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Snow Pressure Zoning for Road Safety: Snow Mechanical Characteristics and Climatic Factors

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Abstract: The purpose of the study was to analyse methods for improving territorial zoning with snow pressure conditions on roads, considering snow mechanical characteristics and climatic factors. The methods used include analytical, functional, statistical methods, classification, and synthesis. The errors and reasons for improving the mechanisms were analysed. The snow density was examined (10-30 kg/m³ for fresh snow, 600-800 kg/m³ for wet firn). The study also considered the impact of climate change. The analysis of snow particle sizes during blizzards showed that 90% fall within the 0.1-0.25 mm range. It was determined that the use of zoning according to the conditions of snow pressure on roads will ensure an improvement in the quality of the geoinformation system.

Keywords: pavement adhesion coefficient; zoning of the territory during snowfalls; safety of transport movement; snow removal mechanisms; icy conditions

1. Introduction

In winter, traffic conditions deteriorate due to low temperatures and the build-up of ice and snow on the roadway. These factors create a number of serious problems for drivers and require appropriate measures to ensure road safety.[1,2] The formation of ice on the road is one of the most dangerous winter problems. Icy conditions can lead to loss of control of the car, which will make it difficult to drive and increase the risk of traffic accidents.[3]

As stated by A. Kairanbayeva et al.,[4] the coefficient of adhesion of the pavement to the road is of great importance for traffic safety and reducing car wear. It can be noted that at the moment it is necessary to improve the mechanisms of zoning the country's territory according to the conditions of snow pressure of roads in order to solve problems related to errors that arise at the stages of development and operation of these machines. These problems arise due to the need to determine and optimise indicators at the stages of design, operation, and development of equipment. In addition, the growing demand for affordable snow removal services from roads leads to the need to reduce costs. According to M. Akbar et al.,[5] roads that are covered with loose snow may take longer to travel as the speed decreases. This confirms the fact that these findings coincide with current trends in the implementation of effective zoning systems for the country's territories under conditions of snow pressure on roads and in investing in research and development of technologies for a more effective understanding of changes in snow mechanical characteristics.

As stated by Zh.K. Isabekova et al.,[6] speed limits are usually introduced when the snow cover is 5-10 cm thick. The speed can be reduced to the calculated speed (set for this road) or to 50 km/h or less. This is done to reduce the risk of loss of traction. However, this paper did not consider the fact that it is important to develop and implement policies aimed at speed limits, which may vary depending on local laws and road conditions. Drivers should follow recommendations for safe driving in the presence of snow cover on the road. According to I.T. Bashikov,[7] in order to ensure traffic safety in mountainous areas, it is necessary to consider many factors when designing and maintaining road infrastructure and develop effective methods for removing and preventing snow accumulation on roads. But it is necessary to consider in more detail the fact that the wind can have a great impact on snow deposits. It can move snow from one area of the road to another, creating snow barriers or snowdrifts. This can make some sections of the road impassable.

D.M. McClung et al.[8] note that avalanches can pose a serious problem in mountainous areas. They can collapse on roads and accumulate large amounts of snow. Roads in mountainous areas are vulnerable to such hazards, and their maintenance requires special attention. It was also not acknowledged that, as a result, various methods such as snow removal equipment, salt reagents, and monitoring and forecasting of weather conditions and avalanche danger in mountainous areas are used to control snow deposits and ensure safe traffic during the winter months. Such measures help to minimise the impact of snowfall on road conditions and ensure traffic safety. According to R. Asimov,[9] in conditions of windless snowfall, road cleaning and safe driving are more predictable than in the case of intense snowfalls with strong winds. However, drivers should still be careful, especially during snowfall, and adapt their speed to the conditions on the road.

The purpose of this study is to conduct an objective analysis of methods for identifying problems and errors in improving the quality of zoning of territories based on conditions of snow pressure on roads. The main focus is on evaluating the effectiveness of snow removal mechanisms using full automation and mechanisation, which are considered key elements of sustainable development of the cleaning system at the current stage of development of mechanisms. The research question is: how can errors be eliminated and quality of zoning a country's territory improved according to snow pressure conditions on roads while accounting for changes in snow mechanical characteristics due to climatic factors?

The issue of slowing down the designing and improving the mechanisms of zoning territories is of particular value, in connection with which it is necessary to investigate ways to overcome this problem and develop a certain range of recommendations. It is also necessary to improve snow removal mechanisms and their systems for the most effective functioning of this process in developing countries.

2. Materials and Methods

At the initial stage of the study, a key theoretical framework was developed, which served as the foundation for subsequent analysis and is the basis for formulating conclusions.

