Chapter 3

DUST EMISSION BY OFF-ROAD DRIVING: FIELD EXPERIMENTS

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1. The worldwide increase in ORV activities and its impacts

Off-road vehicle (ORV) driving is one of the most prevalent and fastest growing leisure activities on public lands worldwide (Cordell, 2004; Cordell et al., 2008). For example, in western Australia the sales of off-road motorcycles and quad bikes (four-wheelers) increased by 67% between 2004 and 2008 (DSR, 2009). In Montana (USA) the number of registered ORV drivers doubled between 2002 and 2007 (Sylvester, 2009). In southern Nevada (USA) the number of off-road drivers has quadrupled in only the last few years (Spivey, 2008). In 2008, the Bureau of Land Management in Las Vegas estimated that the number of off-road drivers in the city had increased to more than 300,000, which is over 15% of the population (Goossens and Buck, 2009a). Elsewhere in the world ORV activity is also increasing, on all continents (Outdoor World Directory, 2010).

Damage to the land from ORV driving is extensive. ORV driving is one of the most destructive types of land use disturbing the top soil, vegetation and even local ecosystems (Adkinson, 1991; Kutiel et al., 2000; Wiedmer, 2002). Also, it creates noise, produces large amounts of exhaust-gases and emits significant quantities of soil dust, especially when the soil is dry (Goossens and Buck, 2009a). Surfaces disturbed may require decades or even centuries to become more or less restored, if recovery is at all possible (Wilshire and Nakata, 1976).

Considering the damage it is not surprising that the first studies investigating the consequences of off-road driving appeared more than 40 years ago. These studies primarily focused on the effects off-road vehicles exert on the soil itself. The increased

compaction of the soil due to ORV driving has been described in detail (Liddle and Greig-Smith, 1975; Wilshire and Nakata, 1976; Sparrow et al., 1978; Voorhees et al., 1978; Wilshire et al., 1978; Anderson et al., 1990; Smith and Dickson, 1990; Adkinson, 1991). Webb et al. (1978), Wilshire et al. (1978) and Griggs and Walsh (1981) investigated how off-road driving affects the soil temperature regime. Other soil parameters studied include organic matter content and pH (Wilshire et al., 1978; Kutiel et al., 2000), soil nitrogen (Belnap, 2002), and hydrologic parameters such as infiltration (Wilshire et al., 1978; Eckert et al., 1979; NPSNM, 2008) and soil water content (Liddle and Greig-Smith, 1975).

Effects on vegetation have been studied as well. A consequent decrease in frequency, cover, abundance, vigor, and maximum height of the vegetation along ORV trails has been observed (Sparrow et al., 1978; Adkinson, 1991; Kutiel et al., 2000; NPSNM, 2008). A review of the literature on the effect on biological productivity was provided by Wilshire et al. in 1978. Effects on the fauna were studied by McEwen (1978), Anderson et al. (1990) and Schlacher and Thompson (2007), and effects on stream environments, such as rivers and washes, by TCAFS (2002) and Wiedmer (2002). Also, soil erosion in and near ORV trails has been examined (Fish et al., 1981; Tinsley and Fish, 1985; Tuttle and Griggs, 1987).

Emissions of soil dust created by ORV activity were hardly studied before the early 1990s but received much attention since then: Moosmüller et al., 1998; Gillies et al., 1999, 2005; Kuhns et al., 2003; Goossens and Buck, 2009b; to cite only a few studies. Most studies focused on direct measurements of ORV emission but others also considered wind erosion in disturbed ORV trails (Goossens and Buck, 2009a) or characterized and mapped surface types in terms of dust production (Bacon et al., 2008; McLaurin et al., in press).

Dust emissions created by ORV activities require special attention because ORV driving is a non-selective process. This means that components that normally stay fixed in the soil may become released and inhaled. This is a special concern if ORV-driven substrata contain chemical or mineral substances, or organisms harmful to the human body. Moreover, the risk of inhaling harmful substances is not limited to the drivers themselves: passive visitors to ORV sites will also be affected, as will residents of downwind located areas. For evident reasons the risk is highest in the area of production, i.e. the ORV site, because of the higher airborne concentrations. The risk in downwind zones is more difficult to predict as it depends on the degree of dilution as the dust blows towards these areas, which is affected by the meteorological conditions and the degree of roughness of the earth's surface.

Because of the very high number of visitors to the Nellis Dunes Recreation Area, emission of dust caused by ORV activity is of special concern at this site. Previous research (Moosmüller et al., 1998; Gillies et al., 1999, 2005; Kuhns et al., 2003) has shown that accurate predictions of emissions caused by driving on unpaved surfaces are

very difficult because the emissions strongly depend on the type of surface driven, the type of vehicle used, the driving speed, and other factors. The large number of surface types in the NDRA, and the highly heterogeneous distribution, especially in the most intensively driven western part of the area, complicate accurate predictions based on previous data. A separate study investigating the emissions on each surface type was thus necessary, for each type of vehicle used in the Nellis Dunes Recreation Area. This chapter describes the results of these measurements.

Apart from the emissions generated during the driving itself, ORV also disturbs the topsoil. The structure of the top layer in ORV trails is very different compared to the original surface in which the trail has been created. ORV trails are much more sensitive to wind erosion than undisturbed surfaces, which are often characterized by physical or biological surface crusts or by a natural protection of surficial rock fragments. This difference is significant in areas rich in silt and clay (such as in the entire eastern part of the NDRA) because in these areas dust production by wind erosion is nearly exclusively restricted to the ORV trails. The difference in dust emission potential between ORV trails and undisturbed terrain is studied in Chapter 4 of this report.

2. The ORV experiment: procedure

2.1 Vehicle types tested

Three types of vehicle were tested in the experiment: the four-wheeler (quad), the dune buggy, and the dirt bike (motorcycle). These vehicles are by far the most commonly used ORV vehicles in the Nellis Dunes Recreation Area; observations during the numerous visits to the site during the project indicated that they should represent nearly 99% of all off-road vehicles driving in the area. Fig. 1 shows a photograph of each vehicle. All vehicles used in the test were equipped with standard type tires. Tire tread was not considered as a parameter in this study.

2.2 Locations

Experiments were performed on 16 of the 17 surface types occurring in the Nellis Dunes area. Surface type 3.5 (bedrock) was not tested because (1) these surfaces contain negligible emittable dust, and (2) in NDRA there is almost no driving on this unit because these surfaces are too rough to be driven and are also usually located on very steep slopes. It is safe to state that, at least in NDRA, the 3.5 units produce negligible ORV-generated dust.

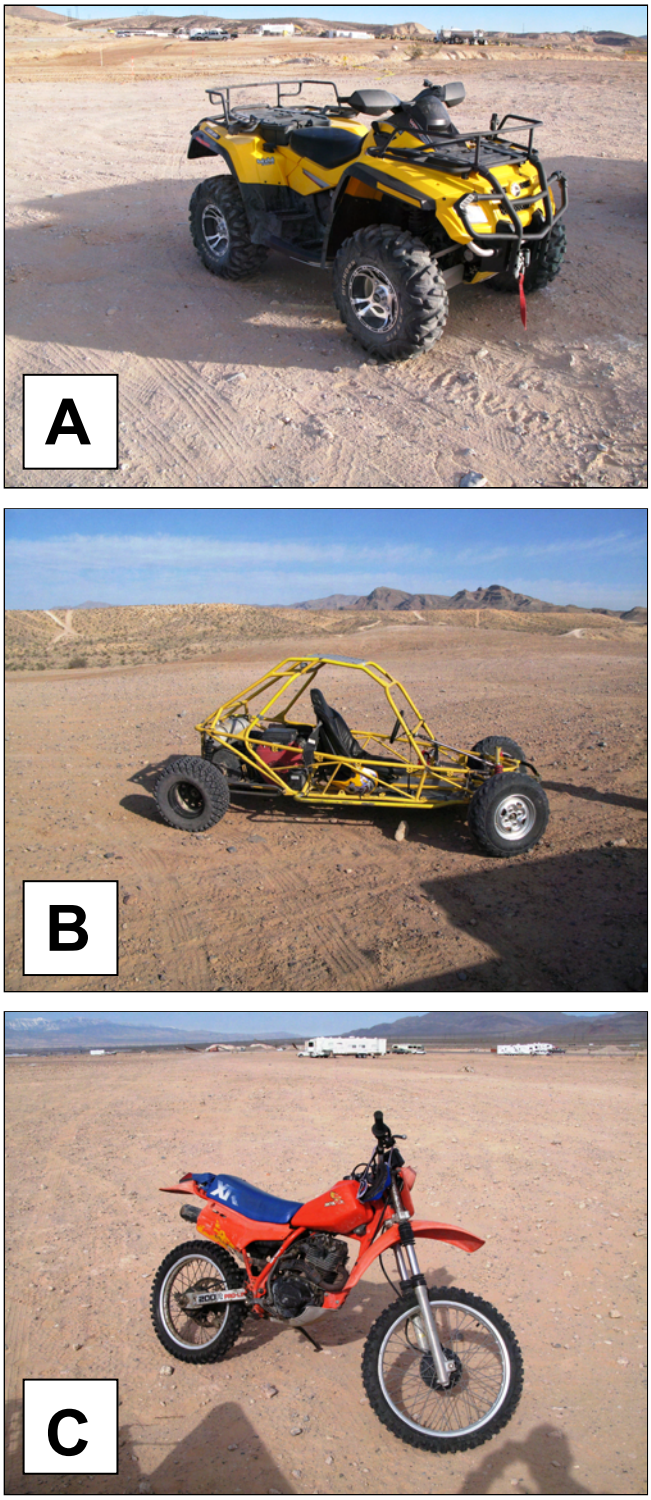

Fig. 1: The three vehicle types tested. A: 4-wheeler (quad); B: dune buggy; C: dirt bike (motorcycle)

Much attention was paid to seeking adequate experimental locations, to ensure reliable as well as representative data. A track long enough to attain high speeds was selected on each surface unit. For safety reasons, and also to ensure homogeneous emissions near the measurement spot, only straight sections without curves were selected. Fig. 2 shows the locations of the sites.

All experiments were performed on dry soils. Moisture content was always very close to zero: relative humidity in the region is extremely low, evaporation rates very high, and no rains occurred during at least 3 weeks prior to the measurements.

