TYRE MODELLING FOR HIGH CAPACITY VEHICLE SIMULATIONS

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Abstract

Tyre friction properties of 21 different heavy vehicle tyres have been measured on smooth ice and dry asphalt using a dedicated flat-bed machine. The purpose of the measurements was to study characteristics of typical heavy vehicle tyres, and to provide representative models for heavy vehicle dynamic simulations for both high and low friction conditions, with focus on lateral friction forces. The results reveal large differences of the cornering stiffness between new and worn tyres, where lower tread depth results in substantially higher stiffness. Cornering stiffness values on smooth ice and asphalt are very similar, suggesting that rubber and carcass stiffness rather than the friction level determines this property. Also, peak friction level on asphalt and relaxation length exhibits higher values for worn tyres compared to new. The measured data is currently being analysed in more detail with the purpose of creating standardized tyre models that can be used for PBS simulations.

Keywords: PBS, high capacity vehicle, tyre model, cornering coefficient, peak friction, relaxation length, flat-bed tyre test machine

1. Introduction

The large increase in the goods transport demands, the growing congestion problem, and the environmental concerns over transport emissions, make High Capacity Vehicles (HCVs) an attractive alternative on the road; an alternative which also results in significant economic benefits. Performance based standards (PBS) is a way of regulating access of HCVs to the road network. Under a PBS approach, standards would specify the performance required from vehicles to ensure safety, rather than mandating length and weight limits. A PBS scheme for existing and upcoming HCVs is under development in Sweden (Kharrazi et al. 2017). An important factor that affects the dynamic performance of heavy vehicles is tyre characteristics, see for instance Domprobst (2016), and therefore should be addressed appropriately in a PBS scheme. Due to the existing variety of tyres and the diversity of road surface condition, especially during winter, choosing one tyre for assessing performance of HCVs is not a trivial task. Therefore, there is a need for defining and modelling standard tyres to be used in assessment of HCVs with respect to a Swedish PBS scheme. In this scope, as a part of the national PBS II project, which is carried out in collaboration with Finnish partners, an initiative for development of standard tyre models to be used for heavy vehicle dynamic simulations has been taken. The purpose of this study has thus been to via measurements investigate the tyre friction properties for a selection of tyres that are commonly used for HCVs in Sweden. The influence of tyre wear has been of special interest, and both high friction (dry asphalt) and low friction (smooth ice) were included in the study. The measurements were carried out at VTI´s tyre test facility in Linköping, Sweden.

2. Methodology

Eleven different tyres were selected for the study. One new sample of each tyre, and for seven of them also worn specimens, were measured. In total 21 tyre specimens were measured (all of them on dry asphalt, and 17 on ice). The tread depths for the new specimens typically were within 13-19 mm, and the selected worn ones were in the range of 2-10 mm. The tyres are listed in Table 1 and belong to three main categories: steer or wide single trailer tyre (denoted by S), twin drive tyre (denoted by D), and twin trailer tyre (denoted by T). Before the measurements, the new test tyres were simultaneously driven in for 300 km, mounted to a fully loaded B-double combination with axles suitable for all the test tyres.

Based on the common axle loads for each category, the typical loads were estimated to 40 kN for S, 22.5 kN for D, and 20 kN for T. We have taken these values as the nominal tyre loads (not to be confused with rated load) for respective category. In addition to the nominal load, the tyres were measured also at 50% and 150% of the nominal load. The test conditions are summarized in Table 2.

The tyres can be further subdivided into multi, fuel or winter type. These different tyre types can briefly be described as:

- Winter tyres: Typically, these tyres have small block pattern and/or dense deep siping. They also have special winter tread compound which can operate in low temperatures.
- Multi tyres: Typically, these tyres are designed for both regional and long distance driving. They have bigger tread blocks and less siping than winter tyres, and have good mileage properties.

- Fuel tyres: Typically, these tyres are designed for long haul driving. They have low tread depth and normally no siping. They have special casing and tread compound designed to get low rolling resistance.