The analysis identified and highlighted problems related to the operation of snowploughs and the entire complex used in the clearing snow from the roadway during snowfalls. Using the statistical method, indicators were considered that help to understand the number and causes of errors in improving the mechanisms of zoning the country's territory according to the conditions of snow pressure on roads, which are the basis for the sustainable development of snow removal systems, improving the operation of these mechanisms, the prospects for using these machines, and the development of stability and productivity of snowploughs in the road cleaning.

Moreover, the role and essence of snow removal operations at different levels of development of road cleaning machines were considered. The advantages and disadvantages of their operation were identified. The impact of the functioning of zoning systems, considering changes in snow mechanical characteristics depending on climatic conditions, on the logistics of developing countries was analysed. Using the structural and functional method, trends, factors, and models aimed at improving snow removal operations were considered, and effective solutions to problems associated with errors in development and improved maintenance of zoning systems and their components were identified and analysed.

Methods of improvement and innovation of mechanisms were additionally investigated to reduce inaccuracies in their functioning and optimise indicators at the development stages. Using the deduction, features of the functioning of integrated automation and mechanisation in snow removal operations were considered by highlighting the snow-mechanical characteristics of these roads necessary for a complete analysis of the work and solving the problems of this process, in particular the introduction of mechanisms for zoning the territory.

The practical part of the study was carried out using computer modelling methods. This part included the study of the basic principles of operation and problems in the development and application of snow removal mechanisms. Their advantages and disadvantages were analysed, including their interaction with the general public utility complex. One of the important stages was the study of the prospects for the use of zoning systems at the international level, which served as the basis for creating a diagram of winter snowstorms in points. The study also analysed the activities of improving snow removal complexes and their operational mechanisms. The developed methods are aimed at reducing possible errors in the improvement of zoning systems of territories, which is important for determining the effectiveness of development and future prospects of public utility potential.

By applying the synthesis, the obtained indicators of theoretical analysis and practical experience were summarised and considered to formulate recommendations aimed at solving problems and achieving progressive growth. Special attention was paid to improving the quality of development of snow removal complex mechanisms and reducing errors. Predictive models and design solutions for component elements were also presented. The methods of logical and functional analysis provided an opportunity to consider in more detail the concept of "zoning of the country's territory according to the conditions of snow pressure of roads, considering changes in snow mechanical characteristics depending on climatic conditions," which in turn helped to analyse situations in which it is difficult to apply zoning of territories.

These methods characterised the features and principles of functioning of the zoning complex and the snow removal from the road, additionally analysed the complexity of the mechanisms during snowfalls with strong winds and their impact on meeting the needs of the population and user requirements, and also considered climatic conditions in which it is more difficult to apply zoning systems and generally carry out snow removal work, based on snow mechanical characteristics.

3. Results

The snow mechanical characteristics referred to in this study include density, hardness, shear strength, and cohesion. The mechanical properties of snow that are discussed in this paper are cohesion, density, hardness, and shear strength. Snow density has an impact on the weight and compactability of snow on roadways; it normally varies between 50 and 500 kg/m³. Vehicle traction and the ease of clearing snow are influenced by hardness, which is rated on a scale from very soft to very hard. Understanding avalanche dangers and snow stability on slopes near roadways requires an understanding of shear strength, or the snow's resistance to deformation when strained. Snow accumulation on road surfaces and how readily it may be cleaned are both influenced by cohesion, or the bonding between snow particles. These factors determine the efficiency of ploughing techniques, the risk of snow compaction and ice formation, and the possibility of unexpected snow movements that could threaten traffic, making them extremely important to snow removal operations and road safety. Moreover, these characteristics are subject to quick changes in temperature, wind exposure, and precipitation patterns. Therefore, taking them into account is crucial when creating flexible and efficient snow management plans for roadways under different climate circumstances.

To ensure reliable zoning of the country's territory and effective operation of the snow removal complex and their mechanisms in various areas of the logistics industry and geodesy, progressive development of automation and mechanisation of snow removal operations is necessary. Special attention should be paid to improving their mechanisms, in particular, accurate design and modelling, since these machines are widely used in the clearing the roadway from snow, which will help to increase the production potential of these works. With heavy snowfall, large accumulations of snow form in a short period of time, which can significantly impede the movement of transport or even completely stop it. Heavy snowfall is characterised by the precipitation of a large amount of snow in a short period of time. As a result, snow accumulates quickly on roads and sidewalks. During heavy snowfall, visibility is greatly reduced, which makes driving dangerous and difficult for drivers. Strong winds can also cause snow drifts; snow moves from one section of the road to another, forming high drifts and blocking the way.[10,11] Nowadays, it is important to solve the problem of errors that arise in the development, improvement, and modelling of zoning mechanisms for the conditions of snow pressure on roads. These errors have a direct impact on increasing the potential of road cleaning, reliability of services, and driving safety during snowfall. Special attention should be paid to the effectiveness of snow removal mechanisms in developing countries and further development of the use of these machines in logistics and geodesy.[12] Heavy snowfall can make it difficult for snow removal equipment to operate, as snow accumulates faster than possible. To ensure safe and smooth driving during heavy snowfall, it is necessary to be careful, reduce the speed of movement, and use winter tires to improve traction.[13]

