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## Effects of soil surface degradation and vehicle momentum on dust emissions and visibility reduction from unpaved roads

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1

### 2 Abstract

3 Unpaved roads are built on the basis of soil compaction. Therefore, the operation of vehicles on these roads results in dust  
4 emissions. As the number of passing vehicles increases, the soil surface gradually degrades under shearing caused by the  
5 tires. This enhances emissions and reduces visibility, increasing health and environmental related issues as well as the  
6 risk of collisions.

7 The present study was conducted to quantify the effect of surface degradation on dust emissions from several types of  
8 vehicles travelling on different soils and assess the evolution of security risks in the vicinity of unpaved roads.

9 Three types of vehicles (a passenger car, a 4WD vehicle and a truck) have been run on an experimental road covered by  
10 four different types of soil particles. Each test consisted in driving one of the vehicles at a given speed (30, 45 or 60 km.h<sup>-1</sup>)  
11 on one of the types of particles previously spread on the road at a given mass per unit area (200, 400 or 600 g.m<sup>-2</sup>). The  
12 mass concentration of resuspended particles was measured from the roadside using an Optical Particle Counter (OPC)  
13 while the visibility reduction was simultaneously recorded at the same location. The results show that PM<sub>10</sub> emission  
14 factors increase linearly with vehicle momentum for vehicles without mud flaps. The presence of such appendices can  
15 reduce dust emissions by a factor of 7. Moreover, although not considered in conventional models, the state of degradation  
16 of unpaved roads may be a key factor regarding dust emissions. The study has also shown that soils with similar silt  
17 content can result in very different emission factors. An emission model has then been developed, based on the clay  
18 content of the particles. Indeed, this geotechnical parameter is more relevant to characterize the fine soil propensity to  
19 generate dust. PM<sub>10</sub> emissions are correlated with the reduction of visibility according to a power law for the truck tests.

20 An interesting finding of this work is the fact that the present results can be extended to earthwork sites where visibility  
21 problems require spraying of water on the traffic lanes. Improving the modeling of the mechanisms generating dust lift  
22 and the associated safety risks is indeed essential for a more efficient use of water on construction sites.

23

24 **Keywords:** Dust re-suspension, Vehicle traffic, Unpaved road, Surface degradation, Test track, Visibility

25

### 26 Nomenclature

27	c	clay content of the particles	(%)
28	C	PM <sub>10</sub> mass concentration corrected	(μg.m <sup>-3</sup> )
29	C <sub>measured</sub>	PM <sub>10</sub> mass concentration measured by the optical particle counter	(μg.m <sup>-3</sup> )
30	d <sub>p</sub>	Particle diameter	(m)
31	D	Soil surface degradation	(kg.m <sup>-2</sup> )
32	EF <sub>industrial</sub>	Mass of PM <sub>10</sub> per vehicle kilometer travelled (vkt) on industrial unpaved roads	(g.vkt <sup>-1</sup> )
33	EF <sub>model</sub>	Model developed in this study for mass of PM <sub>10</sub> per vehicle kilometer travelled	(g.vkt <sup>-1</sup> )
34	EF <sub>public</sub>	Mass of PM <sub>10</sub> per vehicle kilometer travelled (vkt) on public unpaved roads	(g.vkt <sup>-1</sup> )

35	$L_c$	Characteristic length	(m)
36	$M$	Moisture content of the particles	(%)
37	$M_{om}$	Vehicle momentum ( $S \times W$ )	(kg.m.s <sup>-1</sup> )
38	$N$	Number of PM <sub>10</sub> mass concentration values measured	(-)
39	$\overline{PM}_{10}$	Mean PM <sub>10</sub> mass concentration	(µg.m <sup>-3</sup> )
40	$s$	Silt content of the soil (% of particles with $d_p < 75\mu m$ )	(%)
41	$S$	Vehicle speed	(m.s <sup>-1</sup> )
42	$S_{tk}$	Stokes number of the particle ( $\frac{1}{18} \frac{\rho_p d_p U_0}{\mu L_c}$ )	(-)
43	$U$	Sampling velocity	(m.s <sup>-1</sup> )
44	$U_0$	Wind velocity	(m.s <sup>-1</sup> )
45	$V$	Visibility	(km)
46	$W$	Vehicle weight	(kg)
47	$\Delta t$	Duration over which the dust plume impacts the optical particle counter	(s)
48	$\Delta z$	Dust plume vertical interval	(m)
49	$\eta_{asp}$	Aspiration efficiency of the optical particle counter	(%)
50	$\eta_{sample}$	Sampling efficiency of the optical particle counter	(%)
51	$\eta_{trans}$	Transport efficiency in the nozzle of the optical particle counter	(%)
52	$\theta$	Angle between the wind and sampling directions	(°)
53	$\mu$	Dynamic air viscosity	(kg.m <sup>-1</sup> .s <sup>-1</sup> )
54	$\rho_p$	Particle density	(kg.m <sup>-3</sup> )
55			

## 56 1. Introduction

57 The control of dust generated by human activities is a major objective for air quality improvement. The degradation of  
58 soils is a key factor for the resuspension of particles in the atmosphere. In particular, the traffic of vehicles on unpaved  
59 roads is a major source of dust emissions (Thenoux et al., 2007; Flores-Márgez et al., 2014). Unpaved roads are built on  
60 the basis of soil compaction without surface coating. Where contact between the soil and the vehicle wheels is made, the  
61 aggregates of soil particles can be torn off and then crumbled (Le Vern et al., 2020a). This leads to the formation of fine  
62 particles on the road surface, which can be lifted by shear stresses and turbulent aerodynamic processes induced by the  
63 passing vehicles (Etyemezian et al., 2003; Williams et al., 2008; Gérardin and Midoux, 2015; Le Vern et al., 2020b).  
64 Important amounts of dust are emitted through such mechanisms. Unpaved roads, for instance, are responsible for 30%  
65 to 50% of the PM<sub>10</sub> (particles having an aerodynamic diameter below 10µm) emissions in southern United States and  
66 northern Mexico (Kuhns et al., 2005). Studies often focus on PM<sub>10</sub> because it dominates the mass distribution of dust  
67 emitted by vehicles on sandy and silty soils (Pinnick et al., 1985).

68 Airborne dust particles cause environmental and public health related problems (Vardaka et al., 1995; Pope and Dockery,  
69 2006). They are also responsible for reduced visibility (Baddock et al., 2014) associated with significant collision risks in  
70 the areas of vehicle traffic (Lankarani et al., 2014; Ashley et al., 2015; Bhattachan et al., 2019). This concern is particularly  
71 important on earthmoving sites and quarries where the activities are highly dusty (Muleski et al., 2005; Faber et al., 2015;  
72 Noh et al., 2018). It is worth noting that dust emission is ranked as the second most common risk for many professionals  
73 of the construction sector (Serpell et al., 2013). Visibility reduction is often assessed through visual criteria, which lead  
74 to the spraying of water on the traffic lanes of the construction sites (USEPA, 1988). It should be noted, moreover, that  
75 no documents are currently available as guides on how much water should be used to reduce dust emission or on how the  
76 time interval between two sprayings could be accurately defined (NIOSH, 2012). For a better management of water, it is  
77 essential to quantify the evolution of the dust emissions induced by the vehicles on the road.

78 The most widely used model for estimating PM<sub>10</sub> emissions from vehicles on unpaved roads to date is “AP-42:  
79 Compilation of Air Emissions Factors” developed by the US Environmental Protection Agency (USEPA, 2006). For the  
80 vehicles operating on unpaved surfaces of industrial sites like mines and quarries, the emission factor  $EF$  estimation is  
81 given by Eq. (1):

$$EF_{industrial} = 422.85 \times \left(\frac{S}{12}\right)^{0.9} \times \left(\frac{W}{3000}\right)^{0.45} \quad (1)$$

82 and, for publicly accessible unpaved roads, Eq. (2) is used:

$$EF_{public} = 507.42 \times \frac{\left(\frac{S}{12}\right) \times \left(\frac{S}{13.4}\right)^{0.5}}{\left(\frac{M}{0.5}\right)^{0.2}} \quad (2)$$

83

84 where  $EF$  is the  $PM_{10}$  emission factor (mass of  $PM_{10}$  in grams emitted per vehicle kilometer travelled, i.e.,  $gPM_{10}.vkt^{-1}$ ),  
 85  $s$  is the surface material silt content (% of particles smaller than  $75 \mu m$ ),  $W$  is the mean vehicle weight (kg),  $S$  is the mean  
 86 vehicle speed ( $m.s^{-1}$ ) and  $M$  is the surface material moisture content (%).

87 In these models, the  $PM_{10}$  emission factor is considered constant regardless of the number of passing vehicles. They do  
 88 not take into account the evolving mechanisms of soil degradation, in particular tearing off and crumbling of particle  
 89 aggregates by tires (Le Vern et al., 2020a). Moreover, the surfaces on which the vehicles travel are only roughly described  
 90 through the sole criterion of the silt content. These two purely empirical USEPA models (Eq. (1) and (2)) can be applied  
 91 to the sites used to develop them but are difficult to generalize. Indeed, when comparing these models with field  
 92 measurements, some significant differences are observed, up to several orders of magnitude (Gillies et al., 2005; Muleski  
 93 et al., 2005, Kuhns et al., 2010). It is therefore essential to examine the dust emission mechanisms in greater depth in  
 94 order to improve the robustness of estimation models.

