MEASURING LONGITUDINAL TIRE FORCE PROPERTIES OF HEAVY COMMERCIAL VEHICLE TIRES ON SNOW WITH A TYRE TESTING TRAILER




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Abstract
In this paper, a process of measuring longitudinal tire forces in braking of Heavy Commercial Vehicle (HCV) tires with Tire Testing Trailer (TTT) is presented. Overall construction of TTT and measuring equipment with particular attention in the braking setup is shown. Typical process of running longitudinal tire force measurements in outdoor winter conditions is reviewed with an overview of the data processing. Longitudinal tire force measurement results on snow are presented for three tires (steer axle, drive axle and trailer axle) and compared to lateral force measurements on the same tires. Further development needs and studies are discussed.
Keywords: Tire measurements, tire testing trailer, winter road conditions, braking

1. Introduction

Road conditions have a significant impact on tire performance. The grip levels vary a lot in winter road conditions, and one might encounter dry asphalt, wet asphalt, slosh, snow and ice even on a single journey. Tire grip has a direct effect not only on road-holding ability of vehicles, but also enables moving and stopping of said vehicles. The effect of tire performance is emphasized with Heavy Commercial Vehicles (HCV) and Long Combination Vehicles (LCV) with many vehicle units and multiple axles.

For better understanding on how different HCV's and LCV's manage changing winter road conditions, it is important to study the tire-road interaction. Both the tire and the road surface are rather complex systems, so quantifying either in a controlled and repeatable fashion is not an easy task. Tire parameters have significant effect on the tire performance and outdoor road surfaces change all the time. To get a comprehensive overview on how different tires work on different road surfaces, outdoor testing rig can be used to measure tire performance as a reasonable compromise. It can be used to measure tire performance in a relatively controlled and repeatable way in a short amount of time, reducing the effect of road surface and weather variation which is inevitable outdoors.

In this study, University of Oulu's Tire Testing Trailer (TTT) was utilized. It is an outdoor testing rig, that has been successfully used for lateral tire force measurements on snow (Tuutijärvi et al., 2023). TTT has also been used for measuring cornering properties of few different tires on snow and lateral force measurements made with it have been validated against VTI's Tyre Testing Facility (TTF) (Tuutijärvi et al., 2024, Nordström, 1993).

The aim of this paper is to introduce TTT's braking system and the methodology of running the longitudinal tire force measurements and post processing the results. After that, the first longitudinal tire force measurements on snow are performed for three different HCV tires. Performance of these three tires is compared and the longitudinal tire force measurements are compared to lateral force measurements performed with the same tires.

2. Methodology

The tire measurements presented in this study were performed in February of 2024. The tested tire set included typical winter tires used in ADR tanker vehicle combinations in Finland. Tyre set included a single mounted steer axle tire (S), dual mounted drive axle tire (D) and single mounted trailer tire (ST). This categorization and nomenclature loosely follow the one presented by Hjort et al (2021). HCV winter tires have tread pattern that is designed to grip snowy and icy surfaces, and the tread compound is formulated for low temperature operation. Describing tread patterns of this set, S tire had four longitudinal grooves with small block pattern on the ridges between the grooves and continuous shoulders with partial siping. D tire had full large block pattern on the tread with deep siping going across the blocks. ST tire had quite similar tread pattern compared to S tire, but the block pattern on the ridges was larger and shallower, and the siping on the shoulders was shallower and less pronounced. Tested tires were not studded. All the tires were new, and they were scrubbed with the trailer prior to running measurements. The tire set used in this study is summarized in Table 1.

Table 1 - Tested tire set.