Table 1 – The tested tyres

Code name	**Dimension**	**Rim size (inches)**	**Steer (S) / Trailer (T) / Drive (D)**	**Tyre type**	**Condition**	**Load index (kg)**	**Tread depth (mm)**	**Rubber hardness (Shore A)**
S1	385/65	22.5	T	Multi	new	4500	17	63
S1W					worn		10	64
S1W2					worn		6	67
S1W3					worn		3	64
S2	385/65	22.5	S & T	Winter	new	4500	16	64
S2W					worn		8	64
S2W2					worn		5.5	68
S3	385/65	22.5	S & T	Multi	new	4500	15	64.5
S3W					worn		7	67
S4	385/65	22.5	T	Fuel	new	5000	13	70.5
S5	385/55	22.5	S	Winter	new	4500	15	74.5
S6	385/65	22.5	S	Winter	new	4500	16	66
S7	385/65	22.5	T	Multi	new	4500	12.5	65
D1	315/70	22.5	D	Multi	new	3750 (single) 3350 (double)	18	68
D1W					worn	3750 (single) 3350 (double)	3.5	72
D2	315/70	22.5	D	Winter	new	3550 (single) 3150 (double)	19	65.5
D2W					worn	3550 (single) 3150 (double)	6	65
T1	265/70	19.5	T	Multi	new	2725 (single) 2650 (double)	13.5	65
T1W					worn	2725 (single) 2650 (double)	3	64
T2	265/70	19.5	T	Winter	new	2725 (single) 2650 (double)	14	65.5
T2W					worn	2725 (single) 2650 (double)	2	67

Table 2 – Test conditions

Tyre category	Nominal axle load	Wheel load (kN)	Inflation pressure ice tests (cold tyre at +2°C) (bar)	Inflation pressure asphalt tests (cold tyre at +20°C) (bar)	Inflation pressure asphalt tests (heated tyre) (bar)
S	8 ton	20, 40, 60	9.0	9.0	10.0
D	9 ton	11.25, 22.5, 33.75	7.0	7.5	8.5
T	8 ton	10, 20, 30	8.5	8.5	9.5

The measurements were carried out at VTI's Tyre Test Facility (TTF), which is a flat-bed machine specifically constructed for indoor tyre friction measurements on ice (Nordström 1994). It consists of a stationary but steerable tyre test rig (depicted in Figure 1) and a flat moving 55-meter-long steel bar that can be covered with ice. The steel bar representing the road surface is moved back and forth under the measuring wheel, inside a 125-meter-long climate controlled building. The bar is pulled by a hydraulic motor with a steel cable at speeds of up to 36 km/h. The ice temperature can be controlled within a few tenths of a degree Celsius. For high friction tests asphalt filled cassettes can be mounted on top of the steel bar.

The ice tests were carried out indoor on smooth, polished ice with an ice temperature of -5 ±0.2 °C in the TTF. The humidity in the tunnel that contains the ice surface was between 40 and 60 percent, and the tyre temperature was about -2 °C. The high friction tests were made with preheated tyres, where the tyre was warmed up by rolling on a rotating cylinder until the desired (warm) inflation pressure was reached.

Main focus of this investigation has been on lateral friction forces. In this paper friction refers to the friction force normalized with the wheel load. Steady state slip curves were constructed from two different measurement during which the slip angle was swept to -15° and +15° slip angle, respectively. An overlapping slip angle region of the two measurements allowed for relaxation length effects to be compensated for, resulting in steady state curves. The cornering stiffness was estimated using a linear fit of the slip curve within the range ±0.5°. For the ice measurements, slip curves within the ±10° interval was measured for all three loads. For high friction, smaller sweep intervals were used to avoid excessive wear of the tyres, with the exception of one tyre from each category. The full ±15° interval was only used for the smallest load, and a smaller interval was used for the higher loads in order to not cause excessive wear on the tyres for subsequent measurements.

