Vehicle non-exhaust emissions from the tyre–road interface – effect of stud properties, traction sanding and resuspension

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ABSTRACT

In Northern cities respirable street dust emission levels (PM10) are especially high during spring. The spring time dust has been observed to cause health effects as well as discomfort among citizens. Major sources of the dust are the abrasion products from the pavement and traction sand aggregates that are formed due to the motion of the tyre. We studied the formation of respirable abrasion particles in the tyre–road interface due to tyre studs and traction sanding by a mobile laboratory vehicle Sniffer. The measurements were performed on a test track, where the influence of varying stud weight and stud number per tyre on PM10 emissions was studied. Studded tyres resulted in higher emission levels than studless tyres especially with speeds 50 km h−1 and higher; however, by using light weight studs, which approximately halves the weight of studs, or by reducing the number of studs per tyre to half, the emission levels decreased by approximately half. Additionally measurements were done with and without traction sand coverage on the pavement of a public road. After traction sanding the emission levels were not affected by tyre type but by formation and suspension of traction sand related dust from the road surface. The emissions after traction sanding decreased as a function of time as passing vehicles’ motion shifted the sand grains away from the areas with most tyre–road contact.

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1. Introduction

In Northern cities around the globe respirable street dust levels (PM10 or particulate matter with an aerodynamic diameter smaller than 10 μm) are especially high during spring and they have been associated with health effects such as inflammatory responses and irritative symptoms in the respiratory system (Salonen et al., 2004; Brunekreef and Forsberg, 2005). The dust causes also discomfort and soils surfaces. The major suspects for the high dust load are the anti-skid methods that increase formation of particles from abrasion of materials. The anti-skid methods include tyres especially with speeds 50 km h−1 and higher; however, by using light weight studs, which approximately halves the weight of studs, or by reducing the number of studs per tyre to half, the emission levels decreased by approximately half. Additionally measurements were done with and without traction sand coverage on the pavement of a public road. After traction sanding the emission levels were not affected by tyre type but by formation and suspension of traction sand related dust from the road surface. The emissions after traction sanding decreased as a function of time as passing vehicles’ motion shifted the sand grains away from the areas with most tyre–road contact.

tread design and material, for example soft rubber material and more lamellae than summer tyres. These so called friction tyres have several designs in which the properties vary based on what kind of winter conditions they are expected to be used. Most used tyre models in the Nordic countries differ from the ones used in the central European countries in the respect that the Nordic designs emphasise more snow and ice grip, whereas the central European designs performance against aquaplaning.

The studdable winter tyres, also called studded tyres, are frequently used in, e.g. Finland, Scandinavia, Russia and some provinces and states of Canada and the United States. The studded tyres have resulted in enhanced wear of pavements and thus many countries have introduced restrictions on stud weight, protrusion, tip design and number per tyre, to limit the road surface wear. For example according to the requirements in Finland and Scandinavia an individual car must be equipped with the so called light weight studs, which weigh 1.1 g each. For vans and trucks maximum weights required are 2.3 g (C-class winter tyre) and 3 g, respectively. There are also requirements for number of studs per tyre: car tyre with a rim diameter smaller than 13 inches may have 90 studs, whereas 13–15 inch tyres may have 110 studs per tyre and tyres larger than that may have 130 studs per tyre. These stud restrictions

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have been enforced in order to lower the pavement wear. The Finnish legislation has been recently changed so that a studded tyre shall include a maximum of 50 studs per 1 m of tyre rolling circumference. The regulation will enter into force 1 July 2013, and will reduce the amount of studs per tyre approximately 10–15 percent compared with the old regulation.

In many parts of the world the so-called conventional passenger car studs are still allowed. The weight of a conventional stud is higher than of a light weight stud, typically 1.9 g (Zubek et al., 2004). In the winter 2002–2003, in Anchorage Alaska, 60 percent of cars were equipped with studded tyres, of which 65 percent used conventional studs. Some countries, e.g. Japan and Germany do not allow studded winter tyres at all. Additionally more durable pavement materials and designs have been developed. The effect of stud properties on pavement wear has been studied (for a review see e.g. Zubek et al., 2004) but there are no studies currently available that have attempted to quantify the effects on emissions of airborne particles.

