THE SNOW GRIP OF HEAVY VEHICLE DRIVE AXLE WINTER TYRES

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Abstract

Every winter in Sweden, winter roadways pose problems for heavy vehicles. Steep gradients can be difficult to pass when it is slippery, which has implications also for other traffic when congestion occurs. To reduce the problems it has been discussed whether to impose a legal requirement for winter tyres on drive axle for trucks. This papers presents test results of the available snow grip from test track measurements comparing different drive axle tyres. A summer tyre, together with three winter tyres, of which one was retreaded, were selected for tests. The results of the traction tests show that there can be a big difference in grip between winter and summer tyres on packed snow. The difference between the tyres, however, is strongly dependent on the nature of the snow surface, so it is difficult to give general values. Theoretical calculations show that a vehicle's rolling resistance can have a major impact on a vehicles climbing ability. With a high rolling resistance, which may be the result of loose snow on the road, the difference between good and bad grip on the drive tyres becomes even more significant.

Keywords: Heavy Vehicles, Tyres, Snow, Road grip, Traction

1. Introduction

Every winter in Sweden, winter roadways pose problems for heavy vehicles. Steep gradients can be difficult to pass when it is slippery, which has implications also for other traffic when congestion occurs. When really slippery, even moderate gradients can be problematic. To reduce the problems it has been discussed whether to impose a legal requirement for winter tyres on drive axle for trucks. However, nothing has been published so far on the differences in road grip that can be expected between winter and summer tyres on various winter conditions for the category of drive axle tyres.

In a Norwegian study (Vaa and Giæver, 2009) climbing tests were performed with various heavy vehicle combinations on steep snow covered roads to investigate the challenges at hand.
The results show that the weight on the drive axle is of utmost importance for the climbing abilities, and that it could be an advantage to have a bogie on the tractor/truck, allowing for a higher drive axle load. The authors conclude that it would be beneficial if the drive axle load momentarily could be increased beyond the allowed 10 tons, which is possible with a bogie where the supporting axle can be lifted. It is also stated that semitrailer combinations without bogie on the tractor, which are common among foreign vehicles, are more prone to get into problems in slippery hills. Regarding tyres, they conclude that they are important, and that tyres with harder rubber generally result in worse snow grip compared to softer ones.

VTI has conducted two larger studies (Öberg et al., 2000; Hjort et al., 2008) concerning the correlation between heavy vehicle tyre use winter time and traffic safety in Sweden. Neither study could show that winter tyres on heavy vehicles increase traffic safety. In fact, both studies indicate that the tyre fitting that results in the lowest relative risk is summer tyres on the front and winter tyres on the drive axle, although no results were statistically significant. Ice grip measurements that were performed showed that on smooth ice winter tyres for heavy vehicles produce only a very marginal increase in grip compared to summer tyres. With studded tyres the smooth ice grip can be increased by 30%, but will still produce less grip than a typical passenger car summer tyre.

While the grip on really slippery icy roadways seems to be barely improved with winter tyres, the situation may be different for rough ice or snowy roads. This study was therefore conducted to investigate the snow grip of heavy vehicle summer and winter tyres. Since resources were limited, it was only feasible to test a few tyres. A summer tyre, together with three winter tyres, of which one was retreaded, was selected for tests. The tests were carried out on a test track with one type of winter road condition, namely packed snow

2. Method

2.1 Friction measurements

The available friction between drive tyres and a prepared snow track was measured in collaboration with Nokian Tyres, on one of their test tracks in Ivalo, Finland. A test vehicle with fix axle loads was connected to a heavier vehicle via a towing rope with a force measuring sensor, see Figure 1.

Figure 1 – Measurement constellation

A measurement repetition started with both vehicles driven at low speed (about 5 km/h) with the rope stretched, after which the rear vehicle slowly applied an increasing braking force. The driver in the test vehicle then had to gradually apply more throttle, and the measurement continued until both vehicles are at stand still. Via the pulse encoders in the ABS brakes of the test vehicle, the available friction force could be determined as a function of the wheel slip. The average of ten consecutive repetions were used to produce a full slip curve. For snow, the maximum friction forces are normally obtained between 20-30 % slip, and is then diminishing with increasing slip. As it is difficult for the driver to apply the throttle for maximum drive forces, the average friction force in the slip interval 10-70 % was considered to be a better measure of the tyre performance than the maximum friction force.

