# An Economical Snow-melting Approach with Snow and Ice Detection Based on Autonomous Driving Scenarios

Mengjia Yan, Jianqiang Wang, Wenlong Zhao, Hongju Chen, and Yongzhi Chen

*Abstract*—**In the wake of snowfall, it is crucial to restore safe road passage promptly and efficiently. Considering the timeliness of melting operations, comprehensiveness of melting areas, safety of operating personnel, and rationality of the amount of snow-melting agent, this paper proposes a dynamic spraying approach of snow-melting agent based on snow-melting autonomous vehicle. Firstly, a dynamic calculation model is designed based on real-time recognition of ice or snow covered on the road, which uses the first law of thermodynamics to calculate the required amount of snow-melting agent for specific road segments, especially considering the surrounding thermal supply effect and snow-covering depth predicted by micro-regional weather forecasts within the expected operating period to adjust the amount. Secondly, it coordinates the spraying amount with the operating speed, achieving quantitative and uniform spraying of snow-melting agents on specific road segments. In addition, a novel form of snow removal based on autonomous driving is designed, which can move smoothly on particular road segments in multiple scenarios at a speed that matches the amount of snow-melting agent sprayed. Numerical experiments were conducted on the overall approach to verify its feasibility, adaptability, and economic and environmental sustainability in complex and extensive areas. The proposed approach is beneficial for exploring new fields of uncrewed operations. It promotes safe, efficient, and environmental clearance of ice-covered or snow-covered roads.**

*Index Terms*—**Autonomous driving; dynamic spraying model; ice or snow clearance; uncrewed operation**

Manuscript received January 22, 2024; revised April 29, 2024.

This work was supported in part by the Natural Science Foundation of Gansu Province of China (Grant no. 23JRRA900), the “Double-First Class” Major Research Programs of the Educational Department of Gansu Province of China (Grant no. GSSYLXM-04), and the Industry-Academia Collaboration Coordinated Talent Cultivation Foundation of the Educational Department of China (Grant no. 231104575132939).

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## I. Introduction

ACCUMULATION of snow and ice on roadways affects the variability of pavement friction coefficients, causing wet and slippery road surfaces, and presents a hazard to vehicular safety [1-3]. Snow accumulation can also lead to road closures, significantly diminishing the sustainable service capacity of the road network [4, 5]. Consequently, timely road de-icing and snow removal after the occurrence of snowfall have become essential operations for ensuring road traffic safety.

There are two approaches to treating ice and snow: active de-icing and snow removal and passive de-icing and snow removal. Active de-icing and snow removal methods, such as heated pavement systems [6-8] and innovative road surface materials [9, 10], are environmentally friendly but have limitations such as installation difficulties, challenges in implementing across full ranges of snowy areas, and high costs. In contrast, passive de-icing and snow removal methods are more commonly employed for existing roads. These include snow plows, snow blowers, and snow shovels. Manzone *et al.* [11] conducted performance testing on snow blower prototypes tailored for three pavement types and six snow layer thicknesses, showing promising results, but only for loose covering types.

Accordingly, in light of the de-icing and snow removal capabilities of chemical products with melting properties [12], spreading chemical products has become a commonly used way for ice or snow clearance. Initially, this was done either by hand or mechanical spreaders. However, these approaches were limited by the working environment, time, and safety and were also prone to uneven application, over-application, or missed areas. With the swift advancement of autonomous operations technology [13, 14], new spreading approaches for chemical products have been developed. Cheng *et al.* [15] introduced a mobile intelligent anti-ice and snow removal spraying system based on the concept of active intelligent anti-ice, featuring deicing fluid automated mixing and application via an uncrewed vehicle spraying system interfaced with the delivery system of deicing fluid. Although this system has significantly improved the efficiency of automated de-icing and snow removal, we must assess deicing fluid's environmental impacts [16, 17], especially when over-application occurs. Hu *et al.* [18] researched the effects and mechanisms of different snow-melting agents on asphalt in 2023. Ice or snow clearance should utilize more environmentally friendly non-chloride snow-melting agents.

Considering the stringent requirements imposed by environmental ecology and the cost of eco-friendly snow-melting agents, there is an inevitable demand for precise spraying. The intensity and complexity of ice or snow clearance across extensive areas—particularly in extreme conditions, rural roads, remote regions, and so on—and the impact of ice or snow clearance timings on road passage [19] necessitate the adoption of autonomous ice or snow clearance. Therefore, given the requirement for comprehensive coverage, efficiency, safety, and ease of execution in melting operations, and with the support of existing technology [19-21], the uncrewed operation with autonomous driving provides us with a feasible approach. Based on an analysis of the interactions between snow-melting agents and snow or ice on the road surface, and guided by principles of safety, efficiency [22], environmental protection, and operational convenience for ice or snow clearance, we propose a methodology for the dynamic spraying of snow-melting agents using de-icing and snow removal autonomous vehicles. Utilizing their capacity for unattended operation in complex environments, extensive coverage, and round-the-clock functioning, this methodology aims to maintain roads in a continuously passable state through recurrent monitoring, thus paving the way for innovative developments in autonomous ice or snow clearance operations.

The contributions of this study are summarized as follows:

1) By integrating surface condition analysis of snow and ice as a benchmark, this study introduces a novel segmentation approach for operation regions to accurately calculate the required amount of snow-melting agents in specific zones. The precision application strategy considers the environmental conditions during current and expected operation times, ensuring optimal adjustments for adequate snow and ice removal.

2) This study proposes a new concept of operational speed coordination to match the dispensing rate of snow-melting agents along road segments. This innovative approach guarantees that snow-melting agents are applied promptly and uniformly across the road stretch, enhancing overall snow and ice control efficiency.