Dust formation and emissions from studded tyres and traction sanding have been studied in test facilities (Kupiainen et al., 2005; Gustafsson et al., 2008). In these facilities it is possible to minimize the effect of suspendable particles that are often found in on-road conditions. The results have shown that tyre studs increase the emissions compared with tyres without studs in conditions with minimal suspendable material (Kupiainen et al., 2005; Gustafsson et al., 2008). Traction sand was also an important source of PM, increasing also formation of particles from the pavement (Kupiainen et al., 2005; Gustafsson et al., 2008). Dispersion amount, grain size and the traction sand materials’ resistance to fragmentation were found to affect the formation levels (Räisänen et al., 2003 & 2005, Kupiainen et al., 2005). In such tests it is possible to gain important information on dust formation and factors affecting it, but they have limitations especially when attempting to relate the results with on-road conditions. Studies on pavement wear have shown that stud weight and number of studs per tyre influence road surface wear (Zubek et al., 2004). However, there are no studies that have looked at their influence on airborne emissions of respirable dust. It is not possible to directly relate the wear studies with dust emissions, because the road surface in on-road conditions practically always has suspendable material deposited on it. Mobile methods to measure street dust in driving conditions provide an interesting new tool to study these effects (Kuhns et al., 2003; Hussein et al., 2008; Pirjola et al., 2009, 2010).

This paper describes results and conclusions from the on-road tests by a mobile laboratory vehicle Sniffer aimed at studying the effect of stud weight and number of studs per tyre on respirable dust emissions from tyre-road interface in different driving speeds. The test tyres were commercially available studdable winter tyres and the tested studs are common design in commercial winter tyres. Additionally the effect of traction sanding on emissions was assessed.

2. Methods

2.1. Mobile laboratory

The measurements were performed with a mobile laboratory Sniffer (Volkswagen LT35). A detailed description of the van can be found in Pirjola et al. (2004, 2006, 2009; 2010). Road dust sample is collected from behind the left tyre through a conical inlet with the surface area of 0.20 m × 0.22 m into a vertical tube with the diameter of 0.1 m. The conical inlet is placed as close to the tyre as possible so that the lower edge of the inlet is 7 cm above the street surface and the upper edge is as high as the geometry of the fender of the wheel allows. The width of the inlet is around 2 cm less than the width of the tyre, 1 cm less from each side. The distance of the inlet from the tyre is 5 cm (Fig. 1). A stainless tube (diameter 0.1 m) runs through the rear part to the top of the van (Fig. 1b). A constant flow rate of ~ 2000 lpm is produced by an electric engine located on the roof of the vehicle. A sampling air branch-off into the tube of 0.025 m diameter was constructed for the particle mass monitors TEOM (Tapered Element Oscillating Microbalance, Series 1400A, Rupprecht & Patashnick) and ELPI (Electrical Low Pressure Impactor, Dekati Ltd). The total flow rate is 13 lpm (3 lpm for TEOM and 10 lpm for ELPI), and a sampling cyclone (SAC-65, Dekati) with a 9.2 μm cutoff is used. TEOM was installed to save 30 s running average mass concentration every 10 s. Particle number concentration and size distribution are measured by two ELPIs. Another ELPI measures street dust particles behind the left rear tyre, and the other background particles via the inlet in front of the van at 0.7 m altitude. ELPI with the electrical filter stage enables real time particle number concentration and size distribution (1 s time resolution) in the size range of 7 nm–10 μm (aerodynamic diameter) with 12 channels. To calculate the ambient air background PM_{10} from the number concentrations, particle density of 2.6 g cm^{-3} was assumed (Etymetzian et al., 2003) except for exhaust particles (particle sizes smaller than 0.6 μm) for which a value of 1 g cm^{-3} was used. In this work, the ambient air PM_{10} was estimated based on the PM_{2.5} measurements obtained by the two ELPIs and PM_{10} by TEOM behind the tyre as explained in Pirjola et al. (2009). These values were subtracted from the PM_{10} values measured behind the tyre by TEOM.

A weather station on the roof at 2.9 m height provides meteorological parameters. Relative wind speed and direction are measured with an ultrasonic wind sensor (Model WAS425AH, Vaisala). Temperature and relative humidity are measured with temperature and humidity probes (Model HMP45A, Vaisala).

Fig. 1. (a) Conical inlet behind the left rear tyre of Sniffer. (b) The branch-off of sampled air leading to the PM monitors (Pirjola et al., 2009; 2010).
Additionally, a global position system (GPS V, Garmin) saves the van’s speed and the driving route.