In the field of geodesy, it is necessary to analyse zoning and identify the root causes of errors during the operation of zoning systems. Further solving these problems aims to improve the quality of road cleaning services, considering changes in snow mechanical characteristics depending on climatic conditions. The analysis of snowfall and its characteristics is important for various aspects, including safety, infrastructure, and agriculture. The maximum height of the snow cover shows the total amount of snow accumulated as a result of the snowfall. It is important to determine the extent of the impact of snowfall on roads, buildings, and agriculture. The intensity of snowfall determines the rate of snowfall; heavy snowfall with high intensity can cause more serious problems than light snowfall, especially if it is accompanied by wind.[14] The composition of new methods to solve the problems of eliminating errors in the development, design, and improvement of snowplough operations to increase the capacity of mechanisms of land zoning systems in logistics and geodesy, at the moment, has huge progress and prospects. Climate models include snowfall forecasts, including their intensity, frequency, and duration, and these data are important for determining potential impacts on urban infrastructure. The maximum increase in the height of the snow cover reflects the change in the height of the snow cover before and after the snowfall; it allows assessing the degree of influence of snowfall on the snow cover and is important for identifying potential flooding problems as a result of rapid snowmelt. Analysis of snowfall characteristics helps organisations and authorities develop strategies for managing the effects of snowfall, including road cleaning, road safety, and attention to climate changes that may affect snowfall in the future.[15,16]

If modern electronics and computerised processing of transport condition data can be used in the improvement of snow removal machines, which are the basis for sustainable development of the logistics sector, it will help to significantly increase the capabilities of these mechanisms and increase the demand for their use in many areas. The intensity of snowfall is usually characterised by the thickness of the snow cover accumulated over a certain period of time. The thickness of the snow cover is measured in cm or inches and reflects the amount of snow that has fallen in a certain area. This characteristic allows determining the intensity of snowfall and assessing its impact on roads and buildings.[17,18] The tasks of effective management of technological regimes of zoning mechanisms of the country's territories under conditions of snow pressure on roads and their problems with the application and development of innovative parts and devices for use are becoming increasingly relevant and practical at the moment. The thickness of the snow cover is important for determining the effect of the intensity and duration of snowfall on the earth's surface and engineering utilities. For example, if the thickness of the snow cover is significant, it can cause problems with traffic, electricity, and water supply. The thickness of the snow cover is also important information for ensuring road safety and carrying out snow removal and maintenance activities.[19,20]

The revision of the causes of errors in the improvement, automation, and mechanisation of snow removal works and their solutions are of particular importance. In the western part of the Eurasian continent, the average snowfall intensity is about 0.5 cm of snow per hour, rarely reaching 1.2 cm per hour. This means that this region usually gets relatively little snow in a short period of time. In Western Siberia, the average snowfall intensity is about 0.6 cm of snow per hour but can reach 4 cm per hour; this region is more prone to more intense snowfalls than the western part of the Eurasian continent.[21,22] The processing and execution of appropriate procedures in the system of zoning mechanisms for the conditions of snow pressure of roads frequently have certain errors, which worsens the effectiveness of these systems for use in the logistics sector and geodesy. In the East and North, the intensity of snowfall can reach the highest value – up to 4 cm of snow per hour. These regions are often exposed to more intense winter weather conditions. In the eastern part of Kazakhstan and the region, the average snowfall intensity varies from 0.4 to 2.1 cm of snow per hour, which indicates a variety of climatic conditions in this area.[23,24]

The duration of snowfall and the humidity of the snow cover are especially important for the maintenance of roads in a continental climate, for example, in Kazakhstan and Central Asia. Prolonged snowfall can lead to a large accumulation of snow on the roads, which makes it difficult to maintain and clean them. Prolonged snowfall can also worsen road conditions and create traffic safety problems; wet snow with high water content is heavy, difficult to transport and clear, and makes road surfaces icy and slippery; dry snow creates fewer maintenance problems and reduces the risk of slippery road surfaces. The snow cover is compacted under the influence of passing vehicles, which leads to multiple pressures. As a result, a solid and compacted layer of snow is formed as shown in Fig. 1, which is much denser and more durable than the original snow cover. The snow banks on both pictures reach nearly half the height of the utility poles visible in the background. This highlights the challenges faced by the road maintenance crews in clearing such substantial snow deposits.