Code	Dimension	Rim Size	Axle	Tyre type	Load index [kg]
S	315/70	22,5”	Steer	Winter	4000
D	315/70	22,5”	Drive	Winter	3325
ST	385/55	22,5”	Trailer	Winter	4500

Tests were run on airfield with groomed hard packed snow surface, similar to a typical road in northern Finland. Comparing to tracks prepared according to snow grip approval testing of ECE regulation 117, that requires snow hardness to be between 80 and 90 on CTI scale, this surface was around 88 on CTI scale. CTI scale describes the compaction and shear strength of snow, and it is measured by using a CTI penetrometer, that uses a specified projectile dropped from specified height to penetrate the driving surface. The penetration distance is converted directly to CTI compaction numbers with the penetrometer. In the CTI scale, compaction range from 84 to 93 is equivalent to extra hard or hard pack snow according to SAE J1466. Tire loads used in the measurements were based on the common axle loads that were estimated to be 40 kN for S, 25 kN for D and 45 kN for ST. These values are taken as the nominal tire loads for given category and should not be confused with rated loads of the tire. In addition to nominal load, the tires were tested at two other loads. Test conditions are summarized in Table 2.

Table 2 - Test conditions for the tire set.

Code	Wheel load [kN]	Wheel load [% nominal load]	Speed [km/h]	Snow hardness [CTI]	Air temp [°C]	Tire pressure [bar]
S	20,30,40	50,75,100	10	88	-24...-18	9
D	18,75;25;33,25	75,100,133				8
ST	22,5;33,75;45	50,75,100				9

Presented in Figure 1 is the TTT. It is a four-axle drawbar trailer which has special 3-part rig for the tire testing. Middle part of the trailer frame is raised up to house the measurement rig. Rig can be turned around its vertical axle hydraulically ±37°. Middle part of the rig is hinged from its lower end allowing adjustment of camber-angle via threaded rods by hand. Lowest part of the rig can be adjusted hydraulically in vertical direction allowing maximum of 60 kN vertical force on the tested tyre. Axle housing is suspended to the vertically moving part of the rig via 10 suspension rods. Tire forces affecting the suspension rod are measured with strain gages installed in these rods. Passenger car and van tire testing can be done by changing the axle housing on the suspension rods to a smaller axle configuration. Hydraulic system is powered by 10.5 kW internal combustion engine. Hydraulic movements are controlled with electrically controlled proportional valves. Data logging and controlling of the measurement system is done with a PLC-system. I/O units are located in the trailer and control program is executed in a laptop in truck cabin. The trailer has steel plates as ballast and the total mass of the trailer is 34,5 tons.

Figure 1 – University of Oulu's Tire Testing Trailer (TTT).

Brake for the heavy tire testing trailer is constructed at opposite end of the axle from test tire attachment. The brake is a fluid disc brake for heavy machinery. It has two brake calipers with total of eight brake pistons. Brake pressure is generated with a hydraulic cylinder which

uses two brake master cylinders. Brake pressure is measured from brake fluid hose. Brake disc is toothed for the rotation speed measurement of the measured tire. Reference speed of the trailer is measured with Peiseler 5th wheel, that is mounted behind the trailer when performing measurements. Challenges encountered with the brake in HCV tire testing have been related to controllability of the speed of the braking action and acquiring enough pressure to brake the tyre in high friction conditions with heavy vertical loads. A planned solution for these is to install larger master cylinders.
For longitudinal tire force measurements in braking, the TTT measuring system is used in semi-automatic control mode, in which the brake pressure of the system is cycled from zero to desired pressure for requested number of cycles. The slope for brake pressure increase is set to as low as possible with the current braking system setup in low friction conditions. Aim is to halt the tire slow enough to measure the peak of the braking force, with too fast brake actuation the tire slides almost instantly. Another goal is to get as many brake cycles done in one test run as possible, which is done to eliminate some of the variance caused by the uneven and rough snow road surface. This usually limits the driving speed in typical closed area testing and, in these measurements, the driving speed on snow was 10 km/h. Typical measurement run steps, and the measurement data including normal, longitudinal and lateral forces are shown in Figure 2.