The test vehicle that was used was a Volvo FE 300 4x2, with 5100 kg front axle load and 5300 kg drive axle load. The tyre air pressure was 8.25 bar. The rear vehicle was a Sisu 6x6 Fire Engine with a total weight of 26 ton.

2.2 Maximum slope analysis

Given the friction value betwen the drive tyres and the road, the maximum slope that a certain vehicle combination can handle can be calculated. By using the equations of motion, the limiting slope can be determined from computer simulations without algebraic excercises. For a better understanding of how different factors affect a vehicle's climbing ability, it is however well motivated to derive an expression for the maximum slope for various vehicle combinations. The derivation is done for a truck-semitrailer combination, but can readily be extended to a single truck, or truck with trailer using results from the derivation. The derivation is simplified by considering a tractor with a single rear axle. Moreover, fifth wheel coupling has been assumed to be vertically abover the rear axle. The vehicle combination is shown in Figure 2, positioned on plain ground. The tractor has mass m_1 and interaxle distance L, while the semitrailer has mass m_2 and the rear axle positioned a distance L_t behind the tractor drive axle.
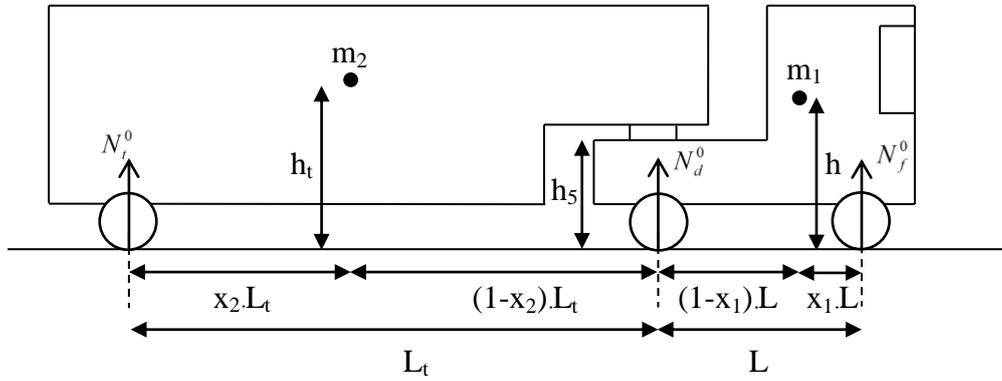
Figure 2 – Tractor with semitrailer

Demanding that the torque in any point is zero gives the following relations between the axle loads on plain ground and the horizontal positions of the two centers of mass:

$$N_d^0 = m_1 g \cdot x_1 + m_2 g \cdot x_2 \tag{1}$$

$$N_f^0 = m_1 g \cdot (1 - x_1) \tag{2}$$

$$N_t^0 = m_2 g \cdot (1 - x_2) \tag{..(3)}$$

The fifth wheel, connecting the tractor and semitrailer, can transmit vertical and horizontal forces, but no torque. For the case when the vehicle is positioned in a slope, the equations of motion have to be formulated separately for the truck and the semitrailer, and then combined. Consider first the tractor in a slope of angle α, as shown in Figure 3. The rolling resistance force F_r is acting in the backwards direction of the slope and is indicated in the figure as acting only on the rear axle, but is actually the sum of forces from all the wheels.
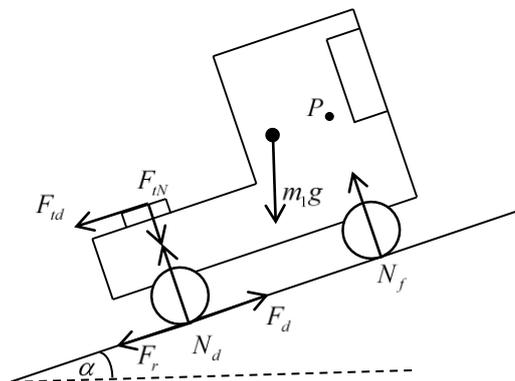
Figure 3 – Forces acting on the tractor

For the vehicle to be able to climb the slope at constant speed, or even accelerate the forces in the direction of the road need to be positive. At low speeds the air drag resistance can be neglected, so the force equations in the road direction and orthogonal to the road, and the torque around point *P* can be written as:

