On the question of the mechanism of dust cloud formation on forest roads

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Abstract. The justification of the model of dust cloud formation during the passage of a forest train on a dry road surface is given. Given the previous studies on sedimentation of single particles and a dust cloud, a formula is obtained that allows one to calculate the initial and average sedimentation velocity of a dust cloud taking into account changes in the concentration of dust in the cloud.

1. Introduction
The main types of coatings of forest roads are gravel, crushed stone and soil. Operation of forest roads with such coatings in dry weather is accompanied by increased wear and tear, and intense dust formation. The movement of the same type of road trains with the same speeds contributes to the emergence of "waves" on the surface. As a result, the road surface disintegrates, the speed and safety of traffic decline, the service life of engines shortens, and the consumption of fuel and lubricants increases. In addition, dust has a harmful effect on humans and the environment.

2. Materials and Methods
Taking into account the theoretical principles of the formation of a dust cloud on roads with gravel and soil surface proposed in [1, 2], the mechanism of dust cloud formation on forest roads with such surface appears to be as follows.

When a timber-carrying road train travels on a dry, untreated with dust-suppressing reagents sand-gravel surface, both fine-grained (dusty-clay particles and fine-grained sand) and large fractions become detached and get transported. This is due to the fact that a compacted mass of air is formed in front of the road train that moves some of the dust. The bulk of the dust along with loose material is captured and rises into the air by the tread of the tires of the road train. Separation of this material from the wheels occurs under the influence of the centrifugal force:

\[ C = \frac{M \nu^2}{R} \]

where, \( C \) is the centrifugal force; \( M \) is the mass of particles of the material pinched between the protrusions of the tires; \( \nu \) is the peripheral speed of the treadmill, equal to the speed of the road train; \( R \) is the radius of the wheel.

The dust raised into the air is carried away by turbulent air flows, which are formed both between the lower parts of the road train (bottom) and the carriageway, and behind the passing road train. When dust particles come off the coating surface, humidity has a decisive effect. The water meniscus
formed at the point of contact between the spherical dust particle and the flat particle of the surface material holds the particle on the surface with a force \([3]\) according to formula (2):

\[
F_k = 4\pi r \delta \cos \theta
\]  

(2)

where, \(F_k\) is the magnitude of the capillary force; \(r\) is the particle radius; \(\theta\) is the wetting angle; \(\delta\) is the surface tension of water.

From equation (2), it can be seen that capillary forces depend on the particle size, the surface tension of the liquid, and the ability of the contacting bodies to wet, i.e., with an increase in the contact angle \((\theta)\), the adhesion forces decrease. Therefore, for dust suppression of gravel coatings, it is advisable to use reagents with a small wetting angle.

A moving forest train causes the formation of turbulent vortices (figure 1). The width of the coverage zone of the turbulent vortices during the passage of a road train can be determined from the expression:

\[
B = G_{sh} + b_v
\]  

(3)

and the height

\[
A = G_v + b_v
\]  

(4)

where, \(G_{sh}\) and \(G_v\) are the width and height of the road train, respectively; \(b\) is a coefficient depending on the streamlining of a car or road train. According to [4], for timber-carrying road trains loaded with “b” whole-lengths, it is 0.28-0.30, and for single vehicles, 0.06 - 0.075; \(v\) is the speed of the train;

![Figure 1. A moving forest train (1) forms a zone of turbulent vortices (2).](image)

Let us determine the height of the perturbed air flow according to expression (4) for a KAMAZ-6426 timber transport train moving with a pack of whole-lengths at a speed of 40 km/h (11.1 m/s), having a height of 3.3 m, a frontal section of 8.25 m² and a streamlining coefficient 0.3. Then we get that the height of the perturbed stream “\(A\)”, and therefore the height of the dust cloud (during calm periods) will be 15.3 m, that is, \(\text{“A” is approximately equal to the two frontal sections of the road train.}\)

Formulas (3) and (4) are in good agreement with experimental studies [5], which established that trucks moving at a speed of 12-17 m/s cause the formation of turbulent vortices in the vertical and transverse directions, the coverage area of which is from two to five frontal sections of the car. Naturally, with a decrease in vehicle speed, the coverage area of the turbulent vortices will decrease. The length of a dust plume depends on the total length of the forest truck and its speed, the height of the dust particles and the speed of their sedimentation.
The length of the dust plume $L$ is proposed to be determined by the formula:

$$L = L_{a,n} - L_a + L_c$$  \hspace{1cm} (5)

where, $L_{a,n}$ is the total length of the forest train; $L_a$ is the length of the car (tractor); $L_c$ is the sedimentation path of dust particles.

The sedimentation velocity of dust particles ($v_{c1}$, m/s) isolated from each other according to [6] can be determined by the formula:

$$v_{c1} = \frac{d^2}{18\mu_b} \cdot \rho g$$  \hspace{1cm} (6)

where, $d$ is the particle diameter, m; $\rho$ is the particle density, kg /m$^3$; $\mu_b$ is the dynamic viscosity of air, Pa*s.

From equation (6) it follows that the sedimentation rate of spherical dust particles with a diameter of 50 μm, a density of 2.65 g/cm$^3$ at an ambient temperature of 20°C will be:

$$v_{c1} = \frac{(50 \times 10^{-6})^2 \cdot 2650}{18 \cdot 17.75 \cdot 10^{-6}} = 0.19 \text{ m/s}$$  \hspace{1cm} (7)

The sedimentation time of such a particle from a height “A” equal to 15 m will be $(15 \div 0.19) = 79$ s.