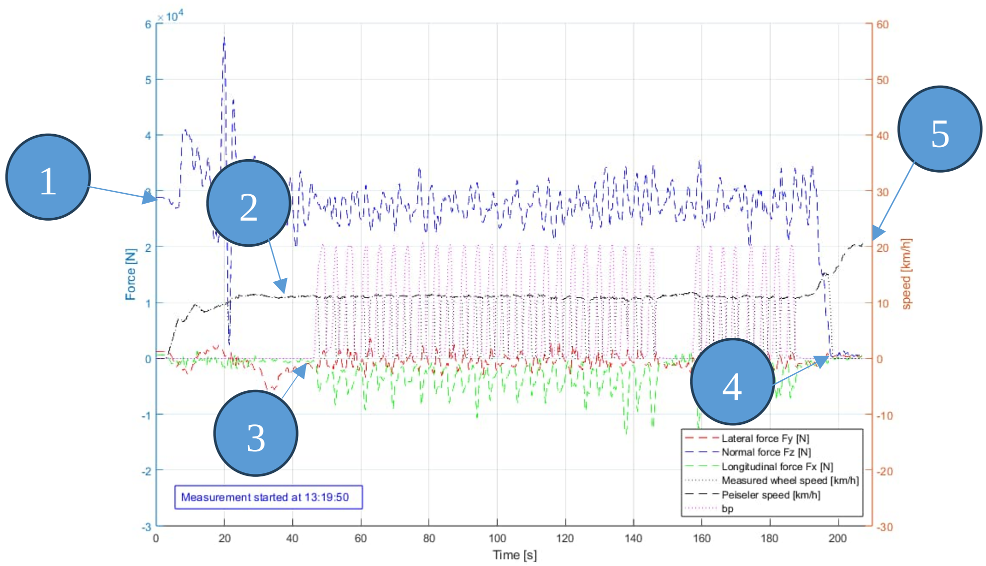

Figure 2 – Measurement data from full measurement run and its steps.

Presented in Figure 2, leading to step No.1 the normal load of the tire F_Z is set manually via the control system while the testing trailer is stationary. After setting the load, the data recording is started in Step No. 1, and the trailer is accelerated to desired constant speed in step No. 2. After reaching steady-state speed the braking sequence is started in step No. 3. Speed is kept as desired for the duration of braking sequence and at the end of it, the tire is lifted off the ground in step No. 4. Measurement data is stored in step No. 5. and the trailer is ready for another test run.
For pure longitudinal tire force measurements in braking, the longitudinal force and normalized longitudinal force (longitudinal force divided by normal force) curves as a function of tire slip are usually of interest. Overview of post-processing measurement data from a single test run is presented here.

As a first step of post-processing, the measurement data is low pass filtered. The slip ratio of the measured tire is determined from difference between Peiseler 5th wheel speed and measured wheel speed. Since the tire size affects the measured wheel speed, tire size calibration is made automatically based on the free rolling wheel speeds of the Peiseler 5th wheel and the measured tire before starting the braking sequence. Slip ratio of 0 means that the measured tire is free rolling and a slip ratio of -1 means, that the measured tire is locked-up. To separate the braking sequences from the full data of the test run, brake pressure peaks and minimums of individual brake cycles are identified and first and last minimums mark the start and end of the braking sequence. The separated braking sequence from the full measurement run, containing multiple brake cycles is shown in top left corner of Figure 3. From the braking sequence, the individual brake cycles are separated based on the brake pressure peaks and minimums. If necessary, time delay can be applied to ensure that the full braking cycle is included. From the full brake cycle, brake application or brake pressure increasement side is taken into account and after that the brake cycles are checked against minimum slip requirement, which can be set to desired level. In this paper, only braking cycles with slip of 100 % (locked tire) were taken into consideration. If needed, each cycle can be reviewed individually and removed from further processing if necessary. Example of measured data from a single brake cycle is presented in bottom right corner of Figure 3.