95 The objective of this research is first to examine the effects of unpaved road surface degradation on dust emissions.  
 96 Therefore, tests are conducted in which the degradation is characterized through the dust loading on the road surface, i.e.,  
 97 the mass of torn-off particles per unit area. Different quantities of particles are spread on the test track before the vehicle  
 98 is run on it. Various types of particles are considered in order to discuss the relevance of the “silt content” parameter in  
 99 emission models. The effect of vehicle momentum on dust emissions is assessed by driving three different types of  
 100 vehicles (a light passenger car, a 4WD vehicle equipped with mud flaps and a heavy truck) over the spread particles at  
 101 different speeds. Dust emissions on the side of the road are considered for this work. A companion paper (Le Vern et al.,  
 102 2021) examines the dust emissions in the wake of the vehicle tires.

103 The second purpose of this study is to investigate the safety risks caused by vehicle-induced dust plumes. Using the  
 104 measurements of the roadside concentrations of particulate matter and the corresponding visibility reduction at the same  
 105 location, a model is established linking visibility and suspended dust. The discussion is conducted with a view to  
 106 optimizing risk management by spraying water on the traffic lanes of the construction sites.

107 The methodology is presented in the second part of the paper, including a description of the vehicles, the test tracks, the  
 108 particles, the experimental procedure and data processing. Then, the results are detailed and discussed. The last section is  
 109 dedicated to conclusions and future research works.

110

## 111 **2. Materials and methods**

### 112 **2.1 Vehicles used and test tracks**

113 Three different vehicles are used for the tests: a Renault Clio III, a 4WD Ford Ranger and a Volvo FMX 450 truck. The  
 114 Renault Clio ranks among the best-selling cars in Europe and is representative of small passenger cars. The 4WD vehicle  
 115 is twice the mass of the Clio and has larger dimensions. Moreover, this car is more likely to be used on unpaved roads  
 116 and earthwork lanes. The Volvo FMX 450 is one of the largest trucks in its class (cab-over semi-trailers) for construction  
 117 and earthmoving works. Prior to testing, the truck's dump box has been filled with material and then used at its maximum  
 118 gross weight (approximately 32 tons). This configuration reflects the most severe conditions of heavy-duty vehicle traffic  
 119 that can generate dust emissions. The three test vehicles are displayed in Figure 1. Their characteristics are detailed in  
 120 Table 1. The tread pattern of the tires consists of longitudinal ribs for the Clio and the 4WD vehicle and of block treads  
 121 for the truck.

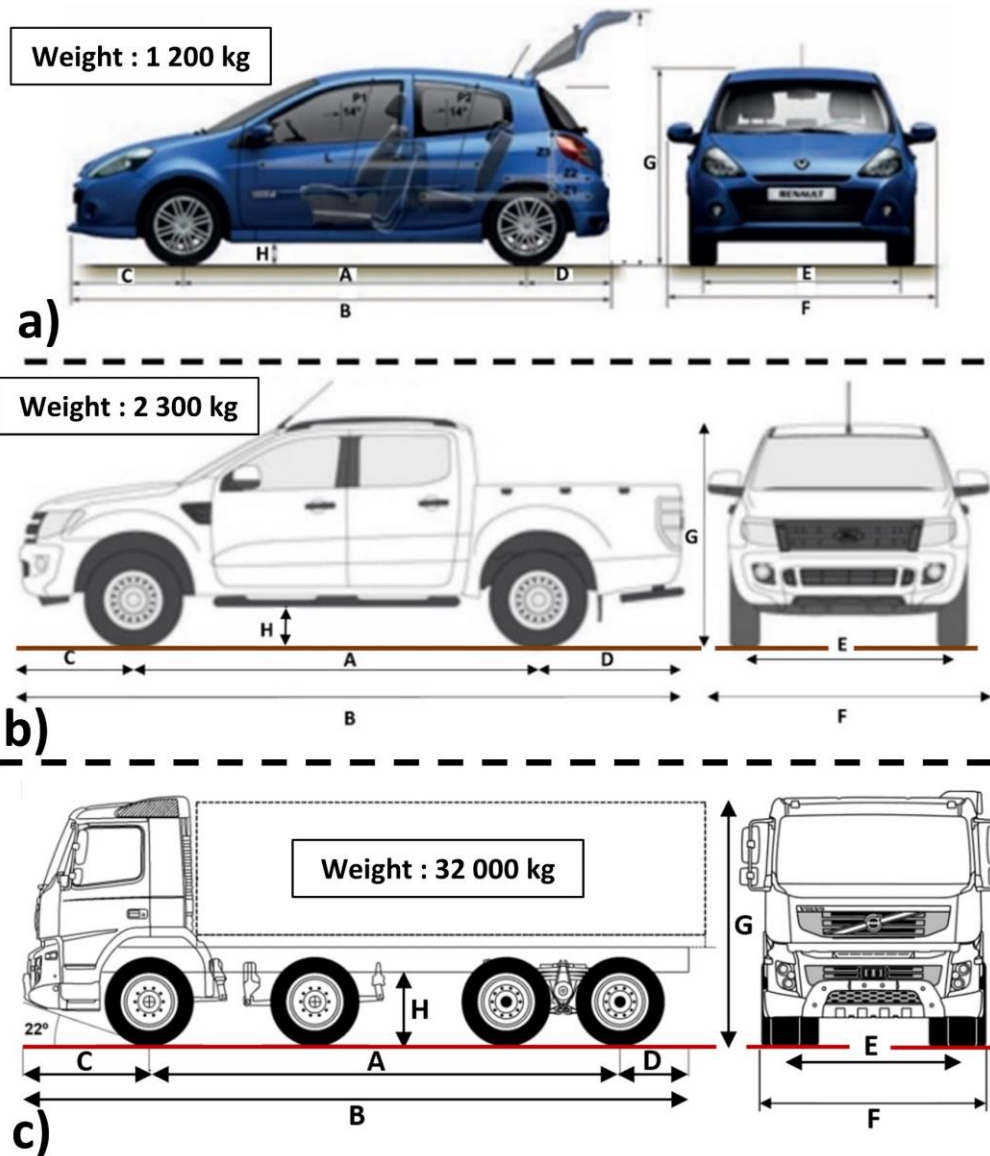


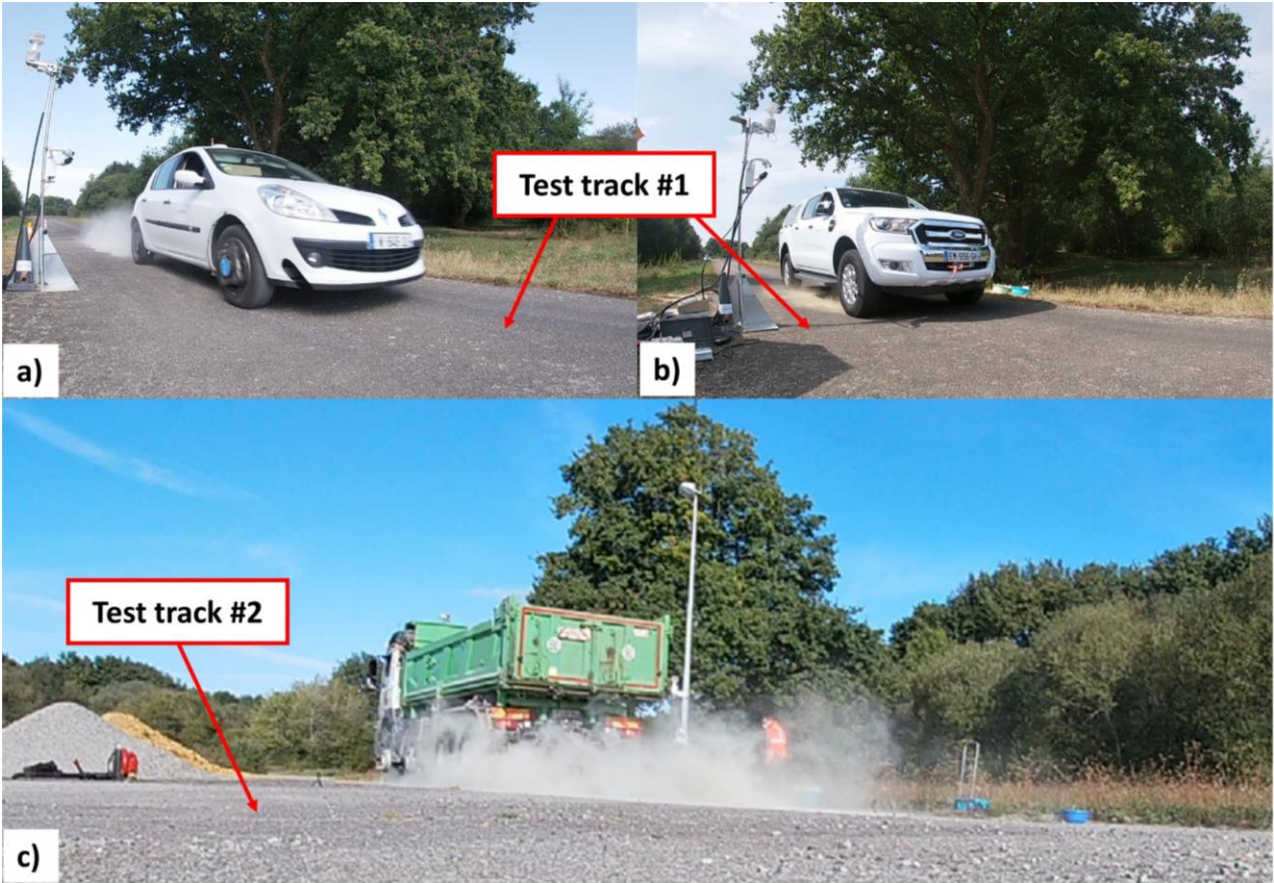
Figure 1: Front and side view of the vehicles: a) Renault Clio III; b) 4WD Ford Ranger and c) Volvo FMX truck

Table 1 : Characteristics of the vehicles

Characteristic (letter corresponds to Figure 1)	Vehicle		
	Renault Clio III	4WD Ford Ranger	Truck Volvo FMX
A: Wheelbase (mm)	2,575	3,220	5,970
B: Overall length (mm)	4,027	5,350	8,665
C: Front overhang (mm)	830	908	1,520
D: Rear overhang (mm)	622	1,226	1,175
E: Front/rear tire spacing (mm)	1,470	1,560	2,180
F: Width with mirrors (mm)	2,025	2,163	2,495
G: Empty height (mm)	1,493	1,820	3,122
H: Ground clearance (mm)	120	229	924
Wheel diameter (mm)	610	780	1,090
Weight (kg)	1,200	2,300	32,000

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126 The tests are carried out on two asphalt test tracks (Figure 2). The tests involving the Renault Clio III and the Ford Ranger  
127 were conducted during summer 2019 on test track #1 (Figures 2-a and 2-b), whereas those involving the Volvo truck were  
128 conducted in September 2020 on test track #2 (Figure 2-c). For both measurement campaigns, the surface roughness of  
129 the two tracks is the same for comparative purposes. For confirmation of similarity, six measurements distributed along  
130 the running zone of each track using a portable ELATextur rotary profilometer have been carried out. The mean surface  
131 roughness Ra, defined as the arithmetical mean deviation of the assessed profile (Whitehouse, 2012), was 662  $\mu\text{m}$  for  
132 track #1 and 689  $\mu\text{m}$  for track #2, respectively. These values are very close (a 4% difference). Consequently, the  
133 experimental conditions can be considered similar regarding surface roughness.