3) A novel autonomous vehicle structure for ice and snow clearance is developed, and the dynamic snow-melting agents spray approach is implemented. The integrated design of the vehicle addresses concerns such as equipment vulnerability to extreme conditions and the challenges associated with installation and maintenance, offering a practical solution for effective winter maintenance operations.

The paper is structured as follows. The problem statement is discussed in Section II. The de-icing and snow-melting mechanism of snow-melting agents is included in Section III. The dynamic spraying approach of snow-melting agents is contained in Section IV. The implementation of this approach in the field of autonomous driving is dealt with in Section V. Numerical examples are presented in Section VI. Finally, the conclusion makes up Section VII.

## II. Problem Statement

As a versatile, efficient, and convenient tool for ice or snow clearance, snow-melting agents are implemented on roads, as shown in Fig. 1. The operational vehicle progresses forward at a steady speed while simultaneously performing the spraying operation of snow-melting agents. With the spatiotemporal changes of the operational vehicle, the environment and the state of ice or snow on the road surface exhibit phase-based dynamic alterations. Mastering the intrinsic relationships between the environment, the state of ice or snow, and the amount of the snow-melting agent is critical in determining the scientific spraying amount for each phase, thus ensuring the complete melting of ice or snow on the road surface in an environmentally friendly manner. As the vehicle proceeds forward, the snow-melting agent is continuously dispensed. The area of contact is one of the primary factors affecting the snow-melting agent's ability to ablate [23]. Consequently, a mass of $G_i$ snow-melting agents must be evenly sprayed onto the corresponding road segment of length $L_i$. Considering the vehicle's continual movement state, matching the appropriate operative speed of $v_i$ for the road segment is essential to ensure the snow-melting agents spray uniformly and in a precise amount.

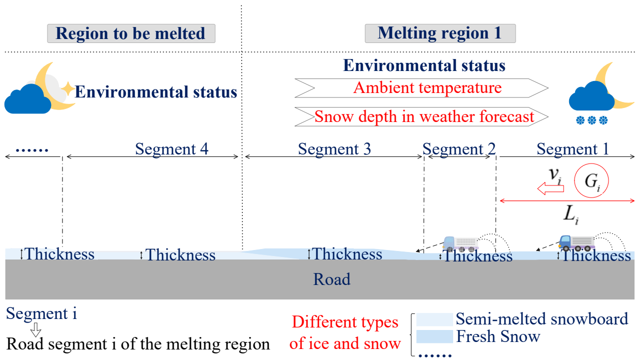



Fig. 1 The ice or snow clearance process with snow-melting agents on the road.

Therefore, to address the issue of uncrewed melting operations using snow-melting agents on roads, the following assumptions are made in this study:

Assumption 1: Modern sensing devices can accurately identify ice or snow conditions on the road surface.

Assumption 2: Experiments are used to obtain the specific heat required for melting different types of ice and snow per unit volume and the heat-generating capability of a unit mass of the snow-melting agents.

Assumption 3: The ice or snow clearance approach is based on road segments, which refer to specific lengths of road determined by the conditions of ice or snow on the segment.

Assumption 4: The melting operation is conducted at a constant speed on the same road segment.

Assumption 5: The accumulated ice and snow on the road surface have been treated with snow-melting agents before forming a smooth, compacted snowboard or ice plate.

## III. The Operating Mechanism of Snow-Melting Agents

For ice or snow clearance, snow-melting agents inevitably involve the interaction between the ice-covered or snow-covered and them. Analyzing the complete action process is necessary to achieve the scientific and rational use of snow-melting agents. However, ice and snow accumulation patterns on road surfaces vary, and their structures are diverse. How do snow-melting agents act upon snow and ice? Is there a difference in efficacy between snow-melting agents on various structures of snow or ice during the melting process?

### *A. The process of snow accumulation and change*

The process of snow and ice on road surfaces from deposition to accumulation and then to the formation of a specific state is a dynamic change over time, influenced by environmental factors and the frequency of vehicular compaction, as illustrated in Fig. 2.

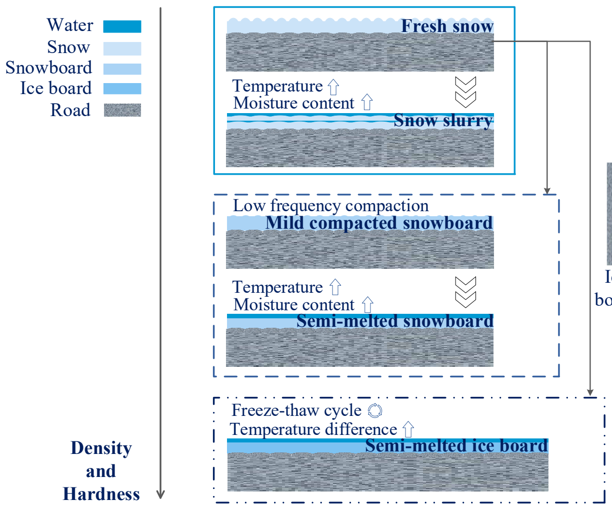



Fig. 2 The states of ice and snow covered on the road.