2.2. Test descriptions

The effect of stud number and stud weight on PM$_{10}$ dust formation was studied at a closed test track in June 2005. The test track is certified for tyre testing and corresponds to a SMA13 (stone mastic asphalt with maximum grains size 13 mm) pavement. The total length of the track is 1.8 km with two straight stretches and two curves (Fig. 2). The temperature during tests was around 15°C, moderate winds, between 1 and 2 m s$^{-1}$, prevailed and relative humidity was between 30 and 50 percent. Pavement surfaces were dry. Test tyres were studdable C-class winter tyres (for vans) of the size 225/70/R15 with no studs installed (No studs), with 110 light weight studs installed (100% car studs), and with 55 (50% van studs) and 110 van studs installed (100% van studs). The van studs had a higher weight (2.2 g) compared with the light weight studs (1.1 g) and they were also thought to represent close enough the weight of the conventional studs. The mass applied to the measurement tyre was 980 kg. The load bearing capacity of the tyre was 1100 kg. The effect of speed on the emissions was studied with constant speeds of 40, 50 and 60 km h$^{-1}$ as well as with the maximum safe driving speed of the Sniffer. In the latter test the speed varied between 60 and 90 km h$^{-1}$ (in average 77.3 km h$^{-1}$) and it included acceleration and braking. The accelerations took place in Straight stretch 1, the braking between the Straight stretch 2 and Curve 2 (Fig. 2).

The effect of traction sanding on respirable dust formation was studied on a public road in October 2005. The sanding tests were not performed at the test track to avoid possible damage to the test pavement due to the sanding material. The pavement of the public road was SMA18 that has a large aggregate grain size (up to 18 mm) and is a very durable pavement type against studded tyre wear. The temperature during tests was 10–16°C, moderate winds prevailed and relative humidity was between 54 and 90 percent. Pavement surface was dry. For these tests studdable passenger car winter tyres at size 235/60/R16 with and without light weight studs were used. A car tyre was used because light weight studs are usually not installed in a van tyre. Stud weight was 1.1 g. The mass applied to the measurement tyre was 980 kg. The load bearing capacity of the car tyre was 800 kg which means that during measurements the capacity was exceeded by approximately 20 percent. However, the tyre pressure was adjusted slightly down (3.5 bar instead of 4.2 bar) to compensate for that. Traction sand was crushed stone that was wet sieved to grain size of 1–6 mm. The dispersion amount was approximately 500 g m$^{-2}$. The material and the amount used correspond with normal operation in municipalities and public roads. The effect of speed on emissions was studied with constant speeds of 40, 50 and 70 km h$^{-1}$.

2.3. Data processing

The PM$_{10}$ from TEOM (called also as emission levels, since sampling is close to the emission source) was further processed by combining it with the position and speed information from the GPS. Additionally detailed notes were kept with timings of the different test phases and sections. This enabled us to specify the emission levels in different parts of the measurement sections. The track and road sections were measured four to five times for the different tyre and speed combinations. Additionally the studless reference tyre was measured in the beginning and after the

Table 1

<table>
<thead>
<tr>
<th>Test tyre (% of studs in place)</th>
<th># of studs per tyre</th>
<th>Test section</th>
<th>Driving speed of the measurement vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Speed 40 km h$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PM$_{10}$ [μg m$^{-3}$]$^a$</td>
</tr>
<tr>
<td>Reference tyre (No studs)</td>
<td>0</td>
<td>Straight 1</td>
<td>650 (209)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 1</td>
<td>560 (146)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straight 2</td>
<td>498 (144)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 2</td>
<td>1033 (251)</td>
</tr>
<tr>
<td>Studded tyre (50% van studs)</td>
<td>55</td>
<td>Straight 1</td>
<td>726 (168)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 1</td>
<td>697 (252)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straight 2</td>
<td>630 (126)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 2</td>
<td>1099 (181)</td>
</tr>
<tr>
<td>Studded tyre (100% van studs)</td>
<td>110</td>
<td>Straight 1</td>
<td>687 (170)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 1</td>
<td>770 (71)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straight 2</td>
<td>848 (114)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 2</td>
<td>1057 (263)</td>
</tr>
<tr>
<td>Studded tyre (100% light weight studs)</td>
<td>110</td>
<td>Straight 1</td>
<td>609 (207)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 1</td>
<td>507 (204)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Straight 2</td>
<td>494 (126)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Curve 2</td>
<td>903 (206)</td>
</tr>
</tbody>
</table>

