

Dynamics of Dust Clouds Produced by Off-road Vehicle Driving

Dirk Goossens¹ and Brenda Buck²

Abstract

Field experiments were conducted in the Nellis Dunes Recreational Area (Nevada, USA) to study the dynamics of dust clouds produced by off-road vehicle (ORV) driving. Tests were performed with a 4-wheeler (quad), for 3 driving speeds between 24 and 40 km h⁻¹ and for 7 different types of surfaces. Fine as well as coarse-grained surfaces were investigated in the tests. Results show that concentration of PM₁₀ (particles <10 μm, which are the most easily inhaled) behind an ORV can be as high as 160 mg m⁻³ or even more at nose level of quad drivers and passive recreants standing near an ORV trail. ORV generated dust clouds are characterized by a main wave of high concentration followed by an exponential decrease with irregularities (secondary waves) until background concentration has again been reached. Peak concentrations usually occur between 5 and 7 seconds after the passage of an ORV and are higher for silty surfaces than for sandy surfaces. Under no-wind and headwind conditions it takes at least one minute before PM₁₀ concentration has returned to the background level. For tailwind the duration of elevated concentration is of the order of 30 seconds. For winds blowing obliquely to the driving path it is only a few seconds. Elevated PM₁₀ concentrations may occur up to several hundreds of meters behind an ORV, even if no dust is visually noticeable. In-echelon driving is thus strongly dissuaded unless appropriate protection is worn against inhaling the dust.

Keywords: Dust, PM₁₀, Off-road driving, Quad, Concentration, Health

1 Introduction

Off-road vehicle (ORV) driving is one of the most prevalent and fastest growing leisure activities on public lands worldwide [1],[2]. For example, in western Australia the sales of off-road motorcycles and quad bikes (four-wheelers) increased by 67% between 2004 and

¹Department of Geosciences, University of Nevada Las Vegas, 4505 S Maryland Parkway, Las Vegas, NV 89154-4010, USA. Also at: Division of Geography, KU Leuven Department of Earth and Environmental Sciences, Geo-Institute, Celestijnenlaan 200E, 3001 Leuven, Belgium.

²Department of Geosciences, University of Nevada Las Vegas, 4505 S Maryland Parkway, Las Vegas, NV 89154-4010, USA.

2008 [3]. In Montana (USA) the number of registered ORV drivers doubled between 2002 and 2007 [4]. In southern Nevada (USA) the number of off-road drivers has quadrupled in only the last few years [5]. In 2008, the Bureau of Land Management in Las Vegas estimated that the number of off-road drivers in the city (residents plus tourists) had increased to more than 300 000 [6]. Elsewhere in the world ORV activity is also increasing, on all continents [7].

Emissions of soil dust created by ORV activity were hardly studied before the early 1990s, but received much attention since then: see [8], [9], [10], [11], [12], to cite only a few studies. The importance of ORV driving on dust production, at least on a local scale, is very well illustrated by the study by Goossens et al. [13], who found that the contribution of ORV to dust production can be of the same order as that generated by wind, even in areas prone to severe wind erosion.

Most studies dealing with ORV dust focus on the emission rates, using active or passive sampling techniques. Surprisingly little attention has been paid to the characteristics of the dust clouds themselves, to their dynamics, and to the implications for health for the drivers and the surrounding passive recreants. For example, Wheeler [14] measured dust concentrations with a real-time dust monitor on a trailing vehicle following an ORV, but did not provide information on temporal or spatial variations of the concentration within the cloud. USEPA [15], with a summary in Lytle and Woo [16] performed experiments with (among others) ORVs to measure exposure to asbestos from natural soils in Clear Creek Management Area, California, USA. Motorcycle riding, quad riding and SUV (Sports Utility Vehicle) driving were compared, but no analysis was made of the dust clouds produced by them. Padgett et al. [17] performed samplings of dust generated by ORVs at Turkey Bay (Kentucky, USA), but did not characterize the structure of the clouds although they pointed out that concentration varied between locations and, thus, measurements taken at a single point are not appropriate for estimating erosion losses. Goossens and Buck [12] measured dust emissions for 3 types of ORVs (motorcycles, dune buggies, quads), 17 different types of surfaces, and 3 driving speeds, but did not provide information on temporal or spatial variations of the concentrations or on the structure of the dust clouds produced. Jia et al. [18],[19] collected dust during experiments with a car on two unpaved roads in Sweden, but no analysis was made of temporal or spatial variations of concentration in the cloud.

Real-time monitoring systems were developed to measure dust concentrations in front and behind a vehicle, such as TRAKER (Testing Re-entrainment Aerosol Kinetic Emissions from Roads, see [20]), or SCAMPER (System of Continuous Aerosol Monitoring of Particulate Emissions from Roadways, see [21]), but these do not measure the temporal or spatial evolution of the concentration in the cloud because they follow the vehicle as it moves along its pathway.

Several attempts were made to model the emissions. For example, Thornburg et al. [22] developed a probabilistic model to calculate the concentration in the trailing wake of a dust source. Parameters considered were: emission rate of the source, velocity (relative to the source) of the measuring point, distance from the source, offset angle from the centerline of movement, and turbulent diffusivity. Their model also contains a module for a quiescent environment scenario. Comparisons were made with experimental data from seven earlier conducted studies, but no information was given on the internal structure of the dust clouds, on temporal dilution patterns, or on total dust concentrations and their variation within the cloud. Jazcilevich et al. [23] developed a stochastic model based on empirical probability distribution functions to estimate human exposure to emissions from the resuspension of

road dust due to isolated wakes from moving vehicles. They describe the pattern of primary and secondary concentration waves in a dust cloud generated by a vehicle, but did not quantify this pattern in their field experiments, which mainly focused on the statistical distribution of exposure classes within the dust cloud.

The work by Mao et al. [24] is one of the rare studies that measured the temporal pattern of concentration in a dust cloud produced by a vehicle. Concentrations were measured with automated particle counters, for a number of vehicle passings, and concentrations were plotted as a function of time so that the changes in concentration could be followed in detail. However, measurements were performed on a single surface only (a dirt gravel road); all measurements were made well off the road, at distances of 67.5 m, 110 m and 160 m from the road, and the vehicle was a $\frac{3}{4}$ ton truck (not an ORV). Although useful for comparisons with the current study, no attempts were made to calculate concentration on the road itself, for different driving speeds, different types of surfaces, or to present the dilution factor in terms of distance traveled along the road. Temporal patterns of dust concentration in a direction perpendicular to the road were also measured by [25], [26], [27] and [28], but these studies do not discuss the temporal and spatial patterns behind the vehicle, or the structure of the dust cloud.