134  
135 *Figure 2: Experimental test tracks in University Gustave Eiffel (Bouguenais, France) used for the tests with the Renault*  
136 *Clio III and the 4WD Ford Ranger (a and b) and with the Volvo FMX truck (c)*

137

## 138 2.2 Characteristics of the particles

139 Four different types of particles are used for the tests: a clay mixture composed of montmorillonite and illite (cosmetic  
140 green clay CATTIER, denoted as “GC”) and three silty soils sampled from various earthwork sites in Europe (Val  
141 d'Europe (SVE) and Strasbourg (SS) in France, Marche les Dames (SMD) in Belgium). The last three types of soils are  
142 the most common soils found on construction sites. They have similar silt contents (between 95% and 100%) but differ  
143 in their other geotechnical properties like clay content or liquid limit (Figure 3 and Table 2). Because silt content is the  
144 parameter used to quantify dust emission in the reference models (Eq. (1) and (2)), the tests are carried out to verify  
145 whether this criterion is sufficient to characterize particle lift or if other geotechnical parameters must be considered. In  
146 Table 2, the Liquid Limit and Plastic Limit are parameters used to quantify the behavior of the soil when it is moistened.  
147 They were measured in accordance with the ISO 17892-12:2018 standard (ISO, 2018). Combined with the granulometric  
148 properties (passing at 2  $\mu\text{m}$  and 75  $\mu\text{m}$ ), they can be used for classification of the particles. The corresponding  
149 classification is presented in Table 2 according to the American Society for Testing Material standard (ASTM, 2017) and  
150 the French Guide for road earthworks (GTR, 2000). The Methylene Blue Value of the soils (ASTM, 2019), which is an  
151 indirect measure of the specific surface of the finest particles, is also presented.

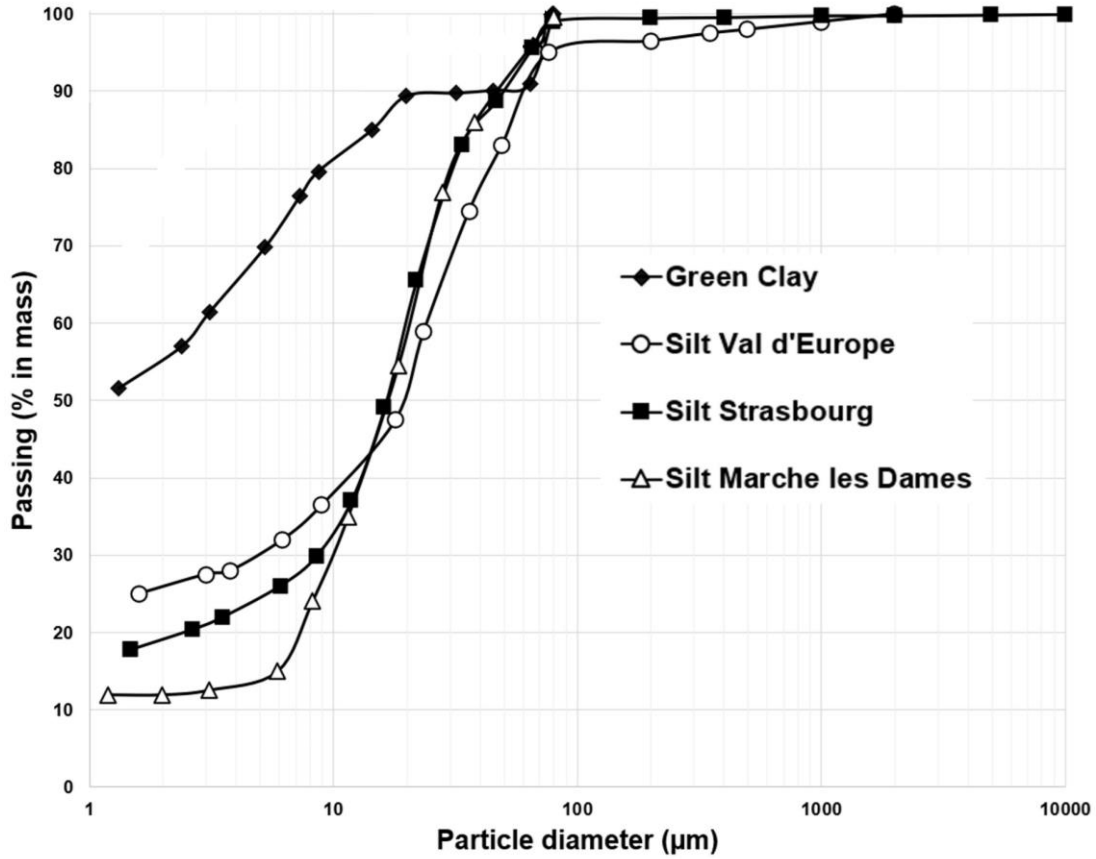


Figure 3: Particles size distributions of the soils

Table 2: Geotechnical properties of the soil particles

Particles (denotation)	% < 2 μm	% < 75 μm	Liquid Limit (%)	Plastic Index (%)	Bulk density (kN/m <sup>3</sup> )	Methylene Blue Value (g/100g)	Classification ASTM*	Classification GTR**
Green Clay (GC)	53.0	100.0	50.7	15.7	26.9	5.6	MH: Elastic Silt	A2: Low plasticity Clay
Silt Val d'Europe (SVE)	26.0	95.0	36.5	15.7	25.4	3.9	CL: Lean Clay	A2: Silt
Silt Strasbourg (SS)	19.0	99.0	40.3	24.9	25.8	3.0	CL: Lean Clay	A2: Silt
Silt Marche les Dames (SMD)	12.0	99.5	31.0	11.0	25.9	2.5	CL: Lean Clay	A1: Loess

\*American Society for Testing Material  
 \*\* Guide des Terrassements Routiers (French guide for road earthworks)

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### 2.3 Experimental methodology

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162 In order to ensure complete removal of moisture from the particles used for testing, they are first dried in an oven at 105°C  
163 during 24 hours (ISO, 2014). Then, they are sieved through a 2-mm sieve to grind aggregates and finally packed in plastic  
164 bags. Before testing, the particles are spread homogeneously on the tracks using a fertilizer spreader. They are divided  
165 over two lines separated from each other by the distance corresponding to the spacing between the tires of the vehicle  
166 (1.47 m for the Clio, 1.56 m for the 4WD vehicle and 2.18 m for the truck, respectively). Each line is 3 m in length and  
167 0.3 m in width for the tests with the Clio and the 4WD vehicle and 6 m in length and 0.54 in width for the truck. The  
168 widths of the lines are voluntarily larger than the widths of the tires (0.20 m for the Clio, 0.25 m for the 4WD vehicle and  
169 0.315 m for the truck). For practical reasons, the lengths of the lines are defined according to the quantities of particles  
170 available and the length of the test vehicles. They are long enough to generate a dust plume on the side of the road, which  
171 is easily measurable and representative of the vehicle actual emissions. Three different quantities of particles per unit area  
172 are considered (200, 400 and 600 g.m<sup>-2</sup>). They correspond to three distinct states of soil degradation: low, medium and  
173 high. These states of degradation have been determined in a previous study by running a wheel on different testing soils  
174 in a traffic simulator (Le Vern et al., 2020a). A mobile weather station is positioned on the side of the track to record  
175 temperature, relative humidity and wind speed and direction. The tests on test track #1 (test track #2) are conducted after  
176 9 days (3 days) with no rainfall, under relative humidity conditions ranging between 50 and 80% (65 and 85 %),  
177 temperature conditions within the range 17-25°C (11-17 °C) and wind speed conditions from 0.5 to 2.4 m.s<sup>-1</sup> (0.7 to 2.6  
178 m.s<sup>-1</sup>). The prevailing wind directions were northwest on test track #1 and southwest on test track #2. Figure 4 presents  
179 the diagram of the experimental setup.