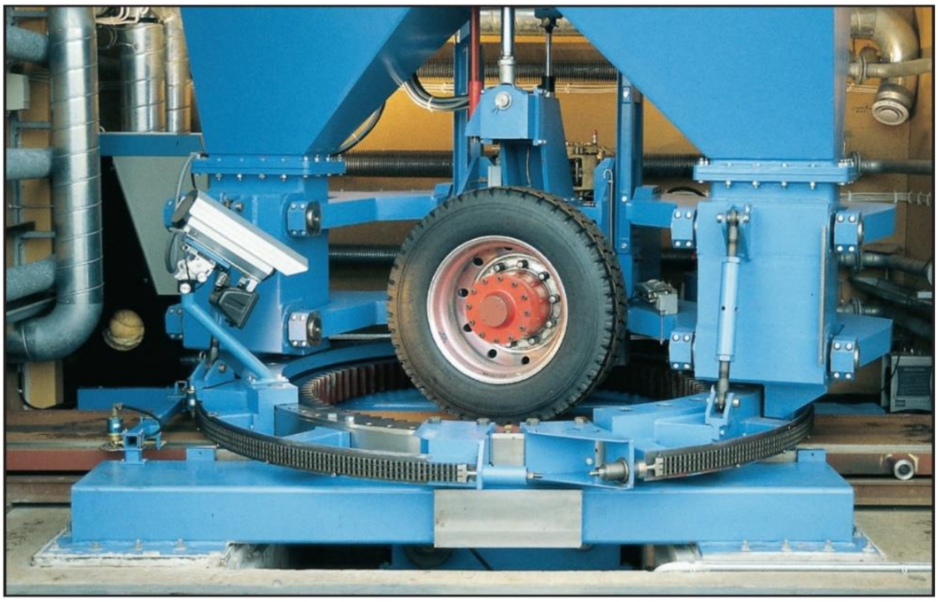

Figure 1 – The VTI Tyre Test Facility tyre rig

3. Results

In Figure 2, the cornering coefficient (cornering stiffness normalized by the load) from the tyre measurements on asphalt is presented. It is clear that the cornering coefficient (c.c.) is strongly affected by the tread depth of the tyre, and that a worn tyre with small tread depth may have c.c. values twice as large compared to a new tyre. Cornering coefficient as a function of load typically falls into two categories: c.c. either decreases with increasing load or exhibits a peak around the normal load. The reason for this different behaviour needs further investigation; most likely, the tread design has a major influence on the load dependence of cornering coefficient.

Plotting the c.c. as a function of tread depth indicates an almost linear relationship between the two entities, as seen in Figure 3. Both of the apparent outliers belong to the subgroup Drive multi, which exhibits a substantially higher c.c. than the other tyre groups. Excluding the two outliers in the line fit, an approximate relationship for the general tyre can be derived:

$$\text{c.c. [1/rad]} = 15 - 0.45 \times \text{tread depth [mm]} \tag{1}$$

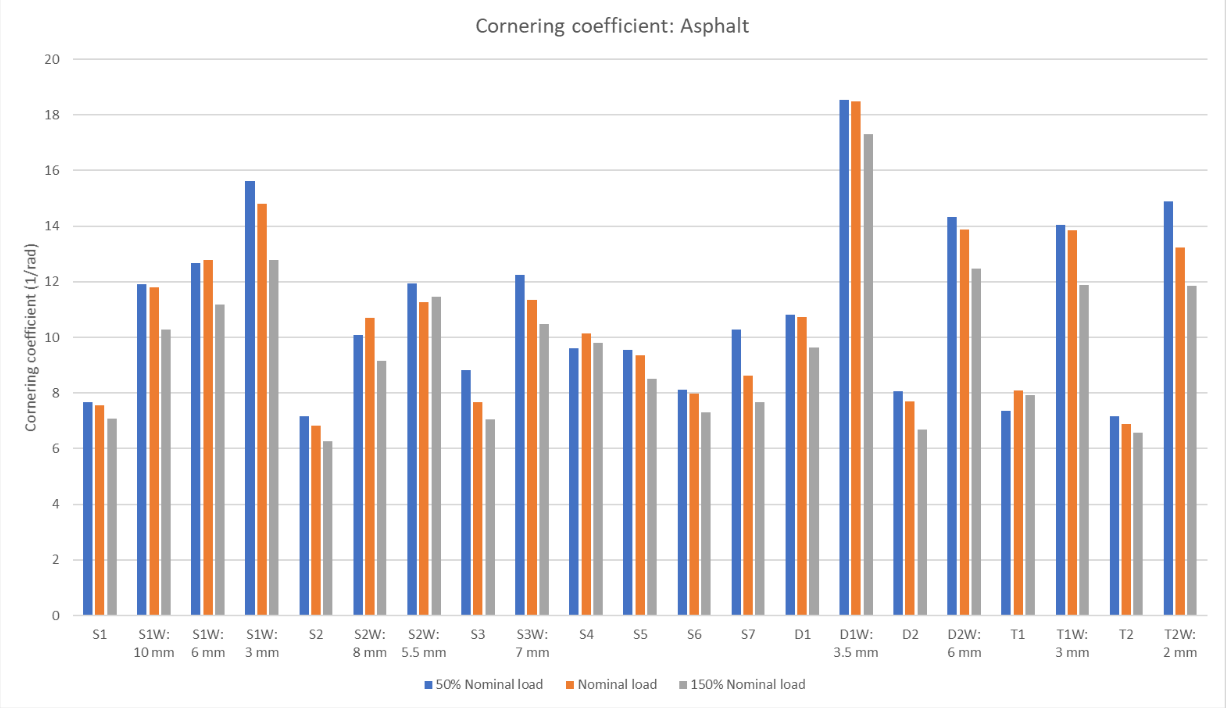

Figure 2 – Cornering coefficient on dry asphalt

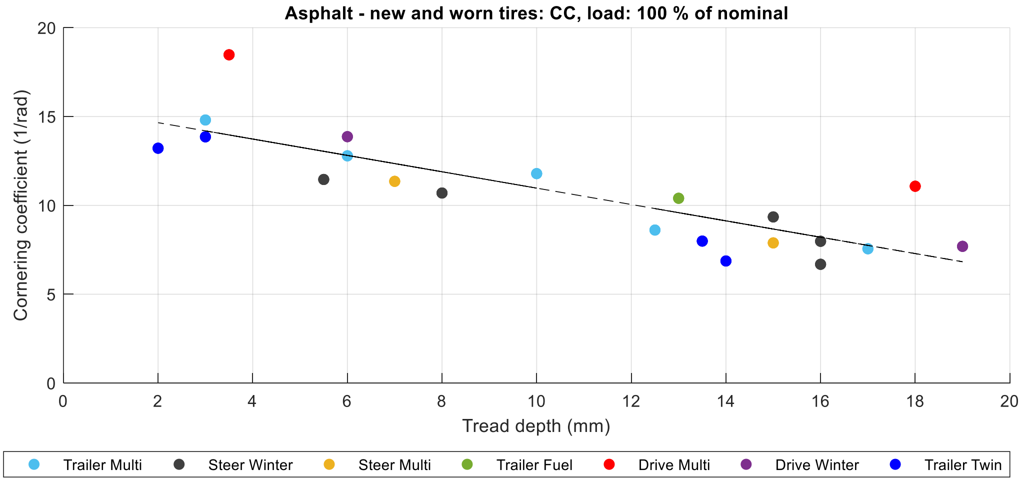

Figure 3 – Cornering coefficient on dry asphalt as a function of tread depth

The cornering coefficient on smooth ice is very similar to that of the asphalt measurement, indicating that rubber and carcass stiffness, rather than the friction level, determines this property. A comparison of the c.c. at nominal load between asphalt and ice is shown in Figure 4. Again, the subgroup Drive multi (represented by D1 and D1W) is an outlier with clearly higher c.c. on asphalt than ice.