Despite the important progress made during especially the last decade, little is thus known as yet regarding the structure of an ORV-produced dust cloud, its characteristics, and its evolution in time and space once the vehicle has passed. Such information is important, however, because ORV driving often occurs as a social activity in a group (Figure 1), with the riders exposed to dust produced by vehicles driving in front of them. Passive visitors near the road are also exposed to the dust. What are the peak concentrations in the dust clouds, and how do they relate to the average concentrations? How fast (or how slowly) does dilution take place? How long does it take before the cloud has disappeared and concentrations have returned to the original background levels? How distant from an ORV should one ride to reduce exposure to levels safe for human health? How does all this information change as a function of ORV type, driving speed and terrain type? How does wind direction affect the data? Despite their importance, these questions currently remain unanswered.

The aim of this article is to provide more details on the characteristics and dynamics of dust clouds produced by ORVs. Field experiments were conducted for that purpose in the Nellis Dunes Recreational Area (NDRA), one of the most popular off-road driving areas in southern Nevada, USA. According to a Bureau of Land Management study [29], 285 000 people visit the NDRA annually and the population exposed to the dust is therefore huge. In addition, the NDRA is characterized by many different terrain types, varying from sand dunes, silt surfaces, rock-covered surfaces, to different types of drainages. Therefore, it is an ideal place to study dust production by ORV activity.

2 Study Area and Selected Surfaces

Nellis Dunes Recreational Area is located some 6 km from the northeastern margin of the conurbation of Las Vegas, North Las Vegas and Henderson, Nevada, USA (Figure 2). It encompasses a terrain of approximately 36 km². More than forty years of unlimited off-road driving have resulted in the creation of thousands of road tracks in the desert floor, with a total combined length of 533 km [30].

For the current study we selected 7 different types of surfaces, representative for the NDRA

and for off-road terrain in general. Special attention was paid to ensure that coarse-grained, medium-grained and fine-grained substrata were tested, as grain size is one of the dominant parameters affecting the intensity of dust emissions from ORV driving [31],[32]. The 7 surface types were as follows:

- surface 1: active sand dunes, devoid of any vegetation
- surface 2: partially vegetated sand dunes
- surface 3: slightly silty sand, without vegetation
- surface 4: sandy drainage
- surface 5: shallow (usually <5 cm) silty layer on limestone bedrock
- surface 6: aggregated silt
- surface 7: fine-grained silt, not aggregated

The grain size characteristic of these surfaces (obtained by dry sieving of the <2 mm fraction) are shown in Figure 3. More details on rock fragment cover, surface crusting and vegetation are given in Table 1.



Figure 1: Off-road driving in echelon. Note driving in dense dust clouds.

3 Experimental Procedure

A 750 Kawasaki Brute Force quad with standard off-road tires was used during the experiments. Riders were asked to drive on a more or less straight road segment representative for the type of surface tested. Three speeds were selected: 24 km h⁻¹ (or 15 mph), 32 km h⁻¹ (or 20 mph), and 40 km h⁻¹ (or 25 mph). No higher speeds were tested for

safety reasons, but 40 km h^{-1} was close to the maximum speed a quad could drive on the experimental terrain. Between 10 and 20 repetitions were performed for each driving speed. A DustTrak DRX 8533 real-time aerosol monitor (TSI Inc., Shoreview, MN, USA) was used to measure the concentrations in the dust cloud produced by the vehicle. For this study we analyzed the PM₁₀ fraction (particles < 10 μm , which are the most easily inhaled); all concentrations presented in this article are thus for PM₁₀. Concentrations were measured at about 130 cm above the ground, which corresponds closely to nose level of most riders driving a quad.

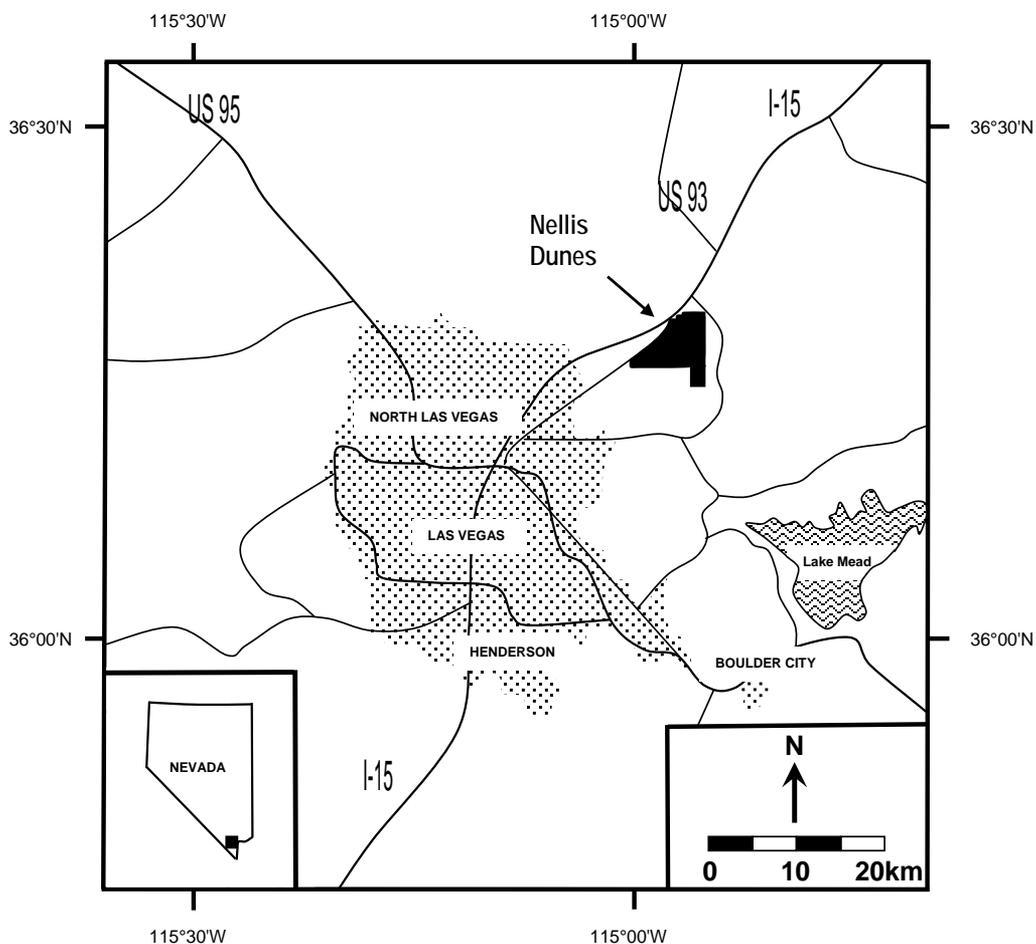


Figure 2: Location of Nellis Dunes Recreational Area

Table 1: Characteristics of the 7 surfaces investigated in this study. For information on grain size characteristics see Figure 3.