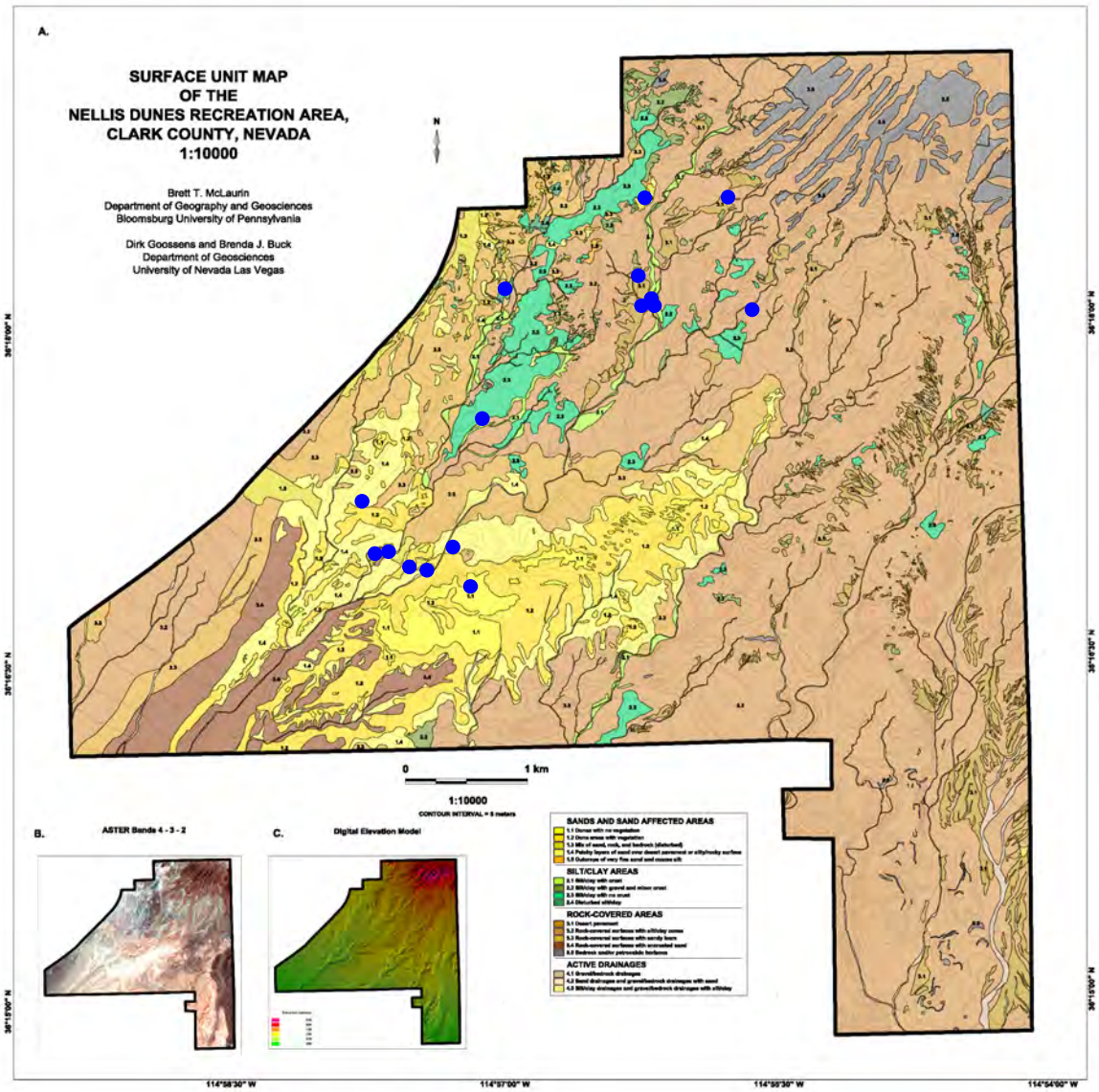

Fig. 2: Location of the ORV-experiment sites (blue dots)

2.3 Field procedure

Big Spring Number Eight (BSNE) samplers (Fryrear 1986; see Fig. 3) were used to collect the dust. We used BSNE samplers because of their relatively large inlet area (10 cm^2), and also because efficiency of the BSNE is known for various grain size fractions (Goossens and Offer, 2000; Goossens et al., 2000; Sharratt et al., 2007). All data were corrected for the efficiency of the traps.

Fig. 3: Pole with four Big Spring Number Eight (BSNE) samplers

Two vertical poles with 4 BSNEs each were erected 1.5 m from the centre line of the track (Fig. 4). BSNEs were installed at the following heights: 0.25 m, 0.50 m, 0.75 m and 1.00 m. Drivers were asked to drive at approximately 1 m from the poles. Observations during the runs revealed that the height of the dust cloud was always between 1.0 and 1.5 m near the poles; dust clouds were thus adequately sampled during the experiment.

Fig. 4: Photo of the set-up of dust poles and dust traps during a dirt bike run

Measurements were done on days when the wind blew perpendicular to the road. During 95% of the runs the two poles were installed on the same side of the road to ensure adequate collection. A few cases occurred where the wind speed was so low that the dust was emitted to both sides of the road; if that happened one of the poles was put on the other side of the road, or if that was not possible, the amounts of dust recorded by the traps were doubled. Careful observations were made of the wind during each run to determine the correction, and all results were later corrected for low wind speed conditions (but this was only necessary for a few tests).

Dirt bikes are normally being driven at higher speeds than 4-wheelers and dune buggies. To ensure representative results it was decided to select the driving speeds according to the type of vehicle. Three speeds were selected for each vehicle at each location, and although the drivers were able to drive with the same speeds on most locations there were a few cases where they had to drive somewhat slower for safety reasons. A portable electronic Schwinn speedometer (Pacific Cycle Inc., Madison, WI, USA) was attached to each vehicle to measure the exact speed during each run. For the dirt bike the speeds averaged 32, 43 and 56 km h^{-1}; for the 4-wheeler: 28, 36 and 48 km h^{-1}; and for the dune buggy: 24, 32 and 40 km h^{-1}.

Between 22 and 30 runs were made for each combination of driving speed, vehicle and surface type. Altogether 3684 runs were made, 144 experiments in total. For safety reasons (very rough and mountainous terrain), and also because of the absence of loose sediment on the surface, no measurements were carried out on surface unit 3.5 (bedrock), as stated earlier. This does not really pose a problem for this study because the emission will be virtually equal to zero on these surfaces.

After each experiment clean BSNEs were installed on the poles. Used BSNEs were immediately stored in a closed box to prevent subsequent contamination of the traps.

2.4 Laboratory procedure

After each field test all BSNEs were taken to a closed laboratory for dust collection. Samples were collected with a brush, and with great care to not affect the grain size distribution. All samples were weighed with an analytical Ohaus Explorer balance (Ohaus Corporation, Pine Brook, NJ, USA). Precision of the measurements was 0.0001 g.

To determine the proportion of individual grain size fractions all samples were analyzed with a Malvern Mastersizer 2000 grain size analyzer (Malvern Instruments Ltd., Malvern, UK). Emissions were calculated for grain size fractions between 2.5 μm and 100 μm. No calculations were made for particles >100 μm since, in the current study, we are only interested in the emission of suspendable particles.

2.5 Calculation of the emission

Two possibilities exist to calculate the emission. The most common procedure is to calculate the emission as a flux, i.e. mass of sediment emitted per unit surface and per unit time (expressed in, for example, kg m^{-2} s^{-1}). However, in the case of off-road driving this option is not very useful because the area of road surface prone to emission depends on the number of wheels of the vehicle, the width of the wheels, and the surface structure of the wheels and the road: only where the wheels effectively touch the road direct emission will occur. Additionally, the problem is more complex because the intersurfaces can also experience emission due to the turbulence created by the driving vehicle. This makes it difficult to determine the exact size of the emission surface and, thus, of the emission flux. A much better option for off-road driving is to calculate the emission in terms of emitted mass per unit length (for example, kg of dust emitted per driven km). If the total length of a run is known, the total mass of dust emitted during that run can be calculated. Of course, for adequate estimations the emission rates should be known for

various driving speeds, and information is needed on the speed (and its variation) during a run.

In this study emission is presented as emitted mass per unit length. The calculation procedure is as follows:

First, the amount of dust passing through the dust cloud is calculated at the height of each trap. By dividing the mass of dust caught by a trap through the trap's inlet area (10 cm^2 for a BSNE), and after correction for the trap's efficiency, the total transport (in g cm^{-2}) at each trap height is calculated. Next, the total mass transported through a vertical strip 1 cm wide and parallel to the road is calculated by vertically integrating the dust profile from the road surface (i.e., at zero height) to the top of the cloud. In the case of aeolian transport of particles <100 μm the horizontal transport flux (*Fh*) usually decays with height (*z*) according to the function $Fh = az^b$, where coefficient *a* and exponent *b* are determined empirically (Buschiazzo and Zobeck, 2005). The vertical transport profile in the dust cloud during the Nellis Dunes experiments showed a similar decay for all experiments. However, for mathematical reasons no calculations of the profile down to $z = 0$ are possible when the power function above is used. Therefore the profile was described with a 4th order polynomial (for several experiments a 3rd order polynomial already gave an optimum fit). All curve fittings were carefully inspected in a graph before calculating any transport to ensure adequate fits.

The result of the calculation is the mass of dust transported through a 1-cm wide strip parallel to the road and with a height equal to the height of the cloud (very close to 1.5 m at the location of the poles in almost all experiments). Since there is no dust above the upper edge of the cloud, this corresponds to the total mass of dust emitted per unit length driven by the vehicle.

3. The ORV experiment: results

3.1 PM10 emissions

For each combination of vehicle and surface type emission data are available for 4 speeds: the 3 speeds tested during the experiments and zero emission at zero driving speed (recall that no wind erosion occurred during the measurements). Since the emission progressively increased with the driving speed, speed-emission curves could be constructed for all experiments. Fig. 5 shows the curves for the 51 combinations of vehicle and surface type for PM10. In order to not overload the graphs and keep the pictures readable the individual data points are not shown, but it should be emphasized that they are very close to the curves shown. For example, for the 4-wheeler graph (upper

graph in Fig. 5) the correlation coefficient R is >0.95 for 16 of the 17 curves (even >0.98 for 14 of the curves), and its lowest value is still 0.89 (surface unit 1.2). The other graphs show similar correlations.

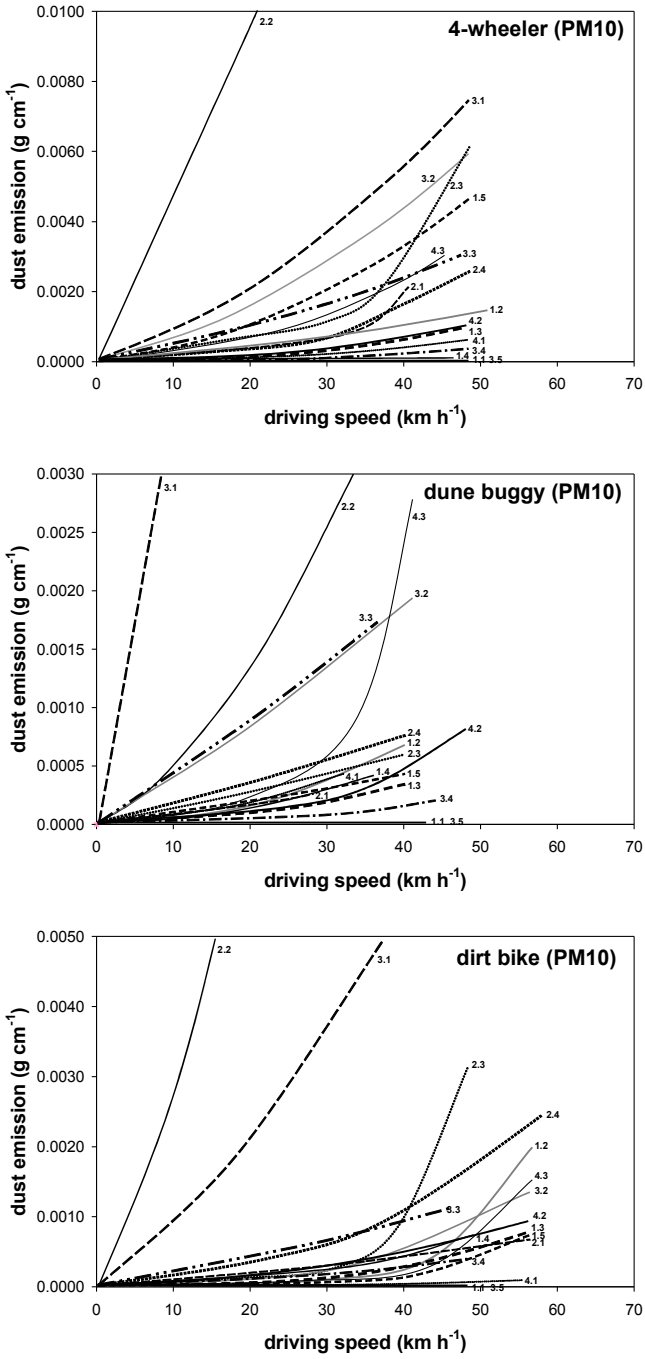

Fig. 5: Basic emission curves for PM10

Although the shape and position of individual curves vary with vehicle and surface type the general trends in the figure are evident: highest emissions were always measured on surface units 2.2 (silt/clay with gravel) and 3.1 (desert pavements) whereas lowest emissions occurred on the uncrusted (or only weakly crusted) sandy surfaces (1.1, 1.2, 1.3, 1.4, 3.4) and the gravel and bedrock surfaces (3.5, 4.1). The thin surficial stone layer of the desert pavements (3.1) did not provide much protection against off-road driving. The silty surfaces (except 2.2 and 3.1) showed intermediate emission values.