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$$F_d - F_r - F_{td} - m_1 g \sin \alpha \geq 0 \tag{4}$$

$$N_d + N_f - F_{tN} - m_1 g \cos \alpha = 0 \tag{5}$$

$$x_1 L \cdot m_1 g \cos \alpha + L \cdot (F_{tN} - N_d) + h \cdot (F_d - F_r) - (h - h_5) \cdot F_{td} = 0 \tag{6}$$

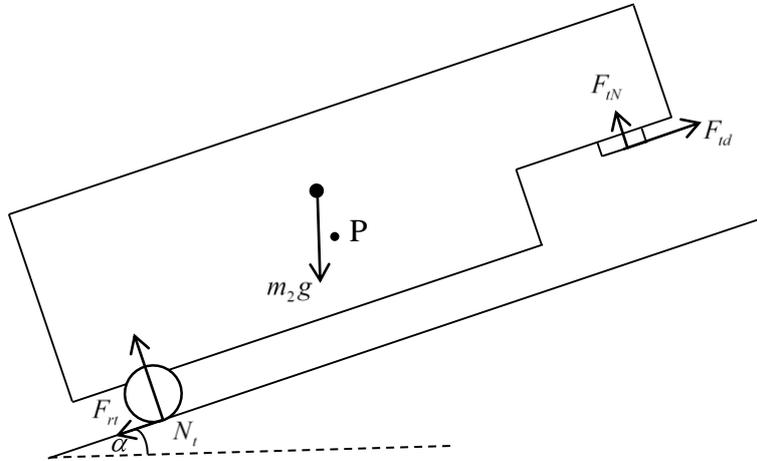The driving force and the rolling resistance force can be formulated as

$$F_d = N_d \cdot \mu \tag{7}$$

$$F_r = (N_d + N_f) \cdot C_r \tag{8}$$

Where μ is the friction coefficient between drive axle tyres and the road, and C_r is the rolling resistance coefficient. Combining Equations $4 - 8$, and defining the slope $i \equiv \tan \alpha$ gives

$$i \leq \frac{1}{(L - \mu h)} \cdot \left[L \cdot (x_1 \mu - C_r) + \frac{F_{tN}}{m_1 g \cos \alpha} \cdot L(\mu - C_r) - \frac{F_{td}}{m_1 g \cos \alpha} \cdot (L - \mu h_5) \right] \tag{9}$$

The two forces F_{tN} and F_{td} are determined from the equations of motion for the semitrailer. The forces acting on the semitrailer in the slope are shown in Figure 4.

Figure 4 – Forces acting on the semitrailer

The force and torque equations are:

$$F_{td} - F_{rt} - m_2 g \sin \alpha \geq 0 \tag{10}$$

$$N_t - F_{tN} - m_2 g \cos \alpha = 0 \tag{11}$$

$$(1 - x_2) L_t \cdot F_{tN} + (h_t - h_5) \cdot m_2 g \sin \alpha - x_2 L_t \cdot N_t - h_5 \cdot F_{rt} = 0 \tag{12}$$

and the rolling resistance is

$$F_{rt} = N_t \cdot C_r \tag{13}$$

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Combining Equations 10 - 13 gives

$$\frac{F_{tN}}{\cos\alpha} = \frac{m_2 g}{L_t + h_5 C_r} \cdot \left(x_2 L_t + h_5 C_r - (h_t - h_5) \cdot i\right)$$

(14)

$$\frac{F_{td}}{\cos\alpha} \geq \frac{m_2 g}{L_t + h_5 C_r} \cdot \left((1 - x_2) L_t \cdot C_r + (L_t + h_t C_r) \cdot i\right)$$

(15)

Equations 14 and 15 can readily be inserted in Equation 9, but will result in an expression with many terms, of which several are negligible. To reduce the expression, small terms were identified by using that L, L_t, h, h_t, h_5 are of order 1, μ and i of order 0.1 and C_r of order 0.01. In addition, using that $L_t / (L_t + h_5 C_r) \approx 1$ and letting M denote the vehicle total mass results in

$$i \leq \frac{L}{m_1 \cdot (L - \mu h)} \left(\frac{N_d^0}{g} \cdot \mu - M \cdot C_r - i \cdot m_2\right)$$

(16)

Denoting $x_0 = \frac{N_d^0}{Mg}$ as the vehicle's relative load on the drive axle on plain ground, Equation 16 can be rewritten as

$$i \leq \frac{L \cdot \left(x_0 \cdot \mu - C_r\right)}{\left(L - \frac{m_1}{M} \mu h\right)}$$