Surface ID	Description	Rock fragments	Surface crust	Vegetation
<i>Sandy surfaces</i>				
Surface 1	Active dunes without vegetation. Decimeter to several meters thick.	Sparse; may have exposed petrocalcic horizons	Absent	Absent
Surface 2	Active dunes with vegetation. Coppice dunes <50 cm may be present.	Sparse, <5 % rock cover	Absent	Isolated, low shrubs
Surface 3	Slightly silty sand. Commonly badlands.	Absent	Physical crust may be present on undisturbed surfaces	Mostly absent
Surface 4	Sandy drainages. Mixture of sand and loose rock fragments.	Abundant: 50-80 % with sand mixture	Absent	Absent
<i>Silty surfaces</i>				
Surface 5	Shallow (<5 cm) silty layer on limestone bedrock	Common, not interlocking, rocks in subsoil may be exposed	Absent	Sparse, isolated shrubs may be present
Surface 6	Aggregated silt deposits, commonly badlands, aggregates <5 mm in diameter	Absent	Physical crust common on undisturbed surfaces	Absent
Surface 7	Non-aggregated silt/clay surfaces	Sparse, <10 %, not interlocking	Physical crust may be present on undisturbed surfaces	Usually absent

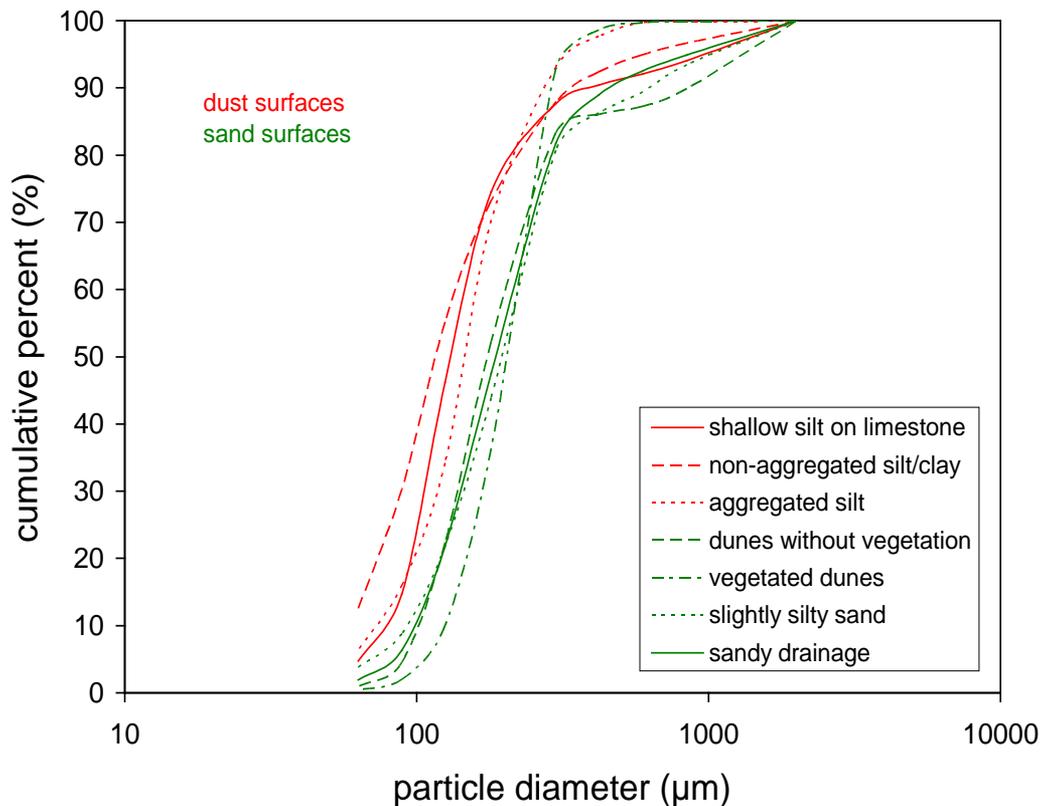


Figure 3: Grain size curves for the 7 surfaces tested in this study. Data refer to the <2 mm fraction and were obtained by standard dry sieving

Before each run, the background PM10 concentration was measured during at least 30 seconds. Runs only took place when the background was very low, less than 0.03 mg m^{-3} , and remained constant over time. After 30 seconds the vehicle performed its run, making sure that the target speed was attained well before the measuring point was reached. Immediately after the vehicle's passage the DustTrak was brought into the road's centerline (roads were usually less than 2 m wide), at a height of 130 cm, and PM10 concentration was measured for at least 90 s, or longer if the background concentration was not yet reached after this time. Concentrations were measured every second, and stored with the same frequency.

Zeroing of the DustTrak was carried out at regular intervals to ensure that the recorded concentrations were correct at all times.

Experiments were performed at episodes when the wind speed was less than 1 m s^{-1} . After completion of the experiments, all data were downloaded to a computer. Results were plotted on a graph for each experiment (given combination of driving speed and surface type), and runs that had been disturbed by wind gusts were removed from the data set. All data presented in this article thus refer to "undisturbed", calm conditions. However, in section 4.5 we also present some data obtained during periods of headwind and tailwind and discuss how concentrations change during these and oblique winds.

Results (concentration as a function of time) were checked for each run, and the average of all selected runs was then calculated for each combination of terrain type and driving speed. Differences between homologous runs were usually small to very small due to the comparable conditions between runs

4 Results and Discussion

The PM10 concentration curves are shown in Figure 4, for all 7 surface types tested. Each diagram shows the results for the 3 driving speeds selected. Note the differences in the vertical scale between the diagrams.

