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Heavy vehicle tyre testing in natural environments

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Summary This study presents developing of a tyre testing trailer for heavy commercial vehicle tyres at the University of Oulu together with introducing the design of the trailer with different design aspects of the trailer systems. Processes regarding running of the tyre measurements with the trailer as well as the data preparation are performed. The first measurement results are conducted on both snow and wet asphalt conditions. Furthermore, current state and further development plans for the measurement trailer are discussed.

Key words: tyre testing, tyre friction, snow, wet asphalt, heavy vehicles

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Introduction

Driving conditions vary significantly, especially in northern countries. Drivers can encounter everything between dry asphalt, slosh, and polished ice even on the same day or driving journey. Driving conditions have a significant effect on the traffic flow and it can affect the mobility and road-holding ability of heavy commercial vehicles significantly [4][7]. Regarding the mobility and road-holding ability of a heavy commercial vehicle, tyres are one of the most important components [1]. They need to perform efficiently to ensure traffic flow and to support the driver's ability operating the vehicle.

Tyre research to date have mainly focused on comparing the performance between different tyres intended for a vehicle in very specific and carefully prepared driving surfaces in testing facilities or laboratories (e.g., indoor drum or rolling roads with steel surfaces) [5]. This is justified in the tyre development procedure, since it is proven that the tyres are complicated and non-linear entities, thus the other variables must be eliminated for less complexity. Since indoor testing procedures are available and they

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generate reliable measurements, they are also used for studies concerning technical requirements for road traffic acts, for example.

However, it is worth to say that differences between tyres on the same surface are small in comparison with the performance of a tyre on different road conditions [2][3]. Regarding decision making about requirements for winter tyres, as an example, this may lead to some unwanted consequences, if the requirements are based on studies made on driving surfaces that do not represent the actual road conditions the tyres are intended for. The actual road conditions are of interest for the studies, but they are impossible to artificially recreate for indoor testing.

In order to present a comprehensive understanding on how various driving conditions and road surfaces affect the tyre performance, new measurements are required on the actual outdoor conditions. Full scale vehicle testing can be employed for comparative tests between tyres, yet in order to fit semi-empirical tyre models [8] or for validation of more advanced tyre models, refined measurements are required. Suitable outdoor tyre testing equipment and trailers for winter conditions exist for passenger cars [6], but none for heavy commercial vehicles in Nordic countries.

In this study, the development of a heavy vehicle tyre testing trailer for all-year outdoor use is presented. The design aspects of the trailer and measuring system are presented with the testing methodology in the Materials and Methods section. This is followed by Results and Discussion, in which wet asphalt and snow measurement results for a tested tyre from 2020 and 2021 are presented and discussed. The snow measurements were the first in the world for heavy commercial vehicle tyres. In the Conclusions, the current state and further development plans for the tyre testing trailer are discussed.

Materials and Methods

Objective was to develop a tyre force measurement system that can complement laboratory measurements. System should be suitable for most heavy commercial vehicle tyre sizes, it should be possible to use in normally operated roads, be fast enough for multiple measurements in dynamic weather conditions and be robust enough to reduce measurement uncertainties to produce repeatable measurements even on high friction and static roads, such as dry asphalt.

Based on the criteria, the measurement system was built on a 4-axle drawbar trailer. The frame was cut off at the centre and lifted 1.2 m and the measurement system was built then under the trailer frame. The schematic view (side and underside) of the measurement trailer is presented in Figure 1. The measured tyre wheel is annotated with red color and the forward direction of travel is to the right of the Figure.

The main driving theme of the design of the measurement trailer was rigidity: a high rigidity is needed for accurate dynamic measurements. The raised frame sections were braced to the trailer frames from both sides with angled frame sections. Also, the raised frame sections were tied together with a thick plate underneath and a cover plate is used on top. of them This results in a very rigid construction. Since weight was not an issue, it was decided to make the structural pieces more robust and then not need so much ballast weight.

