ARBETSRAPPORT 989-2018

Rutting and vibration levels of the On Track concept forwarder on standardised test tracks

Spårbildning och vibrationer för konceptskotaren OnTrack på standardiserade testbanor

FOTO: BRUCE TALBOT, NIBIO

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Rolf Björheden

Sammanfattning

OnTrack är en konceptmaskin, byggd på en Ponsse Buffalo long frame som försetts med Panther gummiband från Prinoth. Maskinen har tagits fram främst med tanke på skotning av mjuka marker med låg bärighet, vilka oftast är relativt jämna. Men eftersom skogsmarken är mycket varierande så måste man kunna ställa kravet att maskinen även skall kunna passera områden med mera besvärande ytstruktur. Skogforsk har genomfört standardiserade tester av vibrationsnivåer, spårbildning på mjuk mark samt framkomlighet på marker med besvärande ytstruktur.

OnTracks vibrationsnivåer mättes på Skogforsks standardiserade bana för vibrationstestning, motsvarande Ytrukturklass 2. Maskinen klarade att passera en 250 m terrängbana med Ytrukturklass 3, enligt terrängtypschemat. Vibrationsnivån hos konceptmaskinen jämfördes med en hjulburen Buffalo. (Testerna utfördes på OnTrackmaskinen innan den byggdes om till bandskotare). I ett test var framvagnens band pivoterande och bakvagnens bandställ fast monterade. Efter ombyggnad, där båda bandställen gjorts pivoterande utfördes ytterligare ett vibrationstest. OnTrack kunde köras i en hastighet av 0,75 m/s utan att nå den kritiska maximala vibrationsnivån 1,1 m/s2 som anges i AFS 2005:15. Detta är en hög hastighet jämfört med vad som var möjligt för den konventionella skotaren. OnTrack kunde köras i en hastghet över 0,5 m/s på banan med ett Hälsovärde för vibrationer under AFS gränsvärde 0,5 m/s2, som anger att hälsopåverkan kan uppstå.

Spårdjupstesterna utfördes enligt Skogforsks standardmetod på en stubbåker med mäktig höghumifierad organogen mark vid Bultebo, 7 km SO om Tierp i Uppland. Har jämfördes OnTrack med Ponsse Buffalo 10W, som är en 10-hjulig specialskotare för obärig mark samt med en konventionall Buffalo 8W som testades både med och utan boggiband. Försöken omfattade banor med rak körning samt ”slalombanor”, med kurvtagning. För att säkerställa att markförhållandena på de olika banorna var likartade och att de inte förändrades på ett olikartat sätt under testets gång så undersöktes markens konpenetrationsmotstånd på alla banor före, under och efter genomfört test. Konpenetrometerundersökningen visade att att samtliga banor var mycket likartade vad gäller penetrationsmotstånd och ingen nämnvärd förändring, t.ex. på grund av kompaktering kunde noteras.

På de 30 m långa raka testbanorna framfördes skotarna med en hastighet av 3-4 km/h och spårdjupsutvecklingen registrerades på fasta mätpunkter på banan som placerats ut med 2 m intervall, dvs 15 värden per överfart. Skotarna kördes dels utan last, dels med 75 % av uppgiven lastförmåga (10,5 av 14 ton). Ponsse Buffalo 8W körde dessa tester såväl med, som utan boggiband. Samma upplägg användes för kurvtestet, där skotarna gjorde 10 överfarter med kurvatgning mellan ”slalomportar”, 7 respektive 10 m in på banan.

Undersökningen visade att OnTrack, trots att konceptmaskinen är tyngre, hade signifikant lägre spårbildning än Buffalo 8W och 10W i samtliga test. Resultatet var väntat då det gäller de raka banorna, men mer oväntat för slalombanan, där långa band normalt sett brukar leda till skjuvning och kraftig spårbildning. Gummibanden verkade vara mindre aggressiva och lättare kunna glida i sidled än hjulskotarnas metallband. Ponsse 10W klarade de raka banorna med liten spårbildning, men gav kraftig spårbildning vid kurvtagning.

skogforsk

Uppsala Science Park, 751 83 Uppsala
skogforsk@skogforsk.se
skogforsk.se

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Preface

This report presents results from the EU-funded project OnTrack, aimed at development of gentler terrain transport of woody biomass on sensitive soils. Damage-free terrain transportation is an important goal for forestry, the solution of which would enable mobilization of large volumes of renewable and carbon-dioxide positive feedstock for the emerging bioeconomy. Technological development is becoming an increasingly arduous task with increased complexity of machines and issues addressed. International co-operation is a key to success and the OnTrack project is an example of this.

The basic ideas came from Norwegian manufacturer Owren (owren.no/index.php/no/) and was developed in cooperation with Konstholmen (www.konstholmen.com/) who contacted Skogforsk for an independent evaluation of the concept. (Reported as a part of the strategic programme for gentle and efficient forest operations: www.skogforsk.se/produkter-och-evenemang/trycksaker/2017/skonsam-och-produktiv-skogsteknik/).

Skogforsk approached leading forest machine manufacturer Ponsse (https://ponsse.com/) and Owren already had the best possible contacts with rubber track specialists Prinoth (www.prinoth.com/) and also initiated the close contacts from the NB NORD network of Nordic-Baltic forest research institutes funded by the Nordic Council of ministers (nordicforestresearch.org/nb-nord/).

Managed by NIBIO, the Norwegian Institute for Bioeconomy research, (www.nibio.no/en) and including partner institutes Latvian State Forest Research Institute SILAVA (www.silava.lv/mainen/aboutus.aspx), Finnish Metsäteho (www.metsateho.fi/) as well as German Kuratorium für Waldarbeit und Forsttechnik, KWF (www.kwf-online.org/en/daskwf.html) an application for a two year project as a Horizon 2020 Innovation Action was prepared and successfully submitted.

The outcomes of the project are as promising as the efficient and open collaboration of all parties and funding organisations mentioned in the above sections. I sincerely thank all involved collaborators and look forward to the further improvement of the OnTrack concept that I feel confident will follow.

Uppsala 2018-10-29

Rolf Björheden, leader of the Skogforsk contributions to OnTrack

Contents

Summary

This report presents results of the OnTrack rubber-tracked concept forwarder, from standardised technical tests of rutting and vibration. The OnTrack is built on a combination of the Ponsse Buffalo long frame forwarder chassis and Prinoth Panther rubber track units. The standardized tests included vibration exposure tests, with pivoting front and fixed rear tracks and with pivoting tracks both in front and in rear and standardized tests of rut formation and shear on homogenous histosol, both laden and empty. The OnTrack was benchmarked against wheeled, commercially available variants with identical load carrying capacity, namely the Ponsse Buffalo 8W AF and the Ponsse Buffalo 10W.

The OnTrack is aimed at forwarding on soft, even to moderately uneven soil, but the heterogeneity of the forest landscape makes it necessary to also traverse patches of firm and uneven ground. Thus, the standard vibration tests were complemented with tests on rough terrain tracks to evaluate passability, ergonomics and operator comfort. Vibration levels were measured on Skogforsks 28 m long standardised vibration track and passability tests were performed on a 250 m terrain track with soil surface roughness class 3 according to the Nordic terrain classification system.

For the vibration tests, the OnTrack was benchmarked against the Buffalo 8W long frame forwarder before it was rebuilt and fitted with track units. Two vibration tests were done for the OnTrack; first with only the front tracks pivoting and, after rebuilding the machine, with pivoting track units both in front and in rear. The vibration levels were lower or equal for an operator of the OnTrack compared to a wheeled Ponsse Buffalo long frame and judged to be ergonomically acceptable. For the first OnTrack configuration with fixed rear tracks, the vibration values were much lower than for the wheeled forwarder. It should be interesting to re-engineer that solution, combined with a more flexible steering hinge between the front and rear. If vibration levels are low, travel speed may be increased, which will improve performance and reduce forwarding costs. The OnTrack could be driven over the standard vibration test track (Ground Roughness class 2) at 0.75 m/s without reaching the 1.1 m/s2 vibration maximum limit value defined by the Swedish worker safety regulations AFS 2005:15. This is a high travel speed compared to what is possible for comparable wheeled forwarders. The OnTrack could travel at over 0,5 m/s over the test track with a Health vibration value under the AFS limit 0,5 m/s2 denoting that no measures have to be taken due to vibration health risks.

The rutting tests were performed according to Skogforsks standard test protocol on farm land with deep homogenous sapric histosol at Bultebo, in northern Uppland county, Sweden. The rutting tests included both straight and slalom driving, with and without load. To make sure that the progress of rutting did not interact with soil compaction, and that the different tracks had similar strength and plasticity, cone penetrometer readings were taken in all tracks, before, during and after the tests. The cone penetrometer tests showed that the whole test field had homogenous conditions and that no significant soil compaction could be observed during the course of the test.

