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Study on a test track of dust resuspension induced by a vehicle

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Abstract

An experimental campaign was carried out on a test track to assess resuspension of dust by vehicle traffic. Two vehicles were driven on a road covered by four different types of particles representing a wide range of fine soils. Each test consisted of running one of the vehicles at a given speed (30, 45 or 60 km.h⁻¹) over one of the type of particles previously spread on the road at a given mass per unit area (200, 400 or 600 g.m⁻²). The concentration of resuspended particles was measured by suction of the dust plume behind the rear tire using a particle counter. The influence of physical (type and quantity of particles, vehicle geometry) and mechanical (vehicle speed, tire/surface interface, dynamical behavior) parameters on particle lift are discussed. In terms of particle mass concentrations, results indicate that doubling the vehicle speed leads to 1.5 to 5.7 times higher PM₁₀ emissions. The lift of fine clay particles is 2 to 9 times more important than that of coarser soils. Significant differences are also observed between the emissions of the two vehicles, pointing out the key role of ground clearance and mud flaps in particles resuspension. It is believed that the present results may be extended to earthworks sites where solutions are expected to reduce dust emissions without watering.

1. Introduction

Dust emissions lead to a reduction of visibility and the worsening of air quality (Pope and Dockery, 2006; Baddock et al., 2014). This phenomenon occurs during the circulation of cars and haul trucks on unpaved roads and earthworks runways (Kuhns et al., 2003; Muleski et al., 2005). The particles on the surface of the road can be re-suspended by the passage of a vehicle due to the shear stress at the tire/road interface combined with the 3D turbulent flow generated in the wake (Gillies et al., 2005; Kuhns et al., 2010). This problem is also present on paved roads due to non-exhaust emissions including tire, brake and road related wear (Hussein et al., 2008; Hichri et al., 2019).

Studies on unpaved roads (USEPA, 1995; Etyemezian et al., 2003; Gillies et al., 2005; Kuhns et al., 2010) have shown that dust emissions are dependent on vehicle weight and speed as well as on the silt content (% of particles < 75 µm) of the road. These roads are built from compacted soils that degrade as vehicles travel, resulting in the accumulation of particles on the surface (Le Vern et al., 2020a; Le Vern et al., 2020b). However, no study has investigated dust emissions as a function of the level of degradation of the unpaved road surface yet. Similarly, Gillies et al. (2005) found that vehicle type did not influence emissions. Nevertheless, the use of accessories to control particle lift (such as mud flaps) has not been studied to date.

The main objective of this study is to analyze the effect of the level of surface degradation of an unpaved road on the dust emission. The degradation is characterized by the dust loading on the surface, i.e. the mass of particles per unit area. Different amounts of particles had been poured on a test track before vehicles were driven on it. Several types of particles were studied in order to identify the convenient parameter governing dust lift. The effect of vehicle type and mud flaps on this phenomenon is also studied. For this purpose, a light passenger car and a 4x4 equipped with mud flaps were driven at different speeds over the particles. An analysis of the mechanical parameters of tire/surface contact is also performed by means of a dynamometric wheel fitted to the passenger car.

The results of the study apply to the topic of unpaved roads but can be extended to the problem of particulate contamination of asphalt roads.

The methodology used for this study is described in the second part of this paper, followed by a presentation of the results and a discussion. This paper ends with the different conclusions that can be drawn from the experiments.

2. Methodology

2.1 Vehicles used and dynamometric wheel

Two vehicles were used during the tests: a Renault Clio III and a 4x4 Ford Ranger. The first one was chosen because it is one of the best-selling cars in Europe and is representative of small passenger cars. The 4x4 is much more massive (unladen weight of about 2 tons against 1 ton for the Clio) and has larger dimensions. Moreover, it is more likely to be used on unpaved roads and earthworks runways. Figure 1 shows these two vehicles. The Clio has about half the ground clearance of the 4x4 (120 mm vs. 229 mm). From a dimensionless point of view, the ratio of ground clearance to empty height (H/G as shown in Figure 1) is also different between the two vehicles (0.08 for the Clio and 0.13 for the 4x4).

The Clio was also instrumented with a Kistler RoadDyn S625 dynamometer wheel. This device was mounted on the right front wheel of the vehicle (see its location in Figure 3-a). It allows the continuous measurement of longitudinal, vertical and transverse forces and torques applied to the wheel using Wheatstone bridge-mounted strain gauges. Its acquisition frequency is 100 Hertz.

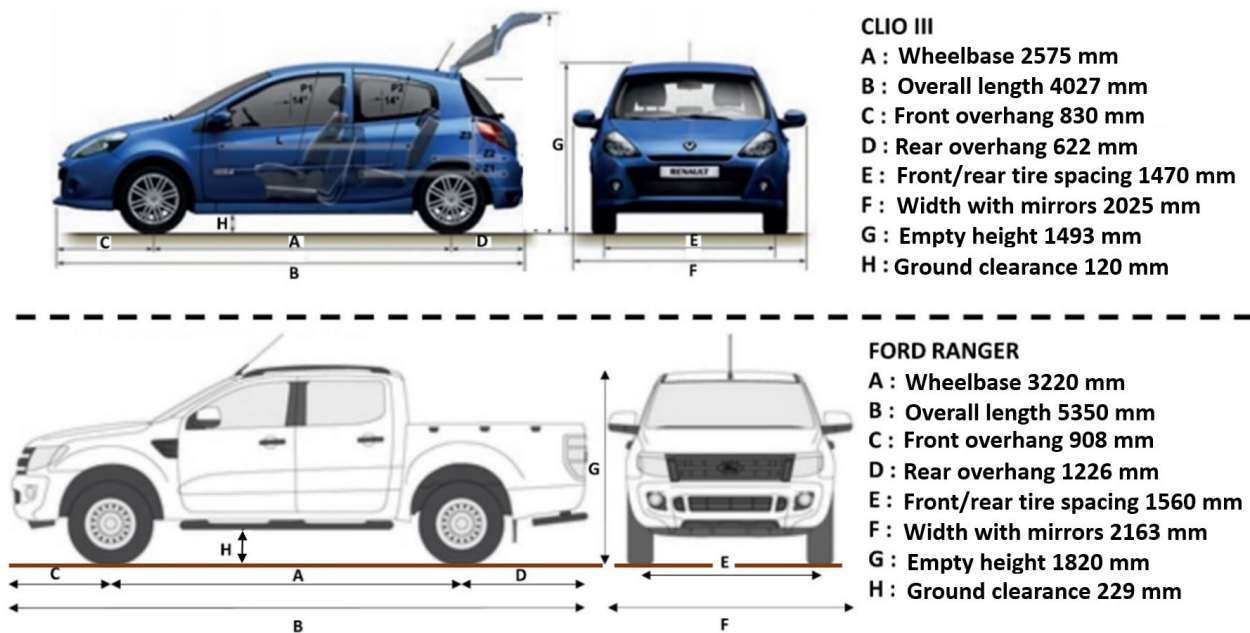


Figure 1: Dimensions of the two vehicles

2.2 Particles under study

In previous studies about dust generation during vehicle traffic on unpaved roads, there is often only one geotechnical criterion for characterizing the soil: the percentage of particles smaller than 75 μm (USEPA, 1995; Etyemezian et al., 2003; Gillies et al., 2005; Muleski et al., 2005; Kuhns et al., 2010). The United Soil Classification System designates this percentage as the “silt content”. Results have shown that the higher the silt content, the more dust will be emitted, all other things being equal. For this study we have chosen to work with particles having approximately the same percentage below 75 μm . Thus, we will be able to verify if this criterion is sufficient to characterize particle lift (if so we will measure similar dust emissions with the different soils) or if it is required to take into account other geotechnical parameters.

