

Modeling Pollution on a Roadside Strip during Winter Period

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Abstract: This research presents a method for reducing environmental pollution within a roadside strip by decreasing air pollution from traffic and anti-icing materials (chlorides) applied to control winter slipperiness. The process formation of ecological pollution on a roadside strip is highly diverse. It is dependent on main meteorological conditions, road factors, and road surface states (dry, wet, icy, hard snow, and friable snow). The state of a road surface and the presence of different ice formations influence traffic speed and, therefore, affect the level of air pollution. The degree to which these parameters depend on each other cannot be explained and solved by conventional research methods. To solve this problem, it is necessary to use mathematical modeling and experimental computations. When modeling a pavement state considering weather and climate factors, it is advised to calculate the level of air pollution, calculate the amount of chloride, and estimate the efficiency of winter road maintenance treatments by different organizations.

Key words: Ecological pollution; Ice formation; Mathematical model; Road surface; Traffic speed.

Introduction

Vehicular traffic on the road is a major source of air pollution that affects the soil, surface water, and groundwater of the adjacent territory. Increases in carrying capacity, vehicle speed, and traffic volume amplify environmental contamination. The determination of ecological safety problems and the ability to reduce the influence of transportation on the environment are possible.

According to Cambridge University, a vehicle emits more than 4 billion tons of carbon dioxide (CO₂) into the air annually. Annual transportation emissions into the atmosphere of Russia consist of approximately 35 million tons of hazardous substances (58% of this amount is from transport). Research shows that air pollution done by 40% depending on road conditions and movement organization [1].

The winter period over a large part of the Russian territory makes travel difficult due to poor road conditions. The level of ecological pollution in the winter depends on the road surface conditions and the amount of chemical agents used to control slipperiness.

Thus, the task of estimating and forecasting ecological conditions on a roadside strip during the winter period and finding ways to improve it by perfecting the road winter maintenance is possible for road and transport complexes. To evaluate ecological problems that consider many factors of interaction between the road and the environment, a system analysis was used with mathematical models to quantitatively estimate the functions of the system with different influences.

System Approach

Mathematical models for estimating and forecasting ecological conditions of a roadside strip during the winter period are developed.

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A theoretical basis for determining problems in need of road maintenance is made by the DCRE (driver-car-road-environment) system.

Subsystems, environment-road (E-R) and road-car-environment (R-C-E), are considered for estimating ecological conditions of roadside territories. The subsystems are connected as presented in Fig. 1.

Ecological parameters for subsystems are defined by weather, climate, and road information [2].

Sets of elements of a highway and environment were considered as a system. Structure of a considered system creates internal connections and connections with the environment. Traffic speed is a basic system factor that is determined by road ecological problems. The levels of emissions into the atmosphere depend on it. It is established that inconsistencies in a road's condition and car characteristics can increase harmful emissions by a third of the volume due to decreased traffic speed and over expenditure of fuel.

During the winter period, traffic speed depends on the condition of the road's surface. The road's surface condition is determined by weather and road factors. Anti-icing materials, which are used to control road slickness, act as ecological conditions. Influences of subsystem elements on the total system are presented in Fig. 2.

To study the R-E and R-C-E subsystems, a general approach for theoretically modeling of complex systems was used.

Subsystem Road - Environment

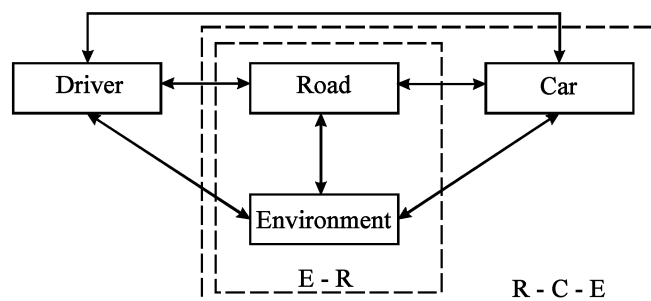


Fig. 1. Subsystems of Environment-Road (E-R) and Road-Car-Environment (R-C-E).

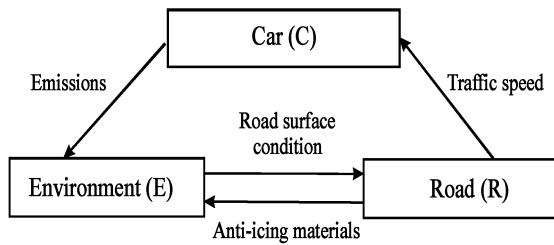


Fig. 2. Schematic Influence of Subsystems (E-R) and (R-C-E) on an Ecological Condition of Roadside Territories.