Over the 30 m long straight course, the forwarders were driven at standard speed (3-4 km/h) and the rut depth development recorded with 2 m intervals, i.e. 15 times per passage. The straight track test was performed unladen and with a 75 % payload (14 tons) and for the Ponsse Buffalo 8W it was also performed with and without tracks. The slalom tests were performed in a similar way, but the forwarders had to complete 10 passages while turning for ‘slalom gates’ at 7 and 10 m distance, imitating a winding strip road.

The results of the rut depth measurements are that the rubber-tracked OnTrack forwarder create significantly shallower ruts than the Buffalo 8W and 10W respectively in all tests. The result was not surprising for the straight track tests but a bit less expected for the 'slalom tests' where long tracks normally lead to extensive shearing during turns. Apparently, the rubber tracks are less aggressive than steel tracks in this respect. The Ponsse 10W performed well on the straight track but created a lot of shearing and deep ruts while turning.

Introduction

In northern Europe, the emerging green bio-economy is strongly depending on the supply of sustainably produced wood in a cascading use from building materials over tissue and fabrics to chemicals and ultimately to energy (Roos et al., 2013). At the same time, increasing problems of forwarding wood from sensitive areas with soft soil are foreseen (Keskitalo et al., 2016). This is a consequence of climate change, entailing milder winter temperatures and an increase of precipitation in the Nordic area, but also due to the ongoing efforts of forestry to develop gentler technologies and methods (Ismoilov, 2016).

Thus, the reduction of negative impact on forest soils by machines used in forestry is an important goal. The OnTrack forwarder concept build on the combination of Ponsses successful Buffalo forwarder chassis (**www.ponsse.com/en**) and the proven heavy-duty rubber tracks of Prinoth (**www.prinoth.com/en**). The aim is to develop and demonstrate a gentle technology for heavy in-terrain transport, addressing the requirements of sustain-
able forestry operation in sensitive areas.

To investigate how the concept machine performs in comparison to available technologies, Skogforsk has subjected it to standardised rutting tests benchmarking the OnTrack to the Buffalo 8W with and without standard metal tracks as well as with the "soft-soil forwarder" Buffalo 10 W, with an extra axle, enabling the use of extra-long metal tracks, doubling the support area of the rear load carrier.

Material and Methods

VIBRATION TESTS

The standardised vibration track consists of three sections, a level starting lane before an obstacle track and a level finish lane after the obstacle track. The starting and finishing lanes allow for the machine to start completely before and finish completely after the obstacle course. The full length of the test track is 50 m. The obstacle track consists of a 28 m long concrete slab with standardized obstacles bolted-on in a specified pattern (Figure 1). The obstacles are placed at right angles in two rows, one for each side of the machine. The obstacles are equivalent to Ground Roughness Class 2, according to the Nordic terrain classification system. A photo of the test facility is shown in Figure 2.

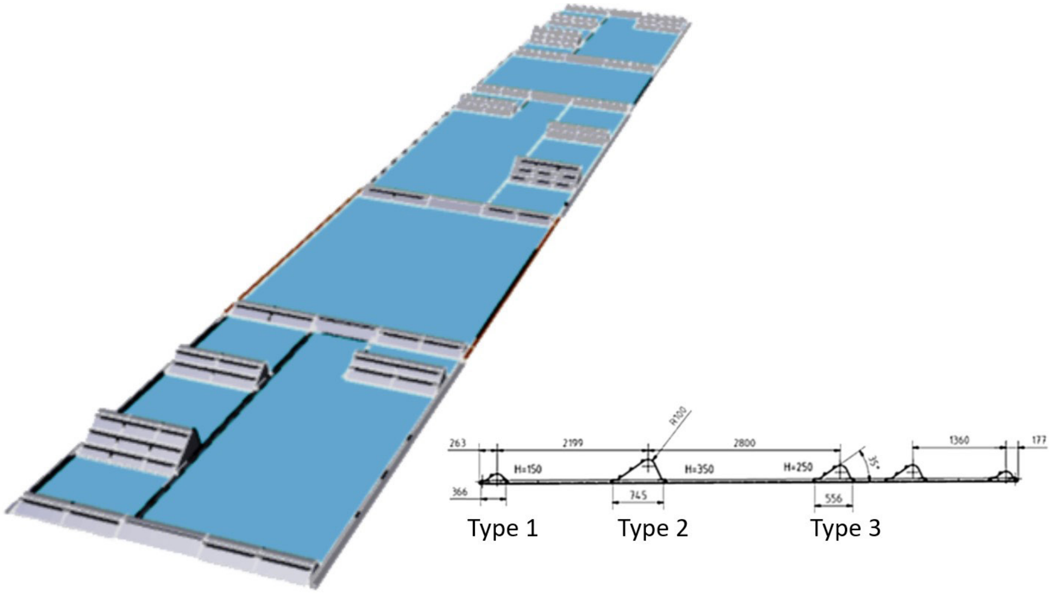

Figure 1. The layout of the vibration test track and the three standardized obstacle types (measures in mm).

Figure 2. The vibration test track in Jälla, outside Uppsala. Foto: Rolf Björheden, Skogforsk.

The vibration levels were measured at different speeds for the 8-wheeled Buffalo long frame (Buffalo LF) forwarder and for the two configurations of the Buffalo OnTrack forwarder: the OnTrack forwarder with pivoting tracks in the front only is referred to as OnTrack PF and the configuration with pivoting tracks in both front and rear is called OnTrack PP. The OnTrack PF and the Buffalo LF were tested both laden and unladen to explore the influence of mass and changing centres of gravity on vibration levels.

The testing speeds used were 0.25, 0.50, 0.75 and 1.00 m/s. The tests were performed averages of multiple (3-5) passes, with 0.50 m/s as the most important speed since it represents a fairly normal driving speed at Ground Roughness Class 2. For the Buffalo LF the tests do not include 1.00 m/s since already at 0.75 m/s the vibration levels were extreme, and the number of passes was reduced to 3 with consideration to the operator. The lower speeds yield interesting high-resolution data on the vibration profile of the tested configurations.

Measurement units and sensors

An *Electronic Computer Unit* (ECU) from Ponsse with two built-in *Inertial Measurement Units* (IMU) were used to record the accelerations in x-, y- and z-directions as well as the angular velocities of roll and pitch movements. The sampling intensity is 100Hz. The data collector logging all signals was coupled to the IMUs through a CAN-PC interface and saved to a file after initial recording by *CAN-alyzer*, an analysis software tool from Vector Informatik GmbH for subsequent analysis in Matlab.

One of the IMUs was firmly placed in front of the chair, above the front bogie axle, to measure cab vibrations (Figure 3). The second IMU was placed above the rear bogie axle centre strapped against a high friction rubber mat.

Figure 3. IMU installed above the front bogie axle under the driver's seat. Foto: Rolf Björheden, Skogforsk.

Machine travel speed measurement

The travel speed of the machine is a critical factor for the vibration test and was measured by timing the 50-m course of the machine over the vibration track, i.e. as an average speed from the start and finish markers (Figure 4). A running start procedure was used through starting the logging of vibration as the start marker was passed and ending when the finish marker was reached. The forwarder speed was regulated by adjusting the accelerator so that the machine reached a constant speed at 'full throttle' thus minimising operator influence. Through controls with wire sensors and rotation sensors on the tested machines it has been shown in earlier tests that this procedure will result in acceptably uniform speeds (Figure 5). The data from this study, presented in table 3 further supports this assumption.

Figure 4. Start position marker (left) and end position marker (right) for timing of travel speed.
Foto: Rolf Björheden, Skogforsk.

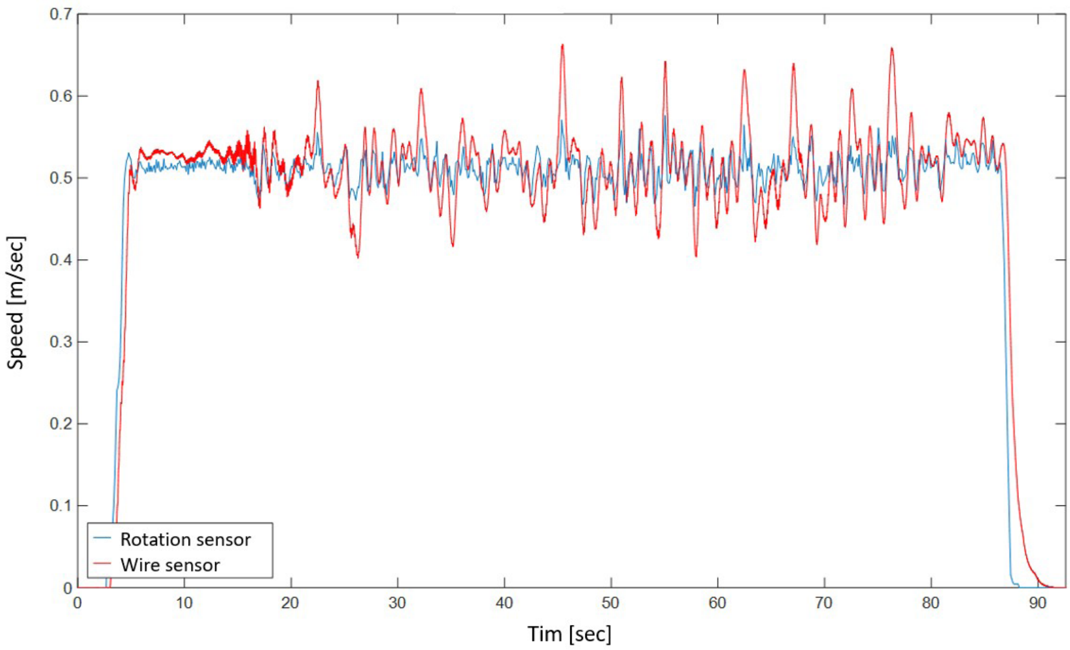

Figure 5. Tests of speed uniformity measured by rotation and wire sensors from earlier tests.