Four types of particles were used for the tests: a clay mixture composed with montmorillonite and illite (cosmetic green clay CATTIER) and three silty soils sampled from different earthwork sites in Europe: Val d'Europe and Strasbourg in France, Marche les Dames in Belgium. These soils have been selected because they have similar silt contents (between 95 and 100%) but their other geotechnical properties differ, as shown in Figure 2. In this Figure, the Liquid Limit and Plastic Limit are parameters that quantify the cohesion of the soil. They have been measured according to ISO 17892-12:2018 (ISO, 2018). Together with the granulometric properties (passing at 2 μm and 75 μm), they allow the classification of the particles. In Figure 2, we present their classification according to the American Society for Testing Material standard (ASTM, 2017) and the French Guide for road earthworks (GTR, 2000).

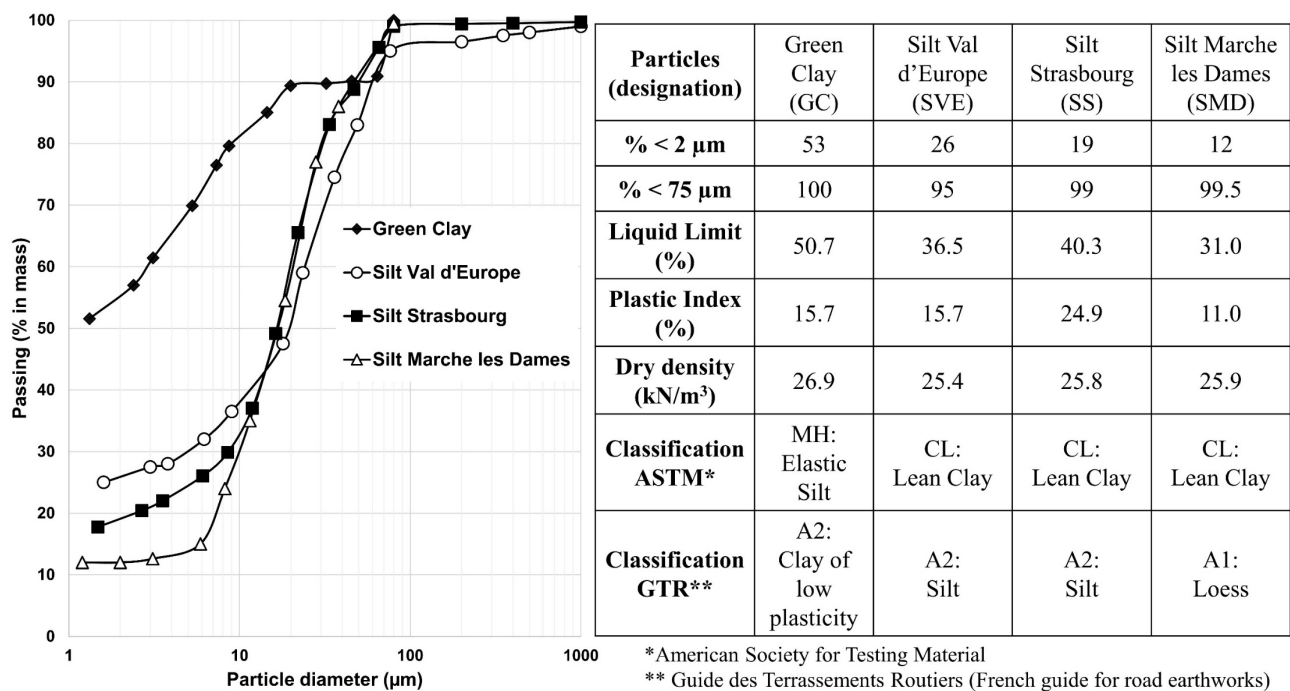


Figure 2: Particle size distributions and geotechnical properties of the soils

2.3 Experimental protocol

In order to ensure particles being free of moisture during the tests, they were previously dried in an oven at 105°C for 24 hours. They were then sieved to break up any aggregates and packed in plastic bags. Before each test, the particles were spread homogeneously on the track along two lines each 3 m long and 0.3 m wide and spaced apart from each other by a distance corresponding to the spacing between the two tires of the vehicle (1.47 m for the Clio and 1.56 m for the 4x4). The width of the lines was chosen to be greater than the width of the vehicle tires (20 cm for the Clio and 25 cm for the 4x4). The length was chosen for practical reasons related to the quantities of particles available. Three quantities of particles per unit area were tested: 200, 400 and 600 g.m⁻². These quantities correspond to three distinct soil degradation states (low, medium and high) highlighted in a previous study (Le Vern et al., 2020b). The two lines were delimited by markings on the ground on which wooden frames were placed. The necessary quantity of particles was poured into these frames and then spread evenly with a brush. A weather station was on the side of the road to measure temperature, relative humidity as well as wind speed and direction. The tests took place after 9 days without precipitations, under conditions of relative humidity ranging from 50 to 80% and temperature ranging from 17 to 25°C. Figure 3 shows the experimental layout.