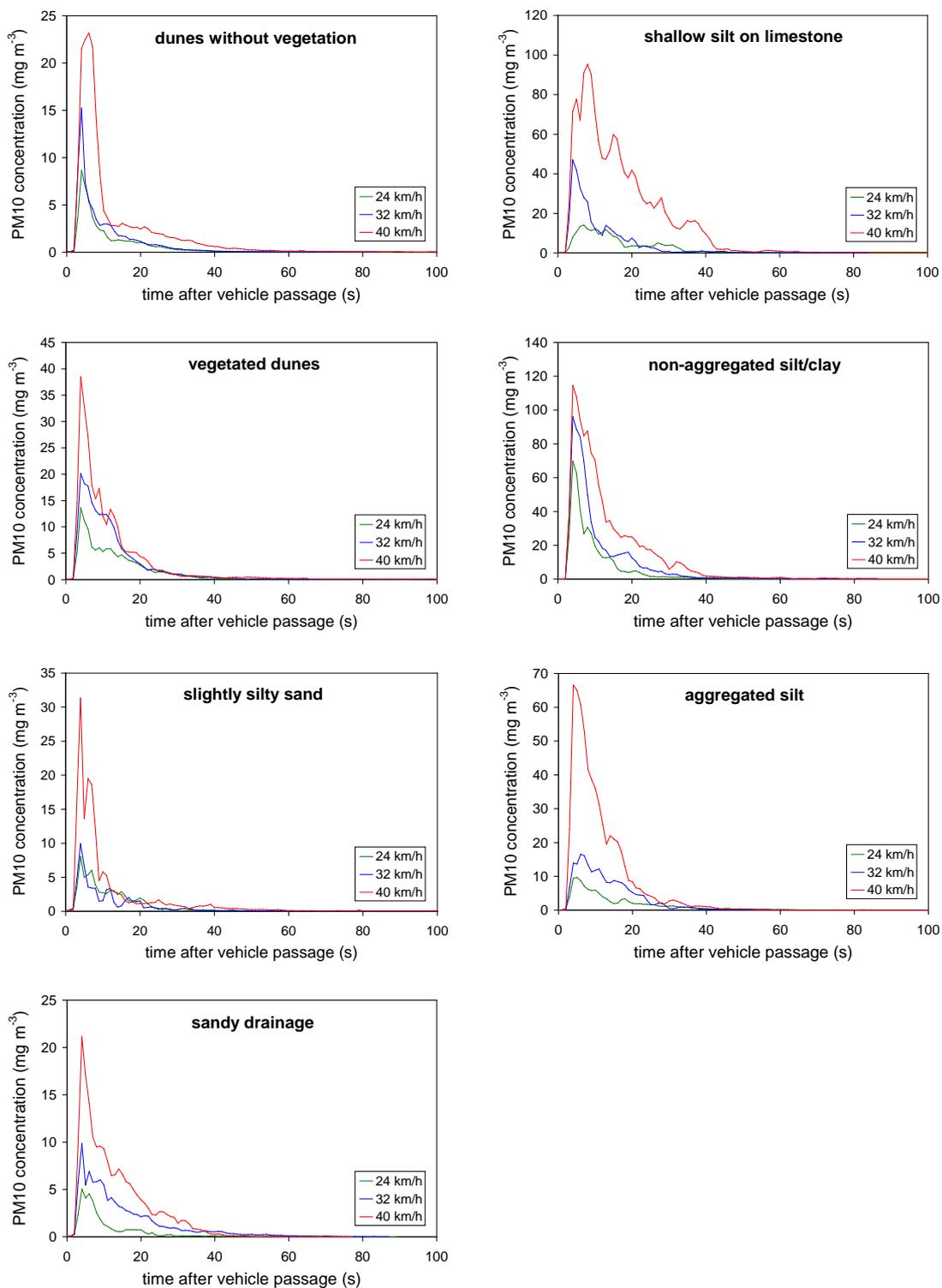


Figure 4: PM10 concentration on the road at 130 cm height, for the 7 tested surfaces. Left: sandy surfaces; right: silty surfaces. Note the differences in the vertical scale

4.1 Structure of an ORV generated Dust Cloud

The PM₁₀ concentration at 130 cm height varies considerably within an ORV cloud (Figure 4). Maximum concentration is reached quickly, followed by a more or less asymptotical decrease towards the background value. Irregularities in the curve occur at any time, but are most pronounced after the maximum.

Jazcilevich et al. [23] published a scheme for the dust concentration in a cloud produced by a road truck (see Figure 5A). Although ORVs are somewhat different in size and weight compared to trucks, Jazcilevich et al.'s scheme resembles the curves in Figure 4 and helps to explain what is happening. According to Jazcilevich et al., a main wave of dust is followed by secondary fronts of lesser amplitude. The first wave is stronger, since it is part of the first swirl of a screw-like wave generated on each side at the rear of the vehicle. Secondary fronts, on the other hand, are part of swirls already attenuated by contact with the ground. Although the pattern generated by an ORV is similar, it can be described in more detail (see also Figure 5B). Dust is released from the ground by two mechanisms: direct uplift due to the contact between the wheels and the surface, and indirect uplift caused by turbulence generated by the vehicle. Pulverization of the top layer by the tires facilitates the emission as it breaks any coarse aggregates and any surface crusts (if present) when the tires drive over them [33]. After having been released, the dust is dispersed in three directions: longitudinally (either forward or backward), laterally, and vertically. Coarse, sand-sized particles will fall back to the surface almost immediately. Finer particles (dust), which are transported in suspension, are affected by the turbulent eddies created by the vehicle and form the largest (and highest) part of the cloud. Because it takes awhile for the lifted particles to get dispersed, concentration at drivers' nose level will be very low immediately behind the vehicle (see Figure 5B). As time elapses, the turbulent eddies expand and the lobes in the dust cloud become better visible (Figure 5B). Maximum concentration is reached after approximately 5-7 seconds; this corresponds to the peak in the concentration curves in Figure 4. The variations in concentration that occur after the maximum (Jazcilevich et al.'s "secondary waves") are caused by these turbulent eddies, as can be seen right in Figure 5B. Note that the "secondary waves" can be very pronounced (Figure 4E) or almost absent (Figure 4A).

The pattern described above is typical for calm (very light wind to no-wind) conditions. During headwind or tailwind, some differences may occur (see section 4.5).

This article focuses on the dust concentration and its temporal and spatial variation above the road. No analysis is made of the temporal and/or spatial variations that occur in the lateral direction; information on these topics can be found in [25], [26], [27] and [28].

4.2 Maximum (peak) Concentration

Because the airborne concentration in an ORV cloud can be very high (Figure 4), it is important to check the maximum values because these occur at distances of the order of a few tens of meters behind the vehicle, i.e., the zone in which trailing drivers usually ride when driving in echelon (Figure 1). Maximum concentrations are plotted in Figure 6A; the time (after passage of the vehicle) at which they were reached is shown in Figure 6B. Maximum PM₁₀ concentration increases with the driving speed, and for 6 of the 7 tested surfaces the increase was exponential (Figure 6A). For the non-aggregated silt the increase was almost linear. These findings are consistent with what was reported in earlier studies, which also found either linear ([10],[12],[34]) or exponential ([12],[26],[34]) relationships.

Also, note that the maximum PM10 concentrations are generally higher for silty surfaces than for sandy surfaces, as could be expected, but the difference is more pronounced when the driving speed is high, about 30 km h⁻¹ or more.