Vibration analyses

Vibration levels can be quantified in different ways, but commonly includes establishment of the RMS value (Root Mean Square) of accelerations in different directions. This study pertains to the procedures of the ISO standard 2631-1 and its specifications for determining values, depending on the purpose of the calculation (health, comfort or operator experience). According to ISO 2631-1 some frequencies are more harmful than others. The standard presents frequency dependencies for the directions of accelerations, evaluation methods and suitable placement of the sensors. In this study, the sensors were placed on the floor just in front of the operator seat, as this was the most suitable placement, ensuring that the quality of the seat and operator weight does not impact on the result. The focus of this study was to evaluate the differences between wheeled and two different configurations of a rubber-tracked vehicle.

The comfort value denotes an average of the RMS vibration value in the dominant directions including the axes of rotation, pitch and roll (Figure 6), while the health value refers exclusively to the maximum values in x, y and z directions with multipliers for their respective impact on the operator. The RMS value is weighted with multipliers (Table 1) for Comfort and Health values respectively.

Table 1. Multipliers for Comfort and Health values according to The ISO 2631-1

	Comfort value	**Health value**
X acceleration: Wd, k x	1.0	1.4
Y acceleration: Wd, k y	1.0	1.4
Z acceleration: Wd, k z	1.0	1.0
Roll at seat surface: We, k rx	0.63 m/rad	
Pitch at seat surface: We, k ry	0.4 m/rad	

In this study, we are presenting both comfort and health values for the two configurations of the rubber-tracked OnTrack forwarder and for the wheeled Ponsse Buffalo long frame forwarder as a reference. The comfort value is the most relevant of the two since it includes roll and pitch rotations if they are dominant.

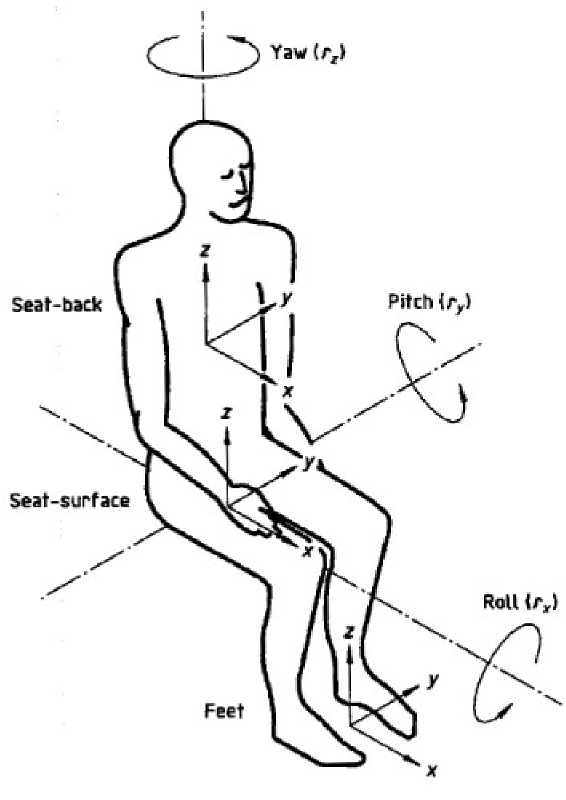

Figure 6. Definition of acceleration directions and axes of rotation according to ISO 2631-1.

Offset calibration and Fourier transformation of accelerometer data

The offset is removed from the accelerometer signals by subtracting the median amplitude from every data point of the measurement. The median amplitude is decided on the plane starting lane before the obstacle course or when the machine is standing still. The purpose is to concur the values before and after Fourier transformation (decomposing the signal over time into the frequencies that make it up) when comparing the weighted and unweighted signal, (Figure 7). The accelerations are Fourier transformed from a time to a frequency domain to enable weighting according to ISO 2631 (Figure 8). As recommended in ISO 2631-1, both the weighted and unweighted RMS values are presented for each data set.

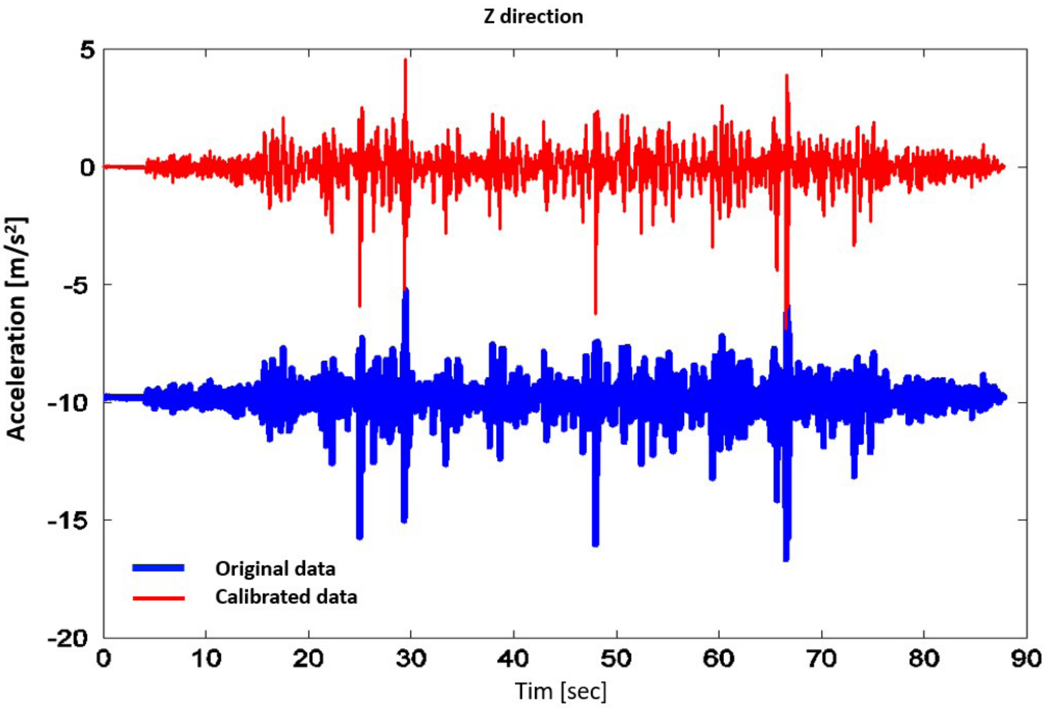

Figure 7. Offset calibration of accelerations I z direction. The blue graph shows the original data, offset by gravity to ~10m/s² and the red graph the calibrated data.

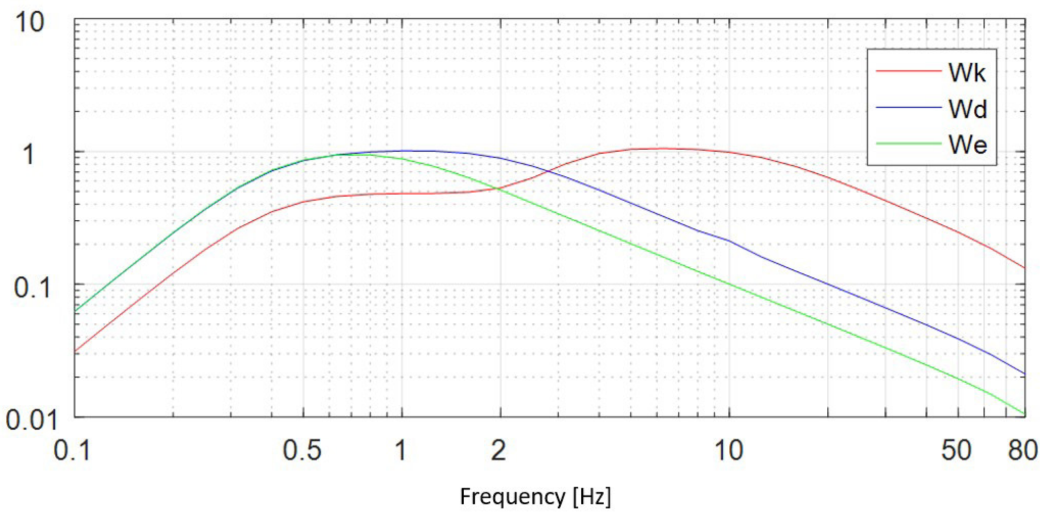

Figure 8. Frequency weighting curves for z direction (Wk), x and y directions (Wd) and rotational vibration (We) according to ISO2631.