The law of the functioning subsystem E-R is presented by the generalized operator F_S , which transforms a set of internal, independent parameters of a subsystem (meteorological and road factors) into external, dependent road surface conditions [3]:

$$\overline{y(t)} = F_S[\overline{v(t)}, \overline{h(t)}, t] \tag{1}$$

where $\overline{y(t)} = \{y_1(t), y_2(t), \dots, y_n(t)\}$ is the vector with components that are determined by road surface conditions during winter; $\overline{v(t)} = \{v_1(t), v_2(t), \dots, v_m(t)\}$ is the vector based on the influence of the environment (weather and climate parameters); F_S is the law of the functioning system; $\overline{h(t)} = \{h_1(t), h_2(t), \dots, h_k(t)\}$ is the vector with parameters intrinsic to the system (road and transport parameters); and t is time.

For estimating ecological conditions of roadside territories during the winter period, the following road surface conditions are accepted: dry, wet, slippery, hard snow, and friable snow.

The slippery conditions of a road surface take place when any kind of winter slipperiness is formed, producing a layer of ice on the pavement (glaze ice, ice, firm strike, and hoarfrost). On a slippery pavement, the conditions for movement are identical because of the low coefficient of cohesion.

For the vector $\overline{y(t)}$, all components are equal to zero except those that correspond to the current surface condition.

Influence from the environment is determined by a set of weather factors, $\overline{v(t)}$, that influence surface conditions, traffic speed, and emission levels from motor transport. Components of the vector for environmental influence are displayed in Table 1.

Internal parameters of subsystem R-C-E, influencing surface conditions and pollution levels, are divided into two groups: road information and weather data. Own subsystem parameters, which are divided into constants and variable road and transport factors, are carried to the first group. The list of own subsystem parameters is shown in Table 2.

Road information can be received from either a road data automated bank or from electronic road passports.

Subsystem Road - Car - Environment

Motor transportation on a highway is one of the basic sources of roadside territory pollution. The law of functioning of an R-C-E subsystem is also presented by the generalized operator F_y , which will transform a set of internal, independent subsystem parameters (meteorological and road factors) into external, dependent parameters

Table 1. Environmental Parameters.

Components of Vector	Type of Parameter
$v_1(t)$	Air Temperature
$v_2(t)$	Atmospheric Pressure
$v_3(t)$	Change of Atmospheric Pressure
$v_4(t)$	Relative Humidity of Air
$v_5(t)$	Dew-point
$v_6(t)$	Deposits (Presence, Kind, Modular Condition)
$v_7(t)$	Quantity of the Dropped out Deposits
$v_8(t)$	Deposits Loss Intensity
$v_9(t)$	Overcast
$v_{10}(t)$	Wind Speed
$v_{11}(t)$	Wind Direction

Table 2. Own System Parameters.

Components of Vector	Type of Parameter
<i>Constant Road Parameters</i>	
$h_1(t)$	Longitudinal Grade
$h_2(t)$	Radius of Curve by Way
$h_3(t)$	Working Mark (Height of Embankment, Depth of Ditch)
$h_4(t)$	Road Direction
<i>Variable Road Parameters</i>	
$h_5(t)$	Road Pavement Temperature
$h_6(t)$	Road Pavement Condition
$h_7(t)$	Width of Carriageway
$h_8(t)$	Width of Road Shoulder
$h_9(t)$	Visibility
$h_{10}(t)$	Surface Smoothness
$h_{11}(t)$	Pavement Roughness
<i>Transport Stream Parameters</i>	
$h_{12}(t)$	Traffic Density
$h_{13}(t)$	Traffic Structure (Quantity of Cars with Carburetor and Diesel Engines)
$h_{14}(t)$	Traffic Speed
$h_{15}(t)$	Power of Emission
$h_{16}(t)$	Charge of Fuel for Cars with Various Type of the Engine
<i>Protective Factors</i>	
$h_{17}(t)$	Forest Belts
$h_{18}(t)$	Snow Protection Constructions

for an estimation of an ecological situation of a roadside strip [3]:

$$\overline{e(t)} = F_y[\overline{v(t)}, \overline{h(t)}, \overline{y(t)}, t] \tag{2}$$

where $\overline{e(t)}$ is the vector of external, dependent parameters used for an ecological situation estimation and F_y is the law of functioning of an R-C-E subsystem.