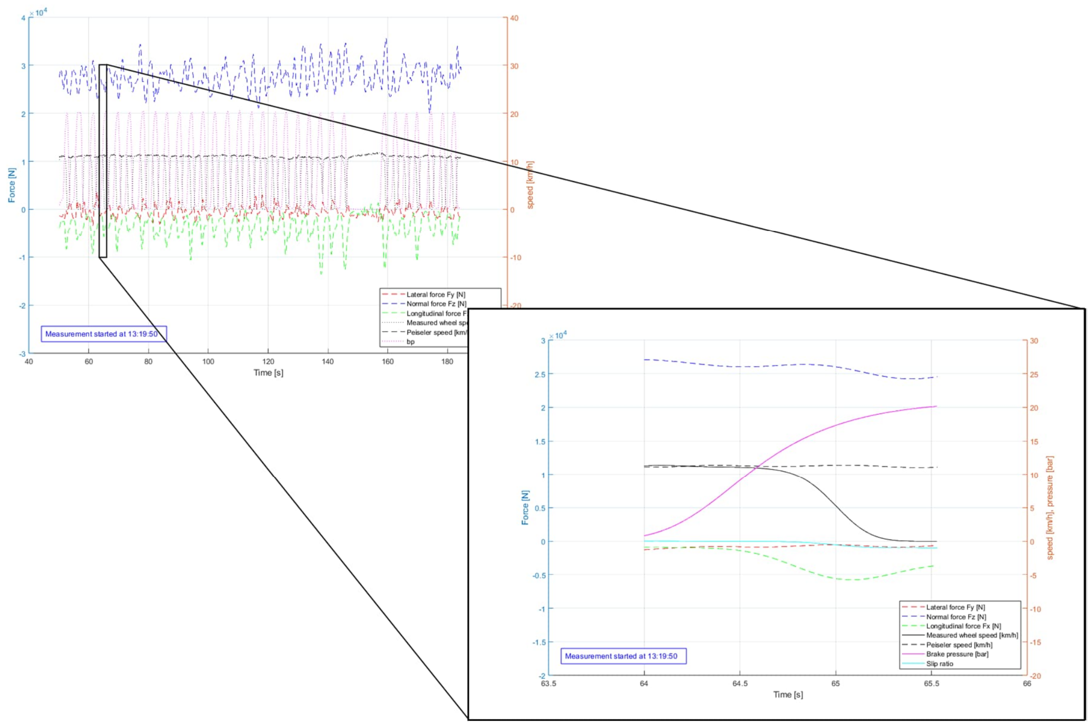

Figure 3 – Braking sequence and a single brake cycle from the measurement run.

The single brake cycle presented in Figure 3 is the 4th braking cycle of the braking sequence from the full measurement run. It has started approximately 64 seconds after starting the data recording for the measurement run. Reviewing the graph of the single brake cycle, brake pressure increases from approximately 0.5 bar to 20 bar in duration of 1.5 seconds, resulting in deceleration of the measured tire and eventually to a lock-up in which the slip ratio goes from 0 to -1.

After reviewing and selecting the cycles to be used for constructing the longitudinal force slip curve, the individual brake cycles are averaged by slip ratio and combined into a single longitudinal force curve. Resulting longitudinal force curves are presented as a function of slip percentage in Figure 4. The slip percentage is derived from the slip ratio, and it is flipped from slip ratio, so 0 % slip means that the tire is free rolling and tire lock-up occurs at 100 %.