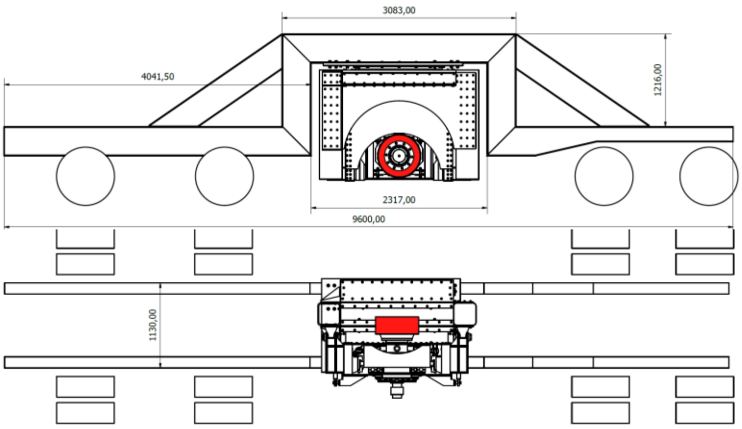

Figure 1. Schematic view of the trailer. The measured tyre wheel is annotated with red color.

Most of the measurement systems pieces were bolted together. This way, welding could be avoided, since the pieces were so large that they could not be normalized after welding. This also made manufacturing a bit faster since there was no need to make jigs or fixtures to hold everything when welding. Bolted connections do require some maintenance to ensure that the bolts stay tight. The measurement system is comprised of several larger components, that are shown in Figure 2:

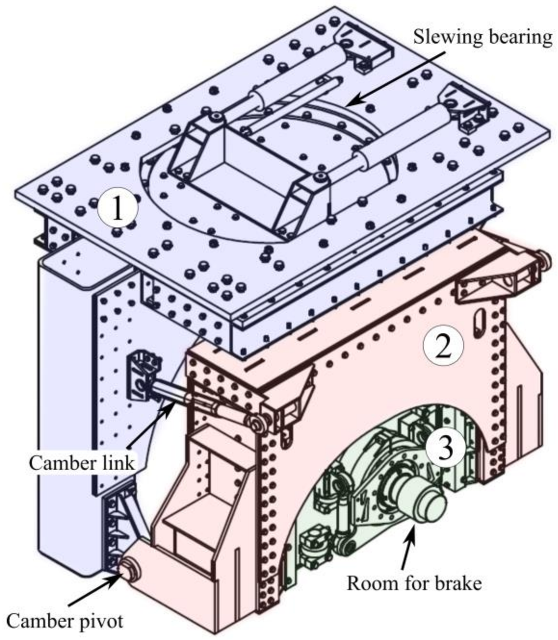

Figure 2. The main components of the measurement system.

The highlighted main components presented in Figure 2 are: (1) slip frame, turns around a slewing bearing and hangs from the raised frame sections, (2) camber frame, is attached to the slip frame and allows for camber adjustment and (3) wheel mount is attached in vertical rails inside the camber frame that allows for lifting and lowering.

Slip frame is the component that is attached to the underside of the raised frame section with a slewing bearing. This allows for steering angle adjustment. Camber frame is then attached to the slip frame with slide bearings (pivot point) and adjustable camber links, allowing for camber angle adjustment. Wheel mount is attached to the camber frame with sliding rails, that then allows for setting the normal force of the tyre by lifting and lowering the wheel mount. The measured wheel is attached to an axle that is attached to wheel mount.

Measurement trailer hydraulics

The turning and lowering of the measurement system, and braking in the future, is done with hydraulics. A 10.5 kW internal combustion engine is used to power the hydraulic system. Internal combustion engine power was chosen for high power output and the ability for long continuous usage of the hydraulics. High power is mainly required for fast turning of the measurement system. The hydraulics are controlled with electrically controlled proportional valves. The valve modules are adjusted for load and simultaneous movements, allowing, e.g., for actuation of the brake and turning at the same time, without them affecting each other.

Measurement system turning – Steering angle adjustment

The measurement system turns on a large slewing bearing, with an outer diameter of 1198 mm. The measurement system is located under the raised frame section so that, the measured tyre and wheel are at the center of slewing bearing and that the center of the slewing bearing is at the center in the transverse direction. So, when the steering angle of the measured tyre is changed, the tyre turns around the center of its area of contact.