In an estimation of an ecological situation, the vector of road surface condition, $\overline{y(t)}$, is one of the basic road parameters of a subsystem, influencing the environmental pollution level during the winter period.

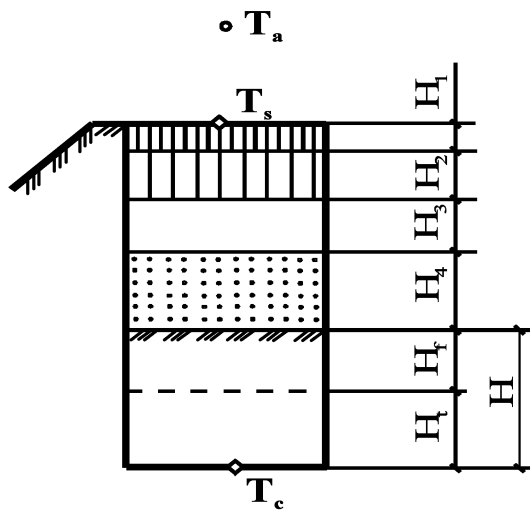


Fig. 3. Scheme for Calculating the Road Surface Temperature.

The target parameter of an R-C-E subsystem accepts vehicle emission levels and anti-icing material quantities needed to liquefy winter slipperiness.

Components of the vector $\bar{e}(t)$ correspond to the pollution level formed at various road surface conditions. The extent of ecological pollution on a roadside strip is determined by the length of time that a surface is at a certain condition.

Eqs. (1) and (2) give a general view of the dynamic mathematical models that reflect the behavior of a system with time. Operators F_S and F_y can be presented in the form of equation systems, logic parities and empirical and analytical dependences connecting entrance and target parameters of an R-C-E subsystem.

Mathematical Models

Traffic Speed

The speed of a stream of traffic was determined by the settlement technique proposed by Professor Vasilev. The technique defines speed coefficients (K_s) from a set of road data [4]:

$$K_s = \frac{V_{f.\max}}{V_{t.\max}} \quad (3)$$

where $V_{f.\max}$ is the maximum speed of a single car in km/h and $V_{t.\max}$ is the traffic speed according to normative documents in km/h.

The speed coefficients considered in the generalized factor are as follows:

- Influence of separate road parameters on change in traffic speed;
- A combination of road conditions.

The final speed coefficient on each road site is determined by the weighted mean complex parameter:

$$k_s^{res} = \frac{\sum_{i=1}^n k_s l_i}{L} \quad (4)$$

where l_i is the length of the site with coefficient k_s in km and L is the general length of the road in km.

The final coefficient is chosen based on the parameter with the minimum value. With the final speed coefficient value, the reverse problem of defining the speed of a transport stream can be solved. For this purpose, it is necessary to take advantage of the settlement formulas offered by Professor Vasilev [4].

The average speed of free movement of a single car under specific road conditions is calculated by the formula:

$$\bar{v}_{fm} = v_{f.\max} - t \cdot \sigma_v = k_s^{res} \cdot v_s - t \left[a_0 + b \left(k_s^{res} \cdot v_s \right)^2 \right] \quad (5)$$

where t is the size of the confidence interval; σ_v is the root-mean-square deviation of the speed and a_0 and b are empirical coefficients that define σ_v .

The average speed of a transport stream is given by the formula:

$$\bar{v} = \bar{v}_{fm} - \Delta v = \bar{v}_{fm} - \alpha \beta N \quad (6)$$

where α is the coefficient considering the influence of traffic density; β is the coefficient considering traffic structure and N is the traffic density.

This calculation technique reflects normative literature and realizes it in the form of an applied program, which is part of the software from a road data automated bank. It calculates and models the speed of transport streams depending on weather conditions and road surface conditions. Calculations can be performed for both concrete roads and road networks.

Results from modeling traffic speed coincide with results from experimental research.

Model for Calculation of Road Surface Temperature

To calculate surface temperature, heat conductivity equations with types II and III of boundary conditions were solved [5].