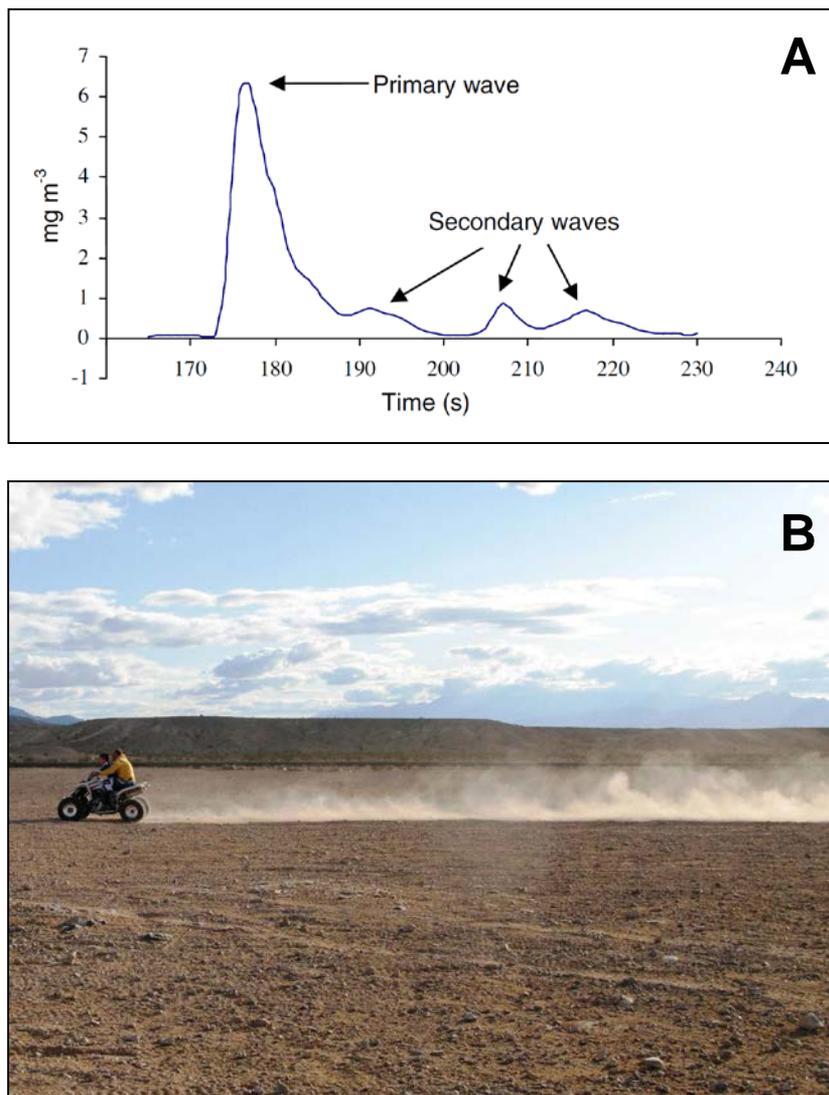


Figure 5: Structure of an ORV cloud. A: Schematic representation of the waves in a resuspension cloud. Reprinted from *Aeolian Research*, vol. 4, Jazcilevich, A., Wellens, A., Siebe, C., Rosas, I., Bornstein, R.D., Riojas-Rodríguez, H., Application of a stochastic vehicular wake erosion model to determine PM2.5 exposure, pp. 31-37, Copyright (2012), with permission from Elsevier; B: Development of a resuspension cloud behind a quad

Time (after the vehicle's passage) after which the maximum concentration was reached varied between 5 and 9 s (Figure 6B); in most of the experiments it was between 5 and 7 s (average for all experiments: 6.2 s). There was no relation with the driving speed, and also no unequivocal relation with the type of surface (sandy or silty topsoil) although for two of the three silty surfaces it took more than 6.5 s to attain the maximum concentration

4.3 Dilution

Dilution of the dust cloud was checked using two criteria: (1) time (after the vehicle's passage) it took for the concentration to return to the original background level, and (2) the speed of decrease of the concentration. The latter criterion quantifies the shape of the concentration curves in Figure 4 after the maximum

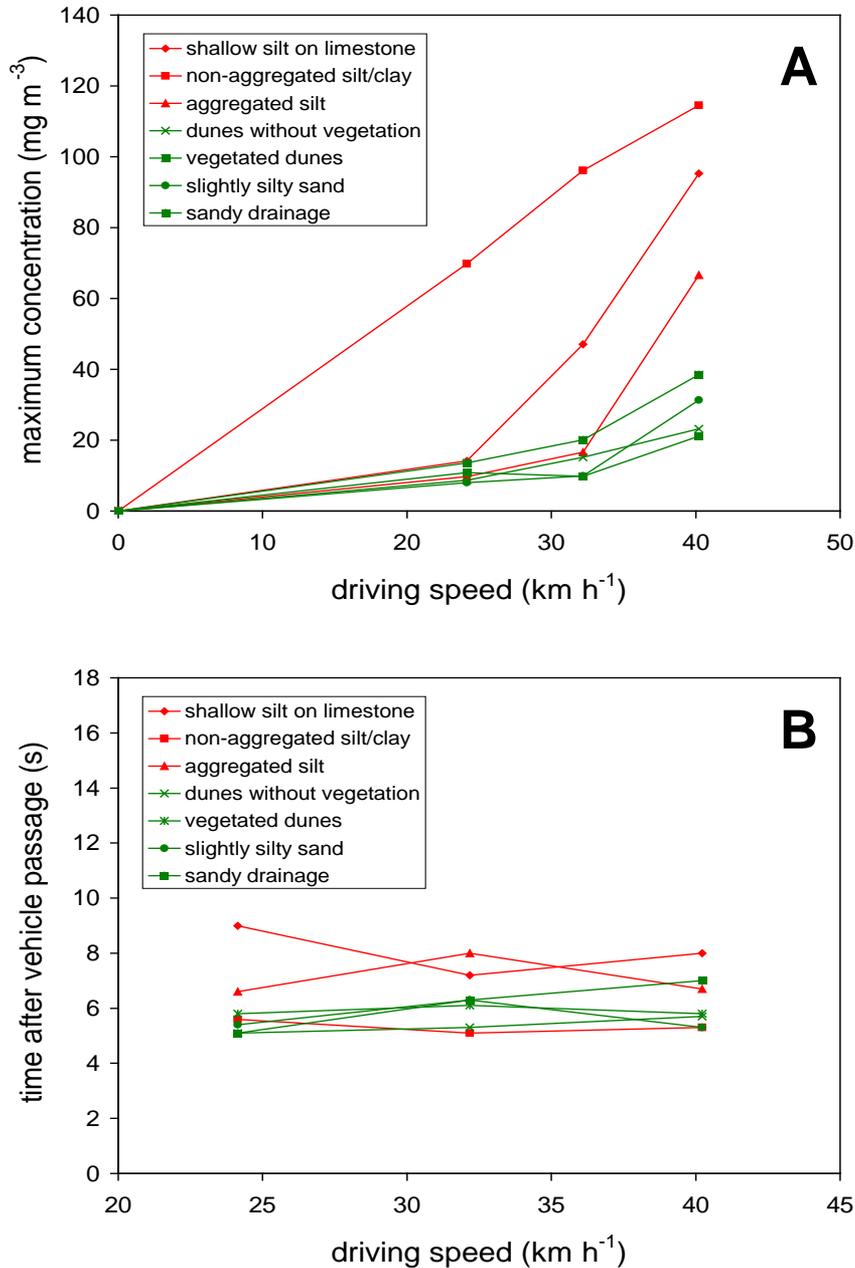


Figure 6: A: Maximum concentration as a function of driving speed; B: Time (after passage of the vehicle) when the maximum concentration was reached.

