Journal of Earth Sciences and Geotechnical Engineering, vol. 7, no.1, 2017, 1-9
ISSN: 1792-9040 (print), 1792-9660 (online)
Scienpress Ltd, 2017

PM10 Emission Effects of New Studded Tyre Regulations

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Abstract

Emissions from road wear is an important contributor to PM10 concentrations in the Nordic countries. Due to new regulations and an alternative test method for approval, studded tyres on the market presently have stud numbers ranging from 96 to 190 studs per tyre (at 205/55R16). In the present study, the particle generation from studded tyres was tested in the VTI road simulator. The results show that the tyre with the most studs (190) generates significantly higher PM10 levels than all other tyres, whilst the tyre that generates the least mass of inhalable particles has 96 studs and follows the stud number regulations. Increased number of studs and increased stud force significantly increases the concentration of PM10. Temperatures in the tyre, pavement and air as well as relative humidity also have an effect on the particle levels. A calculation example using the NORTRIP emission model demonstrated that the effect of variations in the studded tyre wear on both PM10 - levels and the number of limit value exceedances for the current data set used was significant.

Keywords: Studded tyres, regulation, wear, PM10, NORTRIP.

1 Introduction

New restrictions on the number of studs on studded tyres were introduced in Sweden and Finland in 2013. Regulations now allows 50 studs per meter rolling circumference. Alternatively, the tires can be tested in a special wear test, the so-called over-run test, to be approved. This has resulted in that studded tyres following the regulations, but also tyres that pass the over-run test, even though they have considerably more spikes, are present on the market. The over-run test shall ensure that the tested tire will not cause more road wear than a tire with a maximum of 50 studs per meter rolling circumference. Since studded tires are a major source of inhalable particles (PM10) in road and street environments, it is of interest to investigate the difference between the various studded tyre types also from particle emission point of view.

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2 Methods

In the present study, the particle generation from seven studded tyres was tested in the VTI road simulator (Figure 1). The road simulator (Figure 1) consists of four wheels that run along a circular track with a diameter of 5.3 m. A separate motor is driving each wheel and the speed can be varied up to 70 km h¬-1. An excentric movement of the vertical axis is used to slowly side shift the tyres over the full width of the track. Any type of pavement can be applied to the simulator track and any type of tyre can be mounted on the axles. An internal air cooling system is used to temperate the simulator hall to below 0°C. From wear studies it is well known that the wear in the simulator is accelerated but with a good correlation to test surfaces of the same pavements on real road (Jacobson och Wågberg, 2007).
A pavement ring, including 14 different asphalt pavements with different rocks, and constructions, tested for wear in a previous research project was used for the tests. The pavements were mainly stone mastic asphalts (SMA), some with rubber modified bitumen.

Figure 1: The VTI road simulator. Photo: Mats Gustafsson, VTI.

The studded tyres used in the tests were of four types:

1. Studded tyres complying with current regulations in Norway today and regulations in Sweden and Finland before 1/7 2013. 130 studs
   a. Nokian Hakkapeliitta 5

2. Studded tyres complying with regulations in Sweden and Finland after 1/7 2013, but has passed the over-run test. 130 studs
   a. Pirelli Ice Zero
   b. Goodyear Ultragrip Ice Arctic
   c. Continental Ice Contact
3. Studded tyres complying with new regulations in Sweden and Finland after 1/7 2013. 96 studs
   a. Michelin X-Ice North
   b. Gislaved Nord Frost 100
4. Studded tyres that have passed the over-run test despite more studs that both old and new regulations. The only tyre not approved in Norway but with an exemption. 190 studs.
   a. Nokian Hakkapeliitta 8

Tyre 4.a. is used as a reference tyre in the tests.

All tyres were tested at 50 km/h in a statistically optimal sequence for comparing tyres (Table 1) during four test days where various order of tyres used each day of testing. For details on choice of experiment design, see Gustafsson & Eriksson (2015). PM10 were measured during the experiments, as well as environmental parameters (temperature and humidity). In the statistical analysis of particle data was partly analysed as constants and partly as depending on ambient and tire-specific parameters.

Table 1: Chosen design for analyses. Bold numbers refer to a certain set of tyres.

Day	*Order during day*				
	1	*2*	*3*	*4*	*5*
1	**4**	**1**	**0**	**5**	**4**
2	**2**	**0**	**6**	**1**	**2**
3	**0**	**3**	**5**	**6**	**0**
4	**3**	**1**	**4**	**2**	**3**

Test time series data for PM10 for all four test days are shown in figures in Appendix C. The results of the regression analysis are shown in Table 6.