$^a$ Standard deviation in brackets.
$^b$ Studded tyre to studless tyre ratio.
tests. In both study locations the number of measurement values per each section varied between 10 and 25 depending on the driving speed and length of the section. Section averages and standard deviations were calculated for each tyre-speed combination. In June the total number of section averages was 22 and in October 28 without and 36 with traction sand. The PM$_{10}$ background concentration was measured in both June and October and was approximately 20 $\mu$g m$^{-3}$. Statistical differences between the section specific datasets were tested with the Kruskal–Wallis test.

3. Results and discussion

3.1. Effect of stud properties on PM$_{10}$ road dust emissions

Already in the visible inspection it was noticed that although the track was in a very good condition in general, there was loose gravel and visible dust on the surface on Curve 2 and Straight stretch 1. Additionally there were small cracks in the pavement of Curve 2. Fig. 2 shows the PM$_{10}$ emission levels ($\mu$g m$^{-3}$) with the studless reference tyre on the test track and indicates that the background concentration from suspension particles was higher on Curve 2 and Straight stretch 1.

Table 1 presents the average emissions ($\mu$g m$^{-3}$) with the studless reference tyre and the studded tyres in different parts of the test track (two straight stretches and two curves) and different speeds. It also includes the emission ratio of studded to studless results (S/N). With 40 km h$^{-1}$ the track section specific average emission level behind the tyre varied between 494 and 1099 $\mu$g m$^{-3}$ depending on the tyre (Table 1). Only the studded tyres with van studs had statistically significantly higher emissions compared with the reference tyre. However, the differences were limited to track sections with less loose material and were especially clear in Straight stretch 2 where the tyres with 110 van studs and 55 van studs formed statistically significant and distinctive groups with average studded to studless emission ratios, 1.7 and 1.3, respectively (Table 1). With 40 km h$^{-1}$, the emission level with the light weight studded winter tyre (110 car studs) was similar to that with the reference winter tyre (No studs) in all sections. This result is explained by the emissions of earlier formed dust that is on the pavement surface; its suspension masks the additional abrasion emissions caused by the light weight studs.

With 50 km h$^{-1}$ the track section specific average emission levels measured behind the tyre varied between 682 and 2101 $\mu$g m$^{-3}$ depending on the tyre (Table 1). The emission increase by studs with 50 km h$^{-1}$ was more evident than with 40 km h$^{-1}$, e.g. with 50 km h$^{-1}$ the studded tyres with 55 van studs and 110 van studs had statistically significantly higher emissions with all other stud-section-combinations than the test with 55 van studs on Straight stretch 1. With the van studs, the ratios of section specific average emission to the reference tyre varied from 1.3 to 2.0 depending on the test track section (Table 1). Also the section specific emissions with the light weight studs were on average approximately 10–20 percent higher than the reference, but the differences were not statistically significant. The studless reference tyre had higher average emission levels with 50 km h$^{-1}$ compared with 40 km h$^{-1}$, which is explained by enhanced resuspension of the loose material from the track surface.

With 60 km h$^{-1}$ the track section specific average emission levels varied between 907 and 4032 $\mu$g m$^{-3}$ depending on the tyre (Table 1). These average emission levels were higher with studded tyres compared with the studless tyre. The tyre equipped with 110 van studs had the highest average emissions in all parts of the track. The track section specific average studded to studless emission ratios varied from 2.4 to 2.8 (Table 1) and the differences were statistically significant on all track sections. Reducing the van stud number to half (55 van studs) resulted in lower emissions and track specific average emission ratios of 1.4–1.9, compared with the reference tyre (Table 1). Also these differences were statistically significant on all track sections. The track specific average studded to studless tyre emission ratios with the light weight studded tyre ranged from 1.4 to 1.7 depending on the section (Table 1), with statistically significant differences on other sections than Straight stretch 1.

With the maximum safe speed that included acceleration and braking the track section specific emissions were between 2132 and 7911 $\mu$g m$^{-3}$ depending on the tyre (Table 1). The track section specific average studded to studless emission ratios with 110 van studs varied from 2.3 to 3.3 (Table 1) and the differences were statistically significant. The corresponding emission ratios with the other studded tyres (the light weight studded tyre and the tyre with 55 van studs) compared with the reference tyre were 1.2–1.9, depending on the tyre and section (Table 1). Apart for light weight studded tyre on Straight stretch 1, the differences were statistically significant with all other track section and tyre combinations. The tyre with 55 van studs had slightly higher section specific average emissions than the tyre with light weight studs (Table 1), but the differences between these two studded tyre types were not statistically significant.