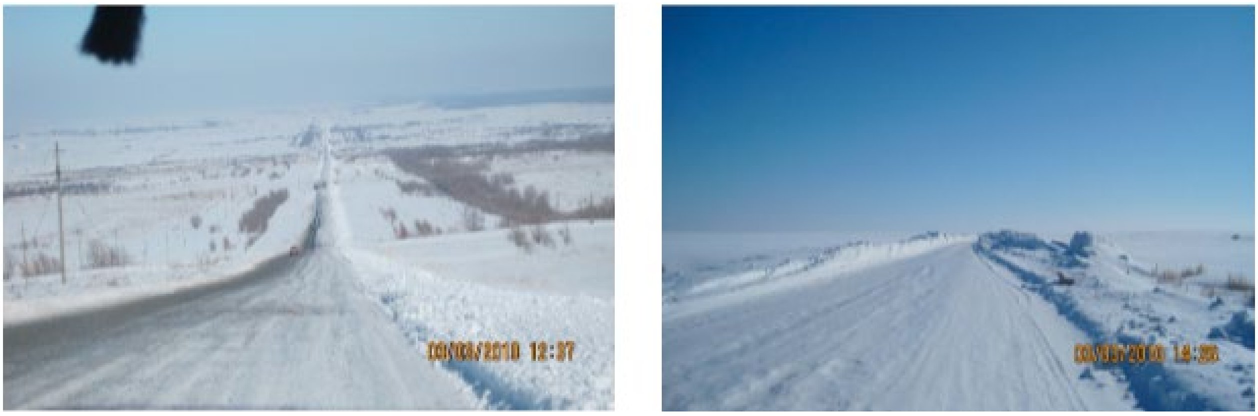

Fig. 1: Accumulation of snow on the roads in the steppe zone, in particular, on the territory of East Kazakhstan.
Source: compiled by the authors.

Road maintenance services should consider the duration of snowfall and the type of snow when developing strategies to clean up and reduce the impact of winter conditions on traffic. This includes the use of special snow removal equipment, the use of salt reagents, and weather monitoring systems for rapid response to snowfall. All this helps to ensure the safety and cross-country roads in the winter months. Seasonal differences are important for understanding snowfall and removal tactics. Early winter snow is typically lighter and drier, which makes it easier to shovel but also more likely to drift. In contrast to late winter, when snow is frequently heavier and wetter due to cycles of partial melting and refreezing, this calls for distinct removal procedures. Additionally, snowfall in late winter tends to accumulate into more compact layers, which puts more strain on road surfaces and may result in greater damage. The efficiency of snow removal machinery and the selection of de-icing materials are both strongly impacted by these seasonal variations. For example, abrasives may be more appropriate for the frequently icy conditions of late winter, but salt-based de-icers work better in early winter circumstances. In addition, snowfall strength and frequency might fluctuate during the winter, requiring flexible management techniques to preserve road effectiveness and safety.

Table 1 shows the average values of density and porosity for different types of snow. These values were derived from extensive field measurements and laboratory analyses. To provide a thorough depiction of snow types, these measurements were made in a variety of settings and climates. Porosity was computed utilising the link between snow density and ice density, while density was ascertained using standardised snow sample methods, such as the use of snow tubes and weighing scales. These values offer important information about the mechanical characteristics of snow, which has an immediate effect on road conditions and snow removal techniques. For instance, the higher density range of 400-700 kg/m³ for dry firn snow suggests a more compact and difficult material to remove, possibly requiring different tools or methods. The porosity values play a crucial role in determining the snow's ability to retain water and its susceptibility to compaction under the weight of vehicles. These characteristics are essential for forecasting road surface conditions and organising necessary repair procedures.

Table 1. Data on snow density and porosity.

Snow type	Density (p), kg/m³	Porosity (n)
Fresh snow		
Loose, fluffy	10-30	0.99-0.97
Crumbly	30-60	0.97-0.93
Slightly blown by the wind	60-100	0.93-0.89
Heavily blown by the wind	100-300	0.89-0.67
Compacted snow		
Loose snow	200-300	0.78-0.67
Dry settled	200-400	0.78-0.56
Wet settled	400-550	0.7-0.5
Dry firn	400-700	0.56-0.24
Wet firn	600-800	0.5-0.2

Source: compiled by the authors.

In the upcoming decades, climate change is predicted to have a major impact on snow pressure and road safety. Long-term trends show a pattern of global warming, which may cause freeze-thaw cycles to occur more frequently in many areas. As partially melted snow refreezes into ice, these cycles may result in more dangerous driving conditions and an increased chance of accidents. Furthermore, variations in precipitation patterns are predicted by climate models, which may lead to less frequent but more intense snowfall episodes. This change may call for modifications to snow removal techniques and apparatus. Raising temperatures in some places may result in less snowfall overall, which might lessen the amount of snow on the roadways but make winter weather occurrences more unpredictable. On the other hand, because warmer air has a larger moisture content, some areas may see more snowfall. These shifting trends highlight the necessity of adaptable and flexible approaches to safety precautions and road maintenance, as well as the significance of continuing study to update zoning and snow management plans in light of changing climate circumstances.