Table 2: Results of the regression analysis of PM10 -data.

	Estimate	*Std. Error*	*t value*	*P-value*
Intercept day1	12.78	0.56	22.93	0.000
Slope day1	-0.43	0.15	-2.90	0.027
Intercept day2	11.92	0.51	23.48	0.000
Slope day2	-0.36	0.15	-2.47	0.048
Intercept day3	10.96	0.52	20.94	0.000
Slope day3	-0.24	0.15	-1.61	0.158
Intercept day4	9.62	0.58	16.59	0.000
Slope day4	0.14	0.15	0.94	0.385
Pirelli compared to ref	**-2.55**	0.40	-6.41	0.001
Goodyear compared to ref	**-4.03**	0.40	-10.04	0.000
Continental compared to ref	**-2.75**	0.40	-6.89	0.000
Michelin compared to ref	**-3.82**	0.40	-9.62	0.000
Gislaved compared to ref	**-6.51**	0.41	-15.92	0.000
Nokian Hakka 5 compared to ref	**-1.77**	0.41	-4.32	0.005

3 Results

3.1 Statistical analyses of PM10 data

The PM10 data are shown in Figure 2. The bullets show the observations and the circles show the fitted values. The vertical distances between circles and bullets are estimates of the random variation. The reference lines represent the general behavior during the days, which is also the fitted emission for the reference tyre if it would have been tested on any day as any number within day.

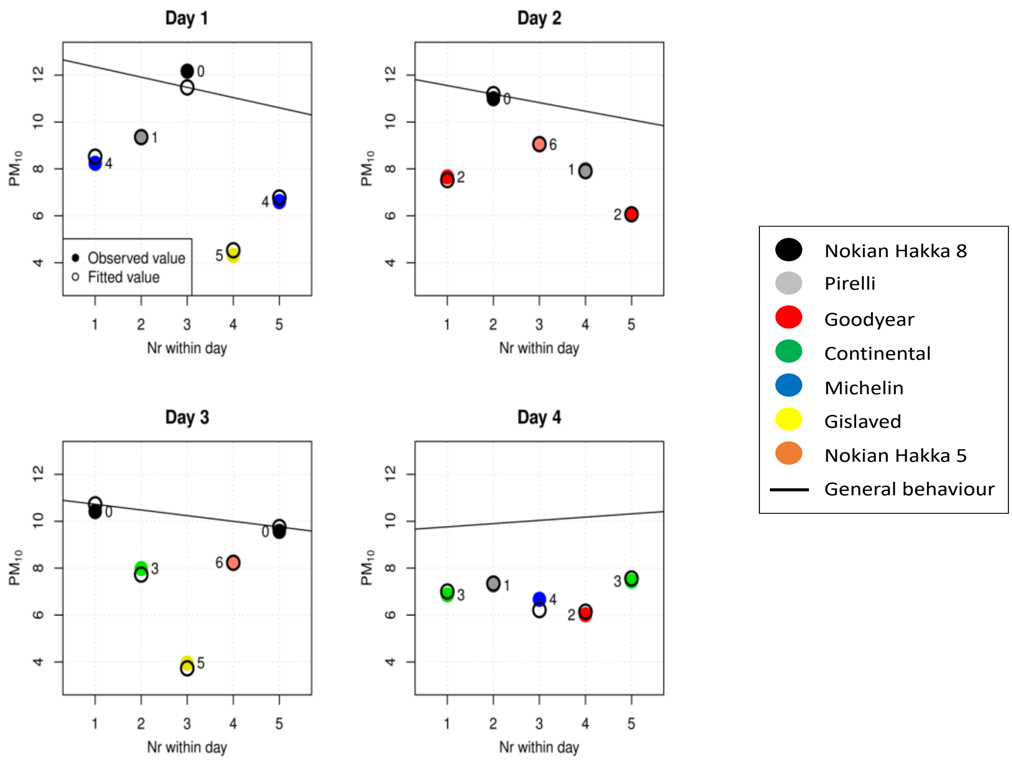


Figure 2: Observed and fitted PM10 values with tyre labels for all days.

Looking at the results in order from highest to lowest emission, we observe that the tyres can be divided into 4 groups (Table 3 and Figure 3), where the tyres within groups do not differ significantly on 5 % level while the P-values between closest neighbors in groups are written in the list. P-values are not corrected for multiple comparisons.

Table 3: Significantly separated tyre groups for PM10 results.