180 Each test consists in running successively one of the three vehicles at a prescribed speed (30, 45 or 60 km.h<sup>-1</sup>) over one  
181 type of particles previously spread on the track at a given mass per unit area (200, 400 or 600 g.m<sup>-2</sup>). The speed of 30  
182 km/h corresponds to the traffic conditions imposed when the risk of dust resuspension is high (especially on construction  
183 sites). The speed of 45 km/h is often observed in cities or on construction sites. Testing at 60 km/h makes it possible to  
184 study what happens when the speed doubles compared with the initial 30 km/h and thus to highlight the impact of vehicle  
185 momentum on dust emission. For practical reasons, the tests with the truck have been conducted at 30 and 45 km/h only  
186 and the 4WD vehicle at 60 km/h only. The tests with the Renault Clio III, on the other hand, have been carried out at the  
187 three testing speeds. The three particle masses per unit area on the ground are tested with each vehicle. For reasons of  
188 stock availability, only the SVE soil is used for the tests with the Renault Clio III and the 4WD Ford Ranger.

189 The test tracks are made of asphalt concrete to ensure that only the particles that have been spread on the track can be  
190 raised by the test vehicle. This parameter could not have been controlled if the tests had been run on an unpaved road.  
191 Because asphalt pavements do not have the same roughness and are stiffer than unpaved roads, which are made of  
192 compacted soils, the tests here are not fully representative of the unpaved roads conditions. Indeed, on actual unpaved  
193 roads, tire tread and weight can remove and suspend particles from a certain depth below the soil surface, especially if  
194 the road presents surface imperfections (ruts, potholes, ...). Soil degradation by tires has already been studied and  
195 discussed in a previous study (Le Vern et al., 2020a). The present study is the second step and was conducted to examine  
196 the effects of the state of degradation of the road on dust emissions. This experimental configuration makes it possible to  
197 extend the results to the problem of particle emissions due to the contamination of asphalt mixes. However, this  
198 contamination generally generates smaller quantities of particles than those studied here (Hussein et al., 2008; Hichri et  
199 al., 2019).

200 During the tests, an Optical Particle Counter (OPC) continuously measures the mass concentration of the suspended dust  
201 by suction from the side of the road at a data rate of 1 Hertz. The measurement station is placed on the side of the road in  
202 the direction of the prevailing wind, as shown in Figures 4-a and 4-b. Dust concentrations are measured at the height of  
203 1.5 m from the ground. Preliminary tests have been carried out to determine the maximum concentration height by varying  
204 the measurement height between 1 m and 1.7 m. The maximum dust concentration is obtained at a height of 1.5 m, which  
205 is approximately the height of the dust plume centerline. The sensor is a PALAS Fidas Mobile dust analyzer equipped  
206 with a pump that sucks the particles contained in the ambient air. The particles then flow through a beam of LED light,  
207 which is subsequently scattered. A photomultiplier measures the angle of the scattered light. According to Mie's scattering  
208 theory (Mie, 1908), this angle depends on the size of the particle. Combined with a counting algorithm, the mass  
209 concentration of particles per unit volume (µg/m<sup>3</sup>) can be estimated. The device provides particle size distribution over  
210 71 sizes ranging between 0.17 and 26 µm (factory settings). The measurement range of the PM mass concentration is  
211 from 1 to 50 000 µg.m<sup>-3</sup>. The apparatus has been previously calibrated using "MonoDust 1500", a calibration dust  
212 recommended by the manufacturer.

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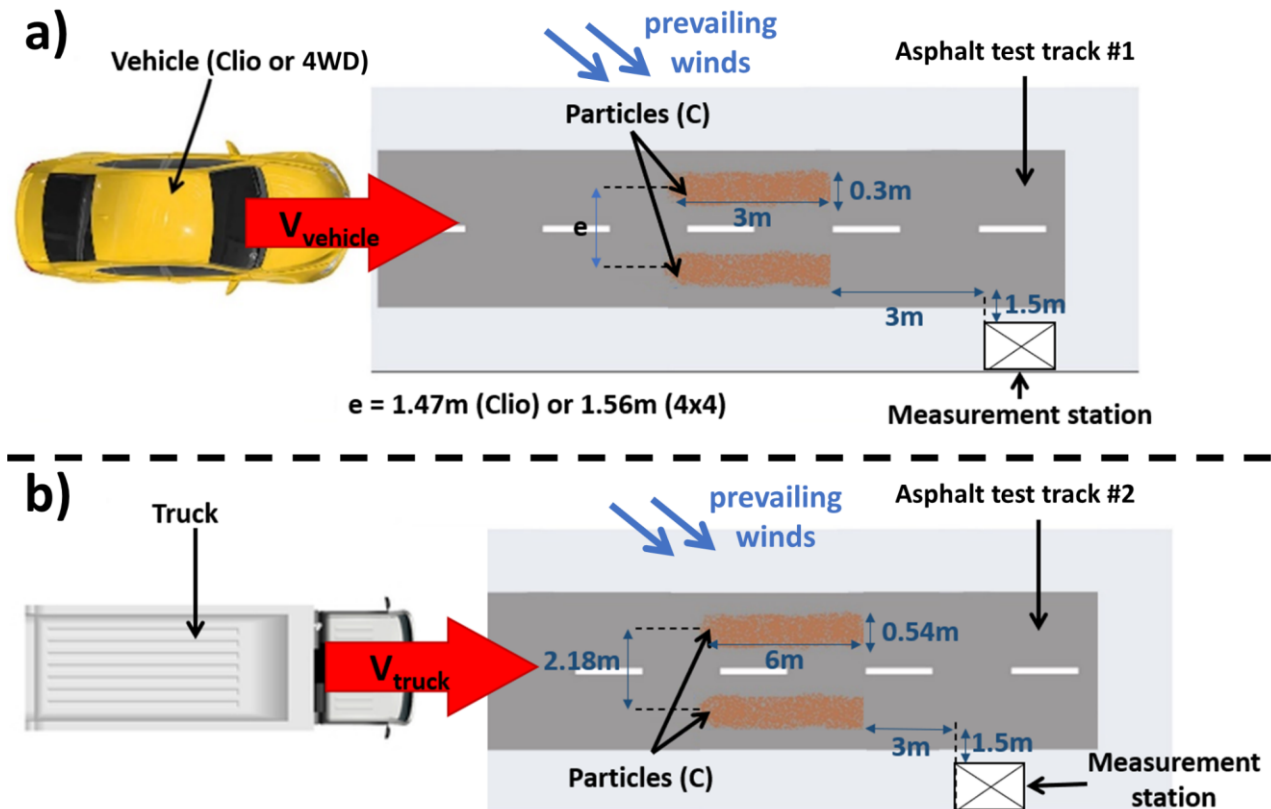


Figure 4: Diagram of the experimental setup on the track for a) Renault Clio III and 4WD Ford Ranger; b) Volvo FMX truck (diagram is not to scale)

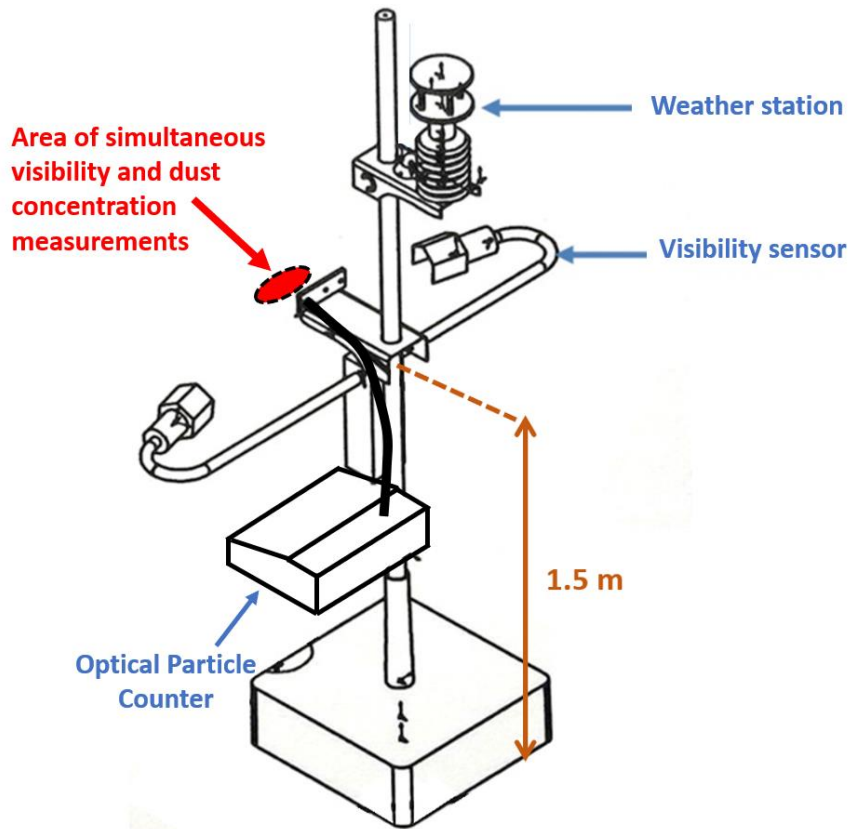
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218 A BIRAL SWS-100 visibility sensor is used to measure the reduction in visibility from the side of the road due to the  
 219 passing test vehicles. The visibility measurements are carried out at the same place than the dust concentration ones to  
 220 establish a direct relationship between both physical parameters. The meteorological optical sensor ranges from 0.01 to 2  
 221 km. This measurement range includes the road safety conditions. In France, for example, the maximum speed must be  
 222 reduced to 50 km/h when the visibility on the road is less than 50 m. Prior to the testing, the visibility sensor has been  
 223 calibrated using a Calibration Reference Plaque as recommended by the manufacturer (BIRAL, 2014). Figure 5 displays  
 224 the diagram of the measurement station with the OPC, the visibility sensor and the weather station.