Road construction and soil half-space are multilayer systems. Each layer is associated with a thermal conductivity constant λ and specific heat c . These parameters are functions of position x , time t , temperature T , road materials density ρ , and moisture content W_r .

The following equation has been solved to define a temperature field in road construction and a surface temperature:

$$c\rho \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} \left[\lambda \frac{\partial T(x,t)}{\partial x} \right] \quad (7)$$

where $T(x,t)$ is the temperature at depth x in road construction at t .

The scheme for calculating this problem is represented in Fig. 3. Thermal and physical properties change from layer to layer (λ_i, c_i, ρ_i) including from frozen (λ_f, c_f, ρ_f) to thawed soil (λ_t, c_t, ρ_t) in the roadbed.

There is a phase transition with heat liberation or heat absorption at layer interfaces. A system of equations following Eq. (7) can be written as:

$$\begin{aligned} c_i \rho_i \frac{\partial T(x,t)}{\partial t} &= \frac{\partial}{\partial x} [\lambda_i \frac{\partial T(x,t)}{\partial x}]_{H_{i-1} \leq x < H_i, (i=1,2,3,4)} \\ c_f \rho_f \frac{\partial T(x,t)}{\partial t} &= \frac{\partial}{\partial x} [\lambda_f \frac{\partial T(x,t)}{\partial x}]_{H_4 \leq x < H_f} \\ c_t \rho_t \frac{\partial T(x,t)}{\partial t} &= \frac{\partial}{\partial x} [\lambda_t \frac{\partial T(x,t)}{\partial x}]_{H_f < x \leq H} \end{aligned} \quad (8)$$

with conditions at a layer interface of:

$$\lambda_f \frac{\partial T}{\partial x} \Big|_{x=H_f} - \lambda_t \frac{\partial T}{\partial x} \Big|_{x=H_t} = Q \rho \frac{\partial H_f}{\partial t} \quad (9)$$

where $H_f = H_f(x, t)$ is the surface of a phase transition and Q is the latent heat of ice melting.

Models from Eqs. (8) and (9) are subjected to boundary and initial conditions.

Heat exchange between the surrounding air and a road surface is complex. It is defined as boundary conditions of type II and III:

$$\lambda \frac{\partial T}{\partial x} + \alpha [T_s(t) - T_{ac}(t)] = 0 \quad (10)$$

$$T_{ac}(t) = T_a(t) + \frac{\rho_s q_s}{\alpha_c} \quad (11)$$

where T_{ac} is the “conditional” air temperature; ρ_s is the incident radiation absorption coefficient; q_s is the intensity of heat flow and α_c is the heat-exchange coefficient.

Intensity of heat flow depends on the energy balance at the road surface R_b , and all its components may be determined by actinometric methods. Formulas for calculations contain such parameters as cloud cover N , celestial altitude, geographical latitude, longitudinal profile I , road bearing RD , vapor pressure E , road surface color, and roughness of road surface h_r .

To calculate the convective heat exchange coefficient α_c the following empirical formula was used:

$$\alpha_c = \frac{0,00058 V^{1,15} h_r^{0,15} \lambda_a}{\gamma_a^{1,15}} \quad (12)$$

where λ_a is the air thermal conductivity; γ_a is the air kinematics viscosity; V is the wind speed in m/s ; and h_r is the roughness of the road surface in mm .

The second boundary condition is a constant temperature at depths of temperature oscillation damping H :

$$T(H, t) = T_c = const \quad (13)$$

The initial temperature distribution was calculated by the formula:

$$T(x, 0) = T_{a.av} + (T_s - T_{a.av}) \frac{R_s + \sum R_x}{R} \quad (14)$$

where $T_{a.av}$ is the monthly average air temperature; R_s is the thermal resistance of road surface; $\sum R_x$ is the sum of road layers higher than depth x ; and R is the total thermal resistance of all road

layers and roadbed until depth H .

To solve the formulated problem by Eqs. (8)-(14) the method of finite differences was used.

Modeling of Road Surface Condition

The road surface condition is presented in the form of logical-mathematical parities. Results from logic calculations can output two values:

- “True”, if at an available combination of parameters, formation of slipperiness of the given kind is possible
- “False”, if at an available combination of parameters, formation of slipperiness of the given kind is impossible.