After snow particles fall to the ground, a natural state of snow known as fresh snow accumulates on the road surface without being compacted by tires, possessing a certain thickness. When the fresh snow is exposed to a rise in ambient temperature, some snowflakes melt and combine with the remaining flakes to form a slushy mixture, resembling "cement" mortar, termed snow slurry. As vehicles pass, the fresh snow, after low-frequency compaction, achieves density and hardness to the extent that its state transitions from loose to firm, referred to as mild compacted snowboard. With continuous compaction, Tire interaction with the snowpack generates heat through friction. If accompanied by a rise in ambient temperature, the snowpack surface will melt faster, forming a layer of water film known as a semi-melted snowboard. On the pre-existing snow-covered road surface, if significant temperature fluctuations occur between day and night or after the rain, the snow melts into water. It refreezes into ice through freeze-thaw cycles, eventually forming an ice board. When its surface is frequently interacted with by tires, especially at higher temperatures, a layer of water film easily forms on its surface, and this condition is known as a semi-melted ice board.

Smooth compacted snowboards and ice boards are formed through multiple phase changes from fresh snow. Considering the limited effectiveness of snow-melting agents on them, cyclical melting operations are conducted to prevent their formation. Thus, the subsequent research will mainly focus on the five types of snow and ice within the wireframe in Fig. 2.

### *B. The melting process of snow-melting agents*

When snow-melting agents are applied to the surface of ice and snow, both the ice or snow and the snow-melting agent undergo a phase change simultaneously, as depicted in Fig. 3.

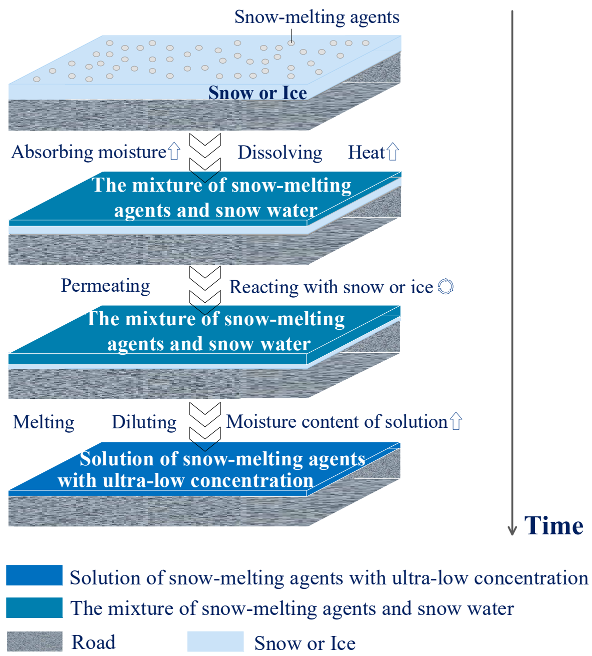



Fig. 3 The melting process of snow-melting agents.

Some snow-melting agents absorb moisture from the surface layer of the ice or snow (the ice or snow has a certain water content or moisture molecules present in the air) and undergo physical dissolution, absorbing heat. It causes particles of the snow-melting agent to leave the solid surface and diffuse into the localized ice and snow. Subsequently, particles of the snow-melting agent form a solution with the relevant particles of the ice or snow, generating heat through chemical processes [24], providing the melting heat for the localized ice or snow with which it interacts. The localized ice or snow melts into water, while part of the snow-melting agent undergoes a phase change to become a saturated solution of snow-melting agents. This solution then permeates deeper layers of ice and snow, continually interacting with them in a cycle. As the solution's water content increases, it gradually becomes diluted, ultimately forming a solution with a lower concentration alongside the melting of the snow or ice.

### *C. The relationship between ice or snow states and snow-melting agents*

The density and hardness of ice or snow will vary with changes in their states, and their differences in physical or chemical properties are provided in Table I.

TABLE I
DIFFERENCES IN PHYSICAL OR CHEMICAL PROPERTIES OF ICE OR SNOW UNDER DIFFERENT STATES

| The degree of density | The degree of hardness | Stability of structure | The difficult degree of downward infiltration |
|---|---|---|---|
| Low | Low | Low | Hard |
| High | High | High | Smooth |

When the density of ice or snow is low, snow-melting agents can fully contact them, resulting in a solution rapidly and permeating smoothly into deeper layers. Conversely, when the density of ice or snow is high, the same amount of snow-melting agents encounter resistance in contact with the ice or snow, making the structural changes of the ice or snow difficult. Therefore, higher-density ice or snow requires more snow-melting agents under the same environmental conditions for the same melting effect.

During melting operations, due to regional and environmental factors, the actual condition of ice and snow may vary, and so does the demand for snow-melting agents. Although eco-friendly snow-melting agents reduce the aggressiveness of pavement and vegetation, over-application can still result in the retention of a solution of snow-melting agents with corrosive concentrations on the pavement, impacting the road's lifespan. In addition, under-application or light application fails to remove snow or ice comprehensively and timely, causing traffic safety hazards. Therefore, calculating the required amount of snow-melting agents based on their melting performance for different types of ice and snow is a prerequisite for scientific, rational, and practical ice or snow clearance on the road.

## IV. MELTING APPROACH

### A. Model formulation of the spraying amount

When snow-melting agents are applied to ice- or snow-covered pavement, on the one hand, the ice or snow needs to absorb enough heat to melt completely. Furthermore, on the other hand, the interaction between snow-melting agents and ice or snow generates heat. From the melting performance, we realized that in a specific environment, when a constant amount of snow-melting agents spray, it will melt a particular volume of a specific type of ice or snow. The amount of snow-melting agents needed for melting varies for different types of ice or snow per unit volume.

Given that the state of ice and snow can be detected, we categorize the types of ice and snow covered on the road. Let $\lambda_j$ denote the ice and snow of type-j, including fresh snow ($\lambda_1$), snow slurry ($\lambda_2$), mild compacted snowboard ($\lambda_3$), semi-melted snowboard ($\lambda_4$), and semi-melted ice board ($\lambda_5$).