(17)

The clearer see the influence of the rolling resistance Equation 17 can with good accuracy be approximated by

$$i \leq \frac{L \cdot x_0 \cdot \mu}{\left(L - \frac{m_1}{M} \mu h\right)} - C_r$$

(18)

The corresponding formulas for a single truck, or a truck with trailer can be deduced in the same way, using Equation 9 and deriving F_{tN} and F_{td} for each case. Doing that will yield the same expression for both vehicle combinations:

$$i \leq \frac{L \cdot \left(x_0 \cdot \mu - C_r\right)}{\left(L - \mu h\right)} \approx \frac{L \cdot x_0 \cdot \mu}{\left(L - \mu h\right)} - C_r$$

(19)

Thus it is clear that the three most important factors for the climbing ability of a heavy vehicle combination are the relative load on the drive axle, the friction between drive axle tyres and the road, and the rolling resistance.

Rolling resistance

From the literature, typical values for rolling resistance of heavy vehicle tyres are in the range 0.005 – 0.007, (Gent and Walter, 2007). Nokian supplied the following typical numbers: 0.006 for steering axle tyres, 0.007 for drive axle tyres, and 0.005 for trailer axle tyres. The rolling resistance coefficient in Equations 18 and 19 are average values for the whole vehicle combination. The difference between the tyre types are however not large enough for it to be meaningful to use different values for different vehicle combinations. On dry road, a value of 0.006 seems reasonable to use. On snow covered roads, however, the rolling resistance will increase since energy is used for compressing and moving the snow. The rolling resistance coefficient will then be the sum of a tyre dependent part and a snow dependent part.

A few studies on rolling resistance in snow exist in the literature (van Es, 1999; Lidström, 1979; Kihlgren, 1977). Although they primarily concern airplane tyres, the tyre sizes and wheel loads are similar allowing a model developed by Lidström (1979) to be used for assessing the rolling resistance for truck tyres. In that model the snow dependent part of the rolling resistance coefficient is proportional to the snow density and inversely proportional to the wheel load. At low speed, it is also proportional to the snow depth. In van Es (1999) the following snow classification is used:

- New snow (50–200 kg/m^3)
- Powder snow (200–450 kg/m^3)
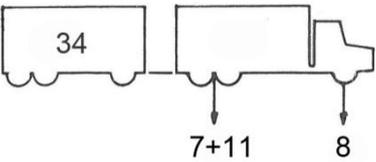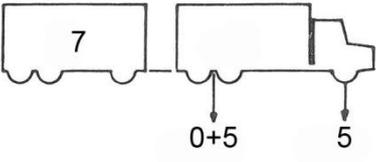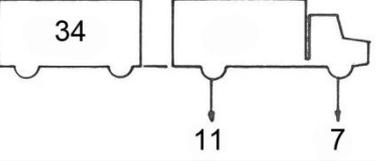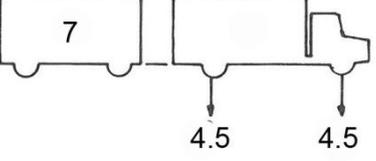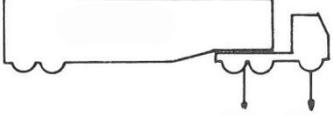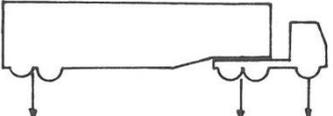- Compressed snow (450–700 kg/m^3)
- Wet snow (300–700 kg/m^3)

According to the model by Lidström (1979) the increase of the rolling resistance coefficient due to the snow would be 0.015 for 5 cm light dry snow (100 kg/m^3), and for heavier snow, e.g. 400 kg/m^3, it would be 0.06. This increase only refers to the front wheel of each wheel track. According to van Es (1999) for high wheel loads (as e.g. for heavy vehicles) the snow is compacted to such a high degree by the front wheels, that the snow dependent part of the rolling resistance for the other tyres is practically zero. Thus, to estimate the increase of rolling resistance due to loose snow for a certain vehicle combination, the theoretical increase for one wheel needs to be adjusted by a factor equal to the number front wheels in the tracks divided by the total number of wheels. A vehicle combination which rolling resistance would be especially affected by loose snow is a truck without trailer, with a single rear axle and twin mounted tyres. For this vehicle combination 4 of the 6 tyres are at the front of a wheel tracks, which results in an increase of 0.67 times the increase for a single wheel. This can be compared to tractor-semitrailer combination with in total 5 axles with twin mounted tyres in addition to the steer axle, for which the increase is only 0.18 times the increase for a single wheel. To estimate the rolling resistance coefficient of a specific vehicle combination for certain snow conditions is naturally difficult. Hence, for the analyses in this paper, a total coefficient of 0.01 has been used for all vehicle combinations. However, it is plausible that the rolling resistance is higher than that for difficult snow conditions, and for which vehicles with a high share of front wheels are especially affected.