225 Six tests are carried out with the 4WD vehicle, ten with the Clio and twenty-two with the truck while varying the different  
 226 parameters (vehicle speed, particle type and mass per unit area). Table 3 summarizes the main characteristics. For practical  
 227 reasons of time and quantity of particles available, all the possible combinations of parameters could not be tested. The  
 228 experimental design is based on the Tagushi method (Tagushi and Konishi, 1987), which makes it possible to highlight  
 229 the impact of the experimental parameters on the final results with a limited number of trials. Because a considerable  
 230 amount of effort has been already devoted to examine the effects of vehicle speed on dust emissions in the literature  
 231 (Moosmüller et al., 2005; Gillies et al., 2005; Thenoux et al., 2007; Kuhns et al., 2010), the test plan has been primarily  
 232 designed to focus on the effects of the “state of degradation of the road”, which is characterized by the quantity of particles  
 233 on the ground. Some configurations are tested several times to ensure the repeatability of the measurements by carrying  
 234 out the same test twice in a row. Nine repeatability tests are thus carried out to assess uncertainties. Error bars are therefore  
 235 presented with the results taking these uncertainties into account.

236 After each test, a sample of the particles remaining on the ground is taken for moisture content measurement ( $M$ , the ratio  
 237 of the mass of water to the dry mass of the particles). For all the tests,  $M = 2 \pm 0.7\%$  (the particles absorbed some moisture  
 238 during the experiments). The soils in hygroscopic equilibrium with the air between 50% and 85% of relative humidity  
 239 have a gravimetric water content between 2 and 7 times higher than the present results (Ravi and D’Odorico, 2005).  
 240 Relative humidity has no effect here because moisture exchanges between dry particles and atmosphere require hours or  
 241 even days (Ravi et al., 2006). This effect, however, is not negligible, as shown by Muleski et al. (2005), according to  
 242 which a soil with a water content changing from 4% to 8% decreases its  $PM_{10}$  emissions by 75%.

243 The test track here is cleaned up between two tests using a leaf blower. Furthermore, the track is also swept up manually  
 244 to make sure that all remaining particles within the asphalt voids are removed.



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Figure 5: Diagram of the measurement station. Wind speed and direction, visibility reduction and dust concentration are measured simultaneously (Sediki et al., 2018)

Table 3: Test configurations

Vehicle	Particles*	Speed (km/h)	Concentration (g/m <sup>2</sup> )	Vehicle	Particles*	Speed (km/h)	Concentration (g/m <sup>2</sup> )				
Clio III	SVE	30	200	Truck Volvo FMX	GC	30	200				
			400				400				
		45	200			600					
			400			200					
		60	200			400					
			600			200					
4x4 Ford Ranger	SVE	60	200		Truck Volvo FMX	SVE	30	200			
			400					400			
			600				600				
4x4 Ford Ranger	SVE	60	200				Truck Volvo FMX	SS	30	200	
			400							400	
			600						600		
		4x4 Ford Ranger	SVE	60		200		Truck Volvo FMX	SMD	30	200
						400					400
						600				600	
* GC: Green Clay SVE: Silt from Val d'Europe SS: Silt from Strasbourg SMD: Silt from Marche les Dames				Truck Volvo FMX		SMD	30		200		
Truck Volvo FMX	SMD	30	400								
			Truck Volvo FMX	SMD		45	200				
Truck Volvo FMX	SMD	45			400						

250 **2.4 Data processing**

251 2.4.1 Sampling efficiency of the optical particle counter

252 The OPC measures PM<sub>10</sub> concentrations by aspiration of the atmospheric aerosol, which are then transported through a  
 253 nozzle to the optical measurement volume. In this study, the sampling efficiency is not 100% because of the sub-isokinetic  
 254 and anisoaxial conditions (non-alignment of wind and sampling directions) as well as some inertial transmission losses  
 255 in the nozzle. The sensor measurement must therefore be corrected by taking the sampling efficiency  $\eta_{sample}$  into account.  
 256 The sampling efficiency is defined as the product of the aspiration and the transport efficiencies (Willeke and Baron,  
 257 2001):

$$\eta_{sample} = \eta_{asp} \times \eta_{trans} \quad (3)$$

258 The aspiration efficiency  $\eta_{asp}$  is defined as the concentration of the particles entering the nozzle divided by their  
 259 concentration in the ambient environment from which the sample is taken. The relationship developed by Hangal and  
 260 Willeke (1990) thanks to quantifying experimentations is expressed as:

$$\eta_{asp} = 1 + \left[ \left( \frac{U_0}{U} \right) \cos\theta - 1 \right] \frac{1 - \left[ 1 + \left[ 2 + 0.617 \left( \frac{U}{U_0} \right) S_{tk}' \right]^{-1} \right]}{1 - \left[ 1 + 2.617 S_{tk}' \right]^{-1}} \left[ 1 - \left[ 1 + 0.55 S_{tk}' \exp(0.25 S_{tk}') \right]^{-1} \right] \quad (4)$$

$$S_{tk}' = S_{tk} \cdot \exp(0.022\theta) \quad (5)$$

261 for  $0^\circ \leq \theta \leq 60^\circ$ , where  $\theta$  is the angle between the wind and the sampling directions,  $U_0$  and  $U$  are the wind and the  
 262 sampling velocities ( $m \cdot s^{-1}$ ), respectively, and  $S_{tk}$  is the Stokes number of the particle (Eq. (6)):

$$S_{tk} = \frac{1}{18} \frac{\rho_p d_p U_0}{\mu L_c} \quad (6)$$

263 where  $\rho_p$  is the particle density ( $kg \cdot m^{-3}$ ),  $d_p$  is the particle diameter (m),  $\mu$  is the dynamic air viscosity ( $18.5 \cdot 10^{-6} kg \cdot m^{-1} \cdot s^{-1}$   
 264 at  $20^\circ C$ ) and  $L_c$  is a characteristic length (here the nozzle diameter, i.e.,  $L_c = 0.008$  m).

265 They extended this relationship for  $60^\circ \leq \theta \leq 90^\circ$  (Eq. (7)):

$$\eta_{asp} = 1 + \left[ \left( \frac{U_0}{U} \right) \cos\theta - 1 \right] \left[ 3 S_{tk} \sqrt{\frac{U}{U_0}} \right] \quad (7)$$

266 The transport efficiency  $\eta_{trans}$  is defined as the fraction of aspirated particles that are transported through the inlet to the  
 267 measurement volume. This parameter depends on both the gravitational deposition and the inertial losses. To our  
 268 knowledge, Okazaki et al. (1987) are the only authors who studied gravitational settling transport efficiency. They carried  
 269 out testing using a 200-mm nozzle so, consequently, their results cannot be extended to the present tests, for which the  
 270 length of the nozzle is 900 mm. However, the settling velocity of the particles ( $\approx 0.008 m \cdot s^{-1}$ ) is negligible compared to  
 271 the aspiration velocity ( $U = 0.47 m \cdot s^{-1}$ ). Hence, the gravitational deposition is not taken into account and only the inertial  
 272 losses are considered. Inertial losses have been studied by Liu et al. (1989) who propose the following inertial transport  
 273 efficiency relationship for sub-isokinetic sampling (Eq. (8)):

$$\eta_{trans} = \frac{1 + \left[ \frac{U_0}{U} - 1 \right] / \left[ 1 + \frac{2.66}{S_{tk}^{2/3}} \right]}{1 + \left[ \frac{U_0}{U} - 1 \right] / \left[ 1 + \frac{0.418}{S_{tk}} \right]} \quad (8)$$

274 Here, the concentrations measured by the OPC are corrected using Eq. (9):

$$C = \frac{C_{measured}}{\eta_{sample}} \quad (9)$$

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284 The present analysis focuses on PM<sub>10</sub> emissions, which corresponds to the particles range generally studied in the  
 285 literature focusing on the problem of dust emissions on unpaved roads (Etyemezian et al., 2003; Gillies et al., 2005;  
 286 USEPA, 2006; Kuhns et al., 2010). We consider that the OPC measurements represent the PM<sub>10</sub> concentration at a height  
 287 corresponding to the vertical distance of the sensor from the ground (1.5 m). For each test, the time series of PM<sub>10</sub> are  
 288 examined regarding the peak of dust concentration induced by the vehicle. This peak value is defined by the measurements  
 289 between the beginning of the concentration rise above the background level and the return to a background concentration  
 290 defined as the average PM<sub>10</sub> concentrations measured between two tests (i.e., 10 µg.m<sup>-3</sup>). The emissions factor (*EF*) per  
 291 vehicle pass is estimated using the sum of the PM<sub>10</sub> concentrations measured per second, according to Eq. (10) (Gillies et  
 292 al., 2005):

$$EF = \sum_{\text{start time of peak}}^{\text{end time of peak}} U_0 \times C \times \Delta z \times \Delta t \times 1000 \quad (10)$$

293 where *EF* is the estimated emission factor of PM<sub>10</sub> in grams per vehicle kilometer traveled (gPM<sub>10</sub>.vkt<sup>-1</sup>), *U*<sub>0</sub> is the 30-  
 294 seconds average wind speed (m.s<sup>-1</sup>), *C* is the 1-s PM<sub>10</sub> concentration (g.m<sup>-3</sup>) measured by the OPC and corrected according  
 295 to Eq. (9),  $\Delta z$  is the dust plume vertical interval represented by the OPC (taken as 1.5 m) and  $\Delta t$  is the time during which  
 296 the plume impacts the OPC (s). A factor 1000 is required to obtain the final result in dust emission per kilometer.

297 The measurements are carried out on the side of the test track, where the dispersion area of the dust plume is not very  
 298 large (within a few meters). It is therefore considered that the measurements from the single sensor are representative of  
 299 the average particle concentration in the plume. The visual observations made throughout the tests confirm this  
 300 assumption. Furthermore, on the roadside, the near-source redeposited dust particles are measured. These are not taken  
 301 into account in the inventories for air quality modelling at regional-scale (Veranth et al., 2003) but they have to be  
 302 considered in visibility reduction studies.