Group	***Tyre***	***Type***
1	Nokian Hakka 8	4
	0.005	
2	Nokian Hakka 5	1
2	Pirelli	2
2	Continental	2
	0.043	
3	Michelin	3
3	Goodyear	2
	0.003	
4	Gislaved	3

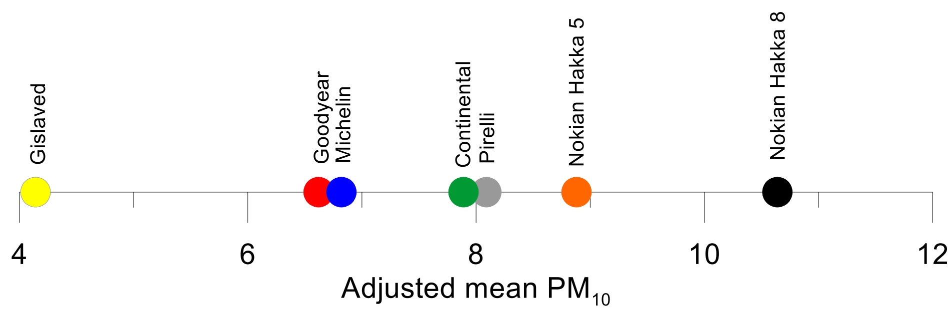


Figure 3: Order of adjusted mean PM10.

3.2 Results for tyre properties and experimental environment

The data supports that a model that does not use stud weight or any interactions is a good choice for PM10. This model is also supported by current knowledge about which variables causes PM10 emissions.

Table 4: Results of statistical analysis of parameters influencing PM10.

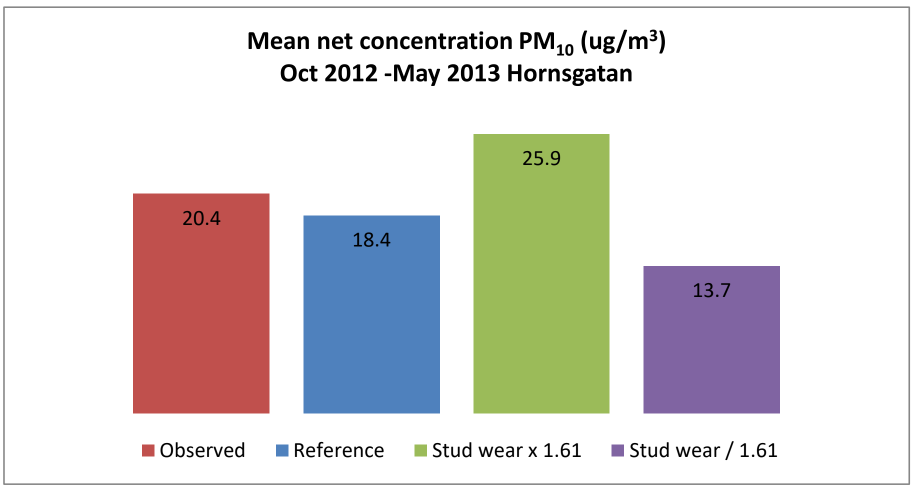
	Estimate	*Std.Error*	*P(>|t|)*
(Intercept)	-23.294	26.319	0.397
Road temp ($mg\ m^{-3}C^{o-1}$)	-2.323	1.289	0.102
Air temp ($mg\ m^{-3}C^{o-1}$)	3.132	1.185	0.025
Humidity ($mg\ m^{-3}\ \%^{-1}$)	0.135	0.052	0.026
Tyre temp ($mg\ m^{-3}C^{o-1}$)	-0.709	0.247	0.017
Speed ($mg\ m^{-3}km/h^{-1}$)	0.298	0.460	0.532
Mean protrusion during test ($mg\ m^{-3}mm^{-1}$)	2.273	1.423	0.141
Number of studs ($mg\ m^{-3}stud^{-1}$)	0.047	0.010	0.001
Stud force ($mg\ m^{-3}N^{-1}$)	0.037	0.009	0.002
Rubber hardness ($mg\ m^{-3}shore^{-1}$)	-0.133	0.075	0.107

R^2 for this analysis is 0.952. The first set of variables describes the environment. Three significant result can be seen, that PM10 emission increase with higher air temperature and humidity and decrease with higher tyre temperature. The second set of variables describes the tyres. Emissions increase with higher number of studs and higher stud force, and

decrease with higher rubber hardness (not significantly, though). Possibly, the studs wearing of the surface should be expressed as the number of studs times the stud force, but adding this interaction to the model did not improve the explanation significantly.
Two types of analyses have been done here. The first type only models tyre effects as constants, the second tries to describe the tyre effects as a function of stud weight etc. Both have high R^2, indicating that both models fit good to the data. Also, in Figure 2, the similarity in level and pattern between circles and bullets indicate that the model fits well and has the same structure as the data.