At the accepted designations: T_a is the air temperature; T_s is the road surface temperature; T_d is the dew-point; t_{ws} is the time at a wet surface condition after precipitation has ended; OS is the type of precipitation; SP is the road surface condition; and q is the amount of precipitation. Logic parities have a true value:

- for glaze ice:

$$(T_a < 0) \ \& \ (T_s < 0) \ \& \ (SP = damp) \ \& \ (t_{ws} < 12) \ \& \ (OS = no) \quad (15)$$

- for black ice:

$$(T_a < 0) \ \& \ ((T_s < 0) \ \& \ (T_s < T_d)) \ \& \ (SP = dry) \ \& \ (OS=no) \quad (16)$$

- for firm strike:

$$((T_a > 0) \ \& \ (T_s < 0) \ \& \ (OS = liquid)) \ \vee \ ((-5 < T_a < 0) \ \& \ (T_s < 0) \ \& \ (OS = wet snow) \ \& \ (q = 0)) \quad (17)$$

- and for ice:

$$(T_a < 0) \ \& \ (T_s < 0) \ \& \ (OS = liquid supercooling) \quad (18)$$

Algorithms have been developed for the realization of models shown in Eqs. (1)-(18), and programs have been written for a PC to carry out calculations.

Modeling of Pollution Level

Calculations can be presented by following a step-by-step algorithm.

Step 1. Modeling of road surface conditions and creation of a statistical information archive about a possible condition of a surface and its duration.

Step 2. Calculation of traffic speed for each road surface condition.

Step 3. Calculation of roadside pollution during the winter period – the level of transport emissions and quantity of anti-icing materials depend on a road surface condition.

Calculations for atmospheric pollution were made by using the Gaussian method for distribution of impurities at small heights [6]:

$$C = \frac{2g}{\sigma V \sqrt{2\pi}} + F \quad (19)$$

where C is the concentration of harmful substances in g/m^3 ; g is the intensity of an issue in $g/s \cdot m$; V is the wind speed in m/s ; and F is

the background concentration of the basic polluting substances in g/m^3 .

Intensity of the emitted pollution of each kind depends on the structure of the transport stream, intensity and speed of vehicles, and operational charge of fuel.

The level of environmental contamination by chlorides will depend on the use of winter slipperiness control and norms of distributing anti-icing materials. Weather factors greatly influence these processes, which drives work done by the organization on winter slipperiness control.

To improve ecological conditions on a roadside strip during the winter period, it is necessary to solve two opposing problems:

- reduce the time of finding the road in adverse conditions for traffic and
- reduce the quantity of anti-icing materials polluting a roadside strip.

To rationally determine the best method for modeling the road's winter maintenance, it is necessary to compare all possible ways of looking at both of these problems from the point of view of traffic safety, ecology, and economy.

To estimate an ecological situation on a roadside strip during the winter period, four techniques for controlling winter slipperiness have been compared. Each variant differs by a degree on account of weather conditions.

Scheme 1. Traditional technique for winter slipperiness control.

Liquidation of winter slipperiness begins at the moment it is detected. The demand for chloride salt corresponds to a supply opportunity for salt distributors. Old techniques for road winter maintenance do not allow differentiation from the norm of using charged anti-icing materials depending on weather conditions. Thus, weather conditions at the given technology are not considered. The charge on chlorides was determined experimentally. For liquefying winter slipperiness, the convention is to use a sand and salt mix. The salt mixture is distributed by a combined road machine (CRM-130) at an average traffic speed of 30km/h. Thus the normal coverage of a sand and salt mixture on pavement is 125.0g/m². The mixture contained 89 grams of sand (71.2%) and 36 grams of salt (28.8%). The general charge of salt for the winter period was determined by the amount of executed distributions by the formula:

$$Q_1 = 10^{-6} BLg_r n_d \quad (20)$$

where B is the width of a processable site in m ; L is the length of a processable site in m ; g_r is the actual norm of the charge of chlorides in g/m^2 ; and n_d is the quantity of processing.

Duration of finding a surface under winter slipperiness conditions was accepted as equal to normative time for cleaning ice sediments [7].

It was supposed that if norms of distributions are chosen correctly, the liquidation of ice sediments is made in normative term. Considered cases include a change in weather conditions necessitating the distribution of anti-icing materials with increased norms and cases when the application of salt is inefficient for the temperature conditions. For these cases, the duration of finding the road in winter slipperiness conditions was accepted equally with

time of finding the weather conditions favorable for their formation.