To facilitate interpretations the data of Fig. 5 are replotted in Fig. 6, for the silty and sandy surfaces separately and also for the ensemble of all surface units. In addition, the emission values were calculated for identical driving speeds for all vehicles. Interpolation was used to calculate the emission at each particular speed. No data are shown for the dune buggy at driving speeds >40 km h^{-1} because the dune buggy was unable to reach such speeds during the experiments.

Fig. 6 shows that, on average, PM10 emission increased exponentially with the driving speed. As could be expected, the silty surfaces produced much more dust than the sandy surfaces. Also, emission varied considerably with the type of vehicle. Most PM10 was emitted by the 4-wheeler whereas, on average, the dune buggy and the dirt bike emitted almost equal amounts of PM10 despite the fact that the dune buggy has twice as many wheels than the dirt bike.

Fig. 7 shows the speed-emission curves for the 17 surface units separately. Although it is relatively easy to recognize the general trend (highest emission: 4-wheeler; intermediate emission: dune buggy; lowest emission: dirt bike) substantial differences occur for individual surface units, both with respect to the relative order of the vehicles and the rate of increase of emission with driving speed. These differences do not appear to be systematically related to a specific type of surface or vehicle but may occur anywhere in the data set (see Fig. 7), which makes it difficult to interpret.

In Fig. 8 the data of Fig. 7 are replotted for the silty and sandy surfaces separately, and also for the ensemble of all surface units. Similar to Fig. 6 the data were recalculated to identical driving speeds to facilitate comparisons. The general trend is clear: most PM10 was emitted by the 4-wheeler, at all driving speeds. On average the dune buggy produced slightly more PM10 than the dirt bike, but from a driving speed of around 35 km h^{-1} the dirt bike seems to produce more PM10 than the dune buggy. This increased production is only discernable on silty surfaces; it does not seem to occur on sandy surfaces.