3.3 Estimation of implications for air quality

Laboratory results in a road simulator are, naturally, not directly applicable for estimating effects on air quality in cities by changing type of studded tyre. Using the NORTRIP emission model, where road wear is included together with meteorological, road operation and traffic related parameters and processes can be used for a rough estimate of effects on PM10 emission for a certain street for changes in road wear (Denby et al., 2013a; Denby et al., 2013b). In Figure 4, a dataset for Hornsgatan in Stockholm, for the winter season 2012-2013, has been used as an example. Hornsgatan is one of the most polluted streets in Stockholm and a studded tyre ban has been in use for some years. Despite the ban, the studded tyre use is about 30 % during the winter season. In the rest of Stockholm the figure is about 50 %.



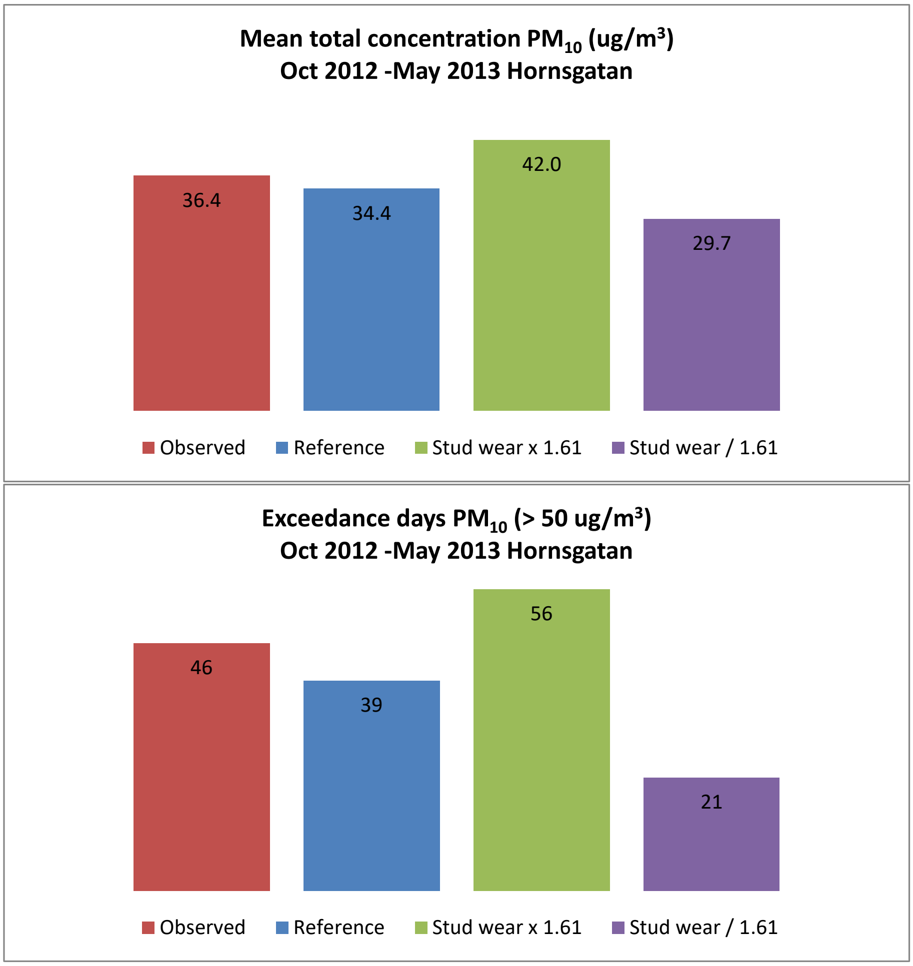


Figure 4: Effects on mean net and total PM10 as well as on limit value exceedance days on Hornsgatan, Stockholm of 1.6 times span of the reference wear (see text for explanation).