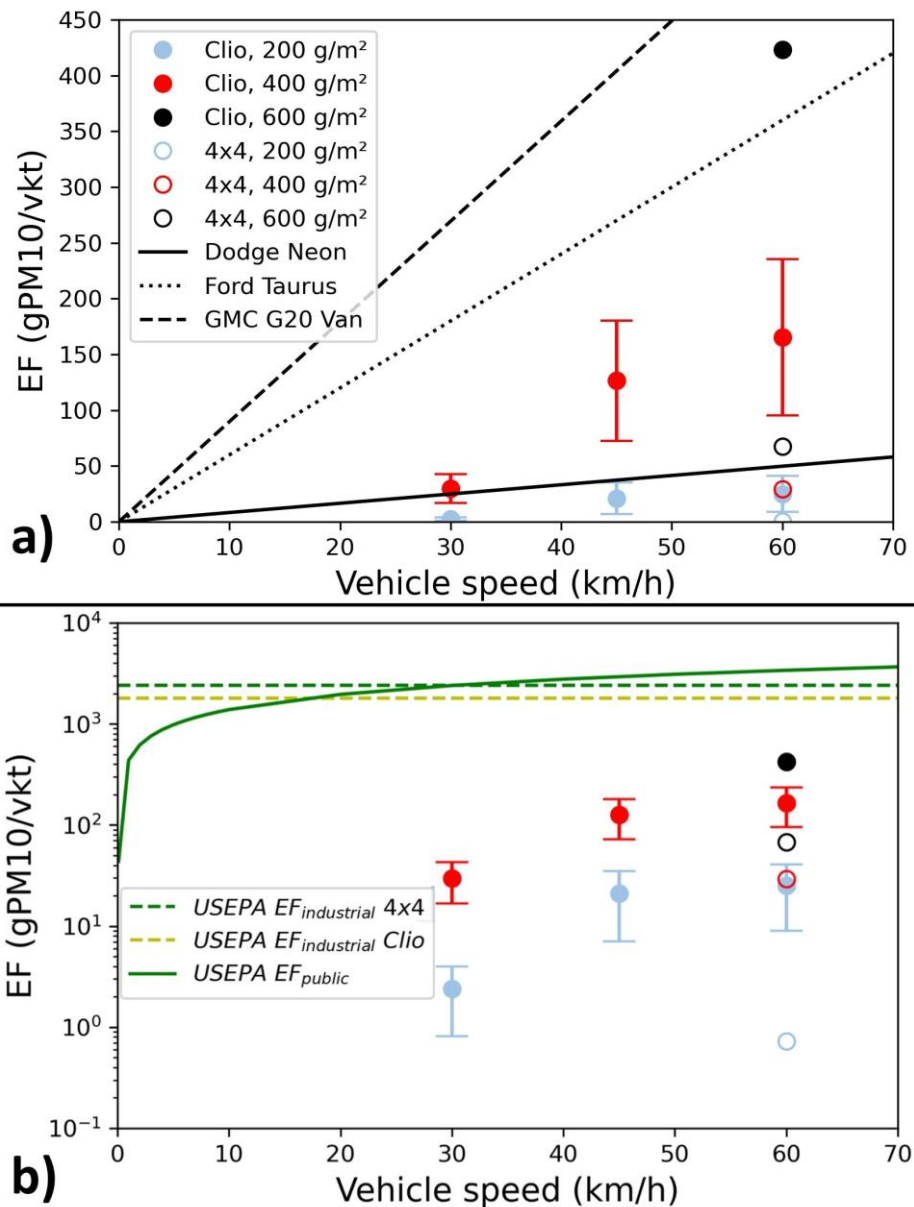
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### 304 3. Results and discussion

#### 305 3.1 Emission factors

306 Figure 6 presents the EFs for the tests with the Renault Clio and the 4WD vehicle. In Figure 6-a, the results are compared  
 307 with those obtained by Gillies et al. (2005) with a Dodge Neon (weight: 1,176 kg), a Ford Taurus (weight: 1,516 kg) and  
 308 a GMC G20 van (weight: 3,100 kg). It should be noted that the curves proposed by Gillies et al. (2005) were obtained  
 309 with nine different vehicle speeds (16, 24, 32, 40, 48, 56, 64, 72 and 81 km.h<sup>-1</sup>). They show that EFs are linearly correlated  
 310 with the vehicle speed and that the slopes of the curves depend on the vehicle weight. According to these criteria, the  
 311 expected EF results for the 4WD Ford Ranger (with a weight of 2,300 kg) should have been between the dotted line and  
 312 the dashed line in Figure 6-a. However, they actually are between one and two orders of magnitude lower. This difference  
 313 may be accounted for by the presence of mud flaps behind the tires of the 4WD vehicle, which may significantly reduce  
 314 emissions. For confirmation, more tests need to be carried out with the same vehicle with and without mud flaps to  
 315 improve our understanding of dust emission mitigation related to the presence of accessories on the wheels. This impact,  
 316 notably obturating discs on the rims, has been studied by Gérardin (2009).

317 The Renault Clio used here is approximately the same weight as the Dodge Neon and generates comparable EF results  
 318 for the lowest quantity of particles on the ground (200 g.m<sup>-2</sup>) whatever the vehicle speed. Indeed, the average difference  
 319 is only 17 g.vkt<sup>-1</sup> between the “Dodge Neon” full black line and the blue dots in Figure 6-a. The test results with the Clio  
 320 show that a doubling of the surface degradation from 200 to 400 g/m<sup>2</sup> increases EF sevenfold (on average). A tripling of  
 321 the degradation from 200 to 600 g/m<sup>2</sup> generates an 18-fold increase in EF. These results demonstrate that it is crucial to  
 322 take unpaved road surface condition into account in order to accurately quantify the unpaved road propensity for  
 323 generating dust. To date, this problem has not been considered in the already available models developed to assess EFs.  
 324 Figure 6-b shows that EF results using AP-42 models (Eq. (1) and (2)) are between 1,800 and 3,400 gPM<sub>10</sub>.vkt<sup>-1</sup>, which  
 325 is more than one order of magnitude above the present experimental results. These models have been developed from  
 326 tests on soils with low silt contents, while this content is significantly high in the particles used here (more than 95%).  
 327 This may explain these large differences. It should also be noted that the USEPA model for public roads (Eq. (2)) does  
 328 not take the vehicle mass into account and, therefore, gives the same dust emission estimate for both the 4WD vehicle  
 329 and the Clio (solid green curve in Figure 6-b).



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Figure 6: EFs as a function of vehicle speed and mass of particles per unit area for the tests with the Renault Clio and the 4WD Ford Ranger. a) Experimental data are compared with the results obtained by Gillies et al. (2005) with a Dodge Neon (solid line), a Ford Taurus (dotted line) and a GMC C20 Van (dashed line); b) Same results in a semi-log scale and comparison with the AP-42 models (Eq. (1): dotted lines, Eq. (2): solid line).

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Figure 7 shows the EF values obtained for the tests with the Volvo truck. These results are compared with those obtained by Gillies et al. (2005) with an US Army M977 HEMTT cargo truck. This vehicle has the same number of wheels but is only half the weight of the Volvo truck (17,727 kg against 32,000 kg). To the authors' knowledge, no data on dust EFs for trucks with the same weight as the Volvo truck used in the present study is currently available in the literature. The results are also compared with USEPA modeling results for public roads (Eq. (2)). Modeling results for industrial roads (Eq. (1)) are not displayed in the figures because EF values are too high (about 8,000 gPM<sub>10</sub>.vkt<sup>-1</sup>, regardless of the truck speed).

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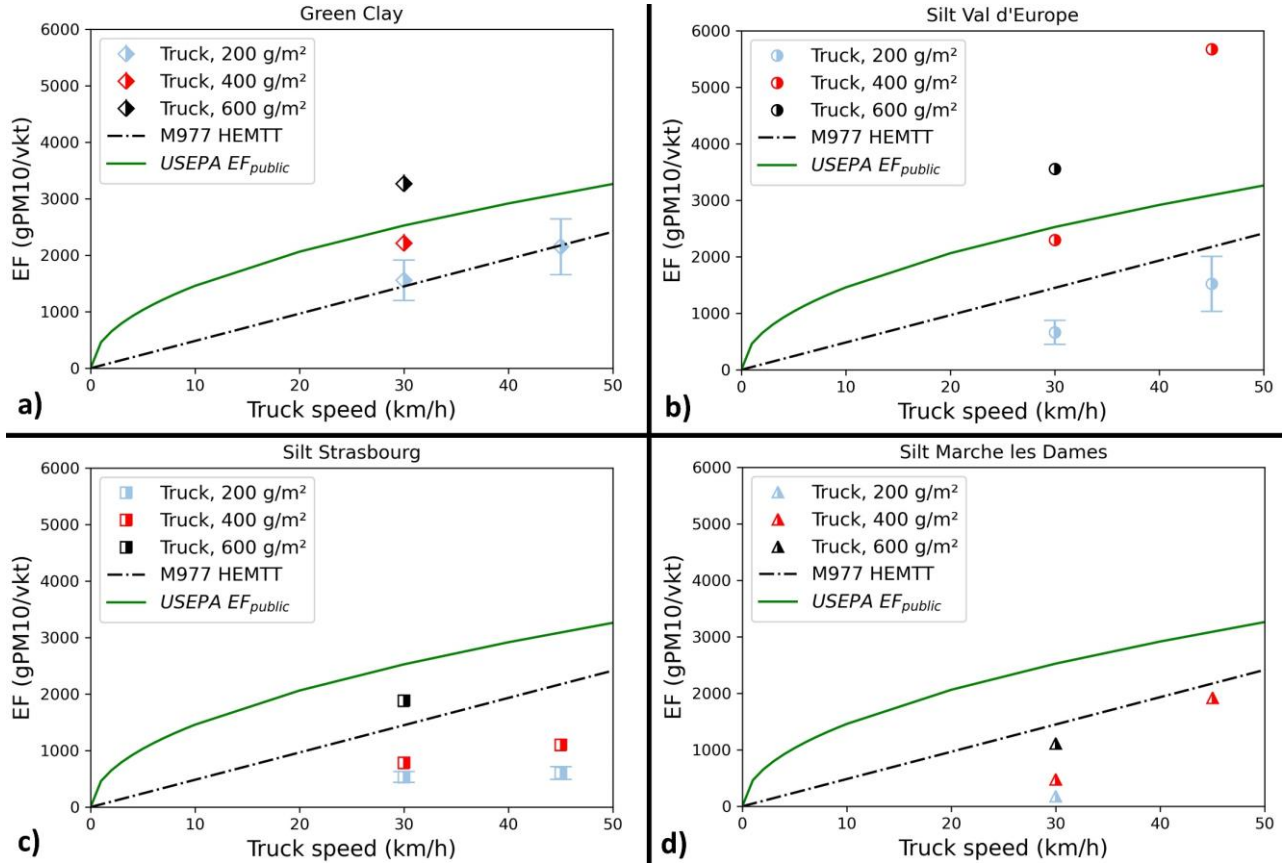
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In the present study, all the particles tested have approximately the same silt content (between 95 and 100%). The USEPA model (green curves in Figure 7) gives similar EFs for all of them. However, there are some significant differences between the results of this study depending on the type of particles. These significant discrepancies prove that the silt content is not sufficient to assess the propensity of a soil to generate dust. As for the Clio and the 4WD vehicle, the results with the truck show that the state of degradation of the soil (mass of particles per unit area above the ground) has a strong impact on the emissions of dust.