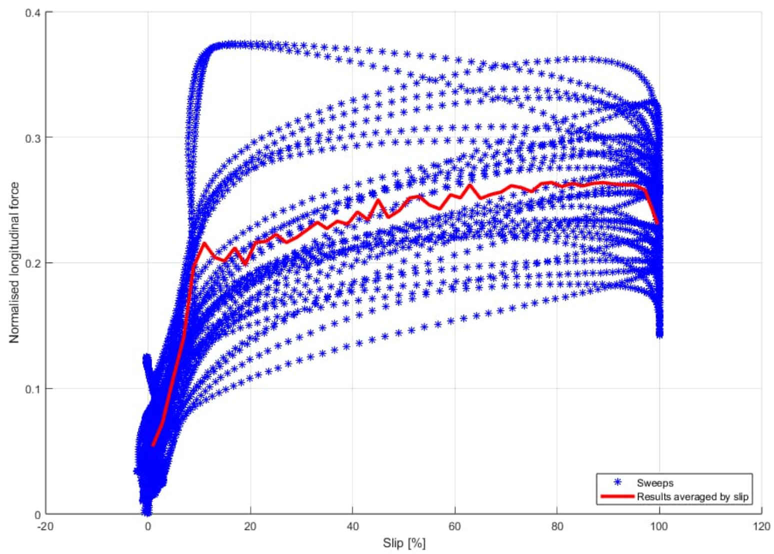

Figure 4 – Braking cycles from a test run averaged by slip.

Measuring pure lateral force and cornering properties of a tire is executed in similar fashion to the longitudinal force measurements. Multiple sweeps are made to eliminate some of the variance caused by uneven, heterogenous and rough snow surface. These sweeps are combined to single lateral force curve for used vertical load, the process is explained in detail in an earlier study (Tuutijärvi et al., 2023).

3. Results

In Figure 5, the normalized longitudinal force and longitudinal force curves on hard packed snow for each tire with three different loads are shown as a function of slip percentage, which is derived from slip ratio presented in chapter 2. Slip percentage of 0 means that the tire is free rolling and 100 % means that the tire is locked up. It is worth noting, that the slip curves have quite different shapes for different tires, especially when comparing S tire to D and ST tires. S tire has peak longitudinal force on small slip ratios, while the D and ST tire have peak longitudinal force on larger slip ratios. This can be possibly caused by higher contact pressure of the S tire due to its width and high wheel loads, helping it to compact and dig into the snow in the small slip ratios. In higher slip ratios the high contact pressure of the S tire might have started to melt and polish the hard packed snow, resulting in decreasing longitudinal force with increasing slip. D tire has the same width as the S tire, but lower wheel loads resulting in lower contact pressure than S tire. D tire also has more aggressive tread pattern which helps it to grip more on the snow with increasing slip, but with low slip it might cause it to break the snow surface instead of uniformly compacting it in similar fashion to the S tire. ST tire has the highest wheel loads, but it was also wider than S and D tire, resulting in lower contact pressure than S tire and it had the least pronounced tread pattern. ST tire had the lowest peak normalized longitudinal force of the tested tires and its longitudinal force generation as a function of slip was a bit of a mix between S and D tire. All the tested tires and loads were braked with same brake pressure increase rate and it is possible, that the peak longitudinal tire force was missed on some of the brake cycles due to fast lock-up. S tires behavior in the low slip range might have helped it to get a more consistent peak longitudinal tire force when compared to D and ST tire, resulting in the quite different looking slip curves.