The amount of snow-melting agents sprayed in a specific target area is determined by the actual states of ice and snow covered on the road and the regional environmental conditions, as shown in Fig. 4. Thus, a dynamic usage model for snow-melting agents is established.

Introducing $G_i$ to denote the total amount of snow-melting agents sprayed to melt ice or snow on the pavement of the segment $i$, the mathematical model can be expressed as Equation (1)

$$G_i = G_i^{pav} + G_i^{tem} + G_i^{for} \tag{1}$$

where $G_i^{pav}$ indicates the applying amount of snow-melting agents for the operating segment $i$, considering only the states of ice or snow (type of ice or snow, average coverage thickness, and distribution area); the remaining part is the adjustment to the amount of snow-melting agents for that segment based on regional environmental conditions. Considering the current environmental thermal effect, the supplemental amount of snow-melting agents for the segment $i$ is denoted by $G_i^{tem}$. The term $G_i^{for}$ represents the pre-application amount of snow-melting agents for the segment $i$, factoring in the micro-regional weather forecast.

Here, $i$ denotes the various road segments under operation, $i = 1, 2, \dots, n$, and $L_i$ represents the length of the operating road segment $i$, measured by the length of the road's centerline in meters. Considering the equipment's detectable range for the ice and snow covered on the pavement, certain constraints have been proposed to $L_i$, as shown in the following Equation (2)

$$0 \le L_i \le L_{\max} \tag{2}$$

where $L_{\max}$ is the maximum permissible length for the division of road segments.

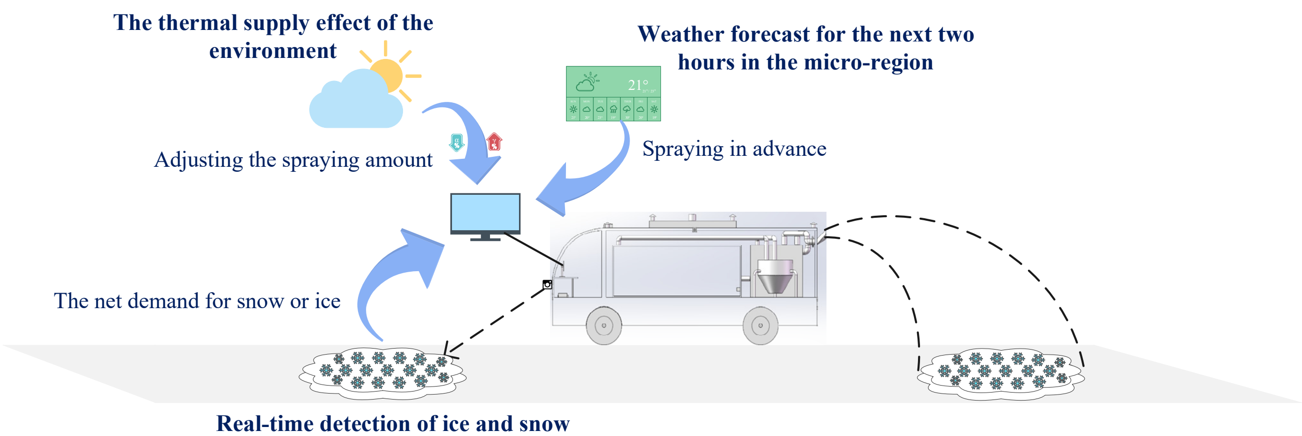



Fig. 4 The constituent factors of snow-melting agents application.

Using $L_{\max}$ and the states of ice and snow (including their types and average coverage thickness) as the boundary for dividing road segments, the determination of the average coverage thickness for each segment is provided by Equation (3)

$$h_i - \sigma \le h_{i,pos\ a} \le h_i + \sigma \tag{3}$$

where $\sigma$ denotes the ice or snow thickness error for the same road segment, whose value may vary depending on different engineering applications or operational areas. Considering the precise application of snow-melting agents, a recommended value range for $\sigma$ is $(0,1]$. $h_i$ represents the average coverage thickness for a specific type of ice and snow on the operational segment $i$. $h_{i,pos\ a}$ denotes the thickness of ice or snow at the location $a$ of the segment $i$.

In light of the First Law of Thermodynamics, to ensure complete melting, the heat required to melt ice and snow on the pavement at a specific ambient temperature must be equal to the heat generated by the action of the snow-melting agents sprayed.

The heat $Q_i^{rel}$ generated by the snow-melting agents' application of a mass of $G_i^{pav}$, considering only the states of ice- and snow-covered, is derived from Equation (4)

$$Q_i^{rel} = G_i^{pav} q \tag{4}$$

where $q$ represents the heat generated unit mass of snow-melting agents.

Define $Q_i^{abs}$ as the heat required for melting the type-j ice and snow covered on the segment $i$ at an ambient temperature of 0 degrees Celsius, as shown in equation (5)

$$Q_i^{abs} = 10 q_{\lambda_j} w_i L_i h_i \tag{5}$$

where $q_{\lambda_j}$ denotes the heat required to melt a unit volume of the jth type of ice and snow at an ambient temperature of 0 degrees Celsius, $w_i$ represents the width of the road for the segment $i$.

The relationship between $Q_i^{rel}$ and $Q_i^{abs}$ can be expressed in Equation (6).

$$Q_i^{rel} = Q_i^{abs} \tag{6}$$

Based on Equation (4-6), $Q_i^{rel}$ is calculated as Equation (7).

$$G_i^{pav} = \frac{10 q_{\lambda_j} w_i L_i h_i}{q} \tag{7}$$

Then, considering the influence of the ambient thermal effect during the operation when the road segment is at a relatively high temperature, the thermal environment will provide part of the heat for melting ice and snow, thereby reducing the actual demand for snow-melting agents; conversely, the lower the ambient temperature, the lower the melting capacity of the snow-melting agents [23]. Under the same volume of ice and snow, more snow-melting agents need to be applied to increase the contact area [23] with the ice and snow, thus compensating for the snow-melting agent's melting capacity loss caused by low temperatures.