RUTTING TESTS

The rutting tests were conducted during the first week of September 2017 on an agricultural field with deep, homogenous, sapric histosol some 7 km SE of Tierp (60°18'49.4"N 17°37'40.3"E). The conditions are highly suitable for comparative studies of rutting tendencies between different alternative vehicles and has been used by Skogforsk in a series of standardised rutting tests over the years. The comparative rutting tests included

- the final OnTrack (PP) forwarder (Figure 9)
- a Ponsse Buffalo 8W with Active Frame (Figure 10 left), which may be considered a reference machine. This machine was tested both with and without metal tracks (Olofsfors Eco-Track Baltic).
- a Ponsse Buffalo 10W (Figure 10 right), a long frame variant with an extra axle allowing extra-long tracks (same type as the Buffalo 8W) to improve capacity for transports on soft soil.

The machines were driven by Anders Mörk, Skogforsk and Anders Jacobsson of Ponsse Sweden AB.

Figure 9. The laden OnTrack during the rut formation tests. Foto: Rolf Björheden, Skogforsk.

Figure 10. The Ontrack was benchmarked against the state-of-the-art high flotation Ponsse 10W to the left and the reference machine, a Ponsse Buffalo 8W Active Frame, to the right. Foto: Rolf Björheden, Skogforsk.

Machine weights and standard loads

The machines' service weights were established with portable wheel-load scales. For the tracked machines, a wooden 'drive-on' ramp was used to support the track. Weights were recorded for each wheel separately for the conventional forwarders, and for the OnTrack weights were taken for each track bogie. The results are seen in Table 2, errors of measurement cause the load weight to differ slightly, but the same load was used for all machines. The errors are small (0,7-1,6 %) and the table gives a fair estimate of the weight distribution.

The rutting tests were performed with unladen machines and with test loads amounting to 75 per cent of the allowable maximum weight (14 tonnes), as declared by the manufacturer. The test load weight for all three machines was 10.5 tonnes. To ensure that the test loads were consistent, the same load of pine pulpwood was used and transloaded between all machines. This load was weighed in before the study on an industrial vehicle scale and transported to the test site.

Table 2. Machine weights and mass distribution between front and rear for the tested machines.

Machine	Total weight, kg	...of which front	...of which rear
Buffalo 8 W (tracks) empty	22670	14360	8310
Buffalo 8 W (tracks) laden	33820	14640	19180
Buffalo 10 W empty	25230	11750	13480
Buffalo 10 W laden	36160	13580	22580
OnTrack empty	28310	13980	14330
OnTrack laden	38630	14710	23920

Layout of test tracks and rut depth measurement

The rutting was measured on a straight track (Figure 11), with the vehicles moving at a speed of 3–4 km/h, ten times over a 30-m long test track. The rut formation was measured and recorded at fixed points with 2 m intervals between every pass of the machine, using a large calliper (Figure 12).

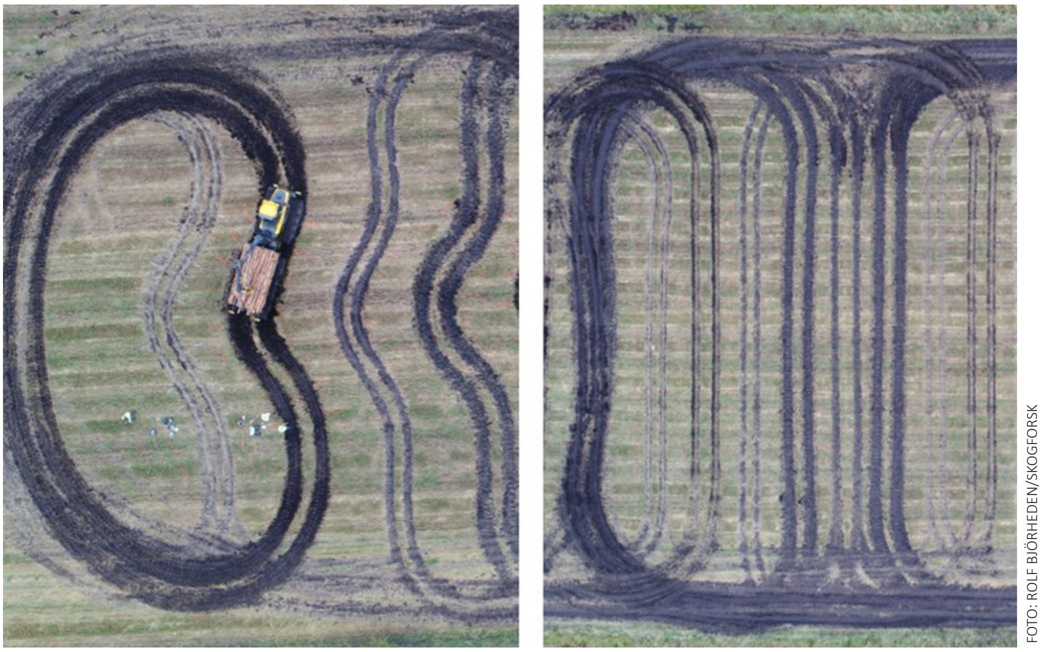

Figure 11. Aerial view showing the layout of the 'slalom' (left) and straight (right) rut formation test tracks.

Figure 12. Rut depth measurement on the straight rutting test tracks. Foto: Bruce Talbot, Nibio.

The rutting was also measured on a ’slalom’ course with 7 and 10 m slalom gate distance and parallel turns (Figure 11) to explore the rut formation when shearing is introduced. Also here, measurements were carried out at 2 m road-centre intervals, measured at right angles with the direction of travel. Here a rotating laser and a measuring stick was used to decide rut formation and measures were recorded at every pass from 1-5 and then after 8 and 10 passes (Figure 13).

Figure 13. Rut depth measurement with rotating laser and measuring stick on the ‘slalom’ rutting test tracks. Foto: Rolf Björheden, Skogforsk.

Measurement of soil properties

The cone penetration resistance of every test lane was measured on before, in the middle of and after the completion of the tests to ensure homogenous test conditions (Figure 14). The measurement was done with an Eijelkamp registering penetrologger equipped with a standard ASAE 30°, 2.1 cm diameter (3.3 cm^2) cone at a penetration speed of approximately 3 cm per second until complete probe penetration (~ 80 cm depth) or a penetration resistance in excess of 1,5 MPa.

Figure 14. Cone penetration resistance was measured before, in middle of and after completion of each rutting test. Foto: Rolf Björheden, Skogforsk.

Results

VIBRATION TESTS

The number of passes per machine and speed is presented in Table 3. Table 4 provides an overview of the total layout of the vibration tests and presents averages of the main results. The weighted vibration values from the tests of Buffalo LF and OnTrack PF are presented in detail in Appendix 1.

Table 3. Number of passes per machine configuration for each goal speed on the vibration track.

	Goal driving speed, m/s				
Machine	**0.25**	**0.50**	**0,75**	**1.00**	**1.25**
Buffalo LF	3	5	3	-	-
Buffalo LF loaded	-	5	3	-	-
OnTrack PF	3	5	5	5	-
OnTrack PF on gravel	-	1	1	-	-
OnTrack PF loaded	-	5	3	-	-
OnTrack PP	4	5	5	4	2
Number of tests/goal speed	10	26	20	9	2

Table 4. Overview of vibration test layout and main results.

Machine/configuration	Avg Speed	Rep	Std Dev Speed	Avg Health	Avg Comfort
Buffalo LF	0.26	3	0.05	0.23	0.28
	0.52	5	0.02	0.59	0.67
	0.73	3	0.00	1.18	1.52
Buffalo LF Loaded	0.55	5	0.04	0.62	0.69
	0.74	3	0.00	1.20	1.45
OnTrack PF	0.25	3	0.01	0.49	0.65
	0.49	5	0.01	0.38	0.47
	0.75	5	0.01	0.91	1.06
	0.97	5	0.05	1.19	1.33
OnTrack PF loaded	0.50	5	0.01	0.39	0.50
	0.74	3	0.01	0.84	1.00
OnTrack PF gravel	0.52	-	-	0.18*	0.21*
	0.77	-	-	0.31*	0.35*
OnTrack PP	0.26	4	0.03	0.20	0.27
	0.50	5	0.01	0.53	0.64
	0.76	5	0.04	1.25	1.42
	0.98	5	0.04	1.45	1.61
	1.14	-	-	1.58	1.74
	1.25	-	-	2.45	2.69

* For tests with only two repetitions, no statistics, except the recorded values, are presented in the table.