The steering angle or the turning of the measurement system is done with two hydraulic cylinders. These are controlled with proportional valves, allowing precise control. With the internal combustion engine powering the hydraulic system, the calculated maximum achievable turning speed is slightly over 10 degrees per second. The maximum steering angle is 37 degrees in both directions.

Measurement system lifting and lowering – Normal force adjustment

The lowering and raising of the measurement system, i.e., setting the normal force for the measured tyre, is also done with two hydraulic cylinders. The wheel mount rides on two vertical sliding rails with nylon bearing materials. The rails have adjustments to account for the wear of the nylon bearing materials. There is some stiction with the rails and this is slightly aggravated by the lifting cylinders not being vertically aligned with the rails. The maximum normal force for the measured tyre is 60 kN.

Measurement system tilt – Camber adjustment

Camber angle is adjusted by adjusting the length of the Camber links that hold the Camber frame to the Slip frame. The links can be changed for hydraulic cylinders or other actuators, that would then allow quick camber adjustment and even during measuring. This was not seen as an important feature, so it has been omitted for now.

Measurement and control system

For controlling and measuring purposes a Beckhoff PLC system was installed. Input/Output modules are in the trailer. I/O-rack in trailer is connected to the towing vehicle by Ethernet-cable. Data logging and controlling the measurement system is done with a laptop in the cabin of the towing vehicle.

Measurements in tyre testing system

At current configuration wheel forces, wheel turning angle and turning angle of front bogie are measured with PLC system. There is already I/O-modules installed for measuring two different wheel speeds and brake pressure.

For measuring the wheel forces and moments bearing housing is mounted with 10 bars all of which has force measurement. Force measurement is implemented with strain gauges on suspension bars. Biaxial 120 Ω and 350 Ω gauges were used. A full Wheatstone bridge circuit was utilized in all bars. In straight bars gauges were connected so that temperature effects and bending in one direction is compensated. In A-form bars temperature effects and bending in two directions is compensated. Bending compensation in this situation was achieved connecting two gauges in series in each arm of the Wheatstone bridge. Force measurements in bars were calibrated in university's load test rig against industrial force sensor. Usually before testing, normal force measurement is tested against scale.

Turn angle of the test wheel is measured with linear position sensor on the turning cylinder. Turn angle of the front bogie of the trailer is measured with a contactless absolute rotary encoder. The magnet of the sensor is mounted in frame of the bogie and the sensor element on the main frame of the trailer. There is also an ultrasonic sensor measuring vertical distance of the bearing housing from the ground, but it is only used for manual controlling purposes.

Normally the measurement trailer is drawn by Sisu truck of University of Oulu. Truck has also a measurement system installed in it. With these separate system trailer's drawbar forces and rear part's angular rates and accelerations are measured. Similar values are measured from truck's side. In addition, basic data from truck's electrical system is recorded such as driving speed, engine speed etc.

Control of the measurement system with PLC

Measurement cycle is controlled with PLC system. Control and measurement program runs on a laptop in the towing truck. Control/measurement program calculates test wheel turning angle with information from linear position transducer and mechanical dimensions of the turning mechanism. Wheel forces on test wheel are calculated using the 10 measured suspension bar forces and the dimensions of the suspension geometry.

Each hydraulic valve is controlled with 2-channel pulse width current terminals. During the test PLC turns the testing rig with constant opening value of the turning hydraulic valve. One cycle is counted when turning system reaches the maximum in clockwise direction. After this end point turning continues near the zero steering angle if set number of the cycles is reached.

Using the testing trailer with current configuration

After long out-of-service period calibration values of suspension bar force measurements are inputted to the system and sensors are zeroed. This is followed by validation against force transducers for lateral and normal force of the tyre. Measurement mechanics can be controlled manually, which is used for example in constant steering angle tests.

With pure lateral slip tests, the measurement system can be used in semi-automatic control mode, where steering angle is swept from side to side to a selected steering angle for requested number of steering cycles. In snow and other loose surfaces, objective is to get as many steering cycles done as possible in order to eliminate some of the variance caused by the heterogenous nature of snow. The length of the testing field limits the number of steering cycles in conjunction with the used speed and steering angle. For snow measurements, typical driving speed has been 10 km/h. Typical measurement run steps and measurement data on snow surface including lateral force F_Y, normal force F_Z and steering angle as a function of time are shown in Figure 3.