In general, the problem of optimising the elimination of errors in the improvement, automation, and mechanisation of snow removal work has not been completely solved. Thus, in the European part of the Commonwealth of Independent States (CIS), snowfalls that last from 2 to 5 hours occur only in 10% of cases. This means that most snowfalls in this region have either a shorter or longer duration, and snowfalls lasting from 2 to 5 hours make up a relatively small proportion of the total number of snowfalls. Snowfall lasts more than 8 hours, most often in the European part of the CIS.

The mechanisms of the snow removal complex and their components are often used because of their efficiency and low cost of work. At the moment, there is an increase of interest in many countries to expand logistical potential. Snowfalls that last 8 hours or more can have a significant impact on the earth's surface, accumulating large amounts of snow and creating winter conditions that can affect traffic, transport, and agriculture. This also indicates that in order to ensure safety and prepare for winter conditions in the European part of the CIS region, attention should be paid to road maintenance, snow removal, and compliance with traffic rules during snowfalls. The main reason for the accumulation of snow on the roads is snow drifts. It is necessary to mobilise financial and technical resources to create infrastructure and zoning systems for areas under conditions of snow pressure on the road. A blizzard is a strong wind accompanied by snowfall and snow eddies. During a snowstorm, snow rises from the ground, moves through the air, and then settles on the surface, for example, on roads. As a result, puddles and cliffs form on the snow, making it difficult for traffic and making it difficult to maintain roads.

Blowing snow is a particular problem in winter conditions, so road owners and operators need to take measures to control snow and accumulation caused by blowing snow. These measures include the use of snow removal equipment, the use of salt reagents and monitoring systems to determine where and when snowfall may become a problem. Effective snowfall management is of great importance to ensure road safety in winter. Snowfall particles carried by a blizzard can have a variety of shapes and sizes ranging from 0.01 to 2 mm.

In the period from 2019 to 2022, a wind diagram was compiled on the section of the Kostanay-Mamlyutka-Petropavlovsk highway (Fig. 2) using data from a local weather station, which covers a multi-year period. This wind diagram includes information about the direction of the wind at 8 key points. In addition, this wind pattern intersected with the axis of the road in accordance with the route plan for this section.

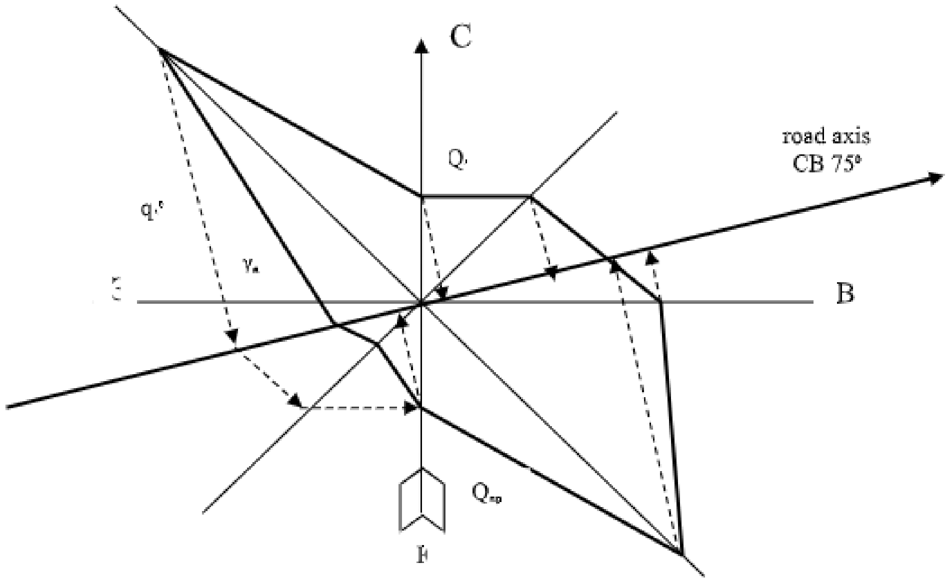

Fig. 2: Diagram of winter snowstorms in points.

Source: compiled by the authors.

Snow may contain small crystals, plates, and needle-like structures. However, in this context, it is important to note that 90% of all snow particles carried by a blizzard are usually in the narrow size range of 0.1-0.25 mm. This indicates that most snow particles in a blizzard are relatively uniform in size and are usually small crystals or particles of similar shape and size. This information can be useful for studying and analysing snowfall in various climatic conditions. The snow surface has adsorption properties, which means that snow can attract and absorb water. When the lower part of the snow sample is saturated with water, it rises up through the capillaries that form between the snow grains, reaching a certain height above the free water level. This height is called the "capillary rise height." In snow, the height of the capillary rise of water can vary from 0.1 to 1 m, depending on the structure and porosity of the snow.