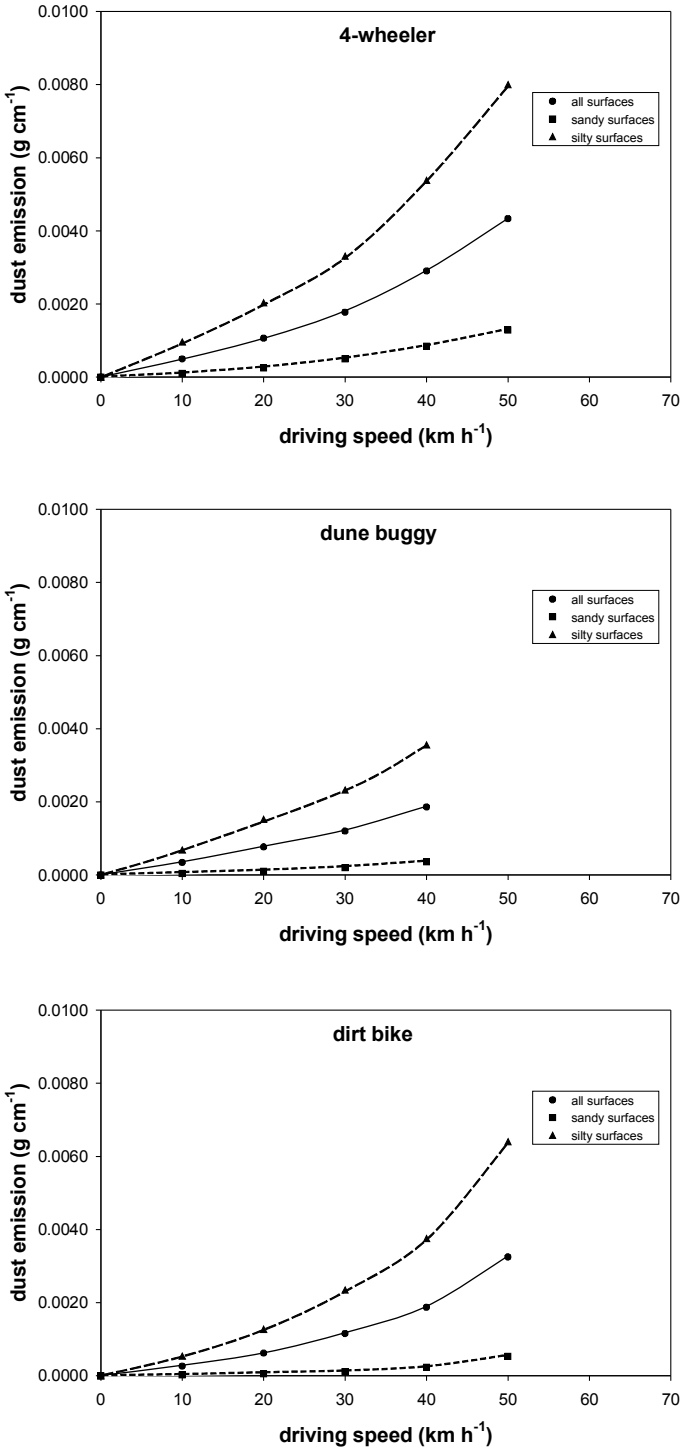

Fig. 6: PM10 emission curves, grouped for the major surface classes

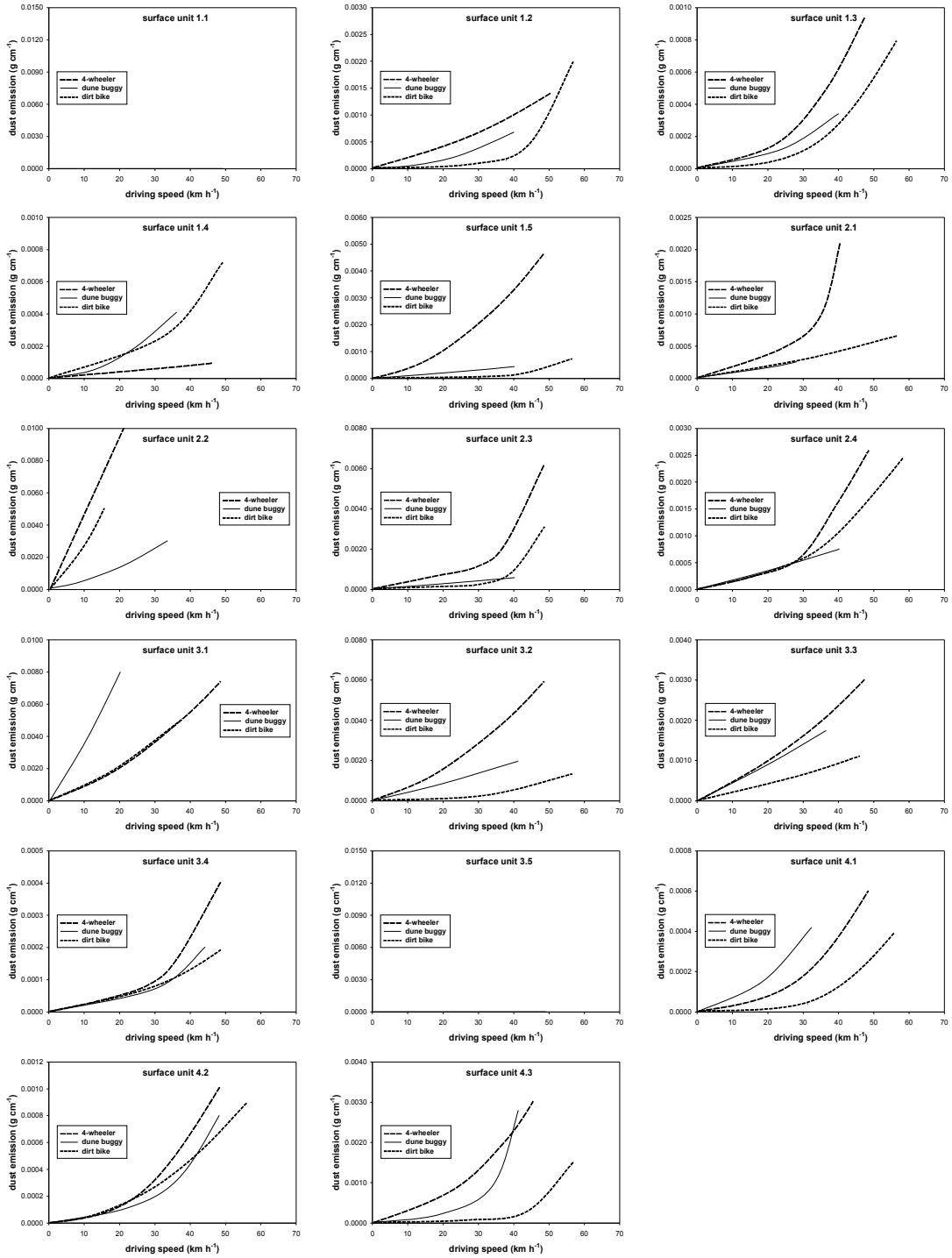

Fig. 7: PM10 emission curves for the individual surface types

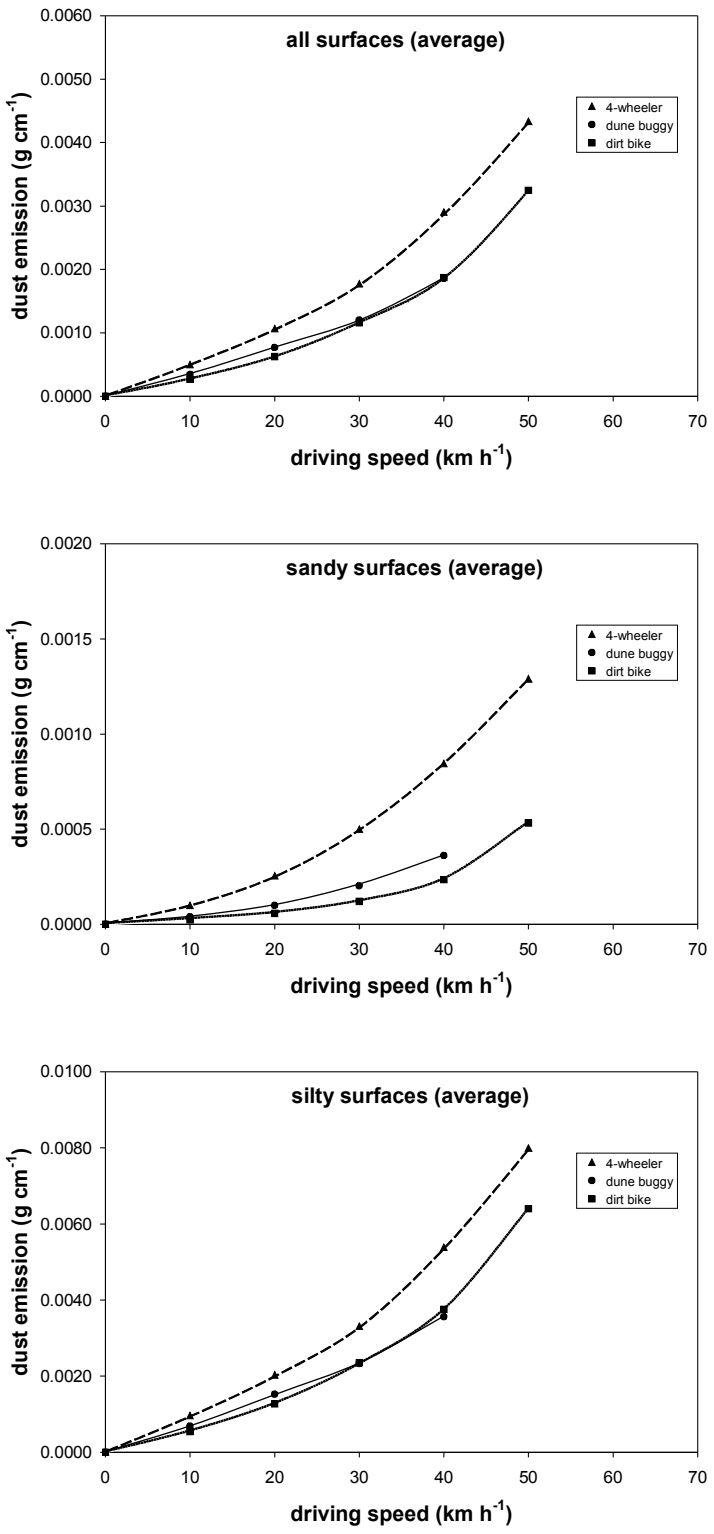

Fig. 8: PM10 emission curves, grouped for the 3 vehicles tested

3.2 TSP emissions

Fig. 9 shows the speed-emission curves for all 51 combinations of vehicle and surface type, for the fraction <60 µm (defined in this study as TSP, or total suspendable particles). We used the 60-µm limit as a cut-off for TSP because it corresponds to the maximum size of those grains that will still be transported in short-term suspension during average conditions of wind speed and turbulence (Pye and Tsoar, 1990). It also nearly coincides with the upper diameter of silt (52 µm or 63 µm, depending on which criterion is used).

The general trends already observed in Fig. 5 also appear in Fig. 9: most dust was produced by surface units 2.2 (silt/clay with gravel) and 3.1 (desert pavements) whereas the sandy surfaces produced the least amounts of dust. Differences between the PM10 and TSP patterns exist for various surface units: a striking example are the 4.3 surfaces (silty drainages), which proportionally emit much more TSP than PM10. Less significant differences can be detected for several other surface units.

Averaging the data for the two major surface groups (silty and sandy surfaces) leads to TSP patterns that are similar to those for PM10 (Fig. 10). Not surprisingly silty surfaces produce much more TSP than sandy surfaces, for all 3 vehicles tested.

Plotting the speed-emission curves for individual surface units shows similar patterns as for PM10 (Fig. 11, and compare to Fig. 7). Differences do occur: examples are the dune buggy on surface unit 3.3 (rock-covered surfaces with sandy loam), and the 4-wheeler on surface unit 3.4 (rock-covered surfaces with encrusted sand). Also here, differences in the mutual behavior of the vehicles do not seem to be systematically correlated to surface type, as for PM10.

Replotting the data for the silt and sand classes (Fig. 12) leads to similar conclusions as for PM10. Most dust is produced by the 4-wheeler whereas, on average for all surface types, the dune buggy and the dirt bike produce almost equal amounts of dust. However, on sandy surfaces the dune buggy proportionally emits much more TSP than PM10 compared to the other vehicles. No such trend was found for the silty surfaces.