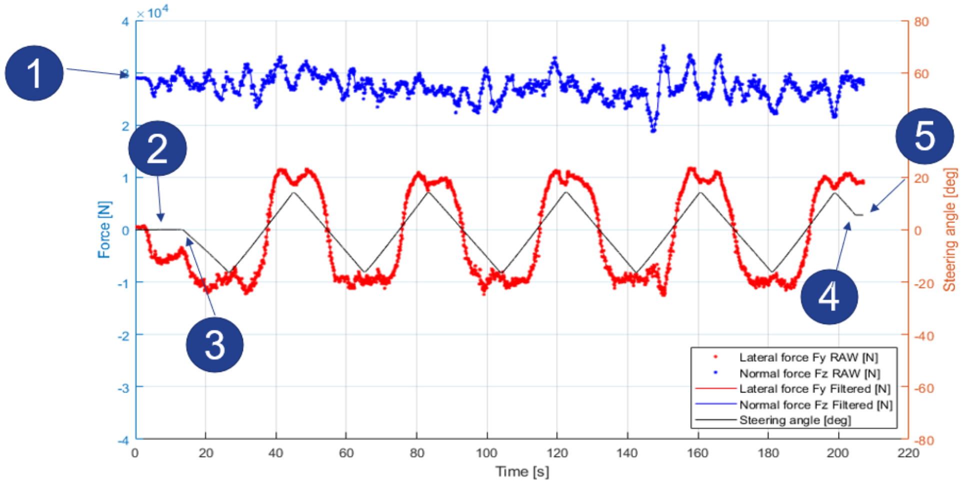

Figure 3. Steps of typical one-way measurement run.

Presented in Figure 3, in step No. 1 the normal load F_Z is set manually while measurement trailer is in a standstill. After the normal load has been achieved, the trailer is accelerated to desired speed in step No. 2. Once desired steady-state speed has been achieved, the test sequence is started in step No. 3. After tests sequence is started, the trailer is kept in desired speed and the control system automatically does the steering cycles as set before starting the test. Once the test sequence is finished in step No. 4, the trailer is stopped. In step No. 5, the measurements are stopped, and data saved, after which the test wheel is lifted manually and returned to the starting position, ready for next measurement run.

Post-processing measurement data

For pure lateral slip measurements with current measurement system configuration, the normalized lateral force curves (lateral force divided by the normal force) as a function of steering angle are usually of interest. As a demonstration, post-processing data from a single test run is looked over. Post-processing of the measurement data starts with low pass filtering of the measured force data from figure 3 and snipping the data from the first steering angle minimum to the last minimum, which in this case leads to 4 full sweeps presented in Figure 4. Full sweeps are used for relaxation compensation in later step.

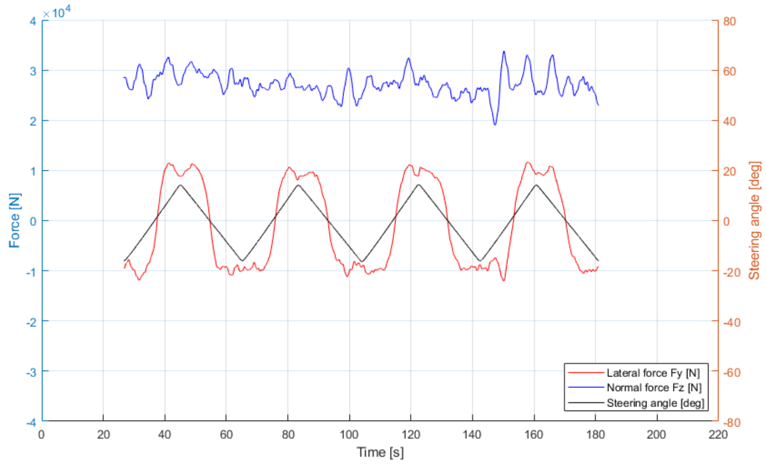

Figure 4. Filtered lateral and normal forces with steering angle in time domain for the 4 full sweeps of the test run.

