOMING		
Climbing power (I)	0,35	+/- 0,05 for every 10 % difference from the reference value
Climbing ability (theoretical) (II)	0,20	+/- 0,05 for every 10 % difference from the reference value
Wheel lift (II)	0,30	+/- 0,05 for every 10 % difference from the reference value
Turning circle (II)	0,15	+/- 0,05 for every 10 % difference from the reference value

Coefficients of cross-country mobility were calculated for one harvester and two forwarders and are given together with the group values in Table 4. Some difference between the vehicles can be observed. The advantage of the harvester is the comparatively low weight, so that despite the fact that the machine has only 6 wheels, the coefficient of cross country mobility is highest. The forwarders in fully loaded condition suffer from a smaller power-weight ratio and higher axle loads. The difference between the two forwarders is to be explained that one machine has a better weight distribution, a somewhat smaller gross weight, better tyres and the design as to obstacle overcoming is more advantageous. Comparing the results to those of the soil impact assessment (Figure 4), Forwarder 2 is rated best there while Harvester 1 scored best in cross-country mobility. This difference is mainly due to the fact that the engine power and the clearance measures of the machine are not used in the soil impact rating and underlines the necessity to assess the two properties separately.

Table 4: Values of cross country mobility coefficients and the group values belonging to them in order of Table 2 for 3 selected machines

	Harvester 1	Forwarder 1	Forwarder 2
Cross country mobility coefficient (group values)	0,52 (1,00; 0,73; 0,95; 0,75)	0,18 (0,95; 0,33; 0,90; 0,65)	0,39 (0,85; 0,60; 0,95; 0,80)
Weight fully loaded [t]	16,6	31,8	28,5
Engine power [kW]	125	180	125
Ground clearance [mm]	585	560	611
Axle load front [t]	6,6	9,0	10,5
Axle load rear [t]	10,0	22,8	18

4 Performance diagram for forest machines

Another question arising with machine testing is the assessment of the performance of machines. In forestall sciences curves of productivity vs. amount harvested or similar are well established (Stampfer and Steinmüller, 2001). Still the assessment of the performance of forwarders and skidders is not always satisfactoring and methods established for commercial goods vehicles and construction machines (Lieber and Woda, 1992; Kunze et al., 2002) may be of interest for these machines. A typical characteristic of a vehicle is the graph of drawbar force vs. forward speed. The diagram can be obtained from the engine data, the technical data of the hydraulic transmission and the gear ratios in the drive train of the machine. Together with a model for the rolling resistance, the load and the inclination and if necessary for the wheel slip it is possible to read from this diagram the theoretically possible speed of the machine depending on the weight of the machine and the actual gradient of the road. However this model does not account for micro relief and bearing capacity of the soil, so it will only be valid if the speeds are comparatively small. Still it is possible to read the maximum possible speed and to compare machines on a reproducible basis. Especially for forwarders with their comparatively small engine power and their high gross weight this approach seems reasonable. An example of the performance diagram of Forwarder 2 is given in Figure 5.

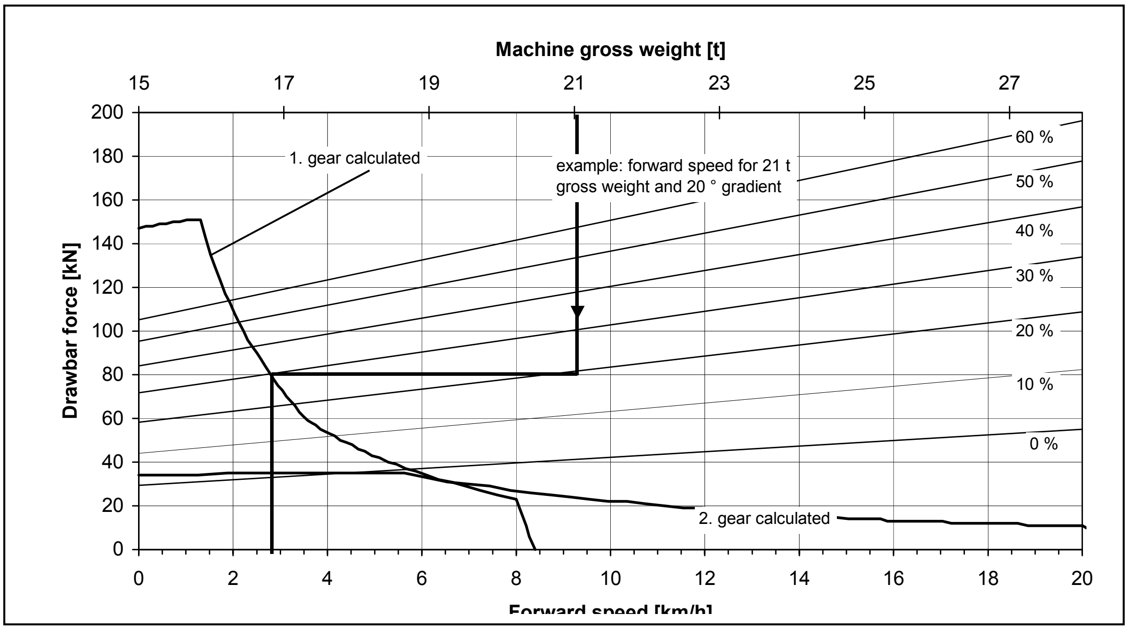

Figure 5: Performance diagram of Forwarder 2. Drawbar force vs. forward speed and driving resistance for various inclinations and machine gross weights. Wheel slip is not taken into account. An example is given how to use the diagram.

The diagram makes the concept of the machine rather clear; it can be seen that gear 1 is to be used for working and gear 2 for re-allocation without load due to the resulting small drawbar forces. Furthermore on can read the maximum available drawbar force (often mentioned in the prospects) and the speed where it is reached (usually not mentioned). And finally it becomes obvious that the maximum speed of the loaded machine, even on small gradients is reduced dramatically.

5 Conclusions

In order to facilitate the assessment of forest machines on a scientifically sound basis and to obtain reproducible results KWF adopted and adapted methods from the agricultural sciences, the science of commercial goods vehicles and construction machines in order to obtain coefficients and diagrams allowing to assess forest machines according to their loading capacity, their soil impact, their cross-country mobility and their maximum attainable speed. With these date we offer buyers, users and manufacturers of forest machines effective means for assessment, decision making and further development of machines.

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