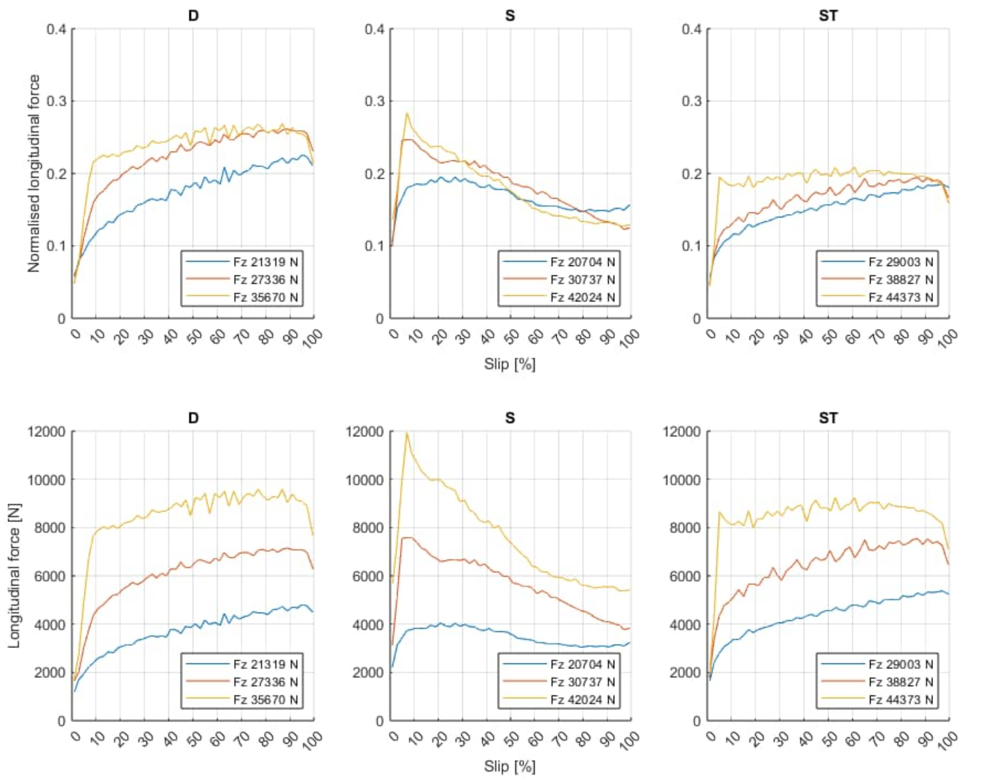

Figure 5 – Longitudinal force curves as a function of slip % on snow.

For all the tires, the peak normalized longitudinal force is increasing with the load, as highlighted in Figure 6 for peak, 10 % of slip and 50 % of slip normalized longitudinal forces. Typically, in hard driving surfaces without loose medium, the peak of normalized longitudinal force is decreasing with increasing load. But in this case with hard packed snow, this is probably partially due to factors in interaction between the snow and the tire tread. Other significant reason is that with higher wheel loads the tire lock up has been less abrupt because of the higher braking moment required. As it was seen also in Figure 6, S tire is working well on low slip ratios, but at around 50 % of slip, the differences between the tires are small and on higher slip ratios S tire is losing performance against D and ST tire.

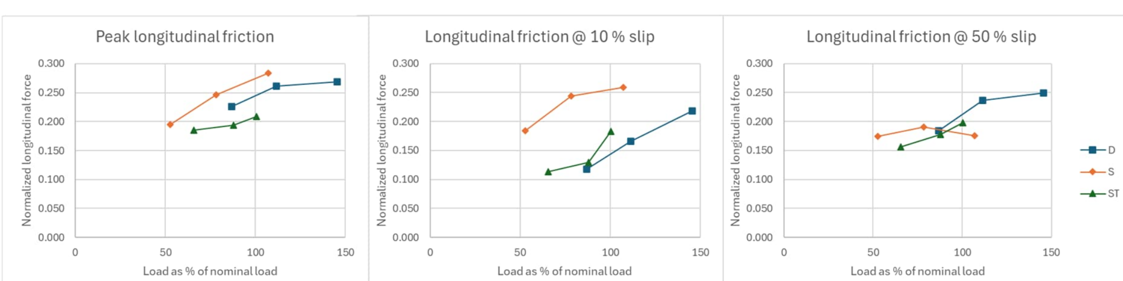

Figure 6 – Comparison of tire longitudinal forces.

In Figure 7, normalized longitudinal and lateral force curves on hard packed snow for the three loads of the measured tires are shown as a function of slip or slip angle respectively. The peaks for normalized lateral force curves are almost twice of the normalized longitudinal force curves. As discussed earlier, it is probable, that the braking rate of the measured tires has been too fast, and the actual peak friction level has not been achieved. Greater stiffness of the tire on longitudinal direction than on lateral direction can cause difference in the curve shape as well, but usually peak longitudinal and lateral forces should be roughly the same. This can also explain, at least partially, the opposite load dependency between the longitudinal and lateral force peaks.