Snowflakes are covered with thin films of water, which can move inside the snow under the influence of molecular and surface tension forces in the narrow spaces between the snow grains. At low snow temperatures, typically around -5°C to -2°C, this film water can freeze on the surface of the grains and, as a result, increase the temperature of the snow. Therefore, when snow is saturated with water, its temperature is usually close to 0°C. The maximum amount of water that snow is able to hold in the form of film and capillary moisture is defined as its maximum water retention capacity. The ability of snow to retain water depends primarily on the size of the snowflakes and the effective surface they provide. Approximate water retention values for different types of snow are shown in Table 2.

Table 2. Water retention capacity of snow.

Snow type	**Density before wetting, kg/m³**	**Ratio of the mass of water that can be stored in the total mass of snow to water**
A snowstorm that just fell	130-210	55-35%
Fine-grained and medium-grained grain size	240-320	32-25%
Recrystalised coarse	390-450	25-15%

Source: compiled by the authors.

When the humidity of the snow reaches a level exceeding its maximum water retention capacity, water begins to penetrate through the snow under the influence of gravitational forces or due to a difference in pressure. The larger the snow grains and the higher the porosity, the greater the filtration coefficient. During the continuous flow of water in the snow, the filtration coefficient increases due to the appearance of microchannels. For typical snow types with a natural cover density, the filtration coefficient is usually estimated in the range of 1-5 m/s. The actual water filtration rates in the snow cover, as a rule, are in the range of 0.02-0.5 cm/s. The heat capacity of dry snow is defined as the sum of the heat capacities of ice crystals, air, and water vapour contained in its composition (Table 3).

Table 3. Density and heat capacity of snow components at 0°C and normal atmospheric pressure.

Snow components	Density, kg/m^3	Heat capacity	
		Specific gravity, J/(kgK)	Units of volume J/(m^{3}K)
Ice	917	2117	110^6
Air	1.293	1005	110^3
Water vapour	0.00493	2010	9.9

Source: compiled by the authors.

The heat capacities of air and water vapour in the snow structure are relatively small compared to the heat capacity of ice crystals. That is why they are usually not considered, and the volumetric heat capacity of snow is defined as the product of its density by the specific heat capacity of ice C_l. Spatial studies have been carried out to measure the volume of snow cover on the highways of the Kostanay-Mamlyutka-Petropavlovsk highway (Fig. 3). The right side of the road is lined with a dense forest plantation, serving as a natural snow fence. This strategic placement of trees demonstrates an effective method for reducing snow drift onto the road surface. This also clearly illustrates the contrast between the protected right lane and the more exposed left lane, highlighting the effectiveness of such natural barriers in snow management along major highways.

Fig. 3: Kostanay-Mamlyutka-Petropavlovsk motorway, right-bank strip is fenced with forest plantations.
Source: compiled by the authors.

From a physicomechanical standpoint, snow-ice formations differ significantly from each other, which is explained by the different conditions of their development. Density is a key indicator of the physicomechanical characteristics of snow and ice, since all other properties directly depend on this parameter.

4. Discussion

In modern conditions, the identification of errors and problems in the functioning of snow removal mechanisms and improving their effectiveness is an important area of research. The quality of the research is important, and some problems require immediate solutions. The mass of particles carried by a snowstorm can vary in a wide range from 0.0001 to 0.005 g. This means that the snow particles that make up a blizzard can have different masses, which can be very low, mostly within the specified values. This study, conducted to improve the machines and mechanisms for zoning territories under conditions of snow pressure on roads that increase the potential of the utility sector in countries, provided a better understanding of the causes of errors during operation, especially during the development of their components, assessing the possibility of solving these problems and identifying at what stage they may arise. During a snowstorm, small particles of snow rise into the air and can move. This information is important for understanding how snowstorms form and what weather conditions affect snowfall and blizzard characteristics.