Hussein et al. (2008) measured van tyres in Sweden and observed that the studded to studless ratios varied between 1 and 3 at 25 km h$^{-1}$ and 5 to 16 at 95 km h$^{-1}$. Our results seem to be in line with those of Hussein et al. (2008), and the differences are explained by the different measurement set ups (Pirjola et al., 2010) and the sites, i.e. the amount of loose material on the pavement. We did not measure as large differences (with similar speeds) as has been observed in laboratory conditions (Kupiainen et al., 2005; Gustafsson et al., 2008). This is explained by the suspension of previously formed dust, which is small or negligible in laboratory conditions but must be taken into account in on-road conditions.

Table 1 showed the speed specific emissions in different parts of the test track as concentrations measured from behind the tyre. The results in Fig. 3 show the average for the whole test track and Fig. 4 as fractions relative to the test with 40 km h$^{-1}$ and no studs. The results show that the emissions with the studless tyre increased linearly as a function of speed, about 30 percent with each 10 km h$^{-1}$ step from 40 to 60 km h$^{-1}$. The average emission increases from light weight studded tyres were 61 percent between 40 and 50 km h$^{-1}$ and 65 percent between 50 and 60 km h$^{-1}$. The heavier van studs doubled the emissions with each 10 km h$^{-1}$ increase, but reducing the amount of studs per tyre to half resulted in a rather similar speed dependency as with light weight studded tyre.

Our results show that studs with a higher mass resulted in higher PM$_{10}$ emissions and reducing the number of studs per tyre decreased the emissions. These findings are in line with the pavement wear studies reviewed by Zubek et al. (2004). The wear is a result of stud impact and abrasion. The impact energy in turn is dependent on the stud mass and vertical speed (10–15 percent of...
the vehicle speed). Abrasion is affected by the vehicle speed, road geometry (straight or curved) as well as acceleration and deceleration. The sharp increase in the dust level observed with the test tyres in the 70–90 km h\(^{-1}\) tests compared with other tests with constant speeds is a result of the acceleration and braking during the test which enhances the wearing effect of tyre. These did not take place in the tests with constant speeds.

### 3.2. Comparison of test track and public road test results

The emission levels measured on the public road (October 2005) were approximately two times higher than in the test track (June 2005). Fig. 5 shows the comparison of the results with 50 km h\(^{-1}\). The difference is an indication that the ‘background emission level’ on the public road was higher compared to the test track. This background emission level is a result of dust on-road surface that is suspended by the tyre. The difference between the test track and public road is expected because the test track is a certified tyre testing location which is cleaned frequently, is not in public use and is kept in good condition. Also the pavement on the test track was denser than on the public road and thus does not provide space for suspendable material to be deposited. It is also possible that the car tyres that were in use at the public road are more efficient in suspending dust from the pavement than the van tyres, since van tyres in general have a different design, i.e. stronger construction and tread design with less sipes. The concentration levels observed in the test locations were similar to those observed in the end of April and beginning of May in urban conditions in Helsinki (Pirjola et al., 2009).

### 3.3. Effect of traction sanding on PM\(_{10}\) dust emissions

In addition to the tyre tests, we also conducted measurements on-road surface immediately after dispersion of traction sand. Fig. 6 shows the relative PM\(_{10}\) emission levels with different tyre and speed combinations with the studless tyre test result with 40 km h\(^{-1}\) and without sand set as one. Error bars show standard deviation.

Fig. 7 shows the emission levels with 40 km h\(^{-1}\) before and after the traction sanding. Dispersion of traction sand took place at approximately 14:30, so the tests with start times 14:11 and 14:55 are the ones immediately before and after the dispersion. At 40 km h\(^{-1}\) the immediate increase in emission level due to traction sanding was approximately 15 times, compared with the level measured before. However, the emissions started to decrease as a function of time (Fig. 7) as more vehicles passed that shifted sand aside from the traffic lane. After 4 h the emission level had decreased 60 percent and was approximately 5 times compared to the pre-sanding level. After this the measurements were stopped because moisture started to condense onto the road surface which suppressed the emission levels and also posed a risk of damage to the measurement devices. Nevertheless, these results are in line with those measured in the United States by Kuhns et al. (2003) where the emissions had decreased to pre-sanding levels 8 h after dispersion, which would have been the case in these measurements if we assume that a similar decreasing trend would have prevailed after the measurements had to be stopped. The dust formation increase due to studs was not observable in the sanded conditions, which can be explained by the drastically high emission from the traction sand material that is enough to mask the abrasion emissions due to studs.