349  
 350 *Figure 7: EFs as a function of vehicle speed and mass of particle per unit area for the tests with the truck Volvo FMX*  
 351 *on a) green clay, b) silt from Val d'Europe, c) silt from Strasbourg and d) silt from Marche les Dames. Experimental*  
 352 *data are compared with the results obtained by Gillies et al. (2005) with a M977 HEMTT truck (broken line) and using*  
 353 *the AP-42 model for public roads (Eq. (2), green line).*

354 Based on these experimental results and observations, a model for the quantification of EFs is developed. The first step  
 355 consists in identifying the most relevant parameters. It is well established in the literature (Gillies et al., 2005; Kuhns et  
 356 al., 2010) that the EF is linearly proportional to the vehicle momentum. The experimental data discussed here also show  
 357 that the soil degradation state is a parameter of paramount importance. Furthermore, the type of particles must be taken  
 358 into account. Regarding the test data obtained with the truck, the silt content is not a relevant parameter contrary to the  
 359 clay content ( $\% < 2\mu\text{m}$ ), which allows to distinguish between the four types of particles. Finally, the tests carried out with  
 360 the 4WD vehicle show that the impact of mud flaps behind the tires is also significant. These appendices are considered  
 361 through a weighting factor. With a form similar to the USEPA models (Eq. (1) and (2)), the following equation is proposed  
 362 (Eq. (11)):

$$EF_{model} = \alpha \times M_{om} \times \left(\frac{c}{c_{ref}}\right)^\beta \times \left(\frac{D}{D_{ref}}\right)^\gamma \times f_{mf} \quad (11)$$

363 where  $EF_{model}$  is expressed in  $\text{kg}\cdot\text{m}^{-1}$  to homogenize the units in the equation (to be multiplied by  $10^6$  to be expressed in  
 364  $\text{g}\cdot\text{vkt}^{-1}$ ),  $M_{om}$  is the vehicle momentum ( $M_{om} = S \cdot W$ , in  $\text{kg}\cdot\text{m}\cdot\text{s}^{-1}$ ),  $c$  is the clay content ( $\% < 2\mu\text{m}$ ) of the particles,  $c_{ref}$  is a  
 365 reference clay content (arbitrarily chosen at 12 %, which corresponds to the minimum value of the particles used in this  
 366 study),  $D$  is the soil surface degradation (mass of particles per unit area above the ground in  $\text{kg}\cdot\text{m}^{-2}$ ),  $D_{ref}$  is a degradation  
 367 reference (arbitrarily chosen at  $0.2 \text{ kg}\cdot\text{m}^{-2}$ , the minimum value studied here) and  $f_{mf}$  is a weighting factor taking the  
 368 influence of mud flaps into account.  $\alpha$ ,  $\beta$  and  $\gamma$  are empirical parameters.

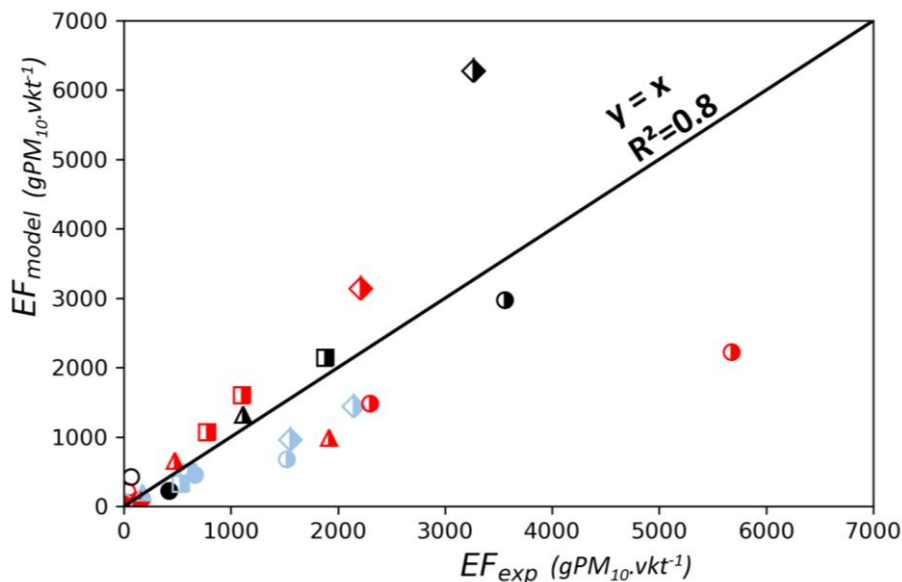
369 Performing a multiple regression on the experimental data obtained with the Clio and the truck and considering a 95%  
 370 confidence interval, the parameters  $\alpha$ ,  $\beta$  and  $\gamma$  of the model can be established. The parameter  $f_{mf}$  is determined by fitting  
 371 the data obtained with the 4WD vehicle with the previously established model. The final model is given by Eq. (12):

$$EF_{model} = 7.6 \times 10^{-10} \times M_{om} \times \left(\frac{c}{12}\right)^{1.05} \times \left(\frac{D}{0.2}\right)^{1.71} \times f_{mf} \quad \text{with} \quad \begin{cases} f_{mf} = 1 & \text{if no mud flaps} \\ f_{mf} = 0.15 & \text{if mud flaps} \end{cases} \quad (12)$$

372 This model shows that the surface degradation state is the parameter that most affects EF. The presence of mud flaps  
 373 behind the tires decreases EFs by a factor of 7. Additional tests need to be carried out to validate this observation and  
 374 generalize this result. It is also important to note that this model is developed using soils with high silt contents. Further

375 research with sandy soils is necessary to extent the application of the model to a wider range of soils. A robust model  
 376 should be able to account for both clay and silt contents.

377 Figure 8 presents the comparison between the EF values determined experimentally and those modeled using Eq. (12).  
 378 There is a good correlation between the theoretical and experimental data, up to an EF value of 3000  $\text{gPM}_{10}\cdot\text{vkt}^{-1}$ . Beyond  
 379 this limit, the model becomes a less reliable tool to quantify the emissions, the differences between prediction and  
 380 measurements reaching a factor of 2. However, these values correspond to very high dust emissions caused by the trucks  
 381 which are not realistic on construction sites. Indeed, water is sprayed on the traffic lanes well before such emission levels  
 382 are reached because of the very significant reductions in visibility such dust plumes would imply.



383

384 *Figure 8: Comparison between the model of Eq. (12) and the experimental data. Symbols are the same as in Figures 6*  
 385 *and 7.*

386

### 387 3.2 Visibility reduction

388 Many studies have established a relationship between  $\text{PM}_{10}$  mass concentration and visibility reduction (D’Almeida,  
 389 1986; Dayan et al., 2008; Jugder et al., 2014; Baddock et al., 2014; Camino et al., 2015). Table 4 summarizes the available  
 390 models, where  $V$  is the visibility in km and  $\overline{\text{PM}}_{10}$  the average mass concentration of particles below 10  $\mu\text{m}$  (in  $\mu\text{g}\cdot\text{m}^{-3}$ ).