In this case, the length of the dust plume at a train speed of 11.1 m/s will be:

$$L = 25 - 6 + (11.1 \times 79) = 900 \text{ m};$$  \hspace{1cm} (8)

However, our observations established that the settling of a dust cloud after passing a forest road train occurs in 10-60 s or at a speed of 0.25 - 1.5 m/s, that is, much faster than it follows from formula (6) for single sedimentation particles.

The faster settling of the dust cloud compared to particles isolated from each other is explained by the following. It is known [6, 7] that a characteristic feature of nonspherical particles is their tendency to take a position at which the medium resistance would be maximum; lamellar dust particles are arranged so that their more developed faces and longer edges appear perpendicular to the direction of motion [7]. This orientation increases as the Reynolds criterion increases, while the angle between the direction of particle fall and the direction of the drag force increases. Therefore, the trajectory of the settling particles deviates from the vertical. For sufficiently large Reynolds numbers, the motion of particles becomes spiral or zigzag. With slow settling of small particles (with a radius of less than 10 μm), this phenomenon is not observed [6, 7].

A zigzag drop of dust particles leads to their clustering and coalescence. Such larger aggregates settle at a higher speed, additionally capturing fine particles along the way, resulting in a decrease in the concentration of dust in the cloud. In addition, a falling large particle or aggregate carries air particles with it, so that the air resistance to the movement of other particles falling in the immediate vicinity decreases, and they acquire additional speed.

Thus, the sedimentation of particles isolated from each other sharply differs from the sedimentation of a system of particles, since each of the particles moving with respect to the medium excites flows in it that act on other particles. If the number of particles in the aerosol cloud is very small, and they do not affect each other during movement, then the sedimentation rate of such a cloud will be the same as in the case of sedimentation of single particles (6). With a large concentration of dust particles, the cloud moves as a unit and is surrounded by a counter flow of air. Under the influence of gravity, falling particles carry the medium along, so that the resistance of the medium to the movement of particles decreases. In this case, the cloud sedimentation rate can be much higher than the speed of individual particles and is expressed by formula (9):
where, \( v \) is the sedimentation rate of the dust cloud; \( R \) is the radius of the dust cloud; \( r \) is the radius of the dust particles; \( n \) is the number of dust particles per unit volume; \( \rho_n \) is the density of dust particles; \( g \) is the gravity acceleration, \( \psi \) is the drag coefficient; \( \rho_v \) is the air density.

From formula (9) it can be seen that it is suitable for use only when a dust cloud consists of uniform dust particles having the same size. In the case when a dust cloud consists of polydisperse particles, which is typical for road dust, the practical application of formula (7) presents significant difficulties. However, one can replace \( r^3 \rho_n \pi = 3Q/4\pi \), where \( Q \) is the mass of dust per unit volume. With this in mind, formula (9) is transformed into an expression that allows us to determine the initial sedimentation velocity \( (v_n) \) of a road dust cloud from its known (or given) concentration in a unit volume of air:

\[
v_H = \left( \frac{32 \ast R \ast n \ast g \ast \rho_n \pi \ast r^3}{g \ast \psi \ast \rho_v} \right)^{0.5}
\]

or

\[
v_H = 5.115 \left( \frac{RQ}{\psi \ast \rho_v} \right)^{0.5},
\]

It should be noted that during the cloud’s existence, the value of \( Q \) varies from a certain maximum (at the beginning of its formation at a given point) to zero.

The results of calculating the sedimentation rates of a dust cloud depending on its size and dust concentration are presented in figure 2. In the calculations, the sedimentation rate of a dust cloud with a reduced radius of 10, 20 and 30 m was determined at a dust concentration in the air from 0.1 to 20 g/m\(^3\). The air density at 20 °C is assumed to be 1.205 kg/m\(^3\). The drag coefficient of the medium to the movement of a dust cloud according to [6, 7] in our case is close to 1.0.

![Figure 2](image_url)

**Figure 2.** Change in the sedimentation rate of a dust cloud from dust concentration and the cloud radius: 1 - 10 m; 2 - 20 m; 3 - 30 m.

Based on figure 2, the sedimentation rate of a dust cloud increases with increasing cloud size and dust concentration in it. However, the sedimentation rate of the dust cloud, calculated by the formula (10) and (11), and shown in figure 2 turned out to be about two times higher than it was observed by
us in the field (0.25 – 1.5 m/s). This can be explained by the fact that over time the concentration of dust in the cloud decreases as indicated above. As a result, the density of the dust cloud decreases, and it no longer settles as a single unit. Therefore, the sedimentation rate of a dust cloud at the end of the sedimentation process will be close to the sedimentation rate of single dust particles. With this in mind, the average value of the velocity \( v_{av} \) sedimentation of a dust cloud can be approximated by the half of the initial sedimentation velocity of a dust cloud:

\[ v_{av} = 0.5 \times v_n \]  \hspace{1cm} (12)

or

\[ v_{av} = 2.558 \times \left( \frac{RQ}{\psi^* \rho w} \right)^{0.5} \]  \hspace{1cm} (13)

3. Conclusions

A design scheme (model) for the formation of a dust cloud during the passage of a forest train on a dry, untreated, dust suppressing sand and gravel surface is proposed. Based on the well-known studies of sedimentation of individual dust particles and a dust cloud, a formula is obtained that allows one to determine the initial and average sedimentation speed of a road dust cloud depending on the concentration of dust in the cloud.

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