After snipping the measurement data for the available full sweeps, the measurement data is separated to individual sweeps based on the steering angle. From the individual sweeps, lateral force is normalized by dividing it with the normal force in time domain. This is done so, that the changes in normalized lateral force due to changes in normal force are mostly eliminated when compared to using average normal force of a sweep. Due to roughness and heterogenous nature of especially snow surface, there is always variation in normal force of the tyre.

With measurement data separated to individual sweeps, it is also easier to detect and remove sweeps with large deviations on the lateral force, indicating a problem during the sweep. One possible cause for large deviations in measurement data can be holes and tears on the track surface. After separating the individual sweeps and normalizing the lateral force, the individual normalized lateral force curves of individual sweeps are presented in Figure 5 as a function of steering angle. For later steps and cornering stiffness estimations, the average normal force of a sweep is also stored.

Once the individual sweeps of the test run in Figure 5 are reviewed and the possibly erroneous sweeps are taken out, the measurement data is used to form the lateral force curve for the tyre after relaxation compensation. In this case, no erroneous sweeps were found, and all the 4 individual sweeps could be used for relaxation compensation. Relaxation compensation is done by averaging all the normalized lateral force curves from the individual sweeps by the steering angle with 0.1-degree steps and resulting force curve is presented in Figure 6. After relaxation compensation the force curve can be used for cornering stiffness estimation by checking the slope of the curve in linear region, which is close to the zero-steering angle.

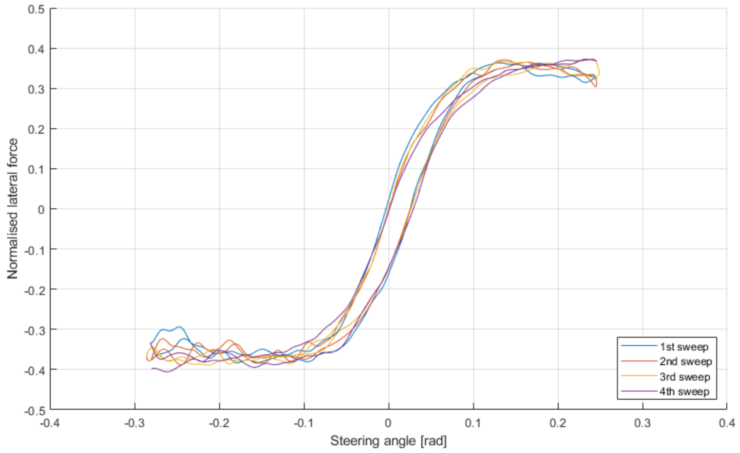

Figure 5. Normalized lateral force curves as a function of steering angle separated to individual sweeps of the measurement run.

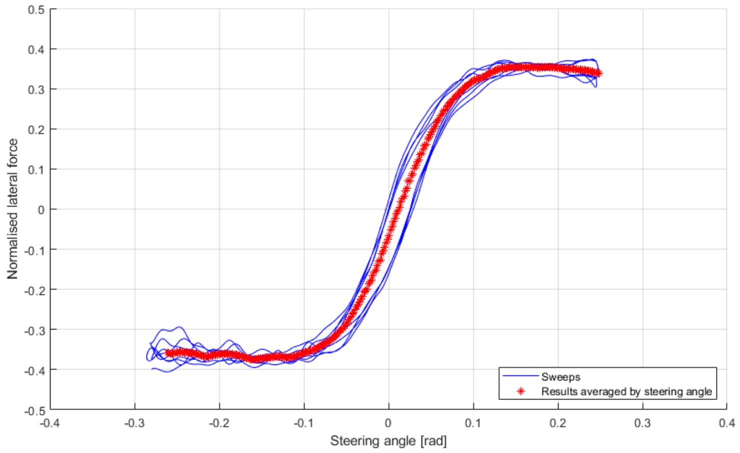

Figure 6. Relaxation compensation for the normalized lateral force curve.