For hard snow and friable snow, the duration of the road slipperiness is equal to the total duration of a snowfall and normative time for cleaning of deposits after it has ended.

As shown in the analysis of the results from calculations, for the given scheme of the works organization, the norm for distributing anti-icing materials, 36.0g/m², is superfluous for friable snow and hard snow at air temperatures up to -10°C and insufficient for fused ice at air temperatures below -2°C. The results show that salt is distributed irrationally in surplus, or it is necessary to carry out repeated processing coverings.

Scheme 2. Norms are differentiated depending on air temperature and quantities of precipitation.

The choice for distributing normal amounts of anti-icing material depends on air temperature at the beginning of work. The duration of finding a road surface in winter slipperiness conditions is accepted in the first scheme of the works organization.

Norms can be corrected at changes in air temperature. At the low end, the additional distribution of salts can be demanded, or frictional materials to increase the coupling coefficient can be applied.

The general charge of salt for this scheme of works organization is determined using the formula:

$$Q_2 = 10^{-6} BL(g_g n_g + g_{sn} n_{sn} + g_{ad} n_{ad}) \quad (21)$$

where g_g is the normal charge of anti-icing materials for liquidation of glazed ice in g/m^2 ; g_{sn} is the same for friable snow and hard snow in g/m^2 ; g_{ad} is the same for additional distribution at lower air temperatures in g/m^2 .

Scheme 3. Forecasting the minimal air temperature at which the distribution of anti-icing materials is the norm.

This scheme allows exclusion of additional distributed salts or to refuse its application in advance.

The necessary amount of anti-icing material for this scheme of the works organization was determined using the formula:

$$Q_3 = 10^{-6} BLg_{\min} n_{qs} \quad (22)$$

where g_{\min} is the norm of the charge of chlorides at the expected minimal air temperature in g/m^2 ; n_{qs} is the number of cases of slipperiness formation.

Scheme 4. Preventive works.

These works allow prevention of slipperiness formation due to timely distribution of anti-icing materials with minimal norms to reduce the time for finding covering in an adverse condition, to raise traffic safety and to lower emissions of motor transport.

For preventive processing, 5-15g of reagent on a 1m² road surface is enough to prevent ice formation.

For preventative maintenance of hard snow, work is performed

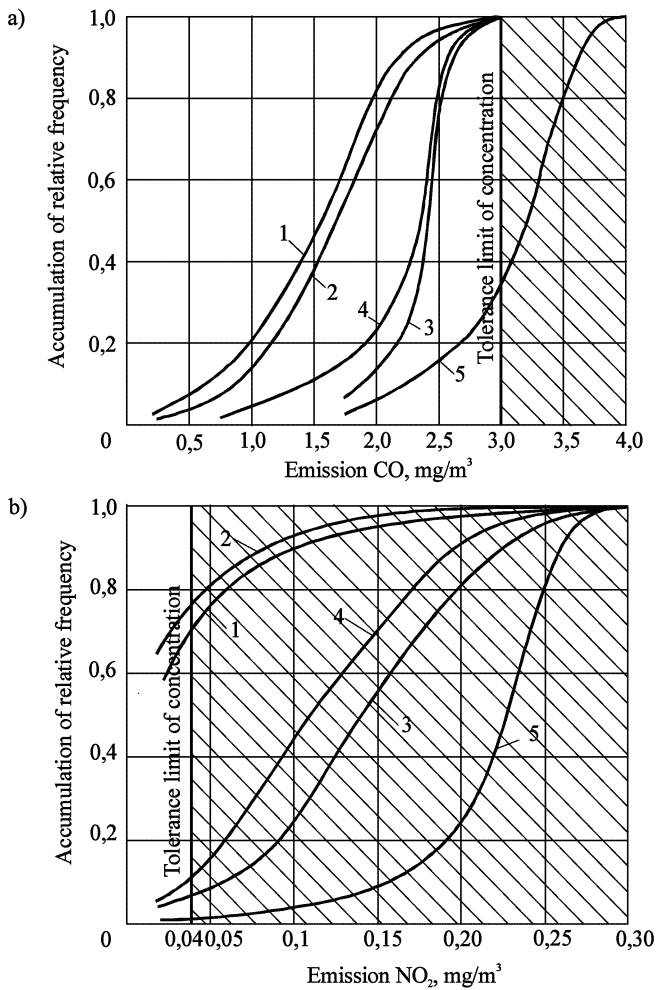


Fig. 4. Probable Distribution of Motor Transport Emissions at Various Road Surface Conditions: 1 - Dry Surface, 2 - Wet Surface, 3 - Presence of Friable Snow, 4 - Hard Snow, and 5 - Glaze Ice.