The modelled PM10 concentrations in a situation where everyone using studded tyres used the lowest and the highest emitting tyres in this study is shown in comparison to the observed and the modelled reference concentrations. The modelled reference is the wear and resulting PM10 emission that the model produces when using standards settings for studded tyre use and wear. The highest emitting tyre has about 2.6 times higher PM10 emission than the lowest emitting tyre. The modelled reference is the wear used in the model. If the reference road wear is assumed to be on a level right between the results of the tyres used in this test, the highest emitting tyre is 1.6 times higher than the reference and the lowest emitting tyre 1.6 times lower. Figure 4 shows the results of this calculation on the mean total PM10 concentration and the number of exceedances of the PM10 directive during October – May. The increase in net (only the local contribution of PM10 from the street environment) and mean total (including background PM10) PM10 concentration is 41 and 22 % respectively compared to the reference case and the limit value is exceed 17 more days. The corresponding decrease is 25 and 14% and 18 exceedance days less.

4 Discussion

All studded tyres tested emit PM10 when wearing the pavement ring, but there are significant differences related to tyre and tyre properties.

The road simulator is a laboratory equipment and as such not directly comparable to reality. The main draw-back of the simulator is the small diameter inducing a rather sharp curve of the track. This, in turn generates a turn-slip motion in the contact between the tyres and the pavement, which is not equivalent to normal driving. As mentioned in the methods chapter, studies at VTI despite this have shown very good correlation between the studded tire wear on the road and in the machine. Jacobson & Wågberg (2007) reported a coefficient of determination (R2) from 0.93 to over 0.95.

Two types of statistical analyses have been used. The first type only models tyre effects as constants, the second tries to describe the tyre effects as a function of stud weight etc. Both have high R2, indicating that both models fit good to the data. The particle emissions have about the same level each day and not a steep slope. The experiment behaves similar from day to day without any major drift during any day. Also the drift during the days does not have the same direction each day meaning that there is no sign of a problem of an ongoing drift in the experiment or the environment itself that reoccurs on each day.

Regarding the tyre properties significantly affecting PM10, higher stud weight and stud number increased both while harder rubber decreased the concentrations. A combination of both stud weight and number of studs into "stud mass per tyre", did not improve the model results. The higher stud weight and number of studs are expected to increase the emissions of wear particles. Rubber hardness, and especially its relation to temperatures are harder to interpret. While higher temperature in tyres and/or pavement should make materials softer and more yielding, which should result in lower wear, harder rubber should also result in higher wear, which is not the case. An interaction is suspected but has not been further analysed. An alternative speculation is that the turn-slip movement of the studs in the simulator is reduced by higher rubber hardness and therefore results in lower wear particle emissions.

The Nokian Hakkapeliitta 8 is producing more PM10 than the rest of the tyres. Even though the stud weight is lower, the number of studs are more than double than the tyres with the lowest number of studs. It also has the softest rubber, which might affect both the movement of the studs in the turn-slip contact and the ability to suspend dust on the tests track surface. The Gislaved tyre is at the other end of the PM10 emission scale and has 96 studs per tyre together with the Michelin tyre. The significantly lower production of PM10 indicate an additional property affecting the emission, which is not covered by the statistical analyses. The shape of the stud pin (trident star) might be an explanation, but a quantitative estimate of the importance of the shape has not been feasible in this study.

The Goodyear tyre has 130 studs and a higher stud protrusion than the rest of the tyres, but still ranks as the second lowest emitting tyres. Compared to the two other tyres of type 2, it has a harder rubber. The Pirelli, Continental and Nokian Hakka 5 tyres have similar emission of PM10. Generally, the type 3 tyres with fewer studs per tyre emit less particles than the rest, except for the Goodyear tyre.

The NORTRIP modelling example shows that the effects on local air quality would be large if all studded tyres were swapped to new low or high PM10- emitting tyres, but the result should be seen as merely an indication since there are many uncertainties to this estimate. E.g. it is not known if the assumption that todays studded tyre fleet is actually emitting PM10 in between the two extremes in this specific test.

5 Conclusion

The combined approval procedure of both regulations and an approval test have resulted in high variation of number of studs in studded tyres. The statistical analysis showed that PM10 levels produced by the tyres could be sorted in four significantly different groups, where the tyre with most studs (approved through the test method) emitted most PM10 while one of the tyres with least number of studs had the lowest emissions. Emissions increase with higher number of studs and higher stud force. Environmental factors also affect the PM10 emissions, which increase with higher air temperature and humidity and decrease with higher tyre temperature. A model simulation for a single street using the NORTRIP model shows a relatively large effect of the span in PM10 emission within this specific range of tyres.

ACKNOWLEDGEMENTS: This work was financed by The Swedish Transport Administration and The Norwegian Road Authority. The authors would like to thank Tomas Halldin for running and maintaining the road simulator.

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