Due to conicity and ply-steer of the tyre, or road surface properties, zero force does not usually occur exactly on the zero-steering angle even when camber angle is at zero. For tyre comparisons it can be beneficial to shift the resulting force curve in to the zero crossing. This can be simply done by checking the minimum and maximum values of normalized lateral force and performing vertical shift accordingly. After the vertical shift it is possible to check how far of the zero steering angle we are and perform lateral shift based on that as presented in Figure 7.

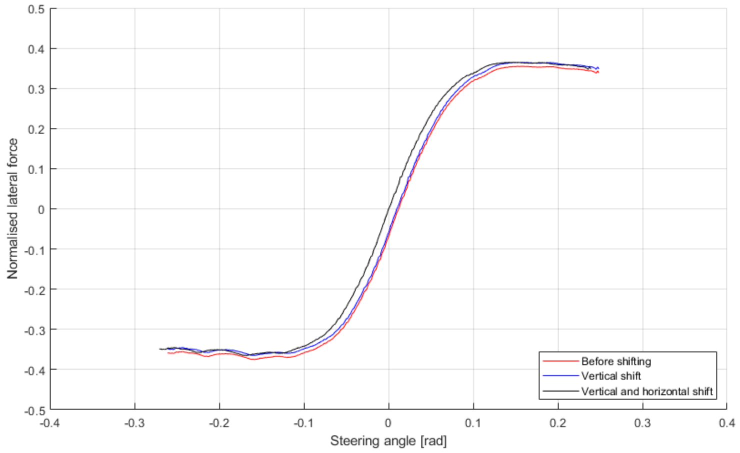

Figure 7. Elimination of lateral force curve shift caused by tyre conicity, ply-steer etc.

Results and Discussion

First pilot tests with manual control were made in March of 2019 and after those, some improvements were carried out and pure lateral slip snow measurements with semi-automatic control were completed in 2020 and 2021. In addition to the pure snow measurements, first wet asphalt measurements were made in November of 2021 and hard packed snowy road measurements made in March of 2022.

Pure lateral slip measurements on snow in 2020 and 2021

The snow measurements have shown rather good repeatability and results have been rational. Even with very well-prepared snow surface, there is usually some roughness on the track resulting in some deviations on the normal force of the tyre, but so far quality of the snow measurements has been encouraging. It has been noted that, the snow itself has a considerable impact on the tyre performance. Shown in Figure 8, on the left there are lateral force curves for a tyre “S2” in March of 2021 and on the right, there are comparable lateral force curves for the same tyre on the same track in March of 2020. In 2020 the start of winter season was a bit warmer resulting in a bit softer base for the snow and, even when the surface hardness was very close between the years, this resulted in quite a bit different result in 2021 and 2020.

Presented in Table 1 are the typical values of interest for pure lateral slip tests shown in Figure 8. These are average normal forces (F_Z), cornering coefficient estimates (CC), peak lateral friction coefficients (F_Y norm. peak) and lateral friction coefficients at 12 degrees of steering angle (F_Y @ 12 degrees).

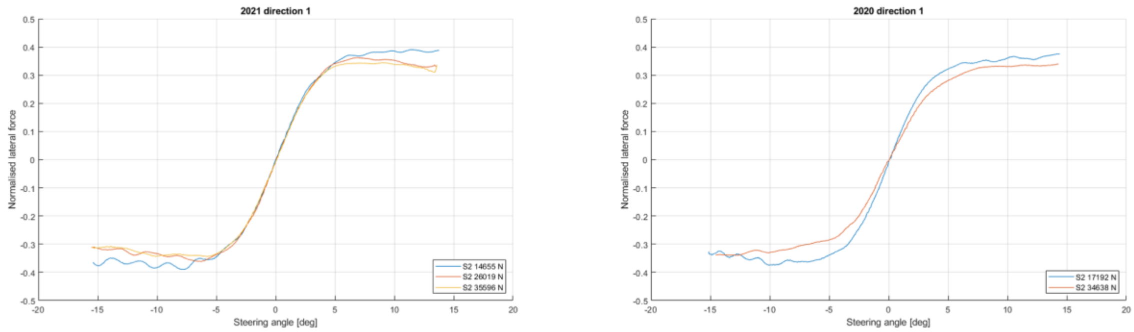

Figure 8. Comparison of ”S2” tyre on snow in years 2021 and 2020.