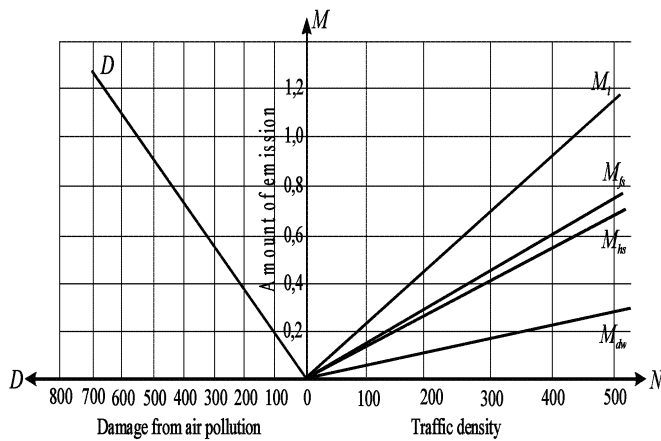


Fig. 5. Definition of the Amount of NO₂ Emissions and Economic Damage from Pollution at Various Road Surface Conditions (over 100km of Motor Transport Travel): *N* - Traffic Density, *M* - Amount of Emissions (*M_i* - at ice, *M_{fs}* - at Friable Snow, *M_{hs}* - at Hard Snow, *M_{dw}* - at Dry and Wet Road Surface Conditions).

cyclically. Each cycle consists of alternating stages between endurance, processing of snow deposits with chlorides, action of a

reagent, shoveling and sweeping snow.

The total amount of anti-icing material was determined using the formula:

$$Q_4 = 10^{-6} BL(n_{qg} + n_{q.sn})[Pg_{ai} + (1 - P)g_r] \tag{23}$$

where *g_{ai}* and *g_r* are the norms of the charge of chlorides at preventive processing and at struggle with winter slipperiness, respectively, in g/m²; *n_{qg}* and *n_{q.sn}* are the quantities of cases of struggle against ice and hard snow, respectively; *P* is the reliability of forecasted slipperiness.

Given a correct forecast, the duration of finding a road surface in the condition of winter slipperiness is equal to zero (due to preventive maintenance). For other cases, calculations for duration do not differ from previous schemes of the works organization.

The results from computing experiments of transport emission levels for various road surface conditions are counted and presented in Fig. 4.

Calculation of Ecological Damage

The damage from environmental contamination by chlorides is determined by the formula:

$$D_i = \gamma \sigma f_i m_i A_x \tag{24}$$

where γ is the coefficient for translating estimations from points to cost; σ is the coefficient estimating structure of recipients that the harmful substance influences; f_i is the dimensionless coefficient for estimating dispersion of impurity; m_i is the total emissions by the *i*-th substance; and A_x is the coefficient for relative aggression of polluting substance.

The damage from air pollution is determined using the formulas:

$$D_i = \gamma \sigma f_i M_i K_{im} \tag{25}$$

where M_i is the total emissions from the *i*-th substance, and

$$M_i = \sum_{j=1}^n A_j m_{ij} \tag{26}$$

where A_j is the coefficient of the relative aggression of the polluting substance; m_{ij} is the weight of the *i*-th substance, which is thrown out by the *j*-th type of internal combustion engine; *n* is the quantity of car types; and K_{im} is the coefficient considering change of emission levels of the *i*-th substance at the *m*-th road surface condition.

The results from calculations using these formulas are presented in Fig. 5.

Conclusions

We can draw the following conclusions from the results of this research:

Estimations of highway influences on the environment should take into account the influence of seasonal weather-climatic factors, particularly winter road maintenance and conditions for motor

transport movement.

For estimations of ecological pollution in roadside territories, it is appropriate to use mathematical models that describe the condition of road surfaces during the winter period. The possibility of their application can be confirmed by experimental data.

Preventing slipperiness reduces the level of CO emissions by 1.6 times, and reduces NO₂ emissions by 4.25 times.

Pollution from a roadside strip with anti-icing materials depends on the technique used for road winter maintenance. Anti-icing can reduce salt consumption by 3-5 times.

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