Elevated PM10 concentrations (defined here as concentrations above the background) were measured for approximately 1 minute after the passage of an ORV (Figure 7A). Even when not visually noticeable, fine particles will thus remain suspended for quite awhile at elevations where they can be inhaled. Therefore, ORV driving poses possible concerns for health even when the atmosphere is visually "clean". No relationship was observed between the duration of the elevated concentrations and driving speed except for the finest soil (non-aggregated silt). There was also no systematic difference between the silty and the sandy soils.

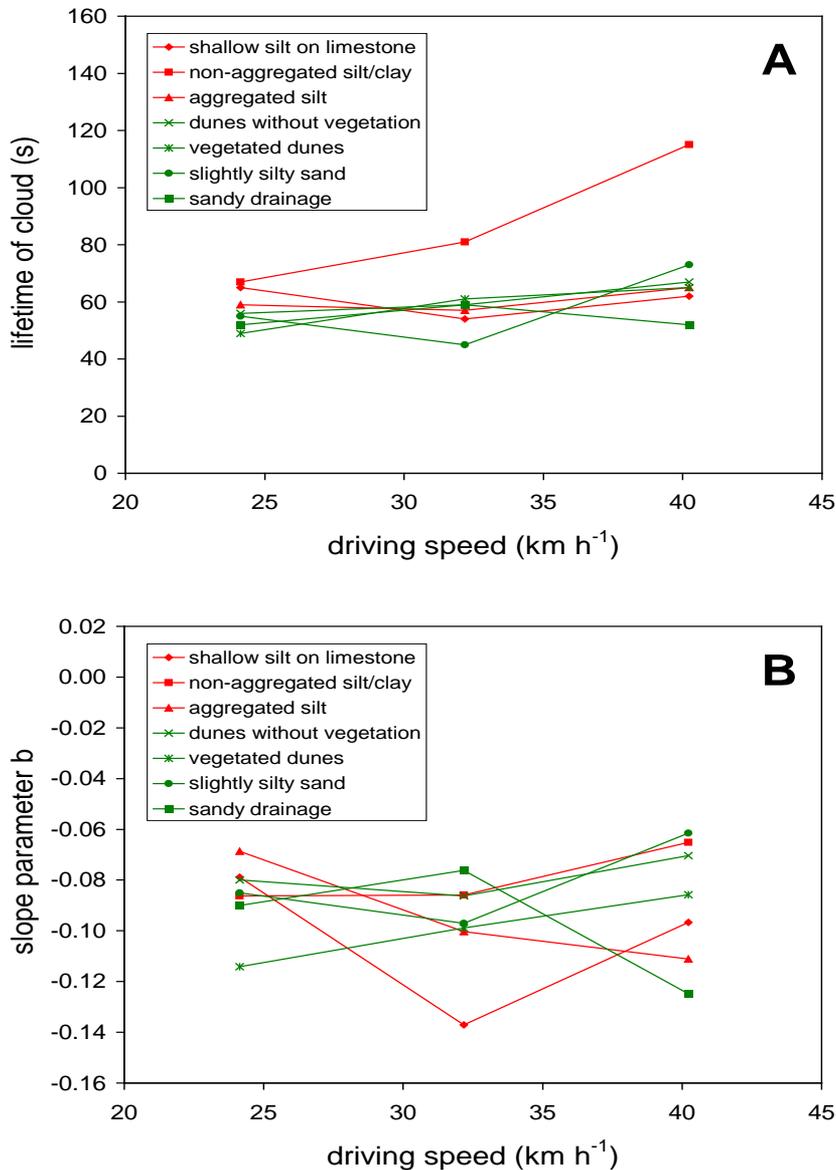


Figure 7: A: Lifetime (on the road) of an ORV produced dust cloud; B: Rate of decrease of PM10 concentration in an ORV produced dust cloud; ordinate shows parameter b of the function $C = e^{(a+bT)}$, where $C = \text{PM10 concentration (mg m}^{-3}\text{)}$ and $T = \text{time (s)}$.

The speed of decreases (after maximum concentration has been reached) can be accurately described by an exponential function $C = e^{(a+bT)}$, where C is concentration, T is time (after the maximum), and a and b are empirical parameters controlled by the driving speed, the type of vehicle and the characteristics of the surface. Parameter b quantifies the rate of decrease in the curves in Figure 4. Other studies (e.g. [24],[25],[26],[27],[28]) also found exponential-like decreases of concentration with time, at least sufficiently close to the road; at larger distances the decrease occurred much more gradually (see [24] and [27]). As can be seen in Figure 7B the rate of decrease in concentration is not related to the driving speed or, somewhat surprising, the type of surface (silty or sandy soil). These findings concur with those observed in Figure 7A and show that dilution of an ORV generated dust cloud is not necessarily related to driving speed or type of surface.

An interesting, and also important consequence is that in-echelon drivers should keep large distances between their vehicles if they want to avoid considerable exposure to dust. In Figure 8 we plotted the distance within which elevated PM10 concentrations occur behind an ORV. For driving speeds as low as 24 km h⁻¹ the critical distance is already around 400 m, and for a driving speed of 40 km h⁻¹ it is between 600 and 800 m or even more. We acknowledge that these values will be considerably lower if there is wind, especially when blowing obliquely to the driving path, but the values shown in Figure 8 will not be far off what happens in wind sheltered zones such as little canyons or wind protected leesides of small and larger hills. Also, one should realize that for most of the cases tested in Figure 4 concentration had already decreased to less than 5 mg m⁻³ after about 20 seconds or shorter. Even for this value, the distance required to obtain it is between 100 and 200 m for common driving speeds (see the 20-second line in Figure 8), which is much more than what is commonly happening during normal ORV recreation (Figure 1). Driving in echelon on unpaved terrain is thus strongly dissuaded unless protective equipment such as a dust mask is worn. An alternative is to drive sufficiently close behind the lead vehicle and stay within the low concentration zone (at least, at nose level) immediately behind it, but this implies following the vehicle as close as only a few meters and is thus not really recommended in terms of safety.