Table 1. Tyre measurement results of “S2” tyre on snow in years 2021 and 2020.

2021				2020			
Fz [N]	CC [1/rad]	FY norm. peak	FY @ 12 degrees	**Fz [N]**	CC [1/rad]	FY norm. peak	FY @ 12 degrees
14655	6.33	0.39	0.38	**17192**	6.3	0.38	0.35
26019	6.22	0.36	0.34				
35596	5.71	0.34	0.32	**34638**	4.5	0.34	0.33

Pure lateral slip measurements on wet asphalt in 2021

First pure lateral slip tests on wet asphalt were made in November of 2021. More static driving surface gave a better look into how repeatable the measurements are. Test track was an old trainyard with some breaks in the asphalt surface, but the trailer seemed to cope with that surface rather well. Presented in Figure 9 are the individual sweeps of a one-way test run with average normal force of 39829 N, showing good repeatability and small deviations between sweeps.

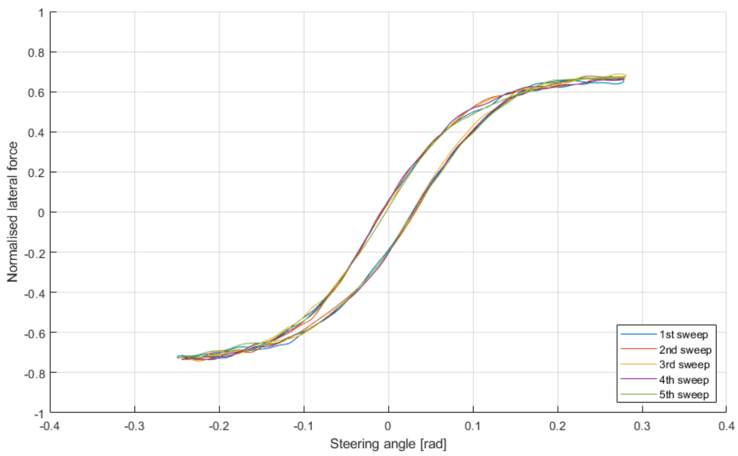

Figure 9. Individual sweeps of pure lateral force test run in wet asphalt with normal force of 39829 N.

Presented in Figure 10 are pure lateral slip test results for tyre “S2” on wet asphalt with three loads. Normal forces, cornering coefficient estimates and normalized lateral force peaks from the results shown in Figure 10 are presented in Table 2.

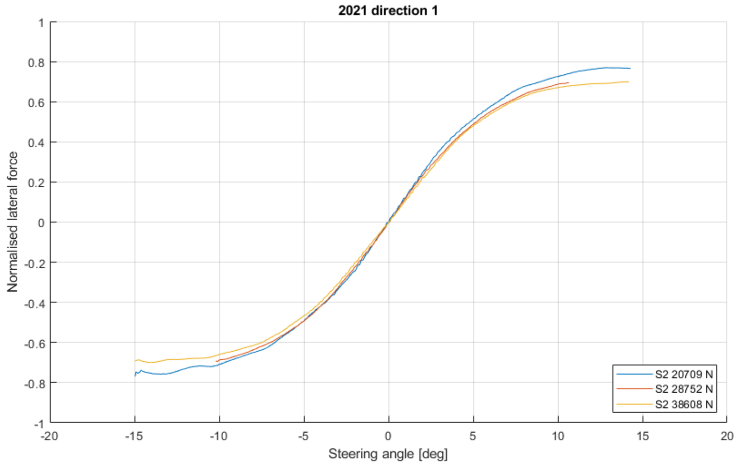

Figure 10. Pure lateral slip force curves of ”S2” tyre on wet asphalt.

Table 2. Tyre measurement results of “S2” tyre on wet asphalt.