In recent years, many countries have made significant progress in the development of design and modelling methods for improving snow removal machines and mechanisms. This area has received significant attention and has undergone significant improvements. There is a fixed height to which snow particles can rise into the atmosphere, and it is sometimes called the lifting limit. This is the maximum height to which snow particles can rise into the atmosphere under the influence of wind. When improving the mechanisms and machines of the zoning complex, their automation and mechanisation, and elements for a better passage of a complex technical process, models should adequately describe the essence of the work, be simple and implementable. Outside of the lifting limit, snow particles usually cannot support the lifting effect and begin to settle to the ground, which leads to the build-up of snow precipitation. The lifting limit may vary depending on meteorological conditions and the characteristics of snow particles.[25]

In order to achieve optimal performance of snow removal mechanisms and increase the potential of the logistics sector in countries, the qualification of personnel and timely diagnostics of equipment are of great importance. Large and heavy snow particles often move across the snow surface in jumping mode.[26] This means that they do not fly through the air like lighter snow particles but periodically bounce, sliding and rolling over the snow surface. This can be observed when large snow particles move under the influence of wind or gravity. According to J. Liu et al.,[27] the abrupt movement of large particles affects avalanches and snowdrifts, especially in strong winds or sleet, when the particles are slippery on the surface. This movement is called saltation. Saltation is a of moving large particles (in this case, snow) at a certain distance as a result of repeated "jumps" on the surface.

At the moment, it is necessary to improve the quality of various methods and devices to improve the mechanisms and machines of the snow removal complex to improve public services. For the effective operation of the entire mechanism, through the use of new methods, it was decided that to begin with, in the improving of these mechanisms, it is necessary to improve the quality of their automation and mechanisation, especially individual parts in them. After conducting a comprehensive analysis of the mechanisms of operation of public utilities, it was found that for the successful implementation of various designs, in particular theoretical ones, it is necessary to have stable fundamental knowledge that allows understanding the physical principles and determining the optimal number of devices, which is important for effective improvement of machines and mechanisms of the snow removal complex, to increase the potential of the logistics sector in many countries, with appropriate conditions.[28-30]

Referring to the definition of J. Schweizer et al.,[31] at high humidity and sub-zero temperatures, surface air may contain frozen water in the form of droplets with a diameter of about 2 mm. This means that moisture in the air condenses and freezes, forming snow droplets with the specified diameter. Such snowdrops can fall to the ground, forming snow precipitation, especially in conditions of high humidity and low temperatures. This confirms the fact that these findings coincide with modern trends in the field of design and modelling of methods for improving the mechanisms of the snow removal complex. In the modern world, much attention is paid to considering all factors affecting the quality of these works to increase the potential of the logistics sector. However, this study did not consider the fact that the presented phenomenon is typical for cold climatic regions, where snowfalls and frosts usually lead to the formation of snow cover.

E. Santiago-Iglesias et al.[32] determined that at low temperatures, the diameter of the particles of unfrozen water decreases. This is conditioned by the fact that at low temperatures, water molecules move more slowly and are less bound into water droplets, and cold air contributes to the formation of smaller particles. At a temperature of about -10°C, water particles can have a diameter of about 0.3 mm, which indicates the formation of snow crystals and droplets that can rise in the air. However, at even lower temperatures, such as -30°C, vaporous moisture can be a supercooled mist. But for utilities and snow removal mechanisms to work more correctly, building checks need to be done regularly, so the logistics sector capacity will soon reach high levels. The difference of this study lies in the fact that the researchers do not emphasise the importance of the features of the use of zoning, nor do they emphasise the need for a careful study of the data and potential causes of failures in the operation of snow removal mechanisms. This is of key importance for the future promising development of the use of snow removal mechanisms aimed at improving the sphere of public services in various cities.

A. Sawtelle et al.[33] note that water particles are in a liquid state, despite low temperatures, and they can retain their liquid form until freezing occurs. This supercooling can be an important aspect in the development of ice crystals and snow precipitation under extreme cold conditions. Snow formation usually occurs due to thermodynamic instability in the atmosphere and environment. The snow formation begins with the condensation of water vapour in the atmosphere on small particles such as dust, gases, or condensation nuclei. The results of this study concerning the formation of snow have been analysed in more detail. It is important to add that increasing the potential in the utility industry directly depends on improving and introducing innovations in snow removal services and providing high-quality service for the machines of this complex and their mechanisms.

S. Han et al.[34] have shown by their work that small particles serve as a starting point for the formation of water droplets or ice crystals. As soon as these water droplets or ice crystals reach a certain size and mass, they begin to settle on the surface of the earth in the form of snow. Thus, snow is formed due to physical and chemical processes occurring in the atmosphere, which include condensation of water vapour and the formation of ice crystals. Atmospheric instabilities may contribute to this, but they are not directly related to snow grains. However, the study did not adequately explore how snow behaves dynamically under stress, especially given how quickly its characteristics might alter in response to changes in moisture or temperature. A minor increase in temperature, for example, can cause snow to become more cohesive and denser, while a decrease can lead to a more brittle structure. Likewise, a rise in moisture content can significantly change the compressibility and shear strength of snow, two properties that are essential to road safety and effective snow removal. It can also be noted that these changes may include the compaction of snow, the transformation of snow crystals into ice crystals, the formation of snow blocks, so there is a difference between this study and the findings of the researcher.