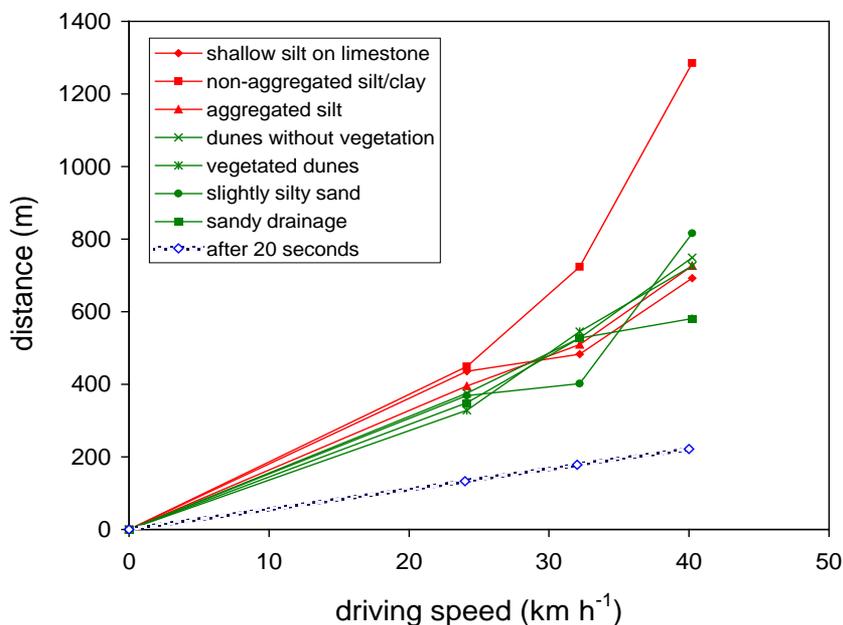


Figure 8: Length of zone behind an ORV where elevated PM10 concentrations occur. Data are shown for all 3 driving speeds and 7 types of surfaces tested. The 20-second line indicates the distance traveled after 20 seconds

Our results do not support the opinion of Jazcilevich et al. [23], who state that the effects of vehicular resuspended dust do not reach more than 50 m from the source. In fact, Mao et al. [24] measured elevated concentrations up to 160 m from the road. On the road itself, and under calm conditions, the numbers can be even much higher, as demonstrated by our study.

4.4 Dosage

The amount of dust in an ORV cloud at riders' nose level (130 cm in this study) can be estimated by multiplying the average concentration, at 130 cm, by the lifetime of the cloud. This very closely approaches the time integrated area under the ensemble mean concentration curves in Figure 4. Mao et al. [24] called this the "pulse area", or dosage. In their experiments they found values of the order of $10 \text{ mg m}^{-3} \text{ s}$ per passage (of a $\frac{3}{4}$ ton truck), but these were measured at distances between 67.5 and 160 m from the road. The dosages in our ORV experiments are much higher, up to $1294 \text{ mg m}^{-3} \text{ s}$ for the silty surface on top of limestone (Figure 9). The figure also shows that dosage increases exponentially with driving speed, and that silty surfaces produce much more dust than sandy surfaces, as expected.

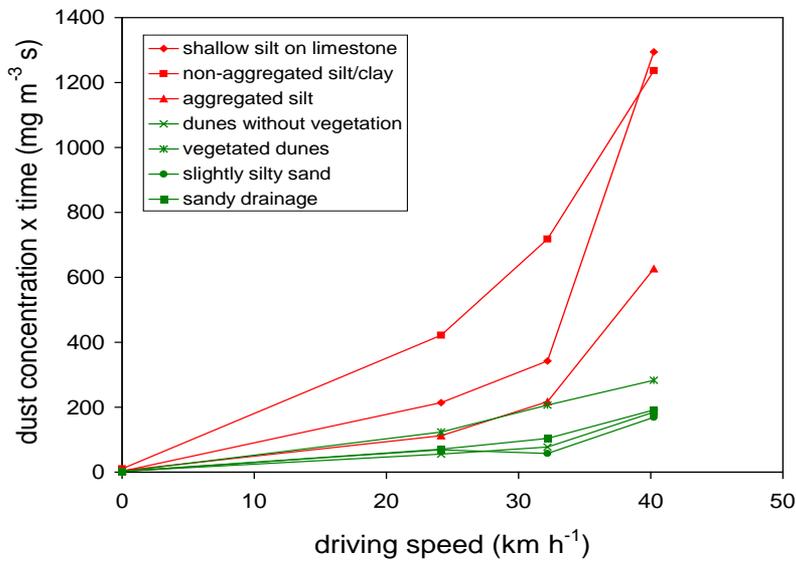


Figure 9: Dosage (product of average PM10 concentration and lifetime of the cloud) for the 3 driving speeds and 7 types of surfaces tested

Another way to quantify the effect an ORV has on dust concentration is to calculate how much more dust is present in the air (in our case: at 130 cm) compared to undisturbed conditions. Results are shown in Figure 10. Even at the lowest driving speed tested, 24 km h⁻¹, the concentration (measured over the entire lifetime of the cloud, i.e., not just at or near peak concentration time) is dozens of times higher than the background concentration. The effect of ORV driving on airborne dust concentration is thus considerable

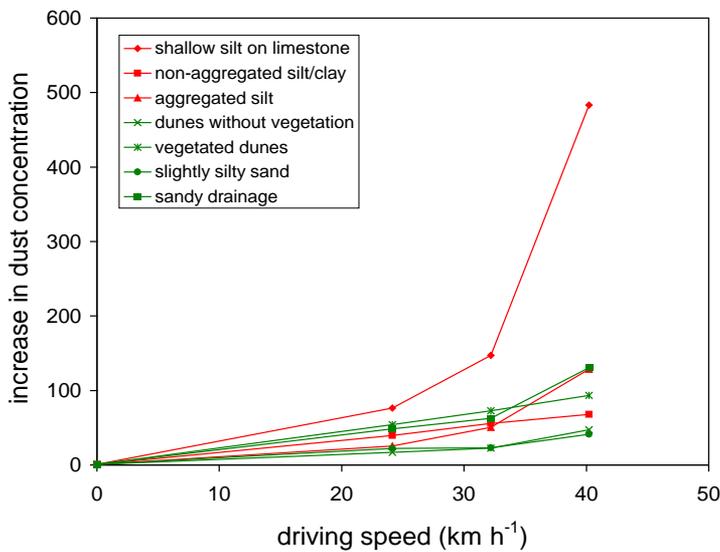


Figure 10: Average (over lifetime of the cloud) PM10 concentration relative to background PM10 concentration

Somewhat surprisingly, and in contrast to the dosage data in Figure 9, no relationship was found with the type of surface (silty *versus* sandy topsoil) in Figure 10 despite the high concentrations for the shallow silt on limestone.

4.5 Wind Effects

The data and conclusions in the previous sections were derived for calm conditions, with no or only very light winds. In this section we investigate what happens to the dust concentration when there is wind.