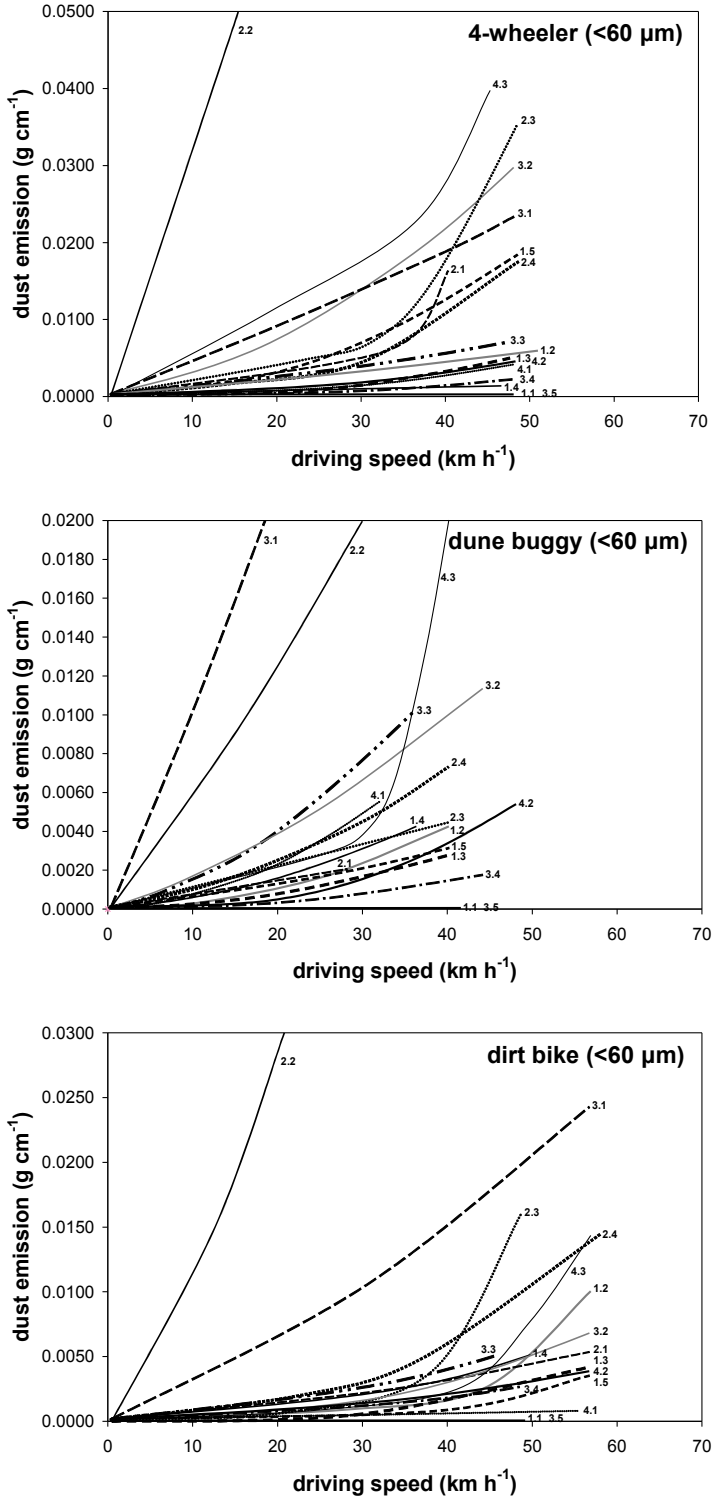

Fig. 9: Basic emission curves for TSP

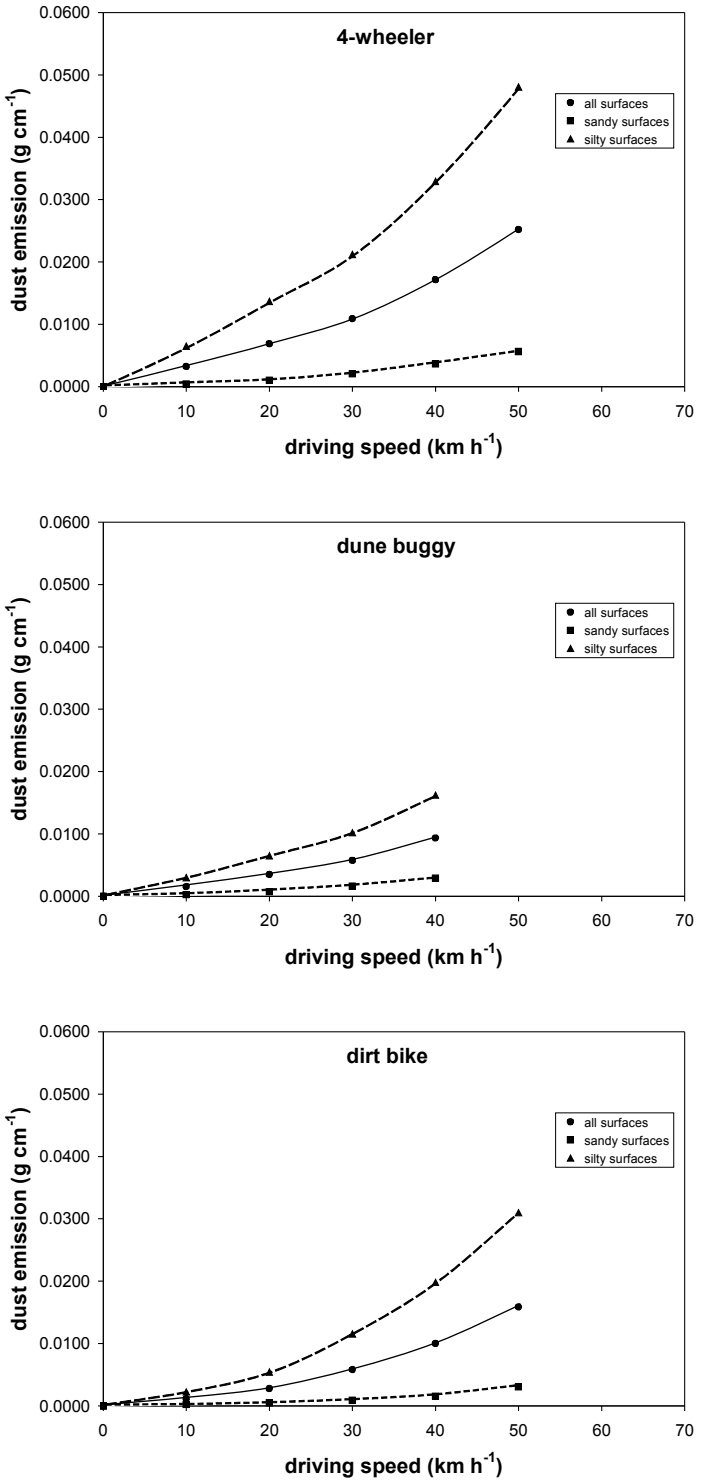

Fig. 10: TSP emission curves, grouped for the major surface classes

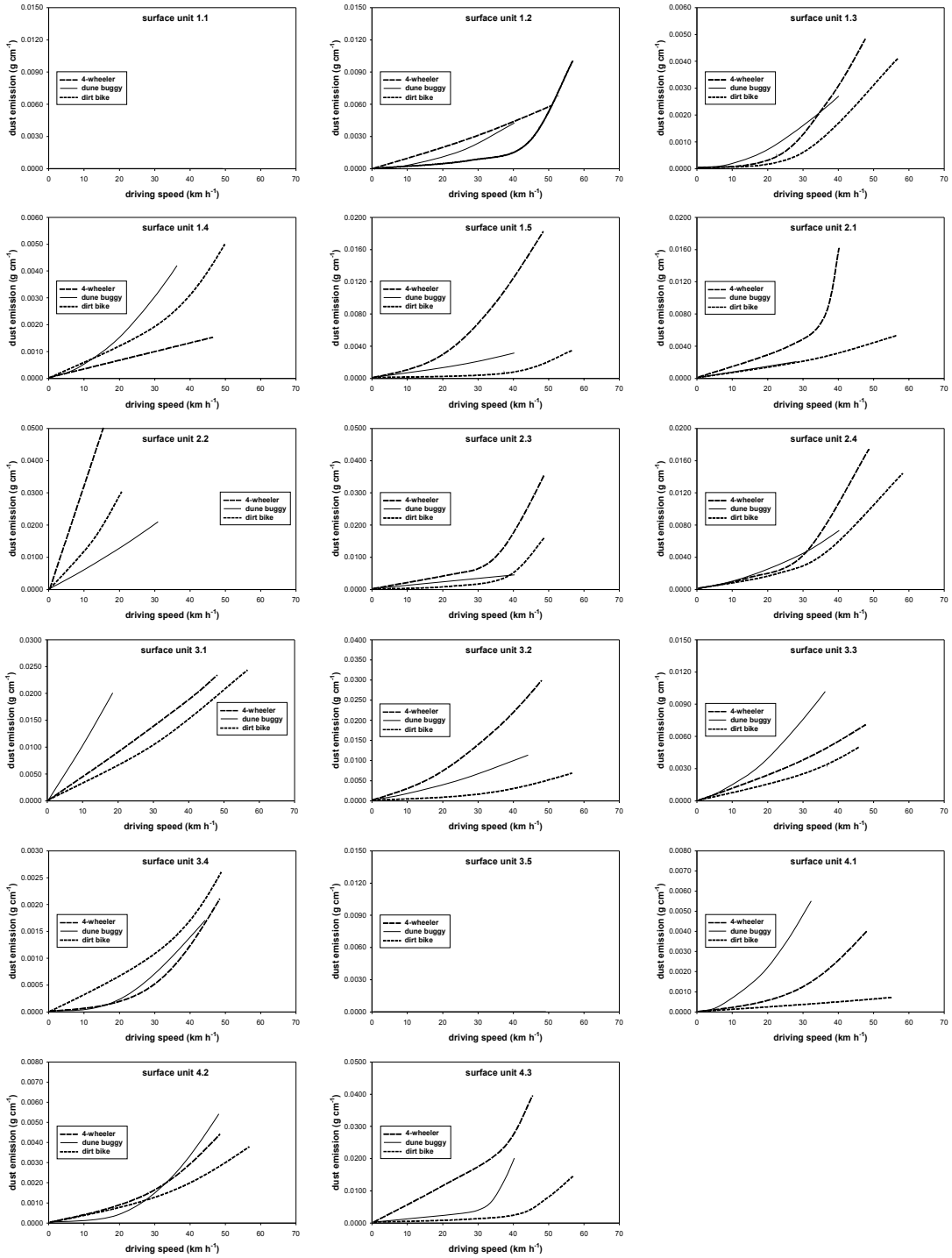

Fig. 11: TSP emission curves for the individual surface types

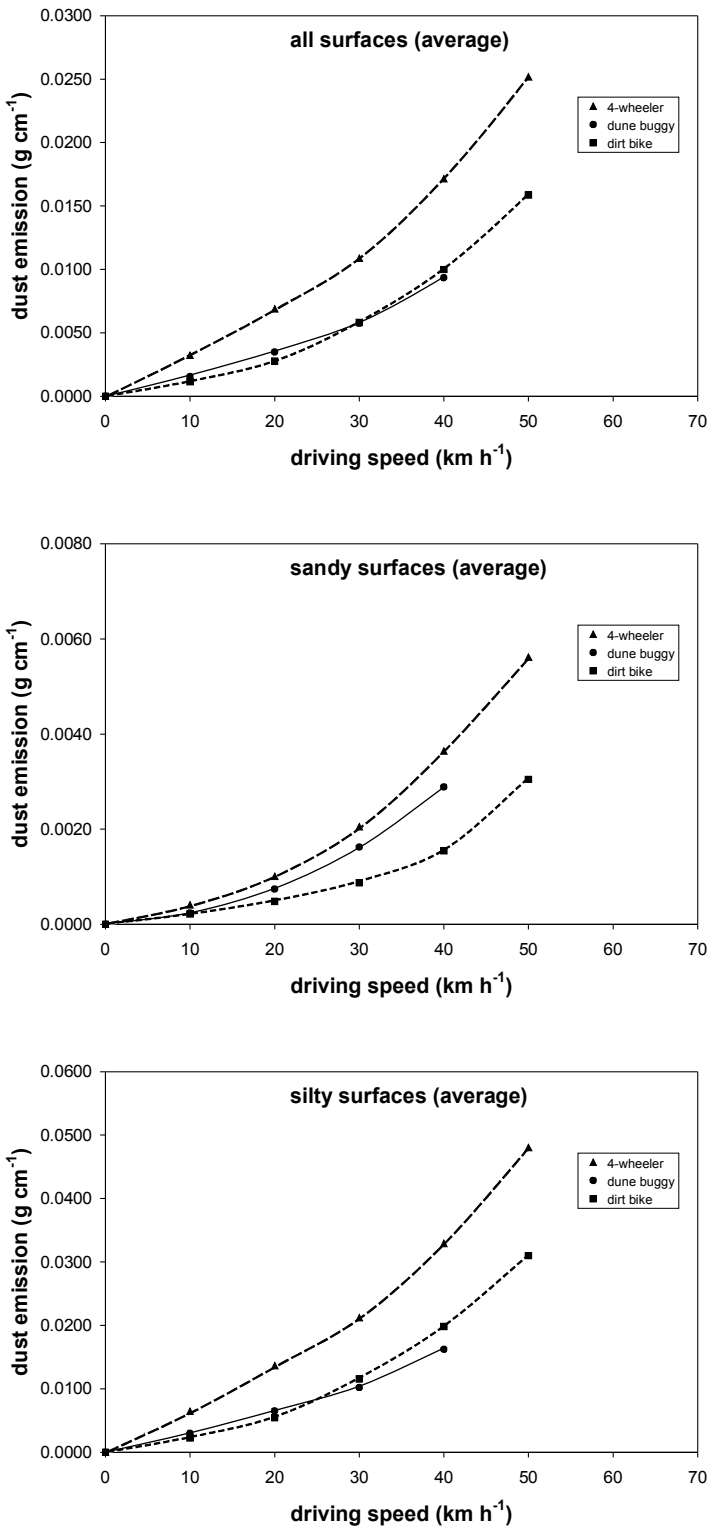

Fig. 12: TSP emission curves, grouped for the 3 vehicles tested

3.3 Discussion

The data show that the amount of dust emitted by off-road vehicles strongly varies depending on which type of vehicle is driving with what speed over what type of surface. This is quite understandable if we consider how the emissions are produced. Most unpaved roads consist of a graded and compacted roadbed usually created from the parent soil material (Gillies et al., 2005). The rolling wheels of the vehicle impart a force to the surface that pulverizes the roadbed material and ejects particles from the shearing force as well as by the turbulent vehicle waves (Nicholson et al., 1989). Previous studies have shown that the emission rate primarily depends on the vehicle speed (Nicholson et al., 1989; Etyemezian et al., 2003a, 2003b), the fine particle content of the road (Cowherd et al., 1990; MRI, 2001), the vehicle weight (US EPA, 1996, 2003; MRI, 2001), and the soil moisture content (Gillies et al., 2005). This is reflected by the 1995 US EPA AP-42 guidance document, where the emission is quantified as

$$EF = 0.161 \cdot s \cdot S \cdot W^{0.7} \cdot w^{0.5} \cdot \left(\frac{365 - p}{365} \right)$$

where EF is the emission factor (g/vehicle kilometer traveled), s the silt content of the road material (%), S the vehicle speed (m s^{-1}), W the weight of the vehicle (Mg), w the number of wheels, and p the number of days per year with measurable precipitation (>0.25 mm). However, later versions (US EPA, 1999) no longer included the vehicle speed as a parameter in estimating emission factors for unpaved roads (Etyemezian et al., 2003b).

Vehicle speed *is* an important parameter, however, as is clearly demonstrated by the Nellis Dunes experiment. In most cases (combinations of vehicle type and surface unit) the increase of emission with vehicle speed was exponential, similar to what has been found in other studies (e.g. Hussein et al., 2008; Etyemezian et al., 2003b). In a few cases the relationship was linear, as suggested by the US EPA (1995) formula. Linear relationships have also been reported by Gillies et al. (2005) and Hussein et al. (2008). The Nellis Dunes experiment did not show correlations between the type of increase (linear or exponential) and the surface or vehicle type.

The effects of wheel and tire parameters (such as wheel diameter, wheel width and tire tread) on dust emission have not yet been adequately quantified and these parameters do not appear in the emission equations currently in use. This study did not consider these parameters, but all vehicles used were equipped with standard-sized wheels and tires.

The large number of surface types tested in this study permit checking of the proposed relationship between emission and silt content of the road material. Samples were taken from the roads at the same locations where the emissions had been measured. The silt

content (<60 µm) was determined with the Malvern Mastersizer 2000 instrument after the non-erodible fractions (>500 µm) had been removed by sieving. Plotting the emission (TSP) as a function of the silt percentage a more or less linear relationship is observed (Fig. 13), but there is considerable spread in the data. This is reflected by the coefficient of determination R^2, which, for the data in Fig. 13, equals only 0.43. The data in Fig. 13 are for the average driving speeds of the distinct vehicles. Looking at the R^2 values for individual speeds we find that the relationship between TSP emission and the silt content of the road becomes better as the driving speed increases. The R^2 values are: 0.27 (10 km h^{-1}), 0.30 (20 km h^{-1}), 0.34 (30 km h^{-1}), and 0.47 (40 km h^{-1}). No R^2 could be calculated for a speed of 50 km h^{-1} because the dune buggy was unable to attain this speed over the surface types tested. Therefore, driving speed is a crucial parameter in off-road driving and formulae calculating the emission *must* include it.