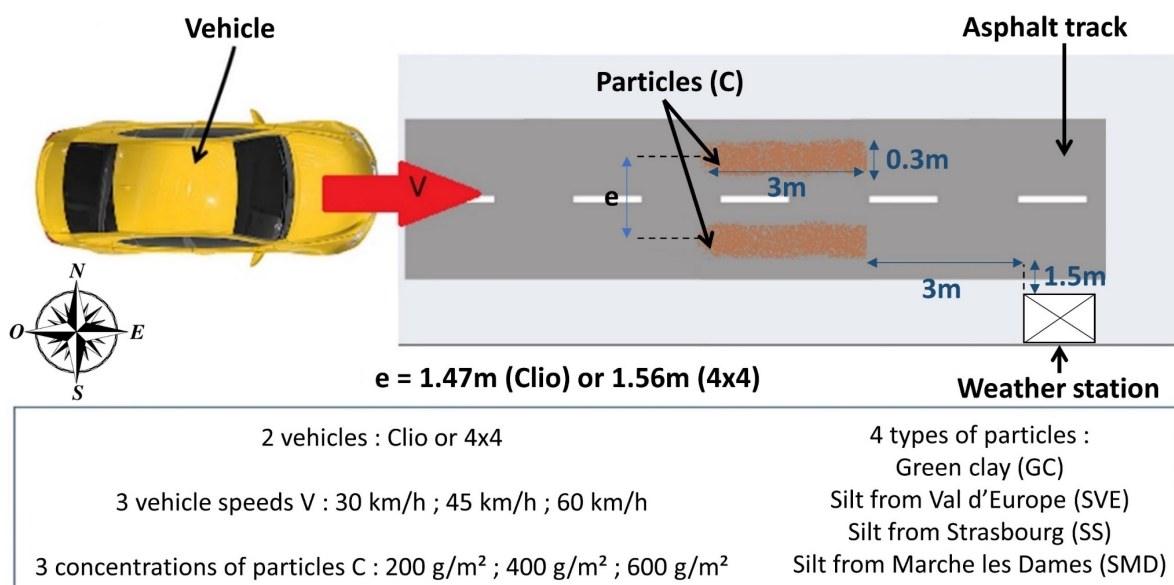


Figure 3: Experimental layout of the tests on the track (diagram not to scale)

Each test consisted in running one of the two vehicles at a predefined speed (30, 45 or 60 km.h⁻¹) over one type of particles previously poured on the ground at a given mass per unit area (200, 400 or 600 g.m⁻²). The speed of 30 km/h corresponds to the traffic conditions generally imposed when the risk of dust is important (especially on construction sites). The speed of 45 km/h is a speed frequently reached in cities or on construction sites. Working at 60 km/h allows to study the effect of doubling the speed compared to 30 km/h.

The test track was made of asphalt concrete to ensure that the vehicle blew away only the particles that had been poured on the surface. Conducting the tests on an unpaved road would not have controlled this parameter. This experimental configuration makes it possible to extend the results obtained to the problem of particle emission due to contaminations of asphalt mixes. These contaminations nevertheless generate smaller quantities of particles than those studied here.

During the tests, an optical particle counter measured the concentrations of suspended dust by particle aspiration directly behind the right rear tire of the vehicle. It is a dust analyzer PALAS Fidas Mobile equipped with a pump that sucks the particles contained in the ambient air. These particles pass through a beam of LED light which is then scattered at an angle that depends on the size of the particle (Mie scattering theory). The estimation of the particle size is performed with a photomultiplier that measures the scattered light. Combined with a counting algorithm, the mass concentration of particles per unit volume (µg/m³) can be estimated.

Figure 4 shows the two vehicles (Figure 4-a for the Clio III and 3-b for the 4x4) as well as the installation of the particle counter in the 4x4 (Figure 4-c). For these measurements, the inlet of the suction pipe for particle aspiration was located in the median plane of the right rear wheel, 30 cm from the rear edge of the tire and 20 cm above the ground (Figure 4-d). The distance between the pipe and the tire was the same for the measurements with the Clio III, except that the pipe was 10 cm above the ground. These pipe positions are related to practical considerations due to the vehicles' geometry.

After each test, the particles remaining on the ground were blown to the sides of the road using a leaf blower. A manual sweep of the road was also performed to ensure that the particles in the asphalt voids were removed.

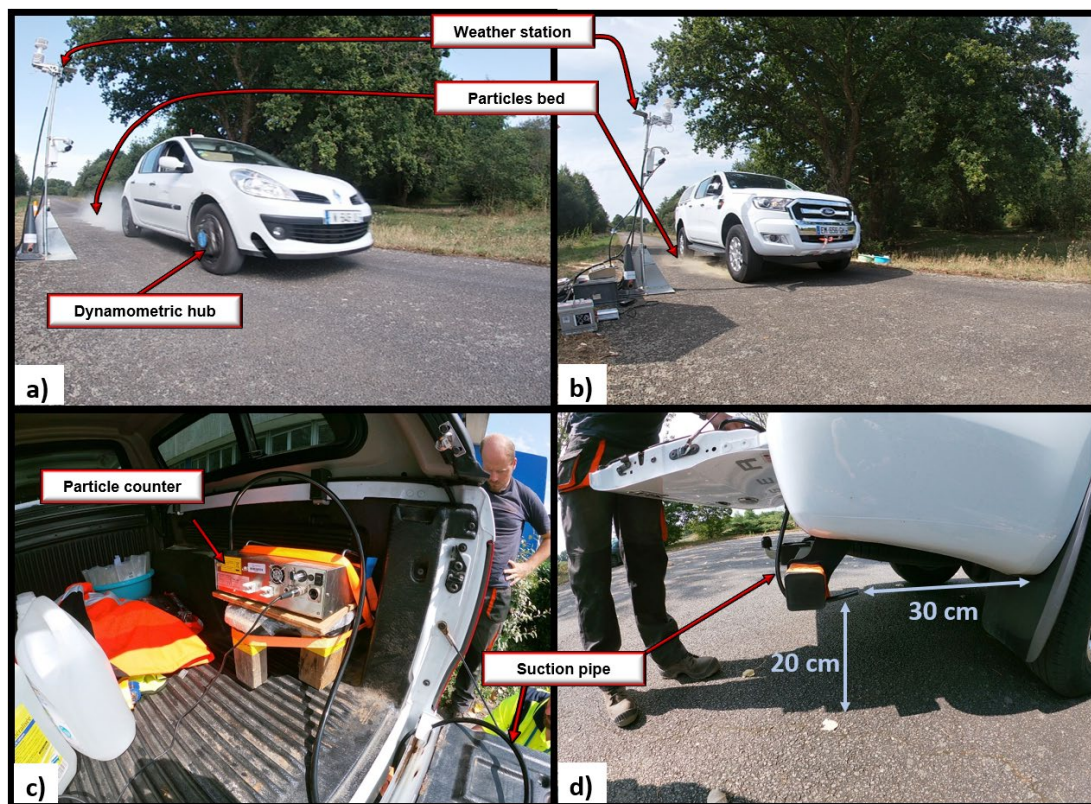


Figure 4: Vehicles used for the experiments: a) Renault Clio III and b) 4x4 Ford Ranger; On-board measurements with c) installation of the particle counter in the 4x4 and d) suction of particles directly behind the tire.

A total of 47 tests were carried out over three days by varying the different parameters (vehicle type and speed, particle type and mass per unit area). Table 1 shows all the tests carried out. Not all the possible configurations of parameters could be tested for practical reasons of time and quantity of particles available. Some configurations were tested several times for two reasons:

- To check the repeatability of the measurements by performing the same test twice in a row;
- To highlight the effect of meteorological parameters on dust emission by performing the same test in the morning and afternoon.