Reference vibration tests

Before the Buffalo long frame providing the chassis for the OnTrack forwarder was rebuilt, it was subject to vibration testing at Jälla. The results of this test are used as a control for the subsequent vibration tests of the OnTrack in different configurations. The vibration tests of the Buffalo LF was done both driving empty and laden, to investigate if the increased mass and the altered centre of gravity on a laden machine will influence the level of vibrations. (The centre of gravity is elevated and moved towards the rear when the machine is loaded). The Comfort RMS vibration levels of the Buffalo LF empty and laden can be seen in Figure 15. There was no statistically significant difference between driving empty or with load.

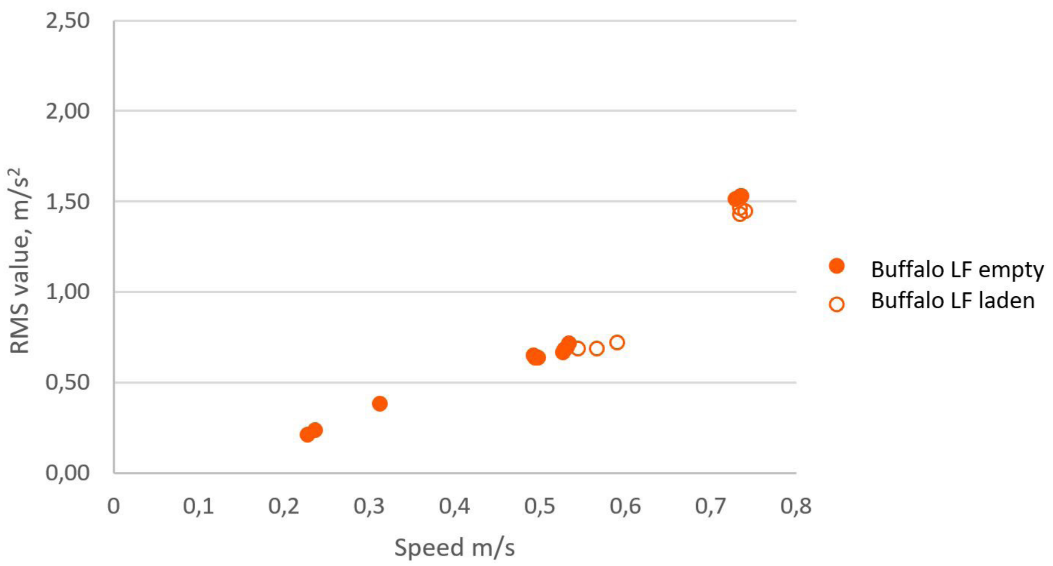

Figure 15. Comfort vibration values for a wheeled Buffalo long frame, Buffalo LF when driving empty and when driving laden on the vibration test track. The increased mass and the centre of gravity elevated and moved towards the rear has not significantly altered the comfort vibration values.

Figure 16. Standardized measurement of the operator’s exposure to whole-body vibrations for the initial OnTrack configuration, OnTrack PF, were performed in March 2017 in Jälla, Sweden.
Foto: Rolf Björheden, Skogforsk.

Vibration tests and evaluation of the initial OnTrack configuration

When the OnTrack had been assembled, with pivoting front tracks and fixed rear tracks as the initial configuration (OnTrack PF), a similar vibration test was repeated on the OnTrack (Figure 16). In addition, the vibration levels were measured when driving empty on a gravel surface. The results of these tests are shown in Figure 17. As for the wheeled forwarder, the vibration levels are not affected by carrying a load. But the difference between driving on a concrete surface, as on the vibration test track, or on a somewhat yielding gravel surface was dramatic. The vibration levels are significantly lower when driving on the softer surface. For a wheeled machine there is no such difference.

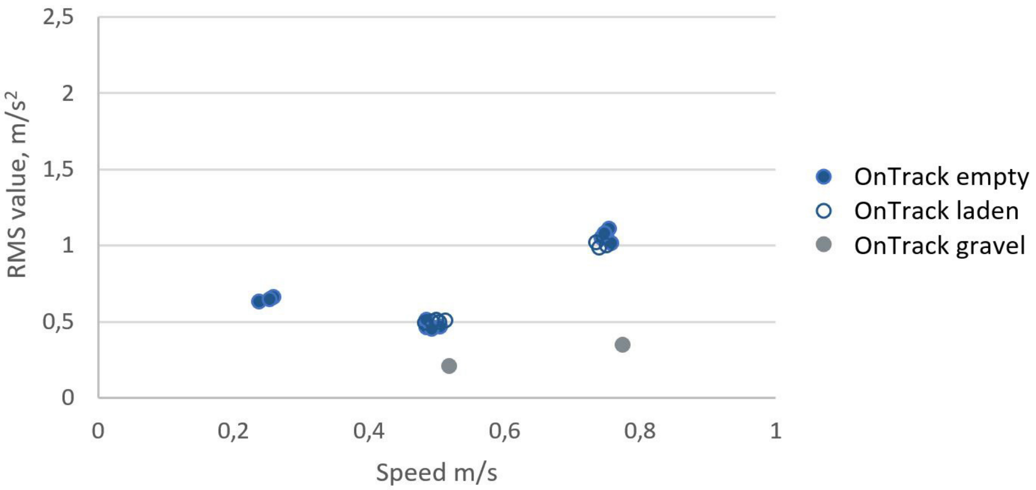

Figure 17. Comfort vibration values for the first configuration of OnTrack, OnTrack PF, empty, laden and when driving empty on a gravel surface instead of the concrete slab of the vibration test track. The increased mass and the centre of gravity elevated and moved towards the rear due to carrying a payload has not significantly altered the comfort vibration values. The test run on the gravel surface next to the vibration test track, however, shows that a somewhat softer surface will reduce a lot of the vibrations caused by the track units.

The next step was to compare the vibration levels between the wheeled forwarder and the initial configuration of the OnTrack. The results, shown in Figure 18, show favourable for properties of the OnTrack PF. There is a tendency of a polynomial relation between vibration levels and speed for the OnTrack PF. At low driving speeds, the vibration levels were higher than for the wheeled Buffalo LF. But, contrary to what is the case for wheeled machines, the vibration levels decreased when the driving speed was doubled from 0.25 to 0.5 m/s. The vibration levels at 0.5 m/s are lower for the OnTrack PF than for the Buffalo LF and the difference between the two configurations is increasing as speed is increased. Driving at 0.75 m/s with the Buffalo LF was extremely awkward for the operator and the tests were stopped to avoid injury. The OnTrack, however, could travel at 1.0 m/s with lower vibration levels. From a vibration exposure point-of-view, the fixed rear track offered advantages, riding over obstacles, rather than following their contours. The results of these tests indicate that the OnTrack could be expected to be reach at least an average 0.65 m/s in terrain, which is around 30 per cent faster than normal travel speeds for wheeled forwarders.

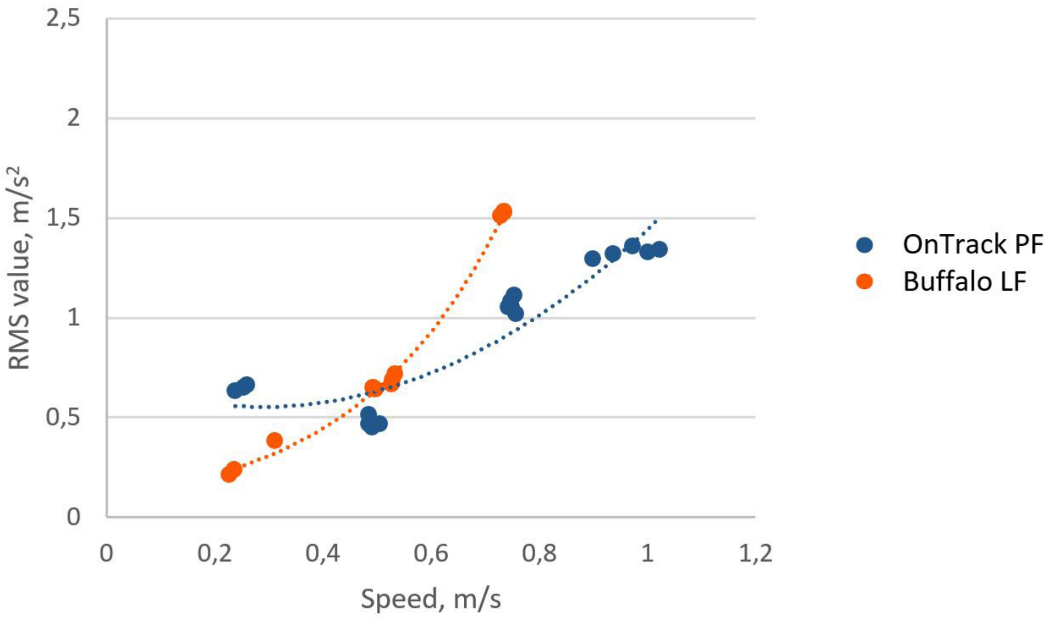

Figure 18. Comfort vibration values for a wheeled Buffalo long frame, Buffalo LF, vs the first configuration of the OnTrack, OnTrack PF, with pivoting front tracks and fixed rear tracks. Dashed lines are polynomial trend lines and not statistical equations of the dataset.