Define $G_i^{tem}$ as the supplement amount of environmental temperature for the snow-melting agent and $t$ as the ambient temperature during the operation on the segment $i$. The specific value of $G_i^{tem}$ is determined by the temperature range to which $t$ degrees Celsius belongs, as shown in Equation (8)

$$G_i^{tem} = \begin{cases} \mu_1 G_i^{pav}, t \in [-a\beta, (-a+1)\beta) \\ \vdots \\ \mu_{c-1} G_i^{pav}, t \in [-\beta, 0) \\ \mu_c G_i^{pav}, t = 0 \\ \mu_{c+1} G_i^{pav}, t \in (0, \beta] \\ \vdots \\ \mu_p G_i^{pav}, t \in ((b-1)\beta, b\beta] \end{cases} \tag{8}$$

where $\mu_z$ ( $z = 1, 2\ldots, c, \ldots, p,\ c < p$ , $\mu_z \in (-1,1)$, $\begin{cases} \mu_z < 0, t > 0 \\ \mu_z > 0, t < 0 \end{cases}$ ) denotes the proportionality coefficient for the supplementary amount of the snow-melting agent when $t$ falls within different ambient temperature ranges, and $\beta$ represents the difference between the maximum and minimum temperatures at which the environmental thermal effect is insignificantly varied, $\beta > 0$ . The positive integers $a$ and $b$ are respectively used to govern the minimum lower and maximum upper bounds of the temperature range to which $t$ belongs, $a,\ b > 0$ .

Next, the micro regions' future environmental state will be considered, and melting applications will be conducted before snowfall. Given the hygroscopic nature of the snow-melting agent and the processing requirements for pre-spreading situations, the expected snow accumulation within two hours after operating on the segment $i$ is utilized as the calculation benchmark for the pre-spraying amount. Predicted snowfall that reaches the ground is in the state of fresh snow. A pre-applied amount of snow-melting agents for the segment $i$ is $G_i^{for}$ , which can be given by the following Equation (9)

$$G_i^{for} = \begin{cases} \dfrac{10 w_i L_i h_i^{for} q_{\lambda_j}}{q}, j = 1 \\ 0, j \ne 1 \end{cases} \tag{9}$$

where $h_i^{for}$ denotes the predicted snow depth for the segment $i$ as forecasted by the micro-regional weather service. When $j = 1$ , $q_{\lambda_j}$ represents the heat required to melt a unit of fresh snow at $0^\circ C$ .

*B. Model formulation of spraying*

When uncrewed, the snow-melting agents for a road segment are dispersed onto the corresponding pavement through spraying. Moving and spraying at a coordinated operational speed is necessary to ensure an even distribution of snow-melting agents across the entire segment.

Generally, the relationship between operational speed, discharge rate of spray nozzle, and applying amount of snow-melting agents can be expressed as Equation (10)

$$v = \frac{60 F^{cro}}{G^{equ}} \tag{10}$$

where $v$ represents the operational speed of the road segment for spraying snow-melting agents, $F^{cro}$ is the amount of snow-melting agents that can be sprayed per minute, and $G^{equ}$ denotes the amount of snow-melting agents applied per kilometer.

Using $f_i^{cro}$ to denote the amount of snow-melting agents that can be sprayed per second during operation on the segment $i$ , the coordinated operational speed for the segment $i$ represented by $v_i^{col}$ is shown in Equation (11).

$$v_i^{col} = \frac{3.6 f_i^{cro} L_i}{G_i} \tag{11}$$

## V. Design of a Novel Melting Form Based on Autonomous Driving

### A. Auto structure of melting autonomous vehicle

To enhance the efficiency, safety, and comprehensiveness of addressing road ice or snow clearance and to achieve the dynamic, precise application and uniform spraying of the snow-melting agents, we have designed a novel melting autonomous vehicle based on autonomous driving technology. The vehicle design incorporates integrated systems for state sensing of ice and snow, storage of snow-melting agents, conveyance, and quantified directional spraying, encompassing internal and external structural designs.

The overall internal structure of the vehicle is shown in Fig. 5. The vehicle's compartment is set with a suit of primary operating devices, including a storage tank, a transition tank for the snow-melting agents, pressurized equipment, and nozzles. The storage tank is equipped with a material level sensor to facilitate real-time monitoring of the remaining snow-melting agents and enable timely replenishment. The first three components are interconnected by transport pipes, which convey the snow-melting agents from the storage tank to the nozzles for spraying, and finally, the flow of the snow-melting agents is ceased by a cutoff valve.

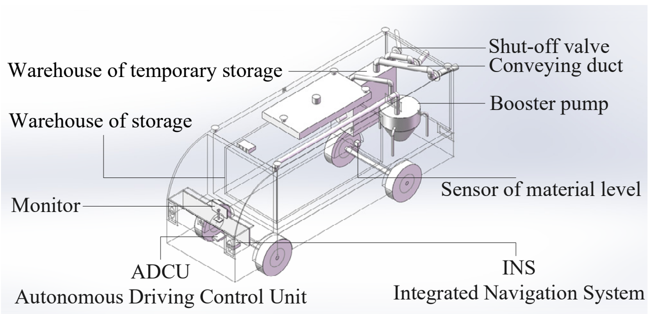



Fig. 5 Three-dimensional design of the overall internal structure.