As noted by M. Mustafa and C. Moormann,[35] the snow cover is compacted under the influence of passing vehicles due to repeated pressure. This occurs as a result of the weight and pressure created by the wheels and suspension of vehicles in the snow. Constant pressure and deformation of the snow cover caused by the movement and weight of vehicles lead to snow compaction, making it more compact and solid.

For zoning plans and snow removal methods to be implemented effectively, relevant parties must be involved. Input from local governments is crucial for tailoring research findings to specific local contexts, as they are influential in the formulation of policies and the distribution of resources. With their hands-on training, road maintenance staff can offer invaluable insights into the viability and efficacy of suggested strategies. Their opinions on the functionality of the equipment and the difficulties encountered during different snowfall circumstances are very helpful in improving zoning and removal plans. Participation from the public in surveys and community gatherings can help pinpoint issues and determine how satisfied people are with the way snow management is currently done. This multi-stakeholder strategy guarantees that research findings are socially and practically acceptable in addition to being solid scientifically.

Using a multifaceted approach, practitioners and policymakers can practically implement the study's results and suggestions. The zoning data can be used by policymakers to create more complex and region-specific winter road management plans. Based on the patterns of snow pressure that have been observed, they may decide to modify budgets and resource allocation. Incorporating the climate change estimates into long-term policy formulation and infrastructure planning is another option. The specific mechanical properties of snow can help road maintenance professionals choose the right equipment and methods for snow removal at the right time. For example, places with frequent light snowfall may benefit from more frequent, lighter clearing operations, whereas areas prone to high-density snowfall may need more powerful removal equipment. Strategies for equipment deployment and adaptive maintenance plans can be developed using the data on seasonal variations. Additionally, the porosity and density of the snow can be used to optimise the choice and application rates of de-icing materials. It is advised that local authorities develop comprehensive, region-specific winter road management plans that take these findings into account to make implementation easier. These strategies must be adaptable enough to take into account any prospective effects of climate change as well as the various circumstances found in the study. Furthermore, road maintenance crew training curricula must be revised to incorporate the most recent knowledge on snow dynamics and removal methods as reported in this study.

It is also necessary to amend the study that compacted snow cover is much less soft and harder than fresh snow and can facilitate traffic. In order to achieve improvements in the design and modelling of methods for improving mechanisms and machines of the snow removal complex and to reduce errors in their automation and mechanisation during complex technological processes, it is necessary to pay attention to two aspects: increasing funding and improving the skills of employees, and the introduction of new technologies. The main purpose of these measures is to improve the quality and efficiency of the enhancement process in the mechanisms and machines for zoning the territory according to the conditions of snow pressure on roads and reduce the risk of errors.

5. Conclusions

The study showed that snow removal equipment management solutions should be economical and cost-effective. In addition, many social and technological adaptations need to be carried out for those areas that cannot be solved technically. In this paper, recommendations were considered to eliminate errors in the design and implementation of mechanisms of the snow removal complex. A thorough analysis of the functioning of these mechanisms has been carried out in zoning of the territory, considering snow pressure on roads. In order to improve the zoning of the territory, snow removal mechanisms were considered, expanding this resource base. The analysis shows that snow removal mechanisms play an important role in maintaining road safety and cross-country ability in the winter months. The zoning technique provides a framework for policymakers to create tailored snow removal plans that may save costs and increase road safety throughout the winter by taking into account both geographic and climatic elements.

The study's conclusions about mechanical properties and snow pressure zoning have a big impact on cold climate snow removal procedures and logistics. More effective and efficient snow management tactics are made possible by this research, which offers a clearer understanding of how snow behaves under different climatic circumstances. The zoning technique provides a framework for policymakers to create tailored snow removal plans that may save costs and increase road safety throughout the winter by taking into account both geographic and climatic elements. Given that typical snow patterns are becoming less predictable due to climate change, these observations are especially helpful.

It is advised that local and regional authorities analyse and update their current snow removal practices in order to actually implement the study's conclusions. Incorporating the zoning strategy described in this study while taking local climate data and traffic patterns into account should be part of this procedure. Public education campaigns to educate locals about modern snow management approaches and training programs for snow removal teams on the most recent understanding of snow mechanics and removal procedures are examples of implementation activities that should be taken.

Additionally, the creation of a centralised database with information on the properties of snow and how well it is removed in various locations could offer important data for continuous improvement of snow management techniques.

Future research should focus on developing advanced predictive models that integrate real-time weather data with snow mechanical properties. The precision of resource allocation and snow removal planning could be greatly improved by such models. Furthermore, research into novel materials for snow removal tools, including stronger and more effective plough blades or substitute deicing agents, has the potential to completely transform snow management techniques. The long-term effects of climate change on snow patterns and their consequences for road infrastructure and safety require more investigation.

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