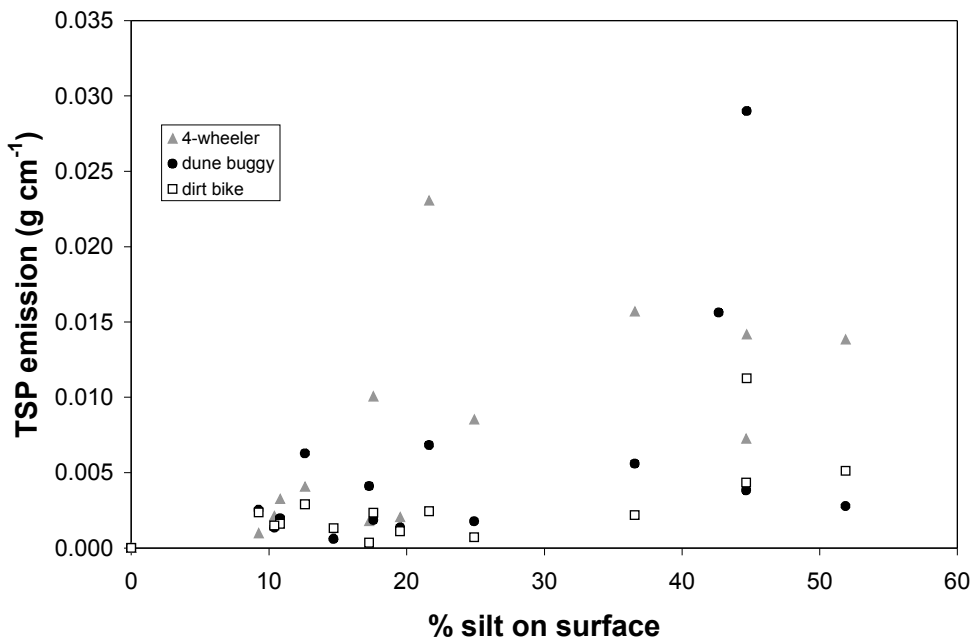

Fig. 13: Relationship between TSP emission rate and silt content of the road surface. Data points of the 4-wheeler and dirt bike for surface unit 2.2 are out of the vertical range and do not appear in the picture.

The proportion of PM10 in the emitted TSP does not seem to vary with the driving speed, regardless of which soil class (silt or sand) or vehicle type is considered (Fig. 14). The graphs on the left of Fig. 14 also show that the proportion of PM10 in the total dust production is almost identical for the dune buggy and the dirt bike. This is unlike the 4-wheeler, for which the dust emitted contains a greater proportion of PM10 compared to the two other vehicles when driving over sandy surfaces, but a lower proportion of PM10

when driving over silty surfaces. As an average for *all* surfaces tested the proportion of PM10 in dust emitted by a 4-wheeler is slightly lower than in dust emitted by a dune buggy or a dirt bike. A replot of the data for each distinct vehicle (Fig. 14, right) leads to the same conclusions. In general, for the surface units tested in the Nellis Dunes experiment the proportion of PM10 in the TSP is between 15 and 25%, slightly varying with vehicle and surface type, but not with driving speed.

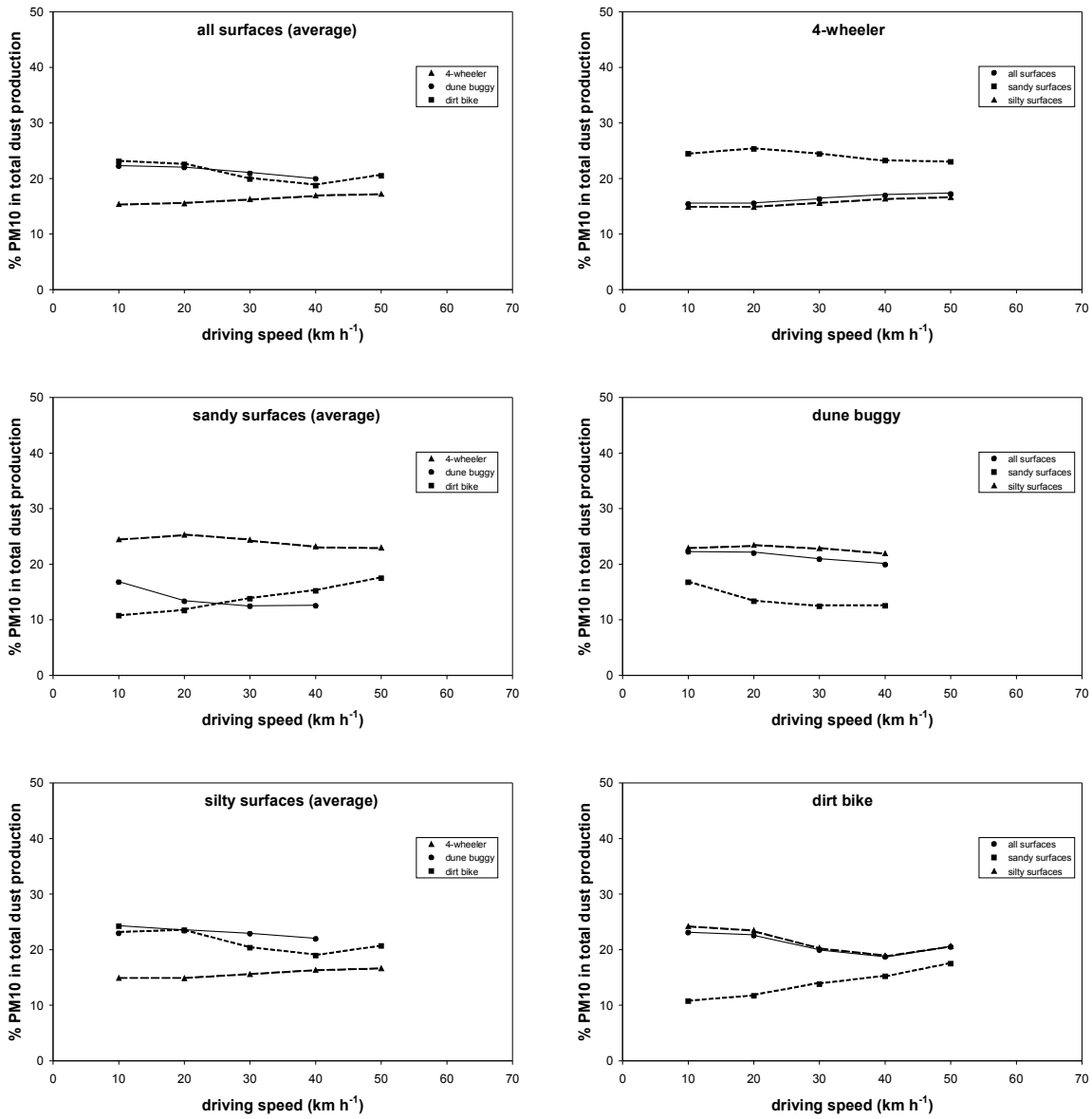

Fig. 14: Proportion of PM10 in TSP

Fig. 15 shows the (average) median grain diameter (*D50)* of the emitted dust. As mentioned earlier, for safety and practical reasons it was not possible to drive with the same speeds over all surface units. Therefore, to be able to calculate average curves (such as in Fig. 15) the raw *D50* data were first plotted in a graph to check how *D50* varied with the driving speed. This was done for all surface units, and for all 3 vehicles. The data showed that *D50* did not vary substantially with the driving speed, and for those cases where a (slight) relationship was observed the relationship was almost linear. To reconstruct the *D50* for standard speeds (3 for each vehicle, see Fig. 15) we thus used linear interpolation (or, in a few cases, extrapolation).

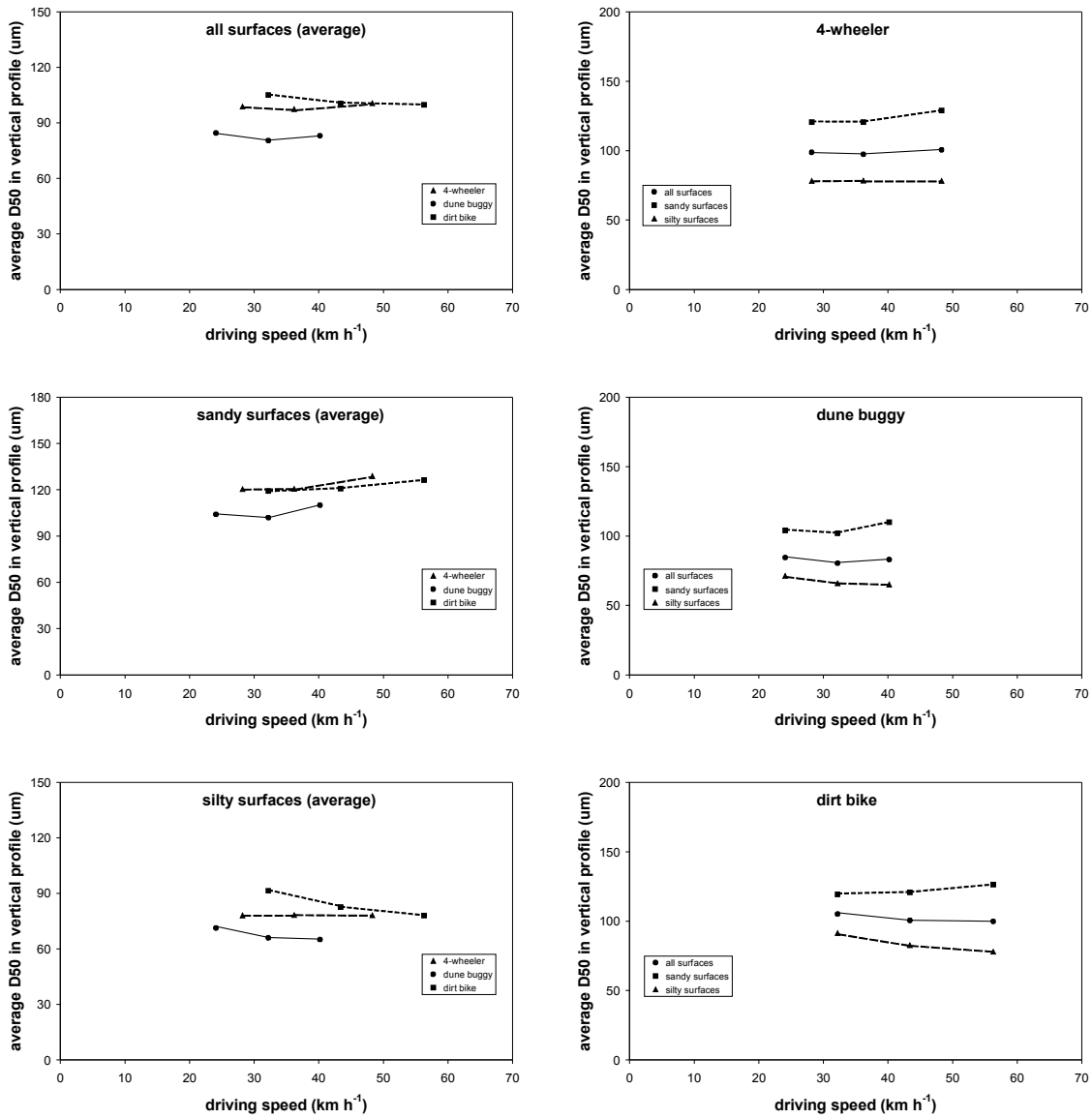

Fig. 15: Average median grain diameter (D50) of emitted dust as a function of driving speed

From this data, two conclusions can be derived. First, the average median grain diameter in the dust cloud remains almost constant as a function of the driving speed. A slight increase in grain size (coarser dust) with speed occurs for sand surfaces, but for silt surfaces a slight decrease in grain size occurs (Fig. 15, left). Secondly, the dust emitted by a dune buggy is finer than that emitted by a 4-wheeler or a dirt bike regardless over which class of soil (sand or silt) the vehicle is driving. The 4-wheeler and dirt bike emit dust with nearly the same grain size. Replotting the data for the distinct vehicles (Fig. 15, right) shows these relationships.