First, it is important to realize that even under no-wind conditions a vehicle creates a zone of moving air as it advances over the road. Air in front of the vehicle is pushed forward, and air in the low pressure zones aside and above the vehicle and in the vehicle's wake is pulled in the direction of movement. This means that even in calm ambient conditions, some of the dust emitted before the vehicle reaches the measuring point will pass through the measuring point and contribute to the concentration measured at it.

If there is ambient wind, the following situations may occur:

- The wind blows obliquely to the driving path (road). This results in the dust drifting away from the road, and dust concentration above the road decreases rapidly. Trailing vehicles will remain (or, depending on the wind speed, largely remain) out of the cloud created by a lead vehicle.
- Tailwind conditions. Part of the dust produced upstream of the measuring point is blown extra fast (faster than caused by the moving vehicle) through the measuring point. Dilution of the dust cloud near the measuring point occurs faster than normal; dust concentration decreases faster than under no-wind conditions.
- Headwind conditions. If this happens, part of the dust emitted down the measuring point is blown in the opposite direction, towards the measuring point. Depending on the strength of the suction force created by the moving vehicle (driving speed is an important factor here), this dust will either be effectively transported towards the measuring point or move slower than normal away from it. In both cases dust concentration at the measuring point will decrease at a slower rate compared to no-wind conditions.

For a person standing in the driving route of an ORV after the vehicle has passed, the order of the risk to inhale large amounts of dust emitted by the ORV is thus as follows: headwind (highest risk), no wind, tailwind, oblique wind (lowest risk). For a rider in an ORV following a lead vehicle, and who maintains sufficient distance from the lead vehicle (see the previous sections), the same order applies.

The effect of headwind and tailwind is illustrated in Figure 11. To adequately compare the patterns the data were normalized in each diagram. The faster dilution during tailwind and the slower dilution during headwind compared to calm conditions are clearly visible in the curves. Also note that the irregularities in the curves (Jazcilevich et al.'s [23] "secondary waves") are more pronounced during headwind conditions than during calm and tailwind conditions, which is a logical consequence of the much more complex and chaotic movement of air and dust during the former compared to the latter.

5 Conclusions

ORV riding can produce dust clouds with PM10 concentrations up to 160 mg m^{-3} and more at nose level of drivers or passive recreants standing near an ORV trail. Total suspended particle (TSP) concentrations are even higher, but were not measured in this study.

ORV clouds may show slight differences according to wind conditions, but are generally characterized by a main wave of high dust concentration followed by an exponential (in time and space) decrease in concentration until the original background level has again been reached. The decrease is characterized by irregularities ("secondary waves") that are especially visible during headwind conditions. Tailwind and no-wind conditions produce more regular dust concentration curves.

Peak (maximum) concentration at nose level in an ORV cloud is reached shortly after the passage of the vehicle, usually after about 5-7 seconds, and peaks become higher as the driving speed increases. Fine-grained, silty surfaces also result in higher peak concentrations than more coarse-grained, sandy soils.

Under no-wind and headwind conditions it takes at least a full minute after the passage of an ORV before PM10 concentration at nose level has returned to the original background level. During tailwind the period of elevated concentration is shorter, but still of the order of 30 seconds or more. At winds blowing obliquely to the driving path it is only a few seconds. No relationship was observed between the duration of elevated concentration and driving speed, except for the finest soil, which consisted of fine, non-aggregated silt.

For driving speeds between 24 and 40 km h^{-1} , elevated dust concentrations may occur up to several hundreds of meters behind an ORV vehicle, even if no dust is visually noticeable. Driving in echelon behind a lead vehicle is thus not recommended unless appropriate protection is worn against inhaling the dust.

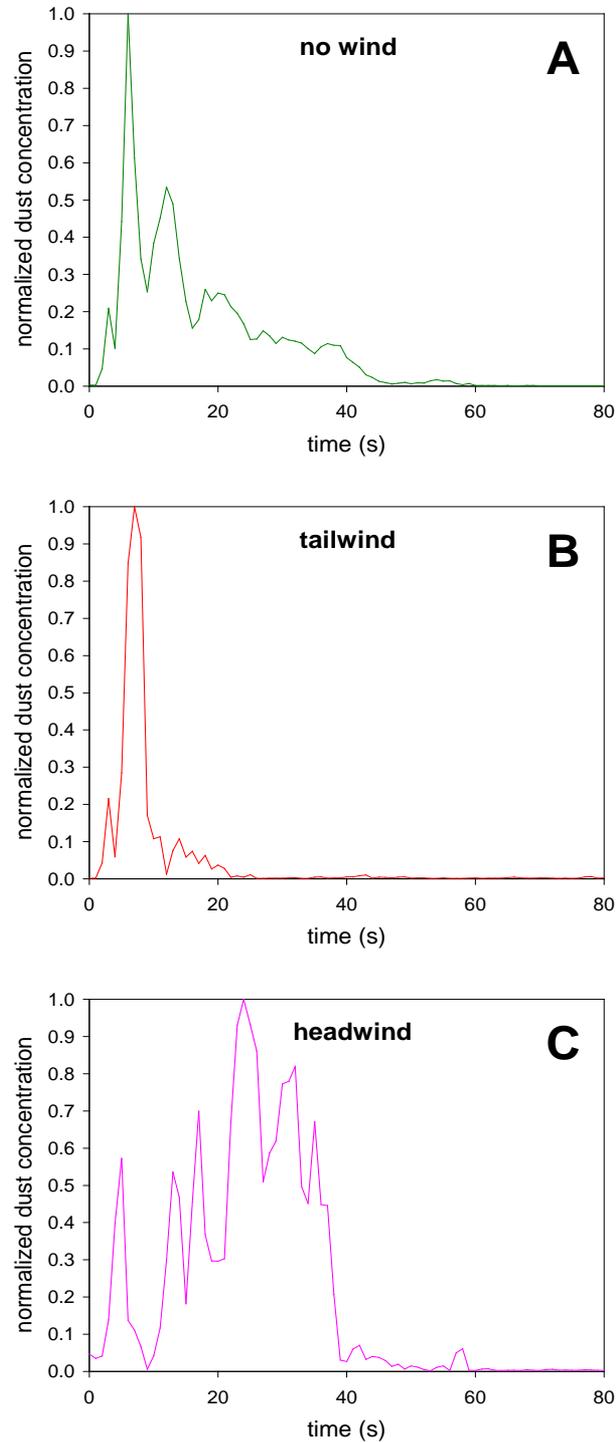


Figure 11: Typical dust concentration curves for (A) no-wind conditions; (B) tailwind conditions; (C) headwind conditions. Curves were normalized to facilitate comparison. A: sandy drainage, 32 km h^{-1} ; B and C: slightly silty sand, 32 km h^{-1} .

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