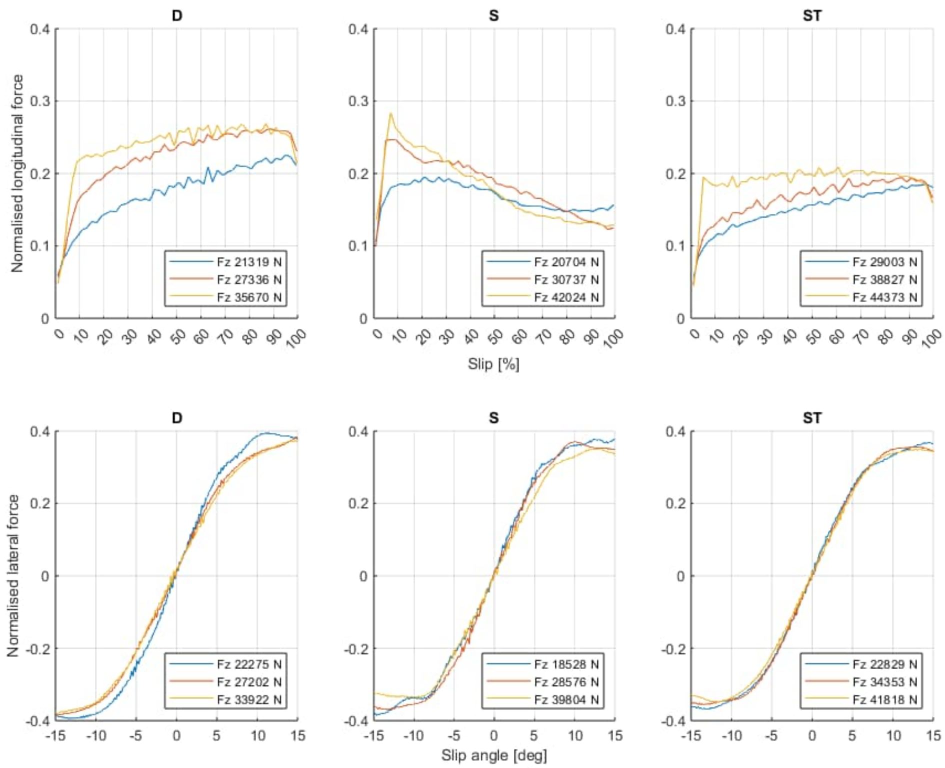

Figure 7 – Comparison of braking and steering on hard packed snow

4. Discussion

In this study, the first pure longitudinal tire force measurements on braking for HCV tires were performed with the TTT. Measurements were made on hard packed snow together with lateral force measurements, which we have more experience with. Results presented in this paper give information about how the TTT is suited for longitudinal tire force measurements in braking and new insight on how HCV tires perform on snow. Both are important steps for more in-depth investigations on the subject and for development of tire models for various driving conditions, which can be used for different vehicle assessment simulations and estimation of braking distances etc.

For the longitudinal tire force measurements, TTT had couple of shortcomings in its current form. Main problem was that the adjustability of the current brake cylinder setup was not enough for low friction conditions. This limited the brake pressure increase rate too high which led to abrupt locking of the tire especially with lower wheel loads. Braking tests were tried on high friction surfaces as well, but in those the maximum brake pressure that the system could achieve was too low, especially on higher wheel loads. Second problem was that the instrumentation used for measuring the wheel speed of the measured tire was not ideal for this usage, resulting in low resolution which caused inaccuracies when determining longitudinal wheel slip. Otherwise TTT was working well for the measurements and one of the redeeming qualities were the ability to do multiple braking sequences in very short time. This way it is possible to get a lot of repetitions in short distance, which is an advantage when doing tire force measurements on rough outdoor conditions. This results in a good overview on the performance of the tire and mitigates some of the variance caused by the heterogeneous and rough (snow) surface.