Continuous off-road driving in a trail leads to a progressive coarsening of the top layer in the trail. Fig. 16 compares the average grain size (represented by the median grain diameter, D_{50}) of sediment emitted during off-road driving to that of the topsoil in the trail. The figure shows that except for the aggregated silt deposits (unit 2.3), the sediment in the trails is consistently coarser than the one emitted (which means that the trails become coarser with time). Also, the speed of coarsening is a clear function of the type of surface. Trails in drainages coarsen the most rapidly, and trails on sandy surfaces coarsen faster than trails on silty surfaces (see Fig. 16). Note that surface unit 2.3 is composed primarily of silt aggregates up to >5 mm in diameter, which are pulverized during off-road driving. Therefore, a value above unity in Fig. 16 is normal.

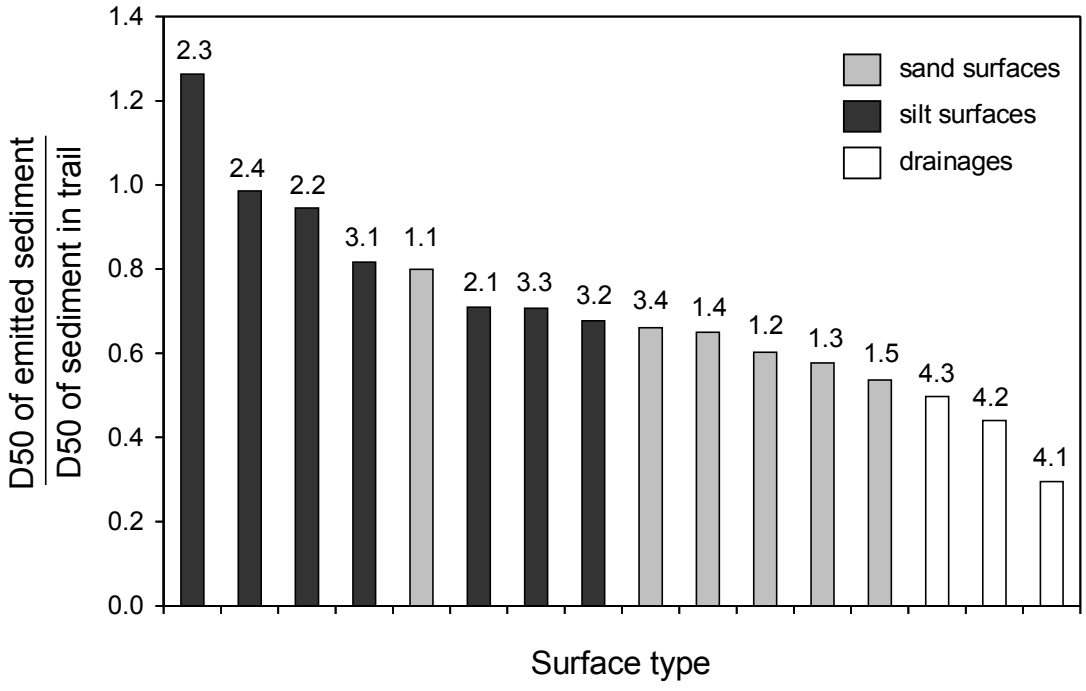

Fig. 16: Ratio of median grain diameter (D50) in ORV-emitted sediment to the median grain diameter in the trail, for the various surface units investigated

Table 1: Proportion of PM10 in emitted dust compared to the parent sediment (average for all vehicle types and driving speeds tested)

surface unit	PM10 content in total sediment (%)		PM10 in emitted sediment / PM10 on road surface
	road surface	emitted sediment	
1.1	0.00	0.00	NA
1.2	4.23	2.32	0.55
1.3	5.92	2.78	0.47
1.4	3.72	1.77	0.48
1.5	7.64	6.76	0.88
2.1	4.78	3.41	0.71
2.2	11.05	6.12	0.55
2.3	13.08	6.63	0.51
2.4	8.27	6.39	0.77
3.1	24.45	8.67	0.35
3.2	14.37	7.61	0.53
3.3	6.46	4.03	0.62
3.4	5.04	2.56	0.51
3.5	NA	NA	NA
4.1	5.51	3.62	0.66
4.2	4.04	3.68	0.91
4.3	5.17	3.49	0.67
		average (= E-factor):	*0.57*

Columns 2 and 3 in Table 1 show the PM10 content on the road and in the emitted dust, respectively. As could be expected, roads with higher PM10 produce PM10-rich dust. However, the PM10 content is always lower in the emitted dust compared to the parent soil (see right column in Table 1). The average value for all surface units (called in this study the E-factor, see Table 1) is only 0.57, or 57%. Therefore, off-road driving emits PM10 less efficiently than it emits the coarser fractions.

The Nellis Dunes data allow one to check for which grain size fraction(s) emission is most efficient. Calculating the E-factor for various grain size classes and displaying the results in a histogram (Fig. 17) we see that emission due to off-road driving is most efficient at a grain size of approximately 60 µm. This value is only slightly smaller than that for wind erosion, which is situated around 80 µm (Bagnold, 1941; Horikawa and Shen, 1960; Iversen and White, 1982). The E-factor drops below unity from a grain size of approximately 25 µm – i.e. for grains <25 µm the emission process is not very efficient

(Fig. 17). Particle and interparticle forces (cohesion and adhesion) hamper the removal of the grains from the road surface.

It should be recalled that all numbers given above were derived for air-dry surfaces; for moist surfaces they will be substantially higher.

4. ORV scenarios for Nellis Dunes Recreation Area

Several scenarios were investigated to study how emissions change when vehicles perform realistic drives over the various surface units occurring in the Nellis Dunes Recreation Area. These scenarios do net yet intend to calculate the real amounts of emission effectively produced in the NDRA. Instead, they aim to check how the composition of a run (proportion of surface units within a run) affects the emissions. The real amounts of ORV dust produced annually in the NDRA are studied in Chapter 6.

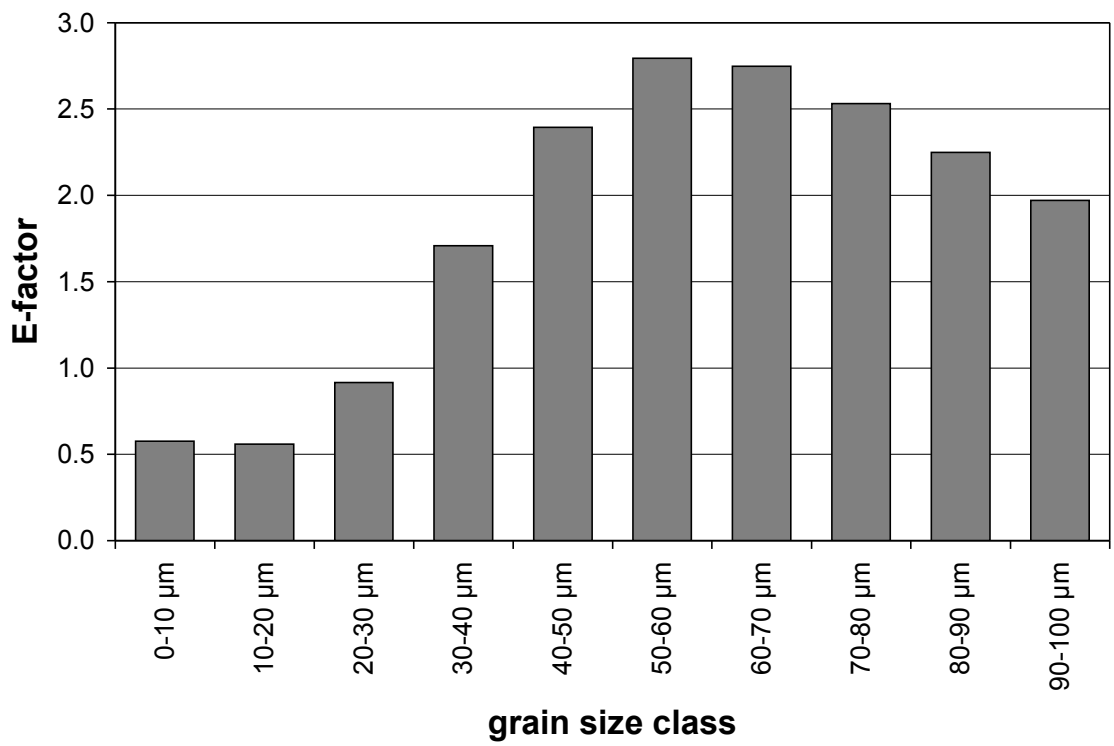

Fig. 17: E-factor for various grain size classes of road dust

When driving off-road, drivers usually drive their vehicles over various types of surfaces. Also, they constantly change their speed due to local factors such as topography, curves in the road, local obstacles, etc. To get an idea of the amounts of dust produced during a realistic drive, various routes were selected in the Nellis Dunes Recreation Area and the emission was calculated for typical drives along these routes. The following scenarios were calculated:

- Scenario 1: drive through a sandy area
- Scenario 2: drive through a silty area
- Scenario 3: drive through drainages
- Scenario 4: drive through mixed terrain

These trajectories are plotted on a simplified surface unit map (Fig. 18). Detailed information for each route is given in Table 2. For each scenario the emission was calculated for both PM10 and TSP, for all 3 vehicles tested, and for 5 driving speeds varying from 10 to 50 km h^{-1} (10 to 40 km h^{-1} for the dune buggy).

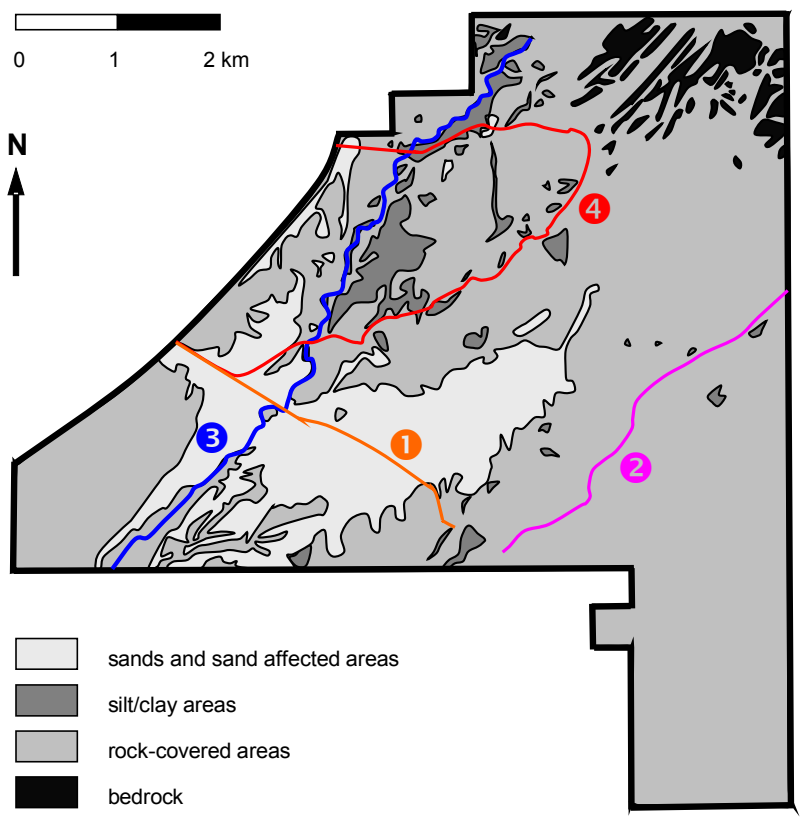

Fig. 18: Trajectories of the 4 driving scenarios, superimposed on a simplified surface map of the NDRA. 1: Scenario 1 (sandy area); 2: Scenario 2 (silty area); 3: Scenario 3 (drainages); 4: Scenario 4 (mixed terrain).