Table 1: Configurations of the tests

Vehicle	Particles*	Speed	Concentration	Vehicle	Particles*	Speed	Concentration		
Clio III	GC	30 km/h	400 g/m ²	4x4 Ford Ranger	GC	30 km/h	400 g/m ²		
		60 km/h	200 g/m ²			45 km/h	400 g/m ²		
			400 g/m ²			60 km/h	200 g/m ²		
			600 g/m ²				400 g/m ²		
	SVE	30 km/h	400 g/m ²		SVE	30 km/h	400 g/m ²		
		60 km/h	200 g/m ²			60 km/h	200 g/m ²		
			400 g/m ²				400 g/m ²		
			600 g/m ²				600 g/m ²		
	SS	30 km/h	200 g/m ²		SS	30 km/h	400 g/m ²		
			400 g/m ²			45 km/h	400 g/m ²		
		45 km/h	200 g/m ²			60 km/h	200 g/m ²		
			400 g/m ²				400 g/m ²		
			200 g/m ²				600 g/m ²		
			400 g/m ²				600 g/m ²		
		SMD	30 km/h			200 g/m ²	SMD	30 km/h	400 g/m ²
						400 g/m ²		60 km/h	400 g/m ²
	45 km/h		200 g/m ²		600 g/m ²				
			400 g/m ²						
	60 km/h		200 g/m ²	* GC: Green Clay SVE: Silt from Val d’Europe SS: Silt from Strasbourg SMD: Silt from Marche les Dames					
			400 g/m ²						
			200 g/m ²						
			400 g/m ²						
	600 g/m ²								

2.4 Data processing

2.4.1 Analysis of particle counter measurements

The particle counter provides the evolution of the concentration of the different classes of particles (PM₁₀, PM₄, PM_{2.5} and PM₁) at a data rate of 1 Hertz. We did not analyse particles beyond PM₁₀ because it is the upper limit of the apparatus. Moreover, particles larger than 10 µm have high deposition velocities (Petroff and Zhang, 2010) and therefore fall rapidly to the ground, within 100 meters from their emission source (Veranth et al., 2003). They are also much less hazardous to health than the finest particles (Autrup, 2010).

Figure 5-a shows an example of particle concentration measured during a test performed with the 4x4 at 30km/h on 400g/m² of Val d'Europe silt particles. Figure 5-b presents the parameters that are taken into account in the present study for each curve, namely: the area under the curve, the maximum value and the mean value. The area under the curve is determined by the trapezoidal method and allows the definition of an "emission coefficient" ϕ given in µg.s.m⁻³. The mean value is assessed by considering the measurements between the beginning of the concentration rise before the peak and the return to a "normal" concentration (defined as the average of the PM₁₀ concentrations measured between two tests, i.e. 10 µg.m⁻³). It is arbitrarily considered that the peak concentration begins when the "normal" concentration is exceeded by a factor of 100 (that is PM₁₀ concentration larger than 1000 µg.m⁻³) and ends when it falls below 10 µg.m⁻³. According to this procedure, it is possible to highlight the moment when the vehicle is driving over the particles.

As the tests were carried out under subisokinetic conditions, the measurements underestimated the concentrations of the finest particles (Wilcox, 1956; Belyaev and Levin, 1974). We therefore focus our analysis on the coarsest particles, i.e. PM₁₀ concentrations. Moreover, it is the range of particles generally studied in the literature on dust emissions on unpaved roads (USEPA, 1995; Etyemezian et al., 2003; Gillies et al., 2005; Kuhns et al., 2010).

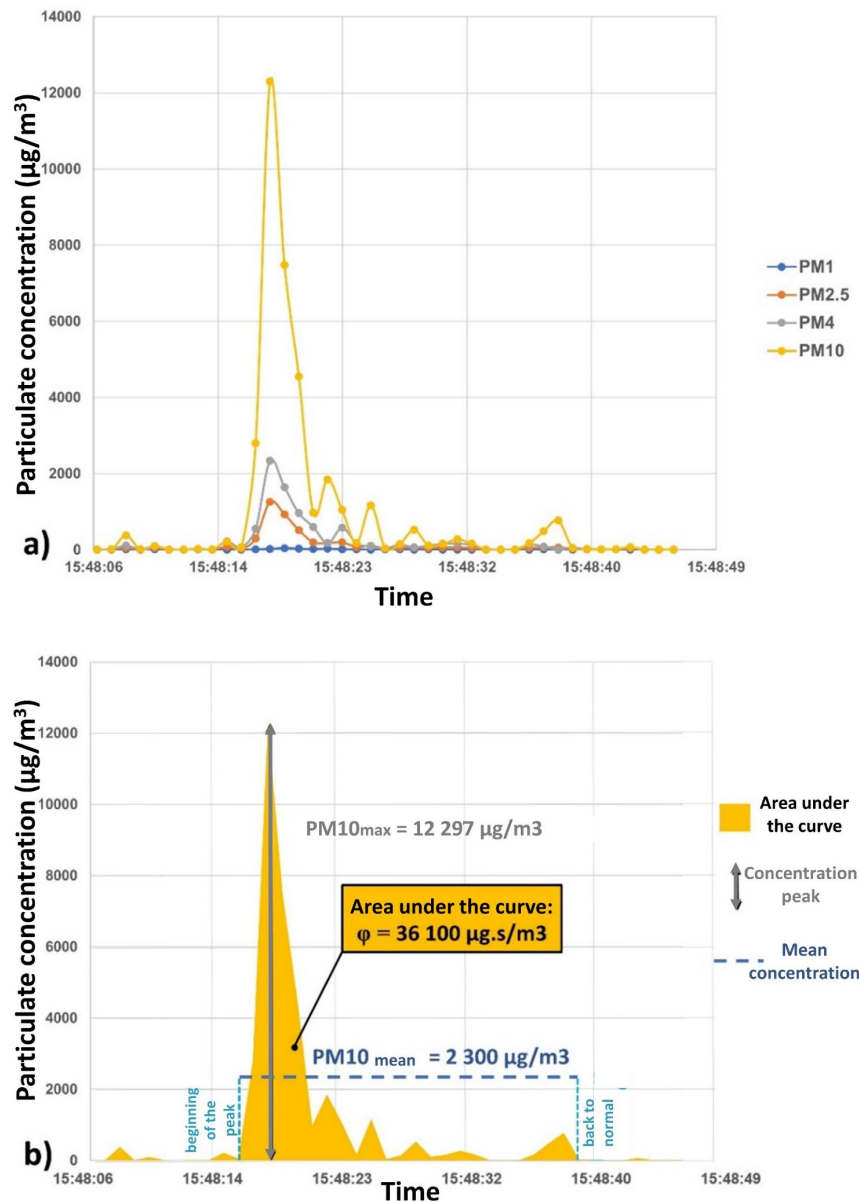


Figure 5: a) Evolution, for one of the tests, of the particle concentrations measured behind the tire as a function of time; b) Highlighting, for the PM_{10} curve, of the parameters considered in the study

2.4.2 Analysis of dynamometric wheel measurements

The dynamometric wheel allows real-time measurement of the forces and moments applied to the right front wheel of the Clio III. In the context of the study, the influencing parameters on the lift of the particles are:

- The longitudinal force F_x which characterizes the friction between the tire and the road;
- The vertical force F_z which characterizes the action of the vehicle weight in the tire/road contact mechanics;
- The moment M_y which also characterizes the tire/road friction.