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*Table 4: Empirical model equations relating  $\text{PM}_{10}$  mean concentration (in  $\mu\text{g}/\text{m}^3$ ) to visibility ( $V$  in km)*

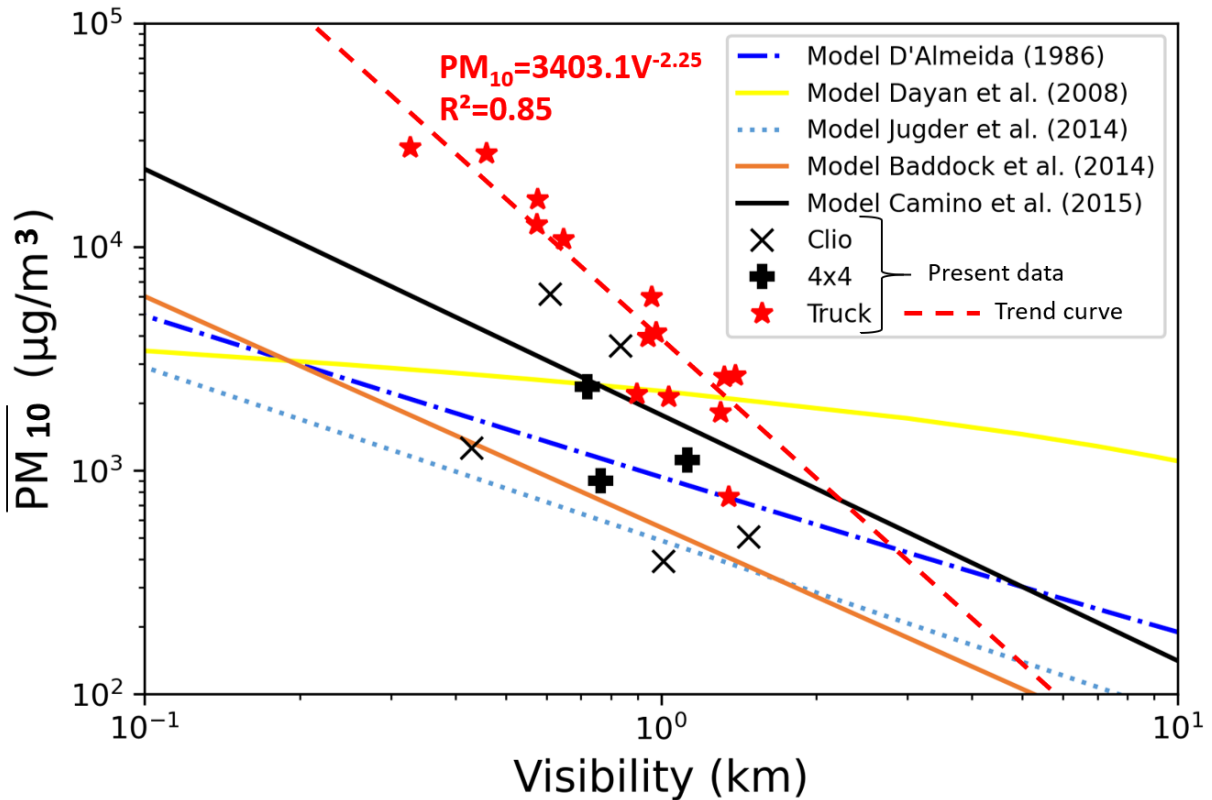
Authors	Empirical equation	Measurement location
D’Almeida (1986)	$\overline{\text{PM}}_{10} = 914 \times V^{-0.73} + 19$	Visibility and $\text{PM}_{10}$ concentration measurements carried out in Agadez (Niger). Source of dust emissions (desert) located several hundreds of km from the measurement sites.
Dayan et al. (2008)	$\overline{\text{PM}}_{10} = -505 \cdot \ln(V) + 2264$	$\text{PM}_{10}$ concentration measurements carried out in the Negev desert. Visibility measurement at Hazerim airport (Israel) located 50 km away.
Jugder et al. (2014)	$\overline{\text{PM}}_{10} = 486 \times V^{-0.78}$	Visibility and $\text{PM}_{10}$ measurements carried out at Zamyn-Uud in the Gobi Desert, near the dust emission source.
Baddock et al. (2014)	$\overline{\text{PM}}_{10} = 556 \times V^{-1.03}$	$\text{PM}_{10}$ concentration measurement carried out in Buronga (Australia). Visibility measurements in the next town (Mildura) located 12 km away. Sources of dust emission are located between 10 and 100 km from these stations.
Camino et al. (2015)	$\overline{\text{PM}}_{10} = 1772 \times V^{-1.10}$	Visibility and $\text{PM}_{10}$ concentration measurements carried out in Izaña (Spain). Source of dust emissions (desert) located at several hundred km from the measurements.

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The main sources of dust emissions in these studies come from deserts. It is also recognized that PM<sub>10</sub> concentration is a good indicator of how visibility on gravel roads can be reduced (Edvarsson and Magnusson, 2009). Figure 9 presents the comparison between the models described in Table 4 and the experimental measurements obtained during the present study. Regarding the test results, PM<sub>10</sub> concentration corresponds to the average value measured between the beginning and the end of the peak of dust concentration generated by the passage of the test vehicle (Eq. (13)). The visibility is averaged over the same period of time.

$$\overline{PM_{10}} = \frac{1}{N} \sum_{start\ time\ of\ peak}^{end\ time\ of\ peak} C \quad (13)$$

400 where  $C$  is the 1-s PM<sub>10</sub> concentration ( $\mu\text{g}\cdot\text{m}^{-3}$ ) measured by the OPC and corrected according to Eq. (9), and  $N$  is the  
401 number of concentration values measured during the period for which the dust plume impacts the OPC.



402

403 *Figure 9: Relationship between the average visibility and the average PM10 concentration on the roadside. The*  
404 *experimental data are compared with the model results of D'Almeida (1986), Dayan et al. (2008), Jugder et al. (2014),*  
405 *Baddock et al. (2014) and Camino et al. (2015). These models are detailed in Table 4.*

406 For the same level of PM<sub>10</sub>, the Renault Clio and the 4WD vehicle reduce visibility more significantly than the truck.  
407 Indeed, the truck emits coarser particles which have a lower mass scattering efficiency compared to the small particles  
408 (Moosmüller et al., 2005). Then, PM<sub>10</sub> concentration is not the best indicator of visibility reduction caused by light  
409 vehicles (Clio and 4WD Ford Ranger), as shown by the scattered corresponding experimental data. On the other hand,  
410 regarding the experimental data obtained with the truck, the following power law provides a relatively accurate estimate  
411 ( $R^2=0.85$ ):

$$\overline{PM_{10}} = 3403.1V^{-2.25} \quad (14)$$

412 By comparing this model with the models of the literature (Figure 9), a steeper slope is observed. This can be accounted  
413 for by the fact that the present model has been developed using simultaneous dust and visibility measurements carried out  
414 at the same location point, which is not the case for the other models. They, indeed, were developed to address this issue  
415 at a regional scale. The model developed here should therefore be more relevant regarding the consideration of visibility  
416 reduction on construction sites, keeping in mind that reduced visibility is mainly localized on the traffic lanes where trucks  
417 are circulating.

418



#### 419 **4 Conclusions**

420 In this study, the dust emissions generated by the traffic of a passenger car, a 4WD vehicle and a truck are examined. In  
421 order to simulate the traffic of vehicles on unpaved roads, four types of particles (green clay, silt from Val d'Europe, silt  
422 from Strasbourg and silt from Marche les Dames) are spread on a test track at different mass per unit area (200 g/m<sup>2</sup>, 400  
423 g/m<sup>2</sup> and 600 g/m<sup>2</sup>). This simulates various states of road surface degradation. Vehicles are driven over the particle beds  
424 at different speeds (30, 45 and 60 km/h) and the concentrations of suspended dust emitted and the visibility reduction are  
425 measured from the roadside.

426 The main findings of this study are:

427 - The state of soil surface degradation appears to have a key influence on dust emission factors. A doubling of the  
428 mass of particles per unit area above the ground generates three times more dust emissions from the vehicles.  
429 However, this is not taken into account in classical models for emission factors estimation;

430 - Silt content (% < 75 µm) should not be the single parameter considered to assess particle lift. For fine soils, the  
431 percentage of clay particles (% < 2 µm) is particularly relevant to quantify the soil propensity for emitting dust;

432 - The vehicle momentum is not a sufficient criterion to characterize dust emission potential. The impact of  
433 appendices like mud flaps behind the tires could significantly reduce vehicle emissions by a factor of 7. The  
434 aerodynamic drag of the vehicles may also play a key role. More work needs to be carried out to understand this  
435 effect through testing with vehicles having the same momentum but very different geometry;

436 - The visibility reduction caused by PM<sub>10</sub> emissions from truck traffic can be accurately modeled using a power  
437 law. This, however, is not the case for lighter vehicles because they raise finer particles with a higher mass  
438 scattering efficiency.

439 Finally, the established emission factor is a first step toward the consideration of the progressive increase in dust emissions  
440 due to the evolution of surface degradation under vehicle traffic. Future experimental campaigns need to be carried out  
441 on unpaved roads to compare actual emissions with those experimentally obtained in this study with particles spread on  
442 an asphalt test track. The present results highlight the crucial need to take the degradation state of the road into account  
443 when modeling dust emissions. This parameter should be further studied in order to establish a robust equation that could  
444 be implemented in atmospheric dispersion models. When used with the visibility reduction model, it would then be  
445 possible to consider safety risks on construction sites and anticipate the watering of traffic lanes. These results are part of  
446 an approach to optimise the use of water on earthmoving sites. When some water is sprayed on the soil, the particles on  
447 the surface form a crust that limits dust emissions. This phenomenon could be examined in future works by spraying  
448 liquid soil suspensions on the road before driving the vehicles. Moreover, the dust mitigation effect of mud flaps is of  
449 particular interest and could be the subject of further research work. Wind tunnel testing could be carried out to examine  
450 how such appendices affect the airflow in the wake of vehicles.

451

#### 452 ***CRedit authorship contribution statement***

453 **Mickael Le Vern:** Conceptualization, Data curation, Investigation, Methodology, Resources, Validation, Writing –  
454 original draft, Writing – review & editing. **Andry Razakamanantsoa:** Conceptualization, Funding acquisition,  
455 Methodology, Resources, Supervision, Validation, Writing – review & editing. **Frédéric Murzyn:** Conceptualization,  
456 Methodology, Supervision, Validation, Writing – review & editing. **Frédérique Larrarte:** Conceptualization,  
457 Methodology, Supervision, Validation, Writing – review & editing. **Véronique Cerezo:** Methodology, Resources,  
458 Validation, Writing – review & editing.

459

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468

#### 469 ***Conflicts of Interest***

470 The authors declare no conflict of interest.

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