Fz [N]	CC [1/rad]	FY norm. peak	FY @ 5 degrees
20709	7.07	0.77	0.50
28752	6.79	0.69	0.49
38608	5.80	0.70	0.48

Discussion

The snow measurements performed in 2020 and 2021 were the first of their kind in the world for heavy commercial vehicle tyres. From the snow measurement results presented in Figure 8 and Table 1, the friction levels gained on snow surface seem believable [1][2] and peak friction levels drop gradually with increase on tyre load with increased tyre surface pressure. It is interesting to see, that with similar surface hardness of the snow between 2021 and 2020 tests, but with softer base for the snow surface in 2020, the lateral force gain with increasing steering angle seems to be a bit slower and at the same time the drop-off at high steering angles is smaller. This can also be seen on the gained cornering coefficients. From this it might be beneficial to have more than just a surface hardness test done for snow surfaces when comparing testing conditions. With outdoor tests, conditions evolve continually and even when doing same day comparison tyre tests, due to rapidly changing testing conditions, the compared tyres should be tested as soon to each other as possible.

With wet asphalt measurements, friction levels gained are rather well in line with expectations. With dry asphalt, it would be possible to get up to or even a bit over 1.00 for peak friction, but with wet asphalt around 0.70 is reasonable [3]. It is also expected to see from Figure 10, that with high friction levels, the lateral force generation of the tyre is not yet saturated with used steering angles. When comparing to the results on snow presented in Figure 8 and Table 1, it can also be noted, that with loose surface the cornering coefficients seem to be a bit lower. This is understandable due to snow layers deforming under the tyre.

Experiences with the measurement trailer have been encouraging so far and the mechanical side of the design is working well. Biggest shortcomings have been with the slip angle estimation and automation of the control systems and data processing. Next step in developing the control and measurement system is to make some smaller adjustments to the measuring cycle control. More accurate measuring of the slip angle of the tested tyre is under investigation. Active adjustment of normal force has been in talks, one possibility is to go with hydraulic pressure adjustment. Although all the results are usually proportioned to the measured normal force, it would be beneficial to have at least faster and more reliable way to set the load on the measured tyre even with semi-automatic control. Rig for loading the measurement mechanism with calibration force and force transducer for easier calibration is also in design phase.

Conclusions

In this study, drawbacks concerning heavy commercial vehicle tyre force measurements in laboratory setting have been addressed. Due to very variable weather and driving conditions in the winter season, laboratory measurements need to be complemented by measurements made in the real life setting in order to examine how heavy vehicle tyres function in the conditions. For these measurements, suitable tyre force measurement system needs to be designed and built, since none exist in Nordic countries.

For design specification, the measurement platform needs to be agile and versatile enough to access real world driving surfaces. It does also need to be fast enough to operate minimizing the effects of weather changes in outdoor testing especially in winter. However, at the same time, it needs to be robust and sturdy enough for reliable and repeatable measurements even in high friction conditions and for validation purposes as well. Based on the basic requirements the measurement system was decided to be built on a 4-axle full trailer and to be drawn by heavy commercial truck.

Aside from building the tyre force measurement trailer, the design specifications concerning fast outdoor measurements for winter season and reliable working on high friction setting have been considered. After pilot tests and snow measurements in 2020 and 2021, the trailer was deemed to be of a working design for pure lateral slip outdoor measurements on snowy conditions. With completion of the tests mentioned, first snow measurements with heavy commercial vehicle tyres in the world have been completed successfully. First high friction measurements for pure lateral slip were made on wet asphalt and the trailer showed good results with satisfactory repeatability and small deviations in measured forces, when the surface is flat.

The results of this study can be used for heavy commercial vehicle tyre measurements in winter conditions, and they will open a good research opportunity for vehicle and tyre manufacturers and research organizations. Possible use cases for the trailer include but are not limited to performing fast and reliable tyre comparisons in various conditions, tyre model fitting for vehicle dynamics analysis, validating more complex tyre models used in tyre development and validating and developing road friction estimation methods for heavy vehicle tyres.

For the moment, measurements with the trailer are limited to pure lateral slip measurements, but braking system is on the works and with it pure longitudinal slip and combined slip measurements can be performed. Developing a reliable slip angle estimation of the measured tyre in variable weather conditions is one of the focus areas on future studies in combination with further development of the control and measurement system.

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