Traction sand is usually applied during snow storms or in icy conditions. During our test the road surface was dry. Our results reflect the formation of dust from traction sanding material during icy conditions. However, the dust formation processes from traction

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**Fig. 4.** Relative PM\(_{10}\) emission levels and their standard deviations. Studless tyre test result with 40 km h\(^{-1}\) is set as one.

**Fig. 5.** Comparison of the June (test track) and October (public road) test sets with 50 km h\(^{-1}\). Error bars show standard deviation.

**Fig. 6.** Relative PM\(_{10}\) emission levels and their standard deviations before and after sanding. Studless tyre test result with 40 km h\(^{-1}\) and without sand is set as one. Error bars show standard deviation.

**Fig. 7.** Dust emission levels in 40 km h\(^{-1}\) tests, before and after traction sanding. Error bars show standard deviation.
sanding are in effect also during snowy conditions, but probably are weaker. Also the sand material itself may contain microscopic dust already during dispersion. Different aspects of PM$_{10}$ formation from traction sanding material have been studied by Kupiainen et al. (2003, 2005) Kupiainen and Tervahattu (2004), Tervahattu et al. (2006) as well as Räisänen et al. (2003, 2005) and a review is provided in Kupiainen (2007). The formation of dust due to studs is only in effect when the studs impact the road surface. The impact can be expected to be weaker or not existent if the road surface is icy or snowy.

4. Conclusions

The main findings from the tests were:

- Tyre studs increased the emission levels of respirable dust from tyre-road interface compared with the studless tyre especially with speeds 50 km h$^{-1}$ and higher. The increasing factors were a higher vehicle speed, heavier studs, and a higher number of studs per tyre.
- The road surface contains loose dust formed earlier that is suspended by vehicle turbulence and shearing motion of the tyre. Emissions of that material were observed in all tests. The level of the suspendable material was higher on the public road compared with the closed test track. The amount of suspendable material explains the differences observed between our results and those measured in laboratory conditions (Kupiainen et al., 2005; Gustafsson et al., 2008). The suspension level in the test locations was similar to that observed in late spring in urban conditions in Finland (see e.g. Pirjola et al., 2009).
- The level of suspendable material should be monitored and documented when measuring dust emissions from tyres especially if the aim is to compare different tyre types, since for example the emission ratio of studded to studless tyre is very sensitive to the suspension level. Additionally it is a factor that should be addressed when comparing results from different studies reporting studded to studless tyre emission ratios.
- Traction sanding increased the formation of PM$_{10}$ particles and subsequent emissions significantly but the duration of the increase was limited to several hours.

These results can be used for estimating ways to lower respirable dust formation from studded tyres. Following recommendations can be made: the stud weight should be lowered and stud number per tyre should be limited. For example in areas where conventional studs are still in extensive use, the use of light weight studs should be promoted. Use of studless winter tyres could be an important alternative to studded tyres, especially in urban areas. However, it has to be noted that studded tyres have been estimated to provide safety benefits in icy conditions (Zubeck et al., 2004) and the safety considerations are not under the scope of this article. In street sections that have high PM levels and a high share of studded tyre traffic, a reduction of speed limit could be a way to lower formation of particles from studded tyres as well as lower the suspension of earlier formed dust. The results of this study indicate that the recent regulation change in Finland that further lowers the number of studs in winter tyres will result in less dust formation from studded tyre traffic, but we recommend further measurement with the actual tyre designs that comply with the new regulation. Traction sanding potentially increases dust formation significantly, but the duration of the increase is limited. The number of traction sanding occasions should be optimized and concentrated into areas where it is necessary, for example hills, crossings, traffic lights or bus stops. The left over traction sand material should be collected as soon as possible away from the road surface and its surroundings, to prevent it from relocating onto the driving lane and thus preventing formation of new particles from it. Alternatives for traction sanding should be promoted.

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