The overall external structure of the vehicle is shown in Fig. 6. The cab controls the vehicle's smooth operation. A vehicle-mounted state sensor of ice and snow is installed at the front of the vehicle for long-range detection of ice and snow on the roadway, providing output information related to states of ice and snow. Considering the chemical nature of the snow-melting agents and their effects on the operational vehicle, the spraying nozzles are located at the vehicle's rear. It ensures the application of snow-melting agents on the regions already traversed, thus avoiding damage to the operational vehicle's undercarriage.

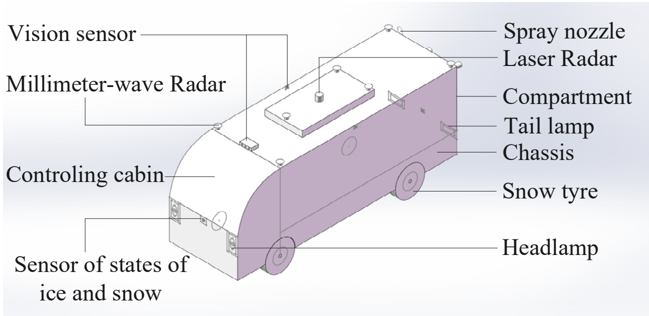



Fig. 6 Three-dimensional design of the overall external structure.

The internal structure primarily facilitates the control of snow-melting agents applied for each road segment. The external structure is tasked mainly with maintaining stable movement to match an appropriate speed for spraying operations.

### B. Manner of Execution

To ensure comprehensive coverage of the snow-melting agents on the pavement during operation, There are three nozzles, each corresponding to cover one lane. Considering the scenario of operating on four lanes, an additional boost gear has been added. The relevant settings for each nozzle under different gears are detailed in Table II.

TABLE II
THE RELEVANT SETTINGS FOR EACH NOZZLE UNDER DIFFERENT GEARS

| Name of the gear | Number of lanes | Fixed available nozzles | Spraying rate of each nozzle /$(kg/s)$ | $f_i^{cro}$ / $(kg/s)$ |
|---|---|---|---|---|
| First gear | Single lane | The second one | $\delta$ | $\delta$ |
| | Two lanes | First and second | | $2\delta$ |
| | Three lanes | Three nozzles | | $3\delta$ |
| Second gear | Four lanes | Three nozzles | First and third: $\delta$ ; The second one: $2\delta$ ; | $4\delta$ |

Using Table II above and Equation (11), one can determine the vehicle's operational speed $v_i^{col}$ on the segment $i$ under various lane conditions. The set $\Pi$ is used to denote the usage status of the three spraying nozzles on the segment $i$ , shown in Equation (12)

$$\Pi = \left\{ k_i^1, k_i^2, k_i^3 \right\} \tag{12}$$

where $k_i^N = \begin{cases} 0, & Don't\ use\ the\ Nth\ nozzle \\ 1, & Use\ the\ Nth\ nozzle \end{cases}$ , $N = 1,2,3$ .

Ultimately, based on the spraying amount $G_i$ for the segment $i$ , the spraying amount $G_{k_i^N}$ and spraying range of each nozzle under scenarios with different lanes are established, as indicated in Table III. This is coordinated with the operational speed $v_i^{col}$ to ensure that the appropriate amount of snow-melting agents is distributed to the respective lanes.

TABLE III
THE SPRAYING RANGE AND AMOUNT OF EACH NOZZLE

| Scenario of lanes | Serial number of the using nozzle | The lane name covered by the nozzle | $G_{k_i^N}/(kg)$ |
|---|---|---|---|
| Single lane | 2 | Full lane | $G_{k_i^2}=G_i$ |
| Two lanes | 1 | Left-lane | $G_{k_i^1}=G_{k_i^2}=\frac{G_i}{(k_i^1+k_i^2+k_i^3)}$ |
| | 2 | Right-lane | |
| Three lanes | 1,2,3 | Three lanes | $G_{k_i^N}=\frac{G_i}{(k_i^1+k_i^2+k_i^3)}$ |
| Four lanes | 1,3 | Outer two lanes | $G_{k_i^1}=G_{k_i^3}=\frac{G_i}{(k_i^1+2k_i^2+k_i^3)}$ |
| | 2 | Inner two lanes | $G_{k_i^2}=2G_{k_i^1}$ |