The vertical force F_z did not vary much during the tests ($F_z \approx 3750 \text{ N} \pm 3\%$) since the masses of the Clio and its driver were always the same. In addition, the road smoothness was of good quality and the speed of the vehicle was constant so the dynamic variations were attenuated by the shock absorbers. The parameter F_z is therefore not taken into account in the analysis.

Figure 6-a shows an example of the evolution over time of the vehicle speed, F_x and M_y for one of the tests (Clio driving at 45 km/h over 200g/m² of Marche les Dames silt particles). The figure shows the total duration of a test characterized by an evolution of the vehicle speed in three phases: acceleration, steady speed and then deceleration. During the acceleration and deceleration phases, the parameters F_x and M_y undergo significant variations due to gear changes and braking. For the analysis, the average values of these parameters ($F_{x_{\text{moy}}}$ and $M_{y_{\text{moy}}}$) are taken into account during the

period when the tire is in contact with the particles (Figures 6-b and 6-c). This period takes place in the stable speed phase, which explains why the variations in F_x and M_y are less important than during the acceleration and deceleration phases.

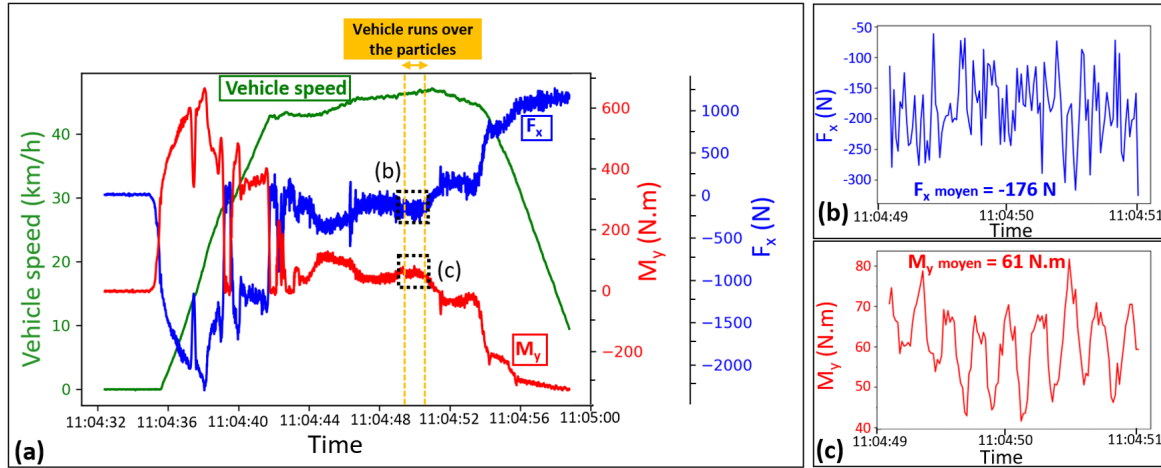


Figure 6: (a) Time evolution, for one of the tests, of the vehicle speed (green curve), the longitudinal force (blue curve) and the vertical moment (red curve) applied to the vehicle wheel. Curves (b) and (c) show respectively a zoom on the evolutions of the longitudinal force and the vertical moment during the passage of the vehicle on the particles.

3. Results and discussion

3.1 Repeatability of the results

Some configurations were tested several times to check the repeatability of the results (the acronyms are those used in Table 1):

- The SS-60km/h-200g/m²-Clio configuration was reproduced twice
- The SMD-60km/h-200g/m²-Clio configuration was reproduced four times
- The SMD-60km/h-400g/m²-Clio configuration was reproduced twice
- The GC-60km/h-200g/m²-Clio configuration was reproduced twice

Repeatability tests were done at 60 km/h because this is the speed for which there are the most disturbances and a priori the most lifted particles. For each configuration, the average value is determined for $PM10_{\max}$, ϕ and $PM10_{\text{mean}}$. The minimum and maximum values are also considered. The average gap for each configuration is given by equation (1):

$$\text{average_gap}(\%) = \frac{\text{Value}_{\max} - \text{Value}_{\min}}{\text{Value}_{\text{mean}}} \times 100 \quad (1)$$

Figure 7 shows the corresponding results.

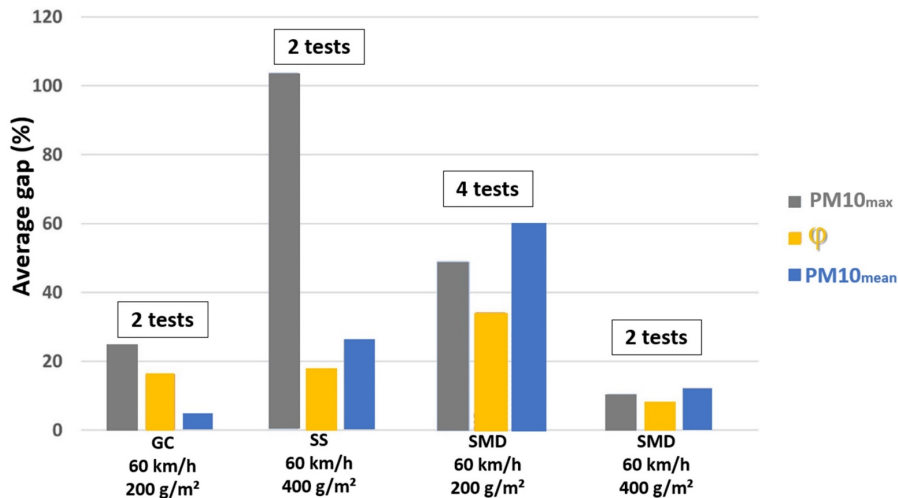


Figure 7: Average gaps for the repeatability tests

The overall average gap is 47% for $PM_{10_{max}}$, 19% for ϕ and 26% for $PM_{10_{mean}}$. The large deviations observed for the peaks of concentration are due to the very strong dependence of this parameter on the particle aspiration kinematics. Indeed, their distribution in a dust plume is chaotic and more or less particles can be recorded at the same time in the particle counter. Thus, for the same dust plume, the concentration peak can vary significantly depending on the location of the aspiration. Therefore, it is more relevant to look at the evolution of the amount of particles sucked up as a function of time. As such, the parameter ϕ appears to be the most appropriate to characterize the dust plume generated. It is also the parameter with the best repeatability.