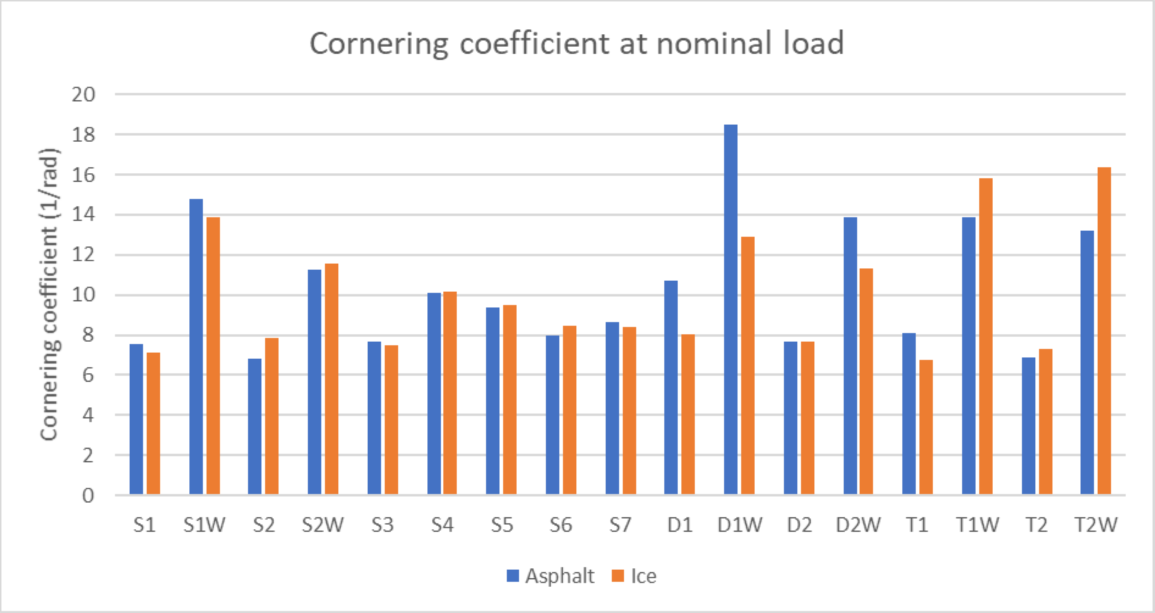

Figure 4 – Cornering coefficient comparison between asphalt and ice at nominal load