Vehicle combinations

The different vehicle combinations that were considered were taken from a report from the Swedish road administration concerning road dimensional guidelines (Vägverket, 1983). The typical vehicle weights and axle loads have been updated with data received from Volvo, and are presented in Table 1.For a tractor without bogie a weight of 7 ton was used, and 9 ton with bogie. For vehicles with two-axle bogie, the bogie can be divided into two types: those with a

trailing axle that that can be lifted to increase weight on the drive axle, and those of tandem type where both axles are driven. To reduce the number of combinations studied, tandem axles were only considered for the tractor-semitrailer combinations. Moreover, combinations where the trailing axle had been lifted were only considered for empty vehicles.

Table 1 – Vehicle combinations studied

Vehicle combination (weights are given in tons)	Drive axle load ratio
a) 34 7+11 8	60 ton combination: 26 ton truck + 34 ton trailer 11 ton drive axle + 7 ton trailing axle Drive axle load ratio = 0.18
b) 7 0+5 5	Empty a) with lifted trailing axle Drive axle load ratio = 0.29
c) 34 11 7	18 ton truck: Is allowed to pull 42 ton, 34 ton more realistic Drive axle load ratio = 0.21
d) 7 4.5 4.5	Empty c) Drive axle load ratio = 0.28
e)	Truck + semitrailer: Axle loads from rear to front: 4x2: 22/11/7 ton => 0.275 6x2: 24/7/11.5/7.5 => 0.23 6x4:24/9.5/9.5/7 => 0.38
f)	Empty e) : Axle loads from rear to front: 4x2: 5/4/5 ton => 0.285 6x2: 5/0/6/5 =>0.375 6x4: 5/2,5/2,5/5 =>0.33

Typical values for the distance between front and drive axle was taken as 5.6 meters for trucks, and 3.4 meters for tractors. The same distance was used both for vehicles with and without bogie. The height of the center of gravity for the truck or tractor was taken as 0.9 meters for an empty vehicle and 1.5 meters for a fully loaded vehicle. Vehicles carrying timber may have a higher positioned center of gravity for a fully loaded vehicle. Calculations using 2.0 meters instead of 1.5 resulted in essentially the same results. Hence, timber carrying vehicles were not considered as a special class, but are included in the combinations of Table 1.

3. Results

The traction tests were performed in March 2012, with the drive axle tyres listed in Table 2. Three different winter tyres and one summer tyre were used, all from large manufacturers. All the tyres were new and tyre D1 and D2 were from different manufacturers, and tyre D4 was a retreaded tyre with the same tread as tyre D1.

Table 2 – The tested tyres

Tyre	Type	Dimension	Tread depth
D1	Winter tyre	315/70R22.5	19 mm
D2	Summer/All season tyre	315/70R22.5	19 mm
D3	Winter tyre	315/70R22.5	21.5 mm
D4	Retreaded winter tyre of type D1	315/70R22.5	19.5 mm

The test track was packed snow and the conditions were windy, which resulted in a track where any loose snow effectively was transported off the track. The air temperature was between -2°C and -7°C, and the snow temperature between -3°C and -8°C. The snow hardness was measured with a special CTI meter. The hardness were in the interval 87-90 on the CTI scale, which represents very hard packed snow, but is within the limits of the ASTM F-1805 standard for snow traction test of tyres.

Nokian has performed identical tests with specimens of tyre D1 and D2 on the same track at an earlier occation on behalf of the magazine Teknikens Värld. The snow surface was softer during those measurements, between 85-87 on the CTI scale, with some lose snow on top and thus represents different conditions compared to our measurements. Hence, we have used the results from those tests for a comparison to see the influence of a softer snow surface.