Tested tires performed quite differently on the braking tests. It should be kept in mind, that the fast lock-up of the measured tire caused variation on the results by missing the peak longitudinal force on a brake cycle, but the brake pressure increase rate was the same for all the tires. S tire had quite pronounced peak longitudinal force on low slip and the longitudinal force went down significantly as the slip increased. On the opposite, D and ST tires had peak longitudinal force on high slip with no pronounced peak on the low slip zone. S and D tires were narrower than ST tire, which in combination with high wheel loads of S tire led to higher contact pressure, which might have helped the tire to dig into snow on slow slip zone, resulting in higher longitudinal force. With higher slip the higher contact pressure might have caused the tire to start polishing the hard packed snow, resulting in decreasing longitudinal force. D tire was run on lower wheel loads than the other tires, and it had more aggressive tread pattern with deep siping. This tread pattern in combination with lower contact pressure might have helped the tire to grip more on to the snow with increasing slip, resulting in low longitudinal force on low slip, which increased with increasing longitudinal slip. This was even more pronounced with low wheel loads. ST tire was run on the highest wheel loads, but it was also the widest tire resulting in less contact pressure than S tire and ST tire performed in similar fashion than D tire, although resulting generally in lower normalized longitudinal force. The differences on the performances of the tested tires might have interesting effect on how they work with Anti-lock Braking System (ABS) HCV's.

Pure longitudinal tire force measurements were compared to pure lateral measurements on the same tires and same driving surface as well. Lateral force measurements yielded higher peak normalized forces than longitudinal force measurements. The difference can probably be explained at least partially by the abrupt locking of the measured tire in the braking tests. Usually, the peak longitudinal and lateral forces are expected to be roughly the same. The load dependency was opposite when comparing the longitudinal and lateral force measurements. With lateral force measurements, peak normalized force was going down with wheel load, which is usually the case at least on hard driving surfaces. In the longitudinal measurements, higher wheel load generally resulted in higher normalized longitudinal force. Higher wheel loads result in higher tire forces requiring more braking torque, which with the same brake pressure increase rate resulted in slower locking up of the tire, increasing the normalized longitudinal force with the wheel load.

This study has been a starting point for investigations on the braking performance of HCV's and HCV tires in different winter and summer road conditions. Braking setup of the TTT will be updated with new master cylinder for adjustability and better suited setup for measuring the wheel speed of measured tire. Further studies will be made on the E! SafeTrucks project in the 2024-2025 winter season. One of the objectives in the project is to evaluate how the braking performance of the tire compares to the actual braking performance of individual HCV's and LCVs on different low and high friction road conditions. This information will be used to improve braking distance estimation for said vehicles.

5. Conclusions

The aim of this paper was to introduce TTT's braking system and use it to measure longitudinal tire forces of HCV tires in braking on snow. This was done by presenting the overall construction of TTT and its measuring equipment with focus on the braking system setup and going through the process of performing longitudinal tire force measurements with TTT and post processing the results. The braking performance of three different HCV tires were measured on snow and the results were compared to lateral force measurements done with TTT on the same day.

Braking system of the TTT performed on satisfactory level, keeping in mind that this was the first running of said system. Measurements were completed and they showed interestingly different characteristics regarding the longitudinal tire force generation as a function of slip for the different tires. The biggest problems with the braking system were that the brake pressure increase rate could not be set low enough with the master cylinders in use at the tests and that the resolution for measuring the measured tires wheel speed was too low. This left some doubt about reaching the peak longitudinal tire force in braking with low slip ratios due to locking up the tire in too fast manner. Lateral force tests showed higher normalized peak forces, and they can be expected to be roughly the same for longitudinal forces as well in the same surface. In addition, with low resolution of measuring the wheel speed of measured tire, specifying the braking stiffness characteristics of the tires was not feasible.

For next steps with TTT, the braking system has been overhauled with new master cylinders providing more adjustment range for brake pressure increase rate and with the new master cylinder higher brake pressures can be reached for high friction surface measurements. Measurement system for measuring the wheel speed of the measured tire has been updated as well, and determining slip ratio during the braking is more accurate with higher wheel speed resolution. TTT and its updated braking system is currently being used for new snow measurements during the winter season of 2024–2025 in the E! SafeTrucks project.

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