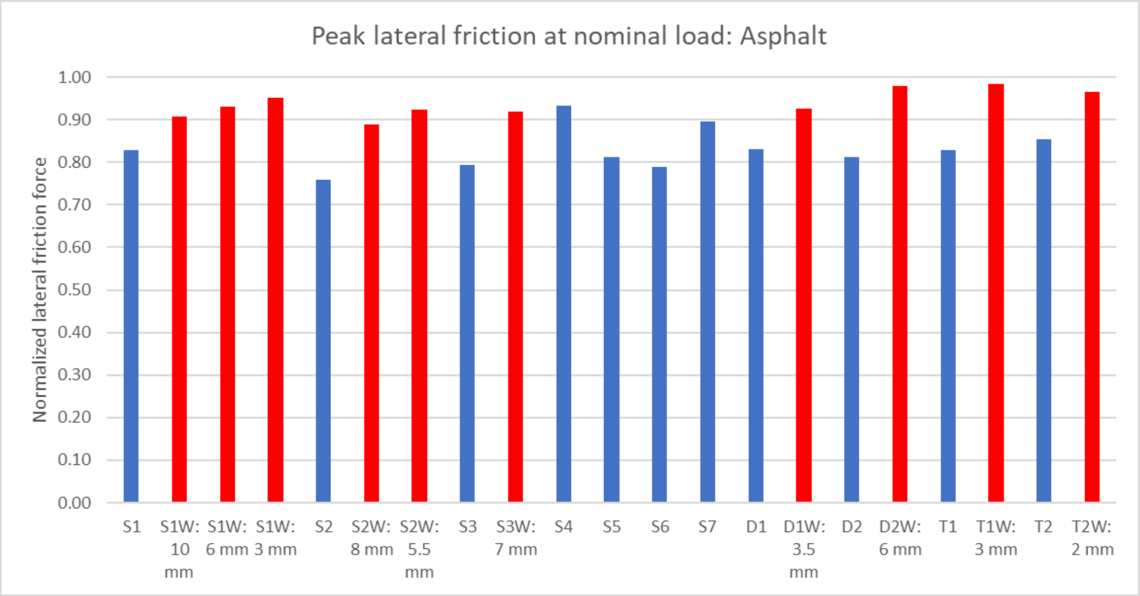

Figure 5 – Peak friction on dry asphalt. Blur bars: new tyres, red bars: worn tyres

The peak lateral friction on dry asphalt at nominal load is within 0.75 to 0.85 for all new tyres, except two which have peak values around 0.9, see Figure 5. The outliers, S4 and S7 both have smaller tread depth compared to the other wide single tyres. It is clear that the worn tyres have higher peak values compared to the new specimens. Plotting peak friction versus tread depth as in Figure 6, shows a clear influence on the tread depth, where smaller tread depth leads to higher friction. The higher friction for worn tyres could possibly be an effect of increased contact area, which leads to lower surface pressure compared to new tyres. Since the friction values are high on asphalt, an increase of peak friction does not necessarily mean increased performance, since the vehicle might roll over before peak friction is reached.

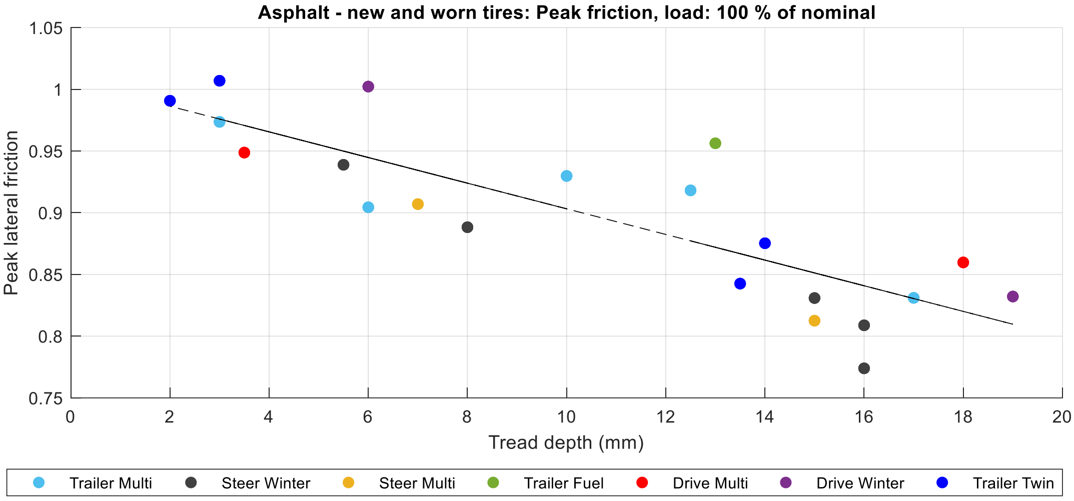

Figure 6 – Peak friction on asphalt versus tread depth

The load dependence of the peak friction was studied for a few new and worn tyres, for which measurements were carried out at the full ±15° interval for all three loads. As seen in Table 3, the different tyres exhibit very similar load dependence, indicating that it may be possible to generalize this dependency to all the measured tyres, although new and worn tyres may need to be treated separately. This dependency values are used to calculate the missing peak friction values at nominal load, plotted in Figure 5 and Figure 6, from the lower load case.