Vibration tests and evaluation of the final OnTrack configuration

In the validating field tests of the OnTrack PF the fixed rear tracks seemed to offer more problems than anticipated. The allowable angle of the articulated frame was relatively limited, and the load carrier and its ground contact was very rigid. This led to high friction resistance and point tensions between machine and soil surface when turning and to extreme point tensions between front and rear of the machine when travelling in uneven terrain. It was decided to rebuild the OnTrack for pivoting rear tracks (OnTrack PP), to reduce the problems. New vibration tests had to be performed after the re-engineering had been completed. A comparison to the reference levels of the Buffalo LF is shown in Figure 19. There is a tendency of slightly lower vibration levels for the OnTrack, but the results are very similar to that of the wheeled forwarder.

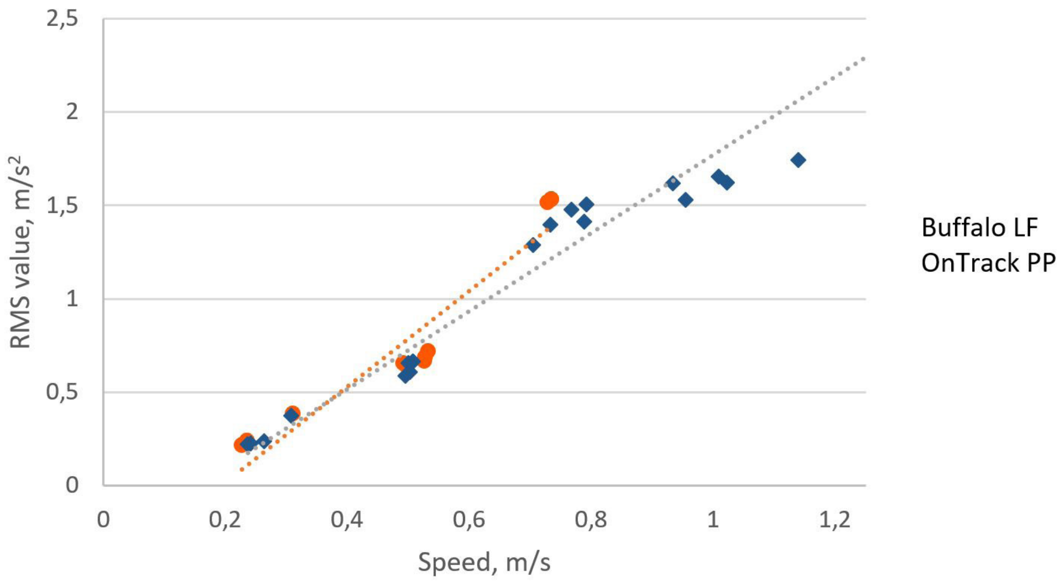

Figure 19. Comfort vibration values for a wheeled Buffalo long frame, Buffalo LF, vs the final configuration of the OnTrack, OnTrack PP, with pivoting front tracks and fixed rear tracks. Dashed lines are simple, linear trend lines and not statistical equations of the dataset.

Comparison of the two tested OnTrack configurations

The final analysis of vibration levels was to compare the two configurations of the OnTrack, graphically presented in Figure 20. The tendency of declining vibration levels at between driving speeds 0.25 and 0.5 m/s, that was shown for the OnTrack PF is not evident for the final OnTrack PP configuration showing slightly lower vibration levels at the lowest test speeds but clearly higher vibration levels at speeds > 0.5 m/s.

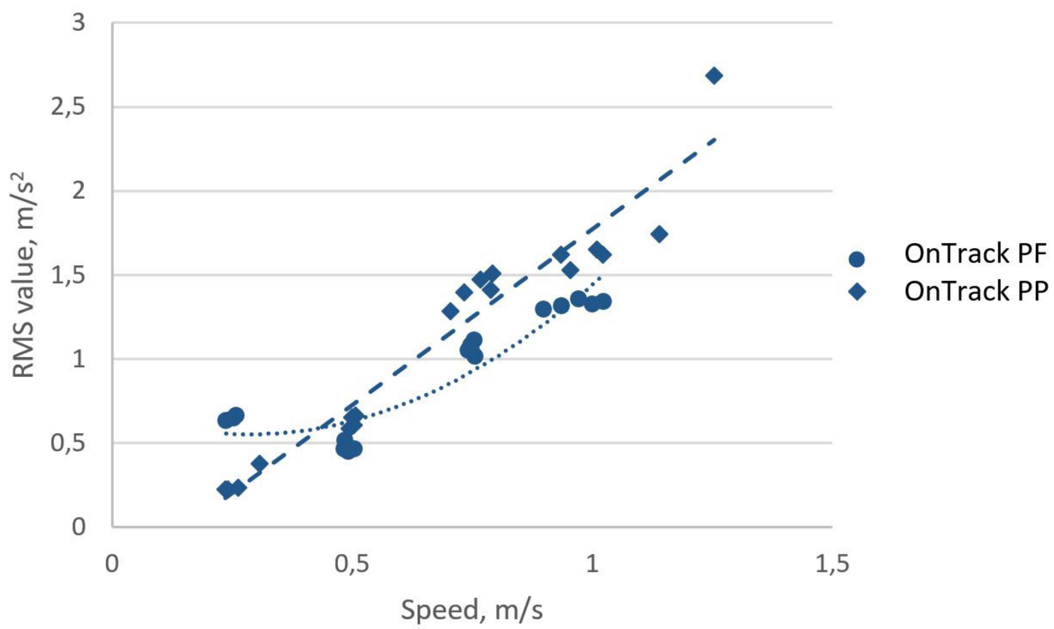

Figure 20. Comfort vibration values for the first vs the final configuration of the OnTrack, OnTrack PF vs OnTrack PP. Dashed lines are simple, linear trend lines and not statistical equations of the datasets.

RUTTING TESTS

Homogeneity and similarity of the testing area

All test lanes were probed to a depth of 80 cm to establish the cone penetrometer resistance. The test lanes were probed before the rutting test, once during the tests and after the tests had been concluded. The purpose of these tests was to ensure that the soil was homogenous and had similar properties for all test lanes and that the soil -machine interaction did not alter this during the course of the test.

In Figure 21, an example of cone penetration resistance is shown for six random test lanes (# 1, 2, 4, 5, 6, 8). The reason that only six lanes is included is that the homogeneity is so great that the graphics becomes blurred and impossible to read if all lanes are included.

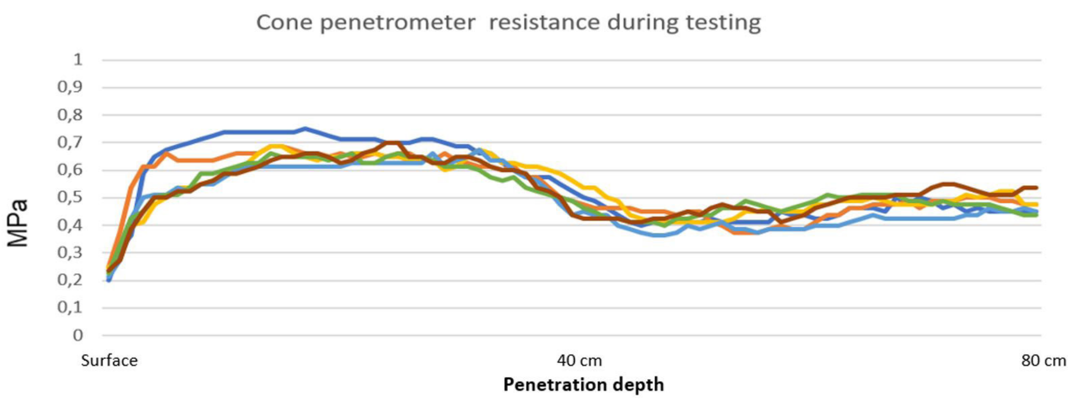

Figure 21. Cone penetration resistance for test lanes 1, 2, 4, 5, 6 and 8, in the middle of testing. The results show that the soil is homogenous and that there are no significant differences between lanes.

Figure 22 shows, also as an example, the recorded cone penetration resistance for test lane 6 (Buffalo 10 W, laden straight lane), before, during and after testing. The cone penetration resistance profiles are almost completely similar, showing that the soil has not been significantly changed by the repeated passes of the machine. The results are similar for all tested machines, all configurations and all lanes.