Table 3 – Measured traction forces

Tyre	Max friction force	Average friction force (10–70 %)	Max friction coefficent	Average friction coefficent (10–70 %)
D1	23.1 kN	18.2 kN	0.44	0.35
D2	20.3 kN	14.9 kN	0.39	0.29
D3	22.5 kN	18.2 kN	0.43	0.35
D4	23.3 kN	18.5 kN	0.45	0.36

Table 4 – Data from tests published in Teknikens Värld (2011)

Tyre	Max friction force	Average friction force (10–70 %)	Max friction coefficent	Average friction coefficent (10–70 %)
D1 (other specimen)	23.6 kN	19.6 kN	0.45	0.38
D2 (other specimen)	14.0 kN	12.1 kN	0.27	0.23

The results from the traction tests are shown in Table 3. It is clear from the data that the friction level of the snow track was indeed high, and thus is not the best representation of a slippery roadway. Data from the tests performed for Teknikens Värld (2011) is shown in Table 4 for comparison. The different test conditions with softer snow and with some loose snow on top seem to affect the summer tyre more than the winter tyre.

From the data in Table 3, it is clear that the difference between the three winter tyres were minimal, so the analysis of maximum possible slopes for the different vehicle combinations were only carried out for tyre D1 and D2. Using Equation 18 and 19 together with vehicle data from Table 1 results in maxim slopes presented in Figure 5 and Table 5.
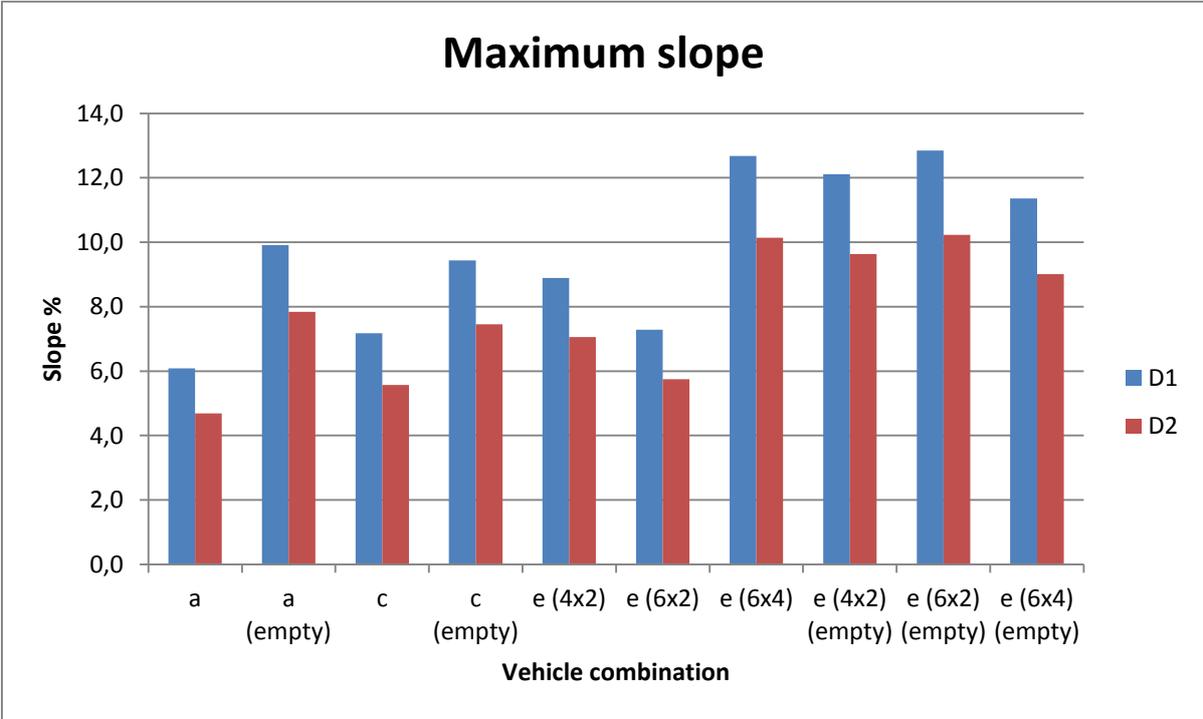

Figure 5 – Maximum possible slopes with road conditions according to the test track

**Table 5 – Maximum possible slopes (%) using data from Table 3**

	a	a (empty)	c	c (empty)	e (4x2)	e (6x2)	e (6x4)	f (4x2) (empty)	f (6x2) (empty)	f (6x4) (empty)
D1	6.1	9.9	7.2	9.4	8.9	7.3	12.7	12.1	12.8	11.4
D2	4.7	7.8	5.6	7.4	7.1	5.7	10.1	9.6	10.2	9.0

It is clear from the data that although the summer tyre has 20% lower grip compared to the winter tyre, this road condition is not slippery enough to pose any problems for either tyre. Using instead the values from Table 4 results in bigger differences between the tyres. Here the 60% extra grip for the winter tyre, for some vehicle combinations allows for slopes with the double inclination to be passed, compared to the summer tyre, as seen in Table 6. Still, even the slopes in Table 6 are relatively large, and it is clear that it would have been preferable to have tests results from more slippery conditions.