Table 2: Characteristics of the driving scenarios tested

scenario 1: sand area		
surface unit	distance driven	
	meters	% in drive
1.1	225	6.62
1.2	1157	34.03
1.3	714	21.00
1.4	925	27.21
3.2	343	10.09
4.2	29	0.85
4.3	7	0.21
total drive:	*3400*	*100.00*

scenario 2: silt area		
surface unit	distance driven	
	meters	% in drive
2.2	11	0.27
3.1	264	6.43
3.2	3654	88.97
4.1	57	1.39
4.3	121	2.95
total drive:	*4107*	*100.00*

scenario 3: drainage area		
surface unit	distance driven	
	meters	% in drive
4.1	4070	51.95
4.2	1590	20.29
4.3	2175	27.76
total drive:	*7835*	*100.00*

scenario 4: mixed area		
surface unit	distance driven	
	meters	% in drive
1.2	125	1.50
1.3	889	10.67
1.4	429	5.15
1.5	154	1.85
2.1	164	1.97
2.3	1239	14.88
2.4	146	1.75
3.1	157	1.89
3.2	3654	43.88
3.3	861	10.34
4.1	321	3.85
4.2	7	0.08
4.3	182	2.19
total drive:	*8328*	*100.00*

PM10 emissions for these scenarios are presented in Fig. 19. The main conclusions are: (1) in all 4 scenarios the largest amounts of PM10 are produced by the 4-wheeler, followed by the dune buggy and the dirt bike; (2) the faster the vehicles are driving, the more PM10 they will emit; (3) typical amounts of PM10 emitted are as follows: for drives in sand areas: 30-40 g km^{-1}; for drives in silt areas: 150-200 g km^{-1} (100 g km^{-1} for dirt bikes); for drives through drainages: 30-40 g km^{-1}; and for drives in mixed terrain: 60-100 g km^{-1}.

Similar curves were calculated for TSP (Fig. 20). The results are similar to those for PM10, although some slight differences can be observed for the dune buggy in the sand and drainage areas. The typical amounts of TSP emitted are: for drives in sand areas, about 200 g km^{-1}; for drives in silt areas, 600-700 g km^{-1} (1000-2000 g km^{-1} for 4-wheelers); for drives through drainages, 300-400 g km^{-1} (100-200 g km^{-1} for dirt bikes); and for drives in mixed terrain, 300-500 g km^{-1} (500-800 g km^{-1} for 4-wheelers).

Although these numbers are based on simulations, they give a good idea of the order of magnitude that can be expected for the various regions in the Nellis Dunes Recreation Area.

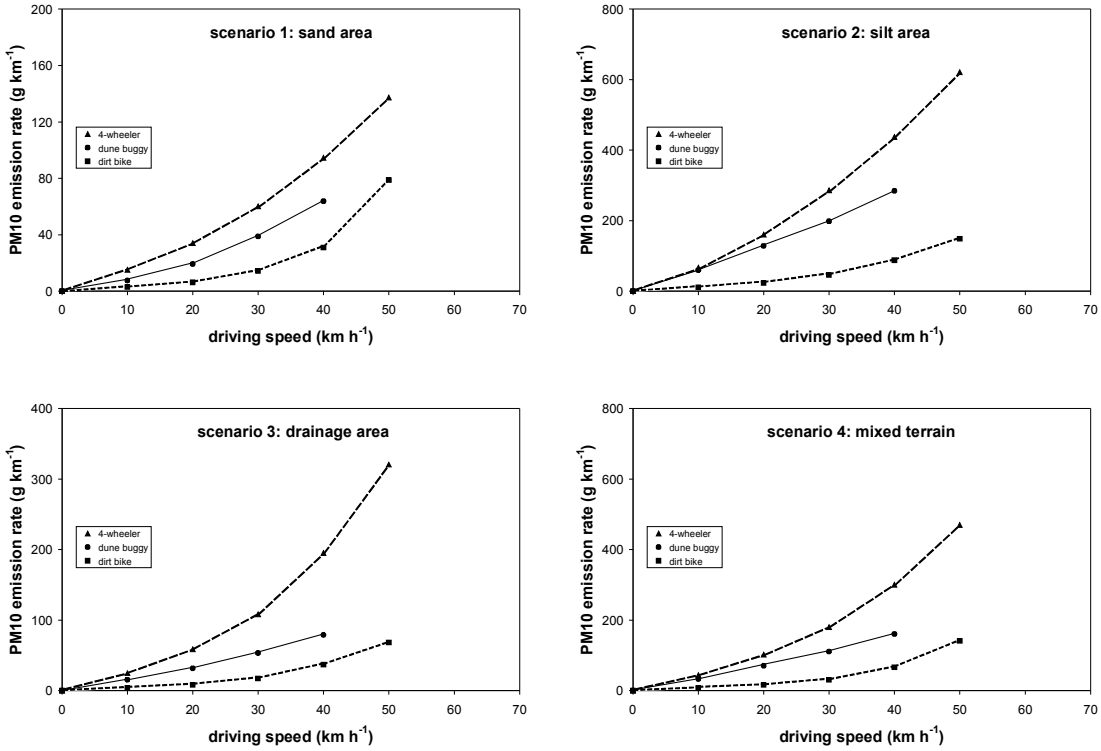

Fig. 19: PM10 emission rates for the 4 scenarios tested

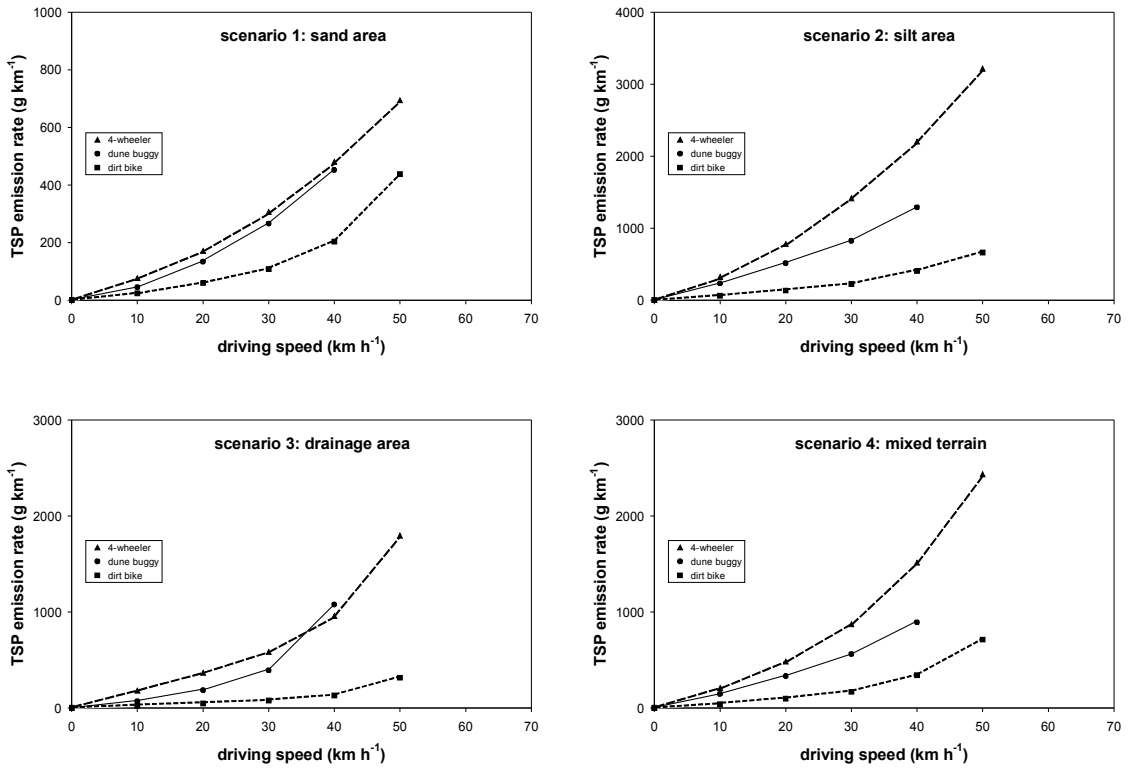

Fig. 20: TSP emission rates for the 4 scenarios tested

5. The ORV experiment: summary of conclusions

The experiments in the Nellis Dunes area show that off-road driving emits significant amounts of dust. This is true for PM10 dust as well as for coarser dust. However, the amounts emitted vary greatly with the type of sediment and the characteristics of the surface over which the vehicle is driving, the type of ORV vehicle, and the speed of driving.

For evident reasons sandy soils produce less dust than silty soils. However the high internal variability within mapped units (rock content, presence of vegetation, contamination of the top layer with locally blown in sediment, etc.) can also significantly affect emission rates. Using only a single soil parameter (such as the percentage of silt, as in the 1995 US EPA AP-42 formula) is thus insufficient to describe the effect of soil on dust emission.

At NDRA the highest PM10 emissions were always measured on surface units 2.2 (silt/clay with gravel) and 3.1 (desert pavements) whereas lowest emissions occurred on the uncrusted (or only weakly crusted) sandy surfaces (1.1, 1.2, 1.3, 1.4, 3.4) and the gravel and bedrock surfaces (3.5, 4.1). The thin surficial stone layer of the desert pavements (3.1) did not provide much protection against off-road driving. The silty surfaces (except 2.2 and 3.1) showed intermediate emission values.

As already reported in many previous studies the emission rates strongly depend on the driving speed. At NDRA, in general, PM10 and TSP emission increased exponentially with the driving speed. However, systematic correlations between the normalized rate of increase of emission with speed and surface type were not found. Similar surfaces can show different rates, which makes it difficult to model the emissions. Therefore, it is critical to collect field measurements for specific locations in order to obtain adequate data in each particular case.

Of the three types of vehicles tested, the 4-wheeler produced the largest amounts of dust, followed by the dune buggy and the dirt bike. It may be worth recalling that in many areas the dirt bike is able to drive faster than the dune buggy (and, sometimes, the 4-wheeler). Also, the dust emitted by a dune buggy is somewhat finer than that emitted by a 4-wheeler or a dirt bike.

Dust emitted by off-road driving is finer than the parent sediment on the road surface. Off-road driving thus results in a progressive coarsening of the top layer on the road.

Removal of particles by off-road driving is most efficient for grain sizes around 60 µm. For particles <25 µm the efficiency (in physical terms) of the process becomes very low: cohesion and adhesion forces hamper emission of the grains. These numbers were derived for air-dry surfaces; for moist surfaces they will be substantially higher. It should be noted, however, that the finest particles (PM10) have the greatest impact on human health.

Realistic emission rates for off-road driving on dry surfaces in the Nellis Dunes Recreation Area with 4-wheelers, dune buggies and dirt bikes are: drives in sandy areas, 30-40 g km^{-1} (PM10) and 150-250 g km^{-1} (TSP); drives in silty areas, 100-200 g km^{-1} (PM10) and 600-2000 g km^{-1} (TSP); drives in drainages, 30-40 g km^{-1} (PM10) and 100-400 g km^{-1} (TSP); and drives in mixed terrain, 60-100 g km^{-1} (PM10) and 300-800 g km^{-1} (TSP).

For information on the annual amounts of dust effectively produced in NDRA by ORV activity the reader is referred to Chapter 6 of this report.

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