## VI. NUMERICAL EXPERIMENT

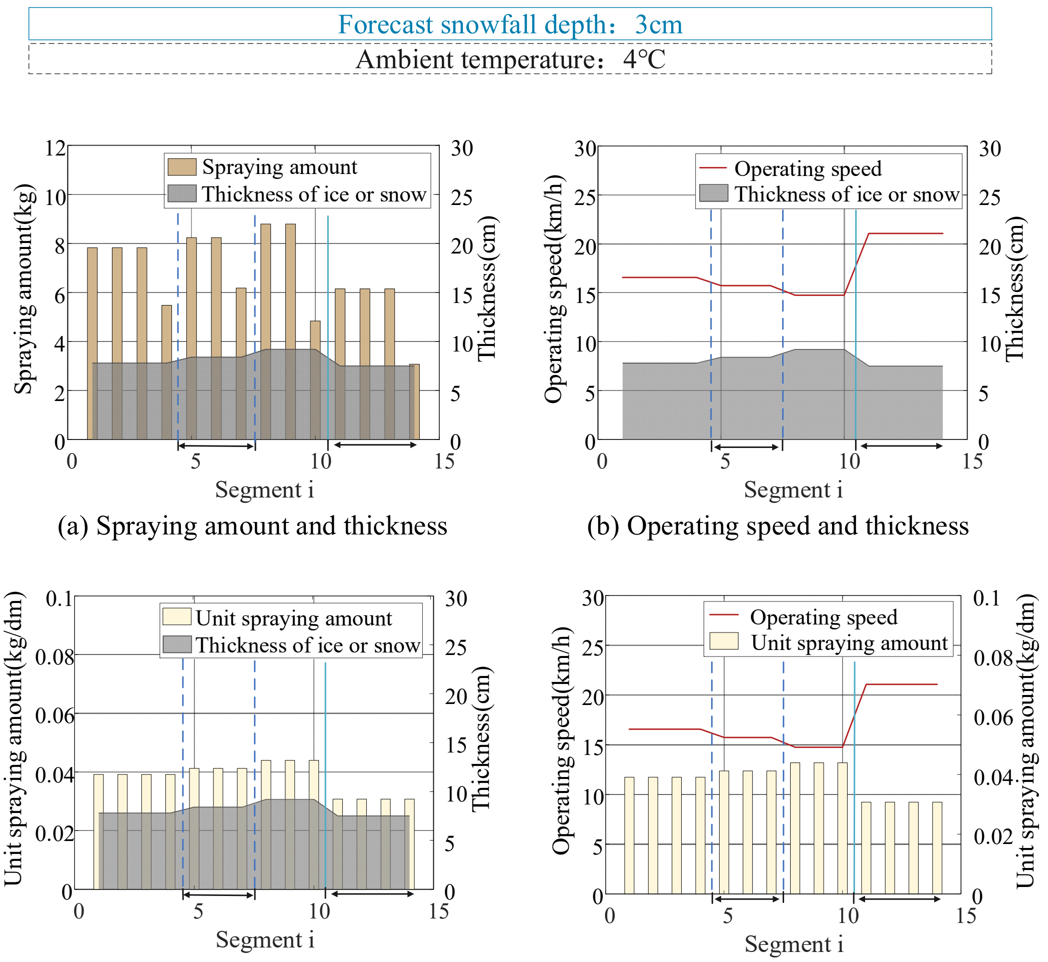
### *A. Feasibility analysis*

A numerical experiment was conducted on a 250-meter-long road with varying snow conditions to verify the feasibility of the approach proposed in this study. This road includes three lanes and has a total width of 11.25 meters. The implementing manner adopts the melting autonomous vehicle designed as described above, with the value of specific parameters assumed, as shown in Table IV.

TABLE IV
THE VALUE OF SPECIFIC PARAMETERS

| Parameters | Value | Unit |
|---|---|---|
| $L_{\max}$ | 20 | $m$ |
| $\sigma$ | 0.25 | $cm$ |
| $\delta$ | 0.60 | $kg/s$ |
| $q_{\lambda_1}$ | $1.3\cdot 10^4$ | $J/dm^3$ |
| $q_{\lambda_2}$ | $1.05\cdot 10^4$ | $J/dm^3$ |
| $q$ | $3.6\cdot 10^7$ | $J/kg$ |
| $\beta$ | 10 | $^{\circ}C$ |
| $t$ | 4 | $^{\circ}C$ |
| $h_i^{for}$ | 3 | $cm$ |
| $\mu_c$ | -15% | - |
| $w_i$ | 11.25 | $m$ |

The states of ice and snow covered on each road segment collected by the operational vehicle are shown in Table V. During the operation, the corresponding operational parameters for each segment, varying with the road segment, are depicted in Fig. 7.




(a) Spraying amount and thickness (b) Operating speed and thickness

(c) Unit spraying amount and thickness (d) Operating speed and unit spraying amount