The observed variations are not due to the wind as it has no effect on the particles directly behind the vehicle tires. On the one hand, the wind speeds were low during the tests (between 2 and 9 km/h). On the other hand, it was visually observed during the experimental campaign that the effect of the wind appears several seconds after the particles are suspended, when they have reached a certain height (about 1 meter). Below this height, it is the aerodynamic phenomena related to the wake of the vehicles that entrap the particles, particularly in the counter-rotating vortices generated behind the wheels (Mercker and Berneburg, 1992).

Some tests were carried out both in the morning and in the afternoon with a strong variation in relative humidity (about 80% in the morning and 60% in the afternoon). However, small differences were observed for dust emissions between these tests (less than 8% for the ϕ parameter). This suggests that relative humidity does not appear to be a parameter influencing the lift of particles directly behind the tire for the presenting tests. Indeed, the vehicle was running on the dry particles few minutes after they were poured on the ground while moisture exchanges take hours or even days to take place between dry particles and the atmosphere (Ravi et al., 2006).

In the following, the results are presented with error bars that take into account the average gaps that were defined above.

3.2 Emission coefficients

For the sake of brevity, we focus the analysis on the parameter with the best repeatability: the emission coefficient ϕ . Figure 8 shows its evolution as a function of the vehicle speed and of the particle concentration for the Clio III tests. Overall, it appears that an increase in speed leads to an increase in ϕ . For the same concentration of particles on the ground, doubling the speed of the Clio III (from 30 to 60 km/h) leads to a multiplication of the emission coefficient by a factor ranging from 1.5 (for green clay at 400 g.m⁻², Figure 8-a) to 5.7 (for Strasbourg silt at 200 g.m⁻², Figure 8-c).

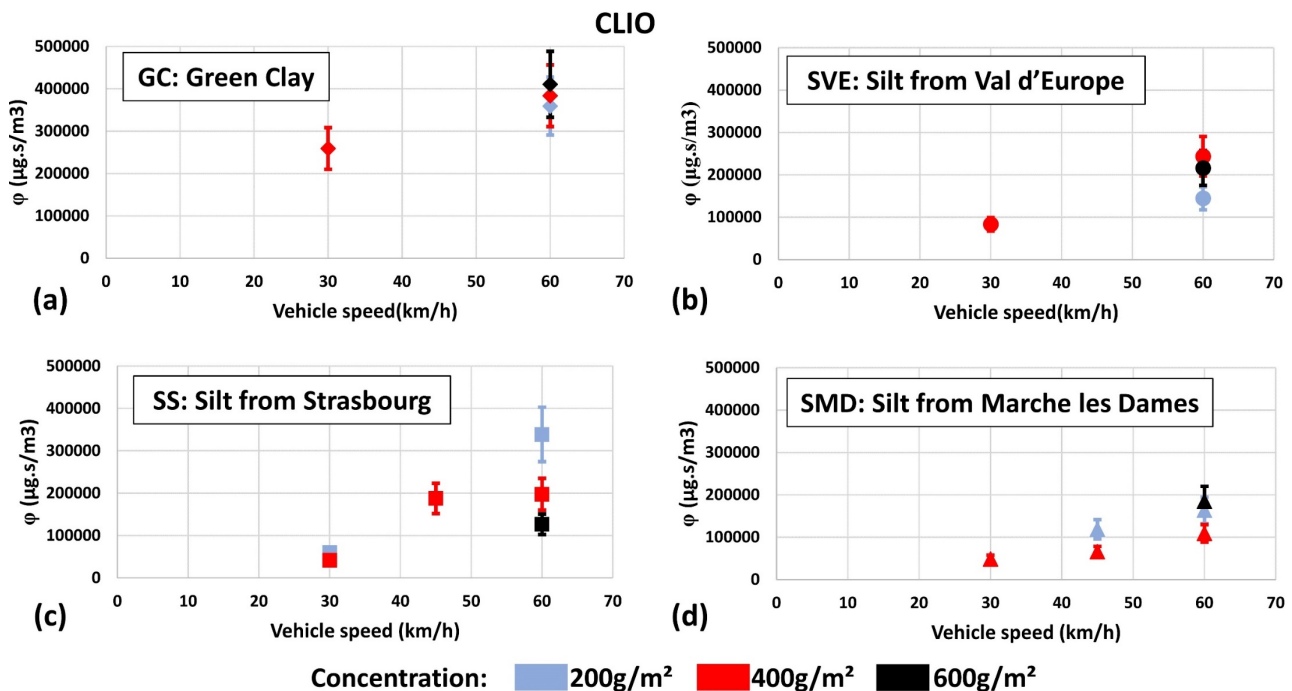


Figure 8: Emission coefficients for the Clio tests with particles of (a) green clay, (b) silt from Val d'Europe, (c) silt from Strasbourg and (d) silt from Marche les Dames

For the same speed of the vehicle, an increase in the concentration of particles on the ground can lead to a decrease in the emission coefficient. Indeed, it is observed for the tests at 60 km/h on the Val d'Europe silt (Figure 8-b), for the tests at 30 and 60 km/h on the Strasbourg silt (Figure 8-c) and for the tests at 45 and 60 km/h on the Marche les Dames silt (Figure 8-d). It cannot be explained by the weather conditions as they do not affect the measurements as indicated in the previous section. To get a better understanding of the processes involved, a Principal Component Analysis (PCA) integrating the longitudinal force F_x and the vertical moment M_y is performed (Figure 9).