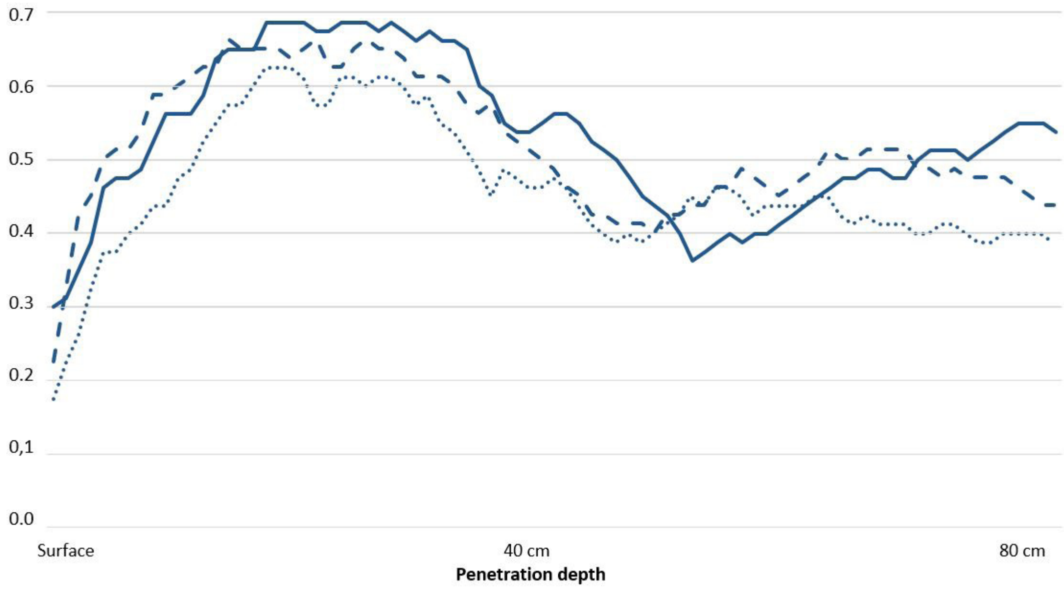

Figure 22. Cone penetration resistance for test lane 6 (Buffalo 10W, laden straight lane). Solid line= before testing, dashed line= during testing and dotted line=after testing. The results show that the soil has not been significantly changed during the test.

Rut formation on straight test lanes

The compared machines were driven empty on the straight test lanes and the rut depth was recorded after each pass. The Buffalo 8W was driven both with tracks and with wheels. The results, graphically presented in Figure 23 show that the two 'soft soil' machines, the Buffalo 10W and the OnTrack are making a shallower rut. This observation is similar to what has been noted in field trials comparing Ponsse Buffalo 8W and 10 W (Fjeld, D. & Østby-Berntsen, Ø., 2017). The Ponsse Buffalo 8W without tracks has the most aggressive rut formation, although it weighs 'only' 19.500 kg, which is nine tonnes less than the OnTrack and seven tonnes less than the Buffalo 10W.

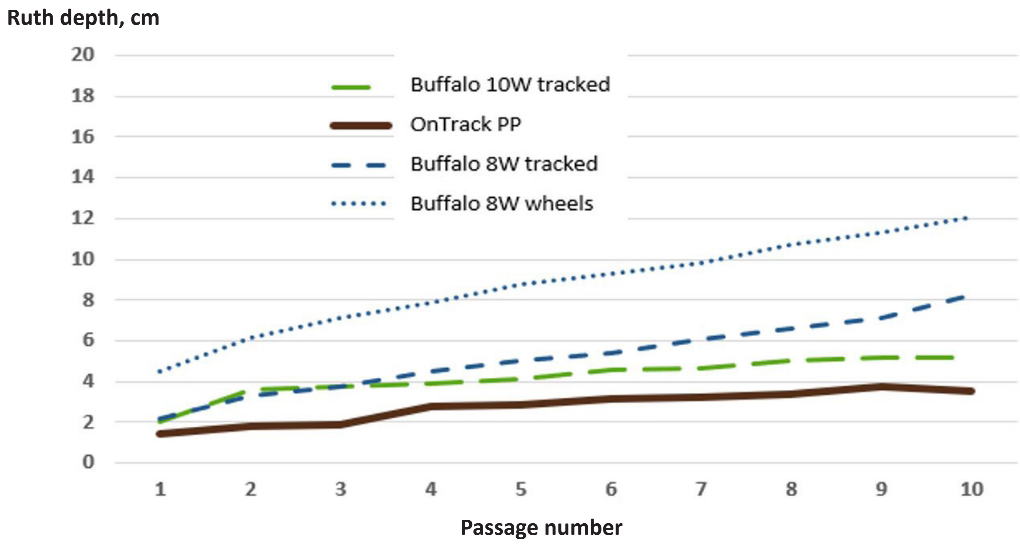

Figure 23. Rut formation while driving empty on straight lane. Average of left and right tracks.

The machines were also driven laden with 10.5 tonnes of pulpwood on a straight test lane. The results are shown in Figure 24. Once again, the 'soft soil specialists' demonstrate superior flotation, and the difference is markedly bigger. For the wheeled Buffalo 8W, the tests were interrupted after six passes when the average rut depth was almost 20 cm, to simplify restoration of the test field. The OnTrack has the least recorded rut formation and the difference to all other tested machines, including the Buffalo 10W, has increased.

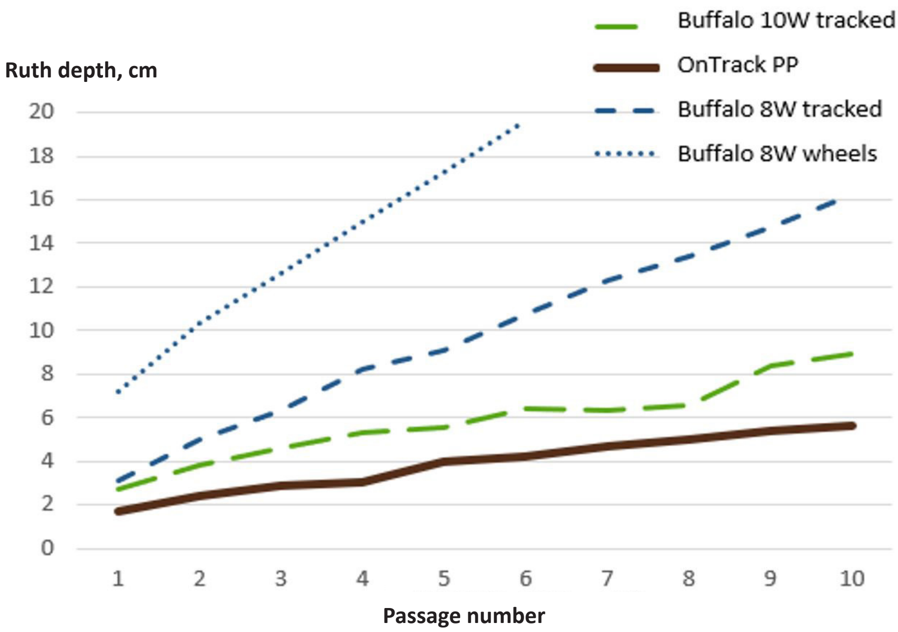

Figure 24. Rut formation while driving laden on straight lane. Average of left and right tracks. The tests for the Buffalo 8W on wheels was interrupted after 6 passes to avoid excessive rutting on the test field.

Rut formation on slalom test lanes

On the slalom test lanes, the compared machines were also driven empty. The rut depth was recorded after each of the five first passes, then after pass 8 and pass 10. The Buffalo 8W was driven both with tracks and with wheels. The results are shown in Figure 25. The OnTrack continues to outperform the other machines, but the other 'soft soil specialist', the Buffalo 10W, now move from second best to worst. Clearly, the shearing of the metal tracks is much more aggressive than for the Prinoth rubber tracks of the OnTrack. Statistically, the only significant difference is the lower rut depth of the OnTrack.

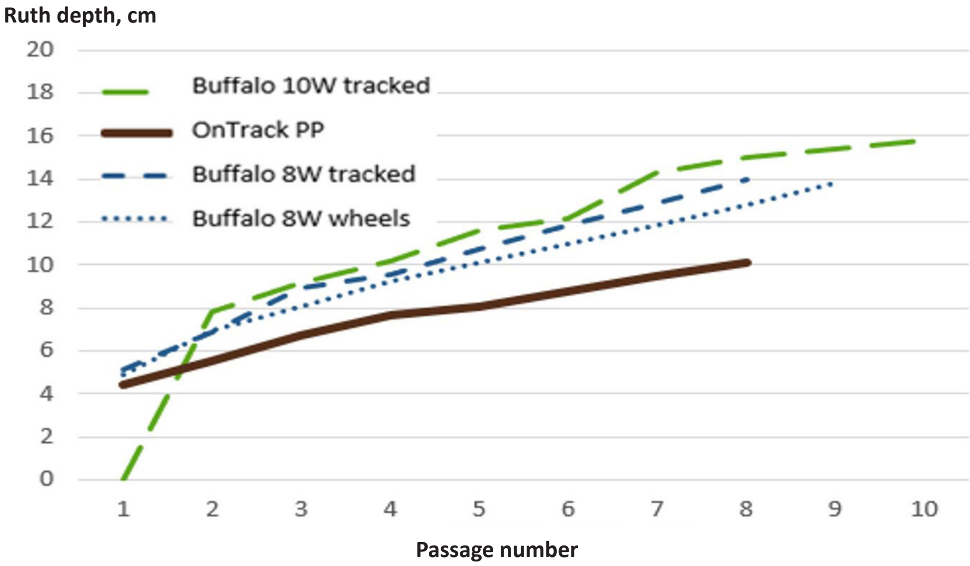

Figure 25. Rut formation while driving empty on slalom lane. Average of left and right tracks.