Table 6 – Maximum possible slopes (%) using data from Table 4

	a	a (empty)	c	c (empty)	e (4x2)	e (6x2)	e (6x4)	f (4x2) (empty)	f (6x2) (empty)	f (6x4) (empty)
D1	6.7	10.8	7.9	10.3	9.7	7.9	13.8	13.2	14.0	12.4
D2	3.3	5.7	3.9	5.4	5.1	4.1	7.5	7.0	7.5	6.6

Earlier measurements conducted in VTI's tyre test facility (Hjort et al., 2008) has shown that the available braking friction with a drive axle tyre on smooth ice at -4°C is within the interval 0.05 – 0.10. It is reasonable to assume that the traction friction is similar. We have calculated the critical friction level as a function of slope for the different vehicle combinations, see Figure 6. It is clear from the figure that for such low friction coefficient the fully loaded vehicles will have traction problems already on plane roads. Additional rolling resistance from snow or slush may have a large impact for very low friction levels, as an increase of the rolling resistance coefficient effectively will reduce the maximum possible slope by one percent unit.
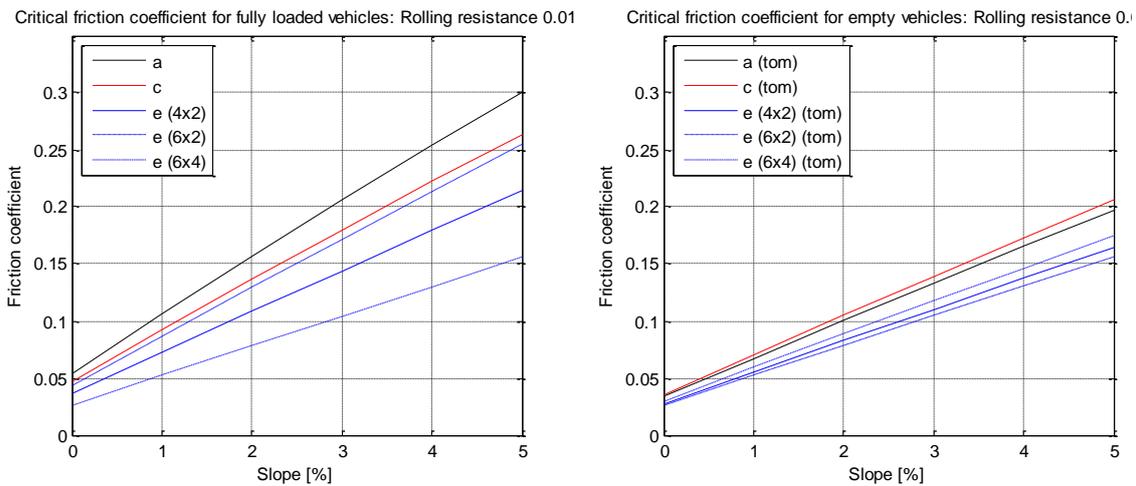
Figure 6 – Critical friction coefficient for different slopes

To summarize, the conducted traction tests on packed snow shows there can be relatively large differences in grip on snow between summer and winter tyres. This is in contrast with earlier brake tests performed on smooth ice for which no practical difference could be seen between the two types of tyres. The difference between the tyres seems to be strongly coupled to the nature of the snow surface, why it is impossible to give general values.

Theoretical calculations show that a vehicle's rolling resistance can have a major impact on a vehicles climbing ability. With a high rolling resistance, which may be the result of loose snow on the road, the difference between good and bad grip on the drive tyres becomes even more significant.

In order to draw further conclusions about the climbing ability for heavy vehicles in winter conditions depend on the use of winter or summer tires on the drive axle would require further tire tests to be carried out at the other surfaces, such as ice and soft snow.

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