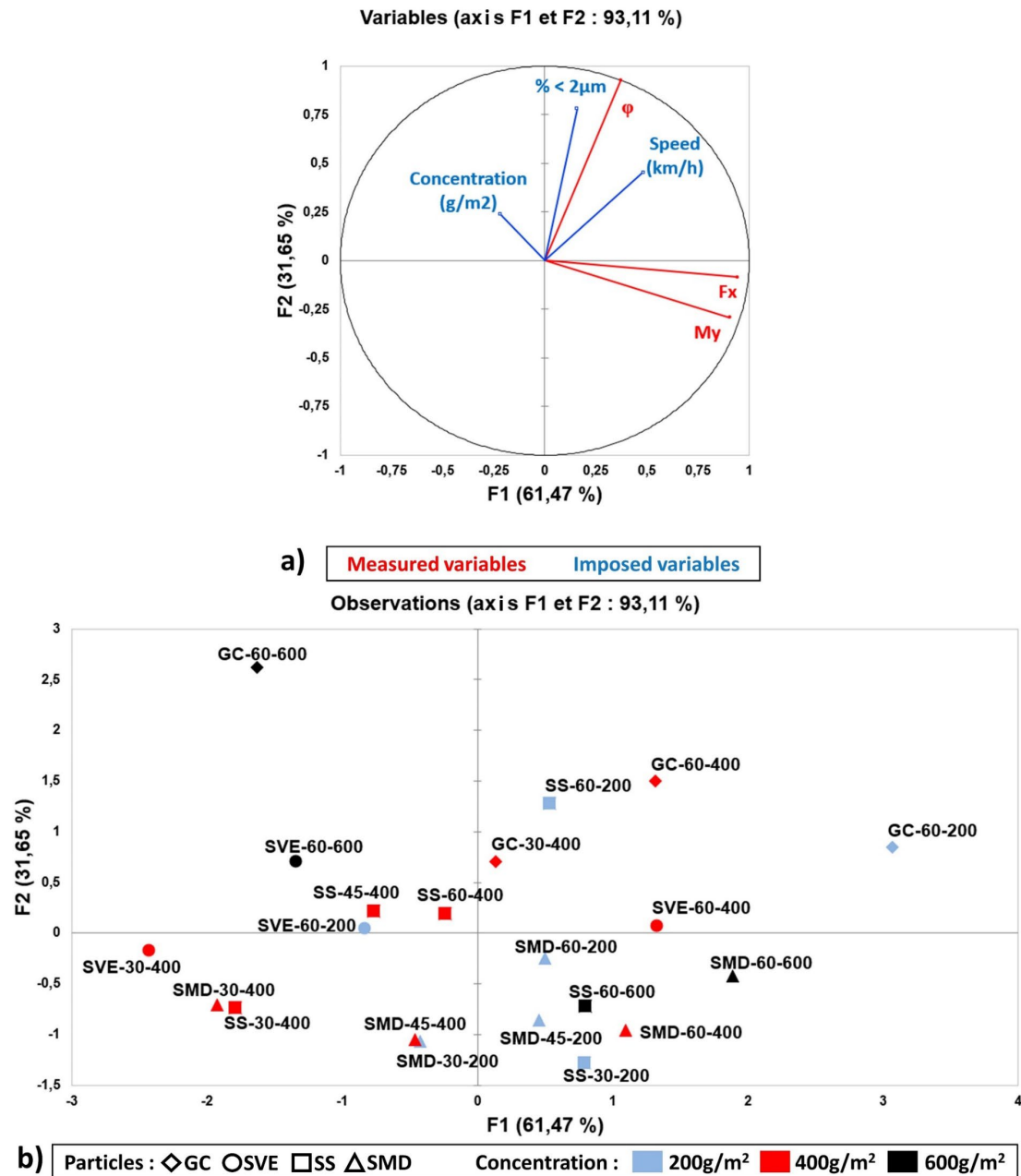


Figure 9: Principal Component Analysis of the Clio tests. a) Circle of correlations for the variables and b) visualization of the tests in the correlation space. Each test is designated by: Type of particles-vehicle speed-concentration

Figure 9-a shows that the emission coefficient ϕ is particularly correlated with the percentage of particles smaller than $2\ \mu\text{m}$ ($R^2=0.77$) and with the vehicle speed ($R^2=0.60$). The variables F_x and M_y are highly correlated with each other ($R^2=0.78$) since they represent the same physical phenomenon. The correlation is not 100% because the F_x measurement is noisy due to slip-free rolling conditions. According to the Principal Component Analysis theory, the F_1 and F_2 axes allow to define the plane that maximizes the dispersion of the experimental data in order to visualize the cloud of results as well as possible. The circle of correlations is such that the abscissa axis F_1 is highly correlated to F_x and M_y (correlations of 94% and 91% respectively). The F_2 axis is highly correlated to ϕ ($R^2=0.93$). Thus, the analysis of the observations on these two axes (Figure 9-b) does not allow to conclude about the effect of the parameters F_x and M_y on the coefficient ϕ for concentrations of $200\ \text{g/m}^2$ and $400\ \text{g/m}^2$. Indeed, the clouds of the blue and red symbols are too scattered. For the highest concentration ($600\ \text{g/m}^2$, black symbols in Figure 9-b), a decreasing trend of ϕ appears when F_x and M_y increase. This is probably a phenomenon of aggregation of the particles caused by the tire. Indeed, the tire compacts the bed of particles as it rolls over it, forming aggregates that are then torn off by shear force (Le Vern et al., 2020b). The greater the shear forces, the more numerous these aggregates are. Many of them have sizes greater than $10\ \mu\text{m}$ and are therefore not measured by the particle counter (hence the decrease of the parameter ϕ which only takes into account PM_{10}). This mechanism seems to appear when the quantity of particles on the ground is large and is particularly marked for coarser particles (silts from Strasbourg and Marche les Dames). This phenomenon of aggregation has been previously highlighted for soil degradation by vehicles (Le Vern et al., 2020b).

Figure 10 shows the emission factors as a function of vehicle speed and particle concentration for the Ford Ranger 4x4 tests. By analyzing Figures 8 and 10, it can be seen that the orders of magnitude of the emissions are lower for the tests with the 4x4 compared to those carried out with the Clio. Since the 4x4 is more massive, one could theoretically have expected a higher generation of particles. This is not the case because semi-rigid mud flaps were present behind the tires of the 4x4 (visible in Figure 4-d). They may prevent dust resuspension.