The machines were also driven laden with 10.5 tonnes of pulpwood on slalom lanes. The results are shown in Figure 26. The OnTrack has a clear, statistically significant, advantage over all the other machines, and the Buffalo 10W clearly demonstrates the most rutting when turning laden on the slalom lane. Clearly, the shearing of the metal tracks is more aggressive than for the Prinoth rubber tracks of the OnTrack. For the Buffalo 10W and the tracked Buffalo 8W, the tests were terminated after 5 passes and for the wheeled Buffalo 8W, after six passes. An interesting observation is that the rutting of the tracked and the wheeled Buffalo 8W is very similar. This indicates that the disadvantage of a small support area was weighed up by a less aggressive ground contact and lower weight in this particular case. The difference between the OnTrack and the other tested machines increased further in this test.

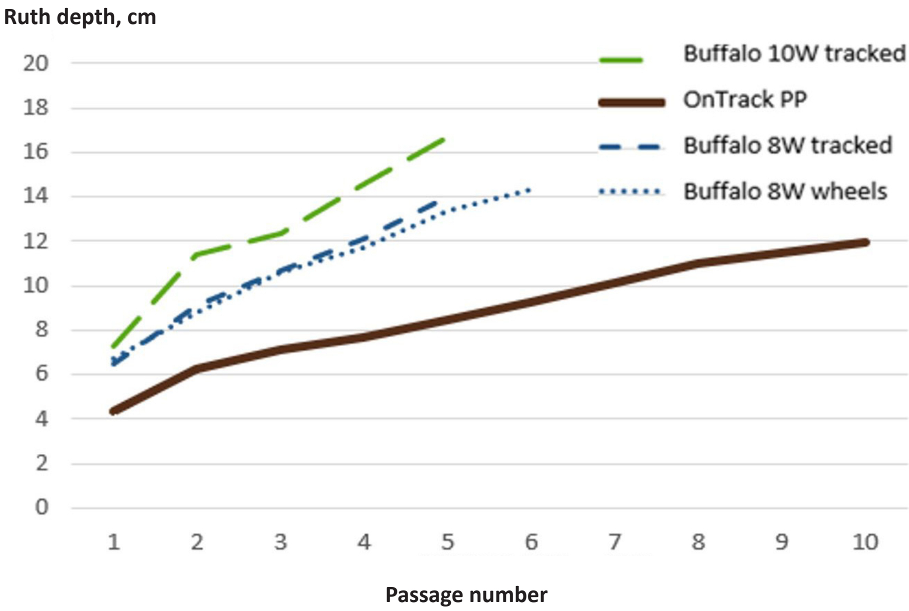

Figure 26. Rut formation while driving laden on slalom lane. Average of left and right tracks. The tests were terminated after five or six passes for all machines except the OnTrack.

Discussion

The OnTrack had the least rut formation of all machines, empty and loaded both on straight and S-shaped test lanes. Interestingly, the Ponsse Buffalo 10W is performing almost as well as the 2 tonnes heavier OnTrack when running on straight lane. But on the S-shaped test course, the Ponsse 10W caused deeper ruts than any other machine, especially when it was loaded. This indicates that

- the Ponsse 10W is a good solution providing that strip roads are kept reasonably straight
- the OnTrack has good flotation and low impact on soil, both running straight and turning.

The results show that the OnTrack technically delivers the benefits set up by the project consortium: low impact on soft and sensitive ground. It remains to be shown if these benefits can be achieved in an economically competitive way. The vibration levels of the first OnTrack configuration were favourably low, allowing considerably higher speed for the OnTrack compared to the wheeled Buffalo forwarder. The long, fixed rear track often rode on top of several obstacles both on the standardised test track and in the terrain (Figure 27). This contributed to decreasing both the frequency and amplitude of vibrations.

Regrettably, the second configuration of the OnTrack, where also the rear tracks were allowed to pivot was only slightly better than a wheeled forwarder. Since driving speed is a key factor for productivity and, thus, unit cost of production it would be interesting if the problems with excess loads on the steering hinge could be solved by re-engineering the steering hinge instead of releasing the rear tracks.

Figure 27. Surface roughness trafficability test in Jälla, Sweden. The OnTrack configuration with a fixed long rear track unit showed favourably low vibration levels. Foto: Rolf Björheden, Skogforsk.

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Appendix 1. Weighted vibration, comfort and health values for the vibration tests

Table A.1 Weighted (not multiplied) vibration, Comfort and Health values for the vibration tests of OnTrack PF according to ISO 2631.

	Speed [m/s]	Time [s]	X [m/s²]	Y [m/s²]	Z [m/s²]	Roll [m/s²]	Pitch [m/s²]	Health	Comfort
Ontrack-2-0.25	0.26	192.88	0.37	0.32	0.45	0.09	0.08	0.52	0.66
Ontrack-3-0.25	0.24	210.10	0.31	0.29	0.47	0.08	0.08	0.47	0.63
Ontrack-4-0.25	0.25	197.18	0.32	0.31	0.47	0.08	0.04	0.47	0.65
Average	**0.25**							**0.49**	**0.65**
Ontrack-5-0.5	0.49	101.76						0.38	0.47
Ontrack-6-0.5	0.48	103.22	0.20	0.21	0.36	0.07	0.02	0.36	0.47
Ontrack-7-0.5	0.48	103.12	0.20	0.20	0.43	0.06	0.02	0.43	0.51
Ontrack-8-0.5	0.50	99.01	0.20	0.21	0.37	0.06	0.02	0.37	0.47
Ontrack-9-0.5	0.49	101.61	0.21	0.20	0.34	0.06	0.02	0.34	0.45
Average	**0.49**							**0.38**	**0.47**
Ontrack-10-0.75	0.75	66.67	0.34	0.44	0.89	0.15	0.04	0.89	1.05
Ontrack-11-0.75	0.75	66.29	0.34	0.43	0.97	0.15	0.04	0.97	1.11
Ontrack-12-0.75	0.74	67.34	0.34	0.42	0.90	0.14	0.04	0.90	1.05
Ontrack-13-0.75	0.76	66.04	0.33	0.43	0.86	0.15	0.04	0.86	1.02
Ontrack-14-0.75	0.75	66.94	0.35	0.43	0.93	0.15	0.04	0.93	1.08
Average	**0.75**							**0.91**	**1.06**
Ontrack-15-1.00	0.90	55.56	0.37	0.47	1.15	0.15	0.06	1.15	1.30
Ontrack-16-1.00	0.94	53.33	0.38	0.47	1.17	0.16	0.06	1.17	1.32
Ontrack-17-1.00	1.02	48.86	0.36	0.48	1.20	0.18	0.05	1.20	1.34
Ontrack-18-1.00	0.97	51.41	0.37	0.47	1.22	0.17	0.06	1.22	1.36
Ontrack-19-1.00	1.00	49.94	0.38	0.46	1.19	0.17	0.06	1.19	1.33
Average	**0.97**							**1.19**	**1.33**

Table A.2 Weighted (not multiplied) vibration, Comfort and Health values for the Buffalo LF (reference) according to ISO 2631.

	V [m/s]	Ti d [s]	X [m/s²]	Y [m/s²]	Z [m/s²]	Roll [m/s²]	Pitch [m/s²]	Health	Comfort
Buffalo-8-025	0.24	211.91	0.13	0.13	0.15	0.03	0.01	0.19	0.24
Buffalo-13-025	0.31	160.38	0.22	0.23	0.21	0.05	0.01	0.32	0.38
Buffalo-14-025	0.23	219.58	0.13	0.12	0.13	0.02	0.01	0.18	0.21
Average	**0.26**							**0.23**	**0.28**
Buffalo-1-050	0.53	93.70	0.35	0.45	0.44	0.09	0.03	0.62	0.72
Buffalo-2-050	0.50	100.44	0.32	0.38	0.40	0.08	0.03	0.53	0.64
Buffalo-3-050	0.49	101.60	0.33	0.40	0.40	0.08	0.03	0.56	0.65
Buffalo-6-050	0.53	94.59	0.32	0.45	0.41	0.09	0.03	0.63	0.69
Buffalo-7-050	0.53	94.87	0.33	0.42	0.40	0.09	0.03	0.58	0.67
Average	**0.52**							**0.59**	**0.67**
Buffalo-1-075	0.73	68.04	0.59	0.86	1.12	0.18	0.07	1.21	1.53
Buffalo-2-075	0.74	67.96	0.63	0.84	1.11	0.18	0.07	1.18	1.53
Buffalo-3-075	0.73	68.61	0.62	0.83	1.10	0.18	0.07	1.17	1.51
Average	**0.73**							**1.18**	**1.52**