Table 3 – Peak friction on dry asphalt at different loads relative to peak friction at nominal load (N.L.)

Tyre code	50 % of N.L.	N.L.	150% of N.L.
S1	112 %	100 %	91 %
S4	114 %	100 %	91 %
D1	115 %	100 %	92 %
T1	113 %	100 %	89 %
Average new	**113 %**	**100 %**	**91 %**
S1W2	108 %	100 %	92 %
S2W2	111 %	100 %	90 %
S3W	110 %	100 %	92 %
Average worn	**110 %**	**100 %**	**91 %**

The peak friction on ice is quite similar within the same tyre category: around 0.14 for S tyres and 0.13 for D tyres without any clear difference for worn tyres. However, the worn T tyres have a larger friction compared to the new ones, 0.20 compared to 0.15. The reason for the high friction values of the worn T tyres is unknown, but it was noted that both of these worn tyres had a very rough surface texture compared to the new ones, which were smooth. This kind of roughness might have an influence on the tyre grip on smooth, polished ice.

The relaxation length from the asphalt measurements is shown in Figure 7. In general, the relaxation length increases almost linearly with wheel load, with worn tyres exhibiting larger values compared to new ones. Just as for the cornering coefficient, relaxation length values on ice are quite similar to those on asphalt.

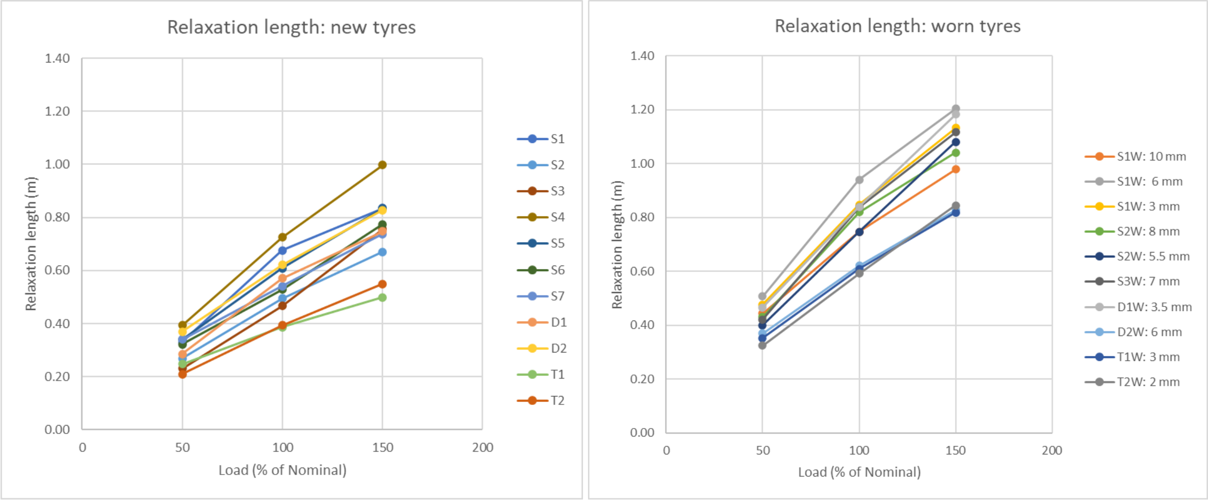

Figure 7 – Relaxation length measured on dry asphalt

4. Discussion

The results presented in this paper are part of the Swedish PBS project, and the present study provides necessary data for development of standard tyre models to be used for heavy vehicle dynamic simulations. Although the tyres have been chosen primarily to be representative for HCVs in Sweden, the tyre sizes and models should be common also internationally, making the result useful also from an international point of view. The development of tyre models and representative parameterizations is an ongoing work, with the aim of being finalized during the fall of 2021.

Acknowledgements

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5. References

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