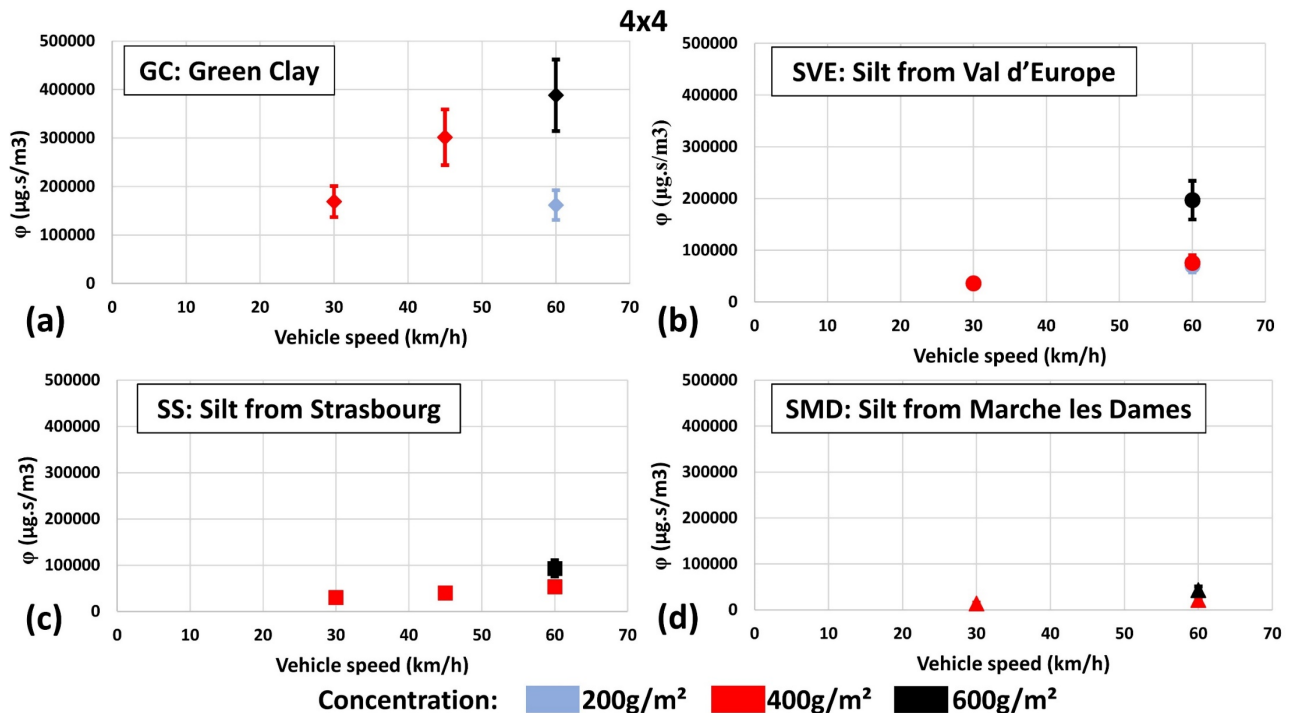


Figure 10: Emission coefficients for the 4x4 tests with particles of (a) green clay, (b) silt from Val d'Europe, (c) silt from Strasbourg and (d) silt from Marche les Dames

In order to quantify the difference in dust emissions between the two vehicles, Figure 11 shows the comparison of the coefficient ϕ corresponding to the tests with the Clio and those with the 4x4. The gaps are calculated using equation (1). It can be seen that the average difference between the emissions of these two vehicles is all the greater the lower the clay content of the particles. The effect of mud flaps seems to be more marked for coarse particles than for very fine particles. For confirmation, it would be necessary to carry out the tests with the same vehicle with and without mud flaps.

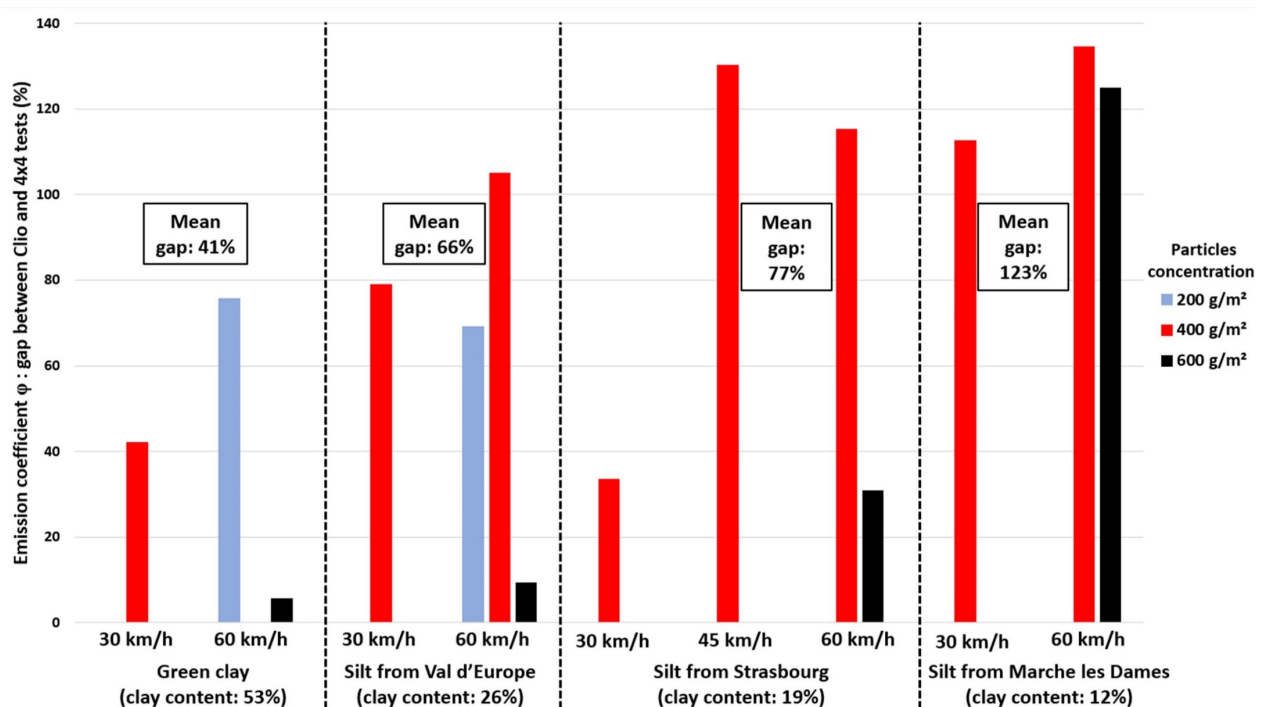


Figure 11: Emission coefficients: gap between Clio and 4x4 tests calculated using equation (1)

In general, Figures 8 and 10 show different dust emissions depending on the type of particle. However, the particles used in the study have almost the same percentages of particles below 75 μm (between 95% and 100%). It is therefore evident that this parameter, although often used in the literature, is not sufficient to characterize the dust emission related to vehicle traffic. Figures 9 and 11 suggest that the percentage of particles below 2 μm would be a more relevant parameter to quantify the lift of particles.

4 Conclusions

In this study, the dust emissions linked to the traffic of a Renault Clio III and a Ford Ranger 4x4 were studied. Four types of particles (green clay, silt from Val d'Europe, silt from Strasbourg and silt from Marche les Dames) were poured on a test track at different mass per unit area (200 g/m², 400 g/m² and 600 g/m²). Vehicles were driven over the particle beds at different speeds (30, 45 and 60 km/h) and the concentrations of suspended dust were measured directly behind the tire of the vehicle. Weather conditions were measured on the roadside.

The results of the study lead to the following conclusions:

- To quantify the lift of particles, it is not relevant to consider only their silt content (% < 75 μm). The percentage of particles < 2 μm seems to be a more appropriate parameter.
- Although it is often the sole data considered in the literature, the weight of the vehicle is not a sufficient criterion to characterize its dust emission potential. It appears from this study that the impact of accessories such as mud flaps behind the tires could be significant. Vehicle aerodynamics is also a relevant criterion that needs to be taken into account.
- The effect of vehicle speed on dust emission is not a linear process. Indeed, doubling the speed can lead to a multiplication of the emission coefficient by a factor of 5.7. The effect of speed depends on the type of vehicle and the type of particles.
- The results suggest that a phenomenon of particle aggregation by the tire may appear. It seems to be all the more marked as the concentration of particles on the ground is important. This phenomenon would be characterized by the suspension of coarser particles (larger than 10 μm). The measurement of the particle size distribution of all suspended aerosols would be necessary to validate this hypothesis.

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