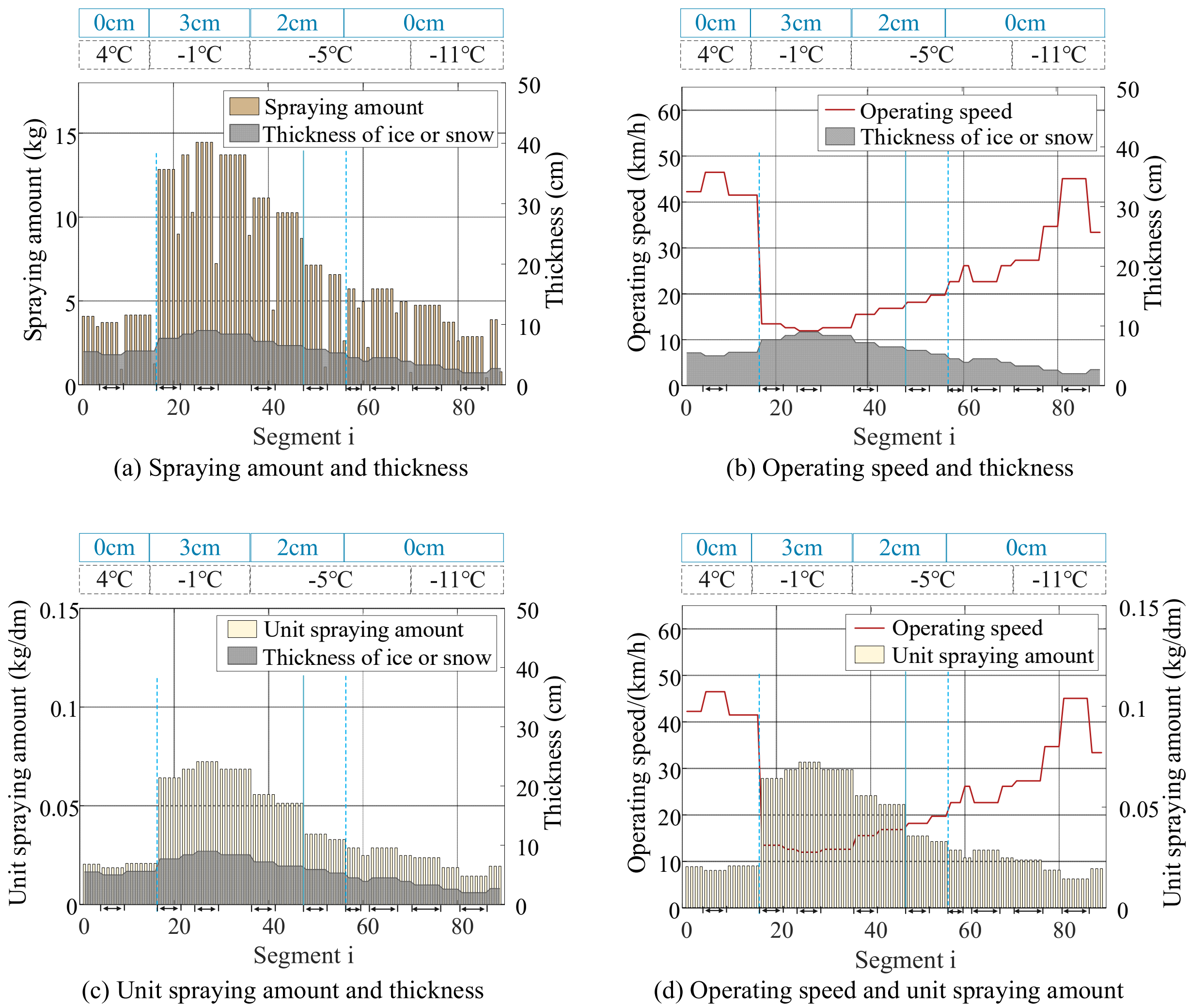
Fig. 7 The trends of operational parameters changing with road segments. Here, the dashed lines represent the change points of the average coverage thickness of ice and snow on the pavement, while solid lines denote the change points of the type of ice and snow. The first ten operating segments are covered by fresh snow. The state changes to snow slurry starting from the 11th segment.

TABLE V
THE LENGTH OF EACH SEGMENT AND ITS ICE AND SNOW STATES

| Segment $i$ | The type of ice or snow | $h_i$ / $(cm)$ | $L_i$ / $(m)$ |
|---|---|---|---|
| 1 | $\lambda_1$ | 7.8 | 20 |
| 2 | $\lambda_1$ | 7.8 | 20 |
| 3 | $\lambda_1$ | 7.8 | 20 |
| 4 | $\lambda_1$ | 7.8 | 14 |
| 5 | $\lambda_1$ | 8.4 | 20 |
| 6 | $\lambda_1$ | 8.4 | 20 |
| 7 | $\lambda_1$ | 8.4 | 15 |
| 8 | $\lambda_1$ | 9.2 | 20 |
| 9 | $\lambda_1$ | 9.2 | 20 |
| 10 | $\lambda_1$ | 9.2 | 11 |
| 11 | $\lambda_2$ | 7.5 | 20 |
| 12 | $\lambda_2$ | 7.5 | 20 |
| 13 | $\lambda_2$ | 7.5 | 20 |
| 14 | $\lambda_2$ | 7.5 | 10 |

In Fig. 7, the trends of the spraying amount on each segment, the operating speed, and the unit spraying amount on that segment changing with the average coverage thickness of ice or snow are respectively represented in Fig.7(a), Fig. 7(b), and Fig. 7(c). Then, the relationship between the operating speed of each segment and the unit spraying amount for that segment is shown in Fig. 7(d).

Comparing the trends in curves, bar charts, or area graphs across Fig. 7, the spraying amount of snow-melting agents and operating speed are adjusting with changes in the type and average thickness of ice and snow covered on the road. Under certain types of ice and snow and conditions of the micro-regional environment, there is an inverse relationship between average coverage thickness and operating speed and a positive relationship with the spraying amount of snow-melting agents. The results show that the proposed approach, which considers states of ice and snow, environmental thermal effects, and weather forecasts for micro-regions, can calculate the dynamic amount of snow-melting agents as needed. This approach with a coordinated operating speed also allows the snow-melting agents to be evenly spread across each unit area of the road segment, addressing issues such as overspray and missed spraying.




(a) Spraying amount and thickness

(b) Operating speed and thickness

(c) Unit spraying amount and thickness

(d) Operating speed and unit spraying amount

Fig. 8 The trends of operational parameters changing with road segments. The vehicle sequentially passes through scenarios with four lanes (a road width of 15 meters) and three lanes (a road width of 11.25 meters), separated by solid lines. The dashed lines represent nodes where the type of ice and snow covered on the road changes. The initial 16 segments are characterized by coverage of snow slurry, segments 17 to 56 feature coverage of fresh snow, and the pavement consistently covers mild compacted snowboard starting from segment 57. The dashed-line boxes in Fig. 8 indicate the ambient temperature within the expected operating time for the respective segments. Meanwhile, the solid-line boxes denote the forecasted snow depth for the corresponding segments during their operations. The horizontal axis of Fig. 8 is marked with solid lines with arrowheads intermittently demarcating segments of the 1600-meter that have a consistent average coverage thickness of ice or snow.

*B. Adaptability analysis*

To verify the approach's applicability for practical operations in more extensive, remote, and hazardous areas and its automatic adaptability to more complex, variable road conditions and regional environments, numerical experiments were conducted in a 1600-meter area with complex snow conditions. Table VI provides values for specific parameters.

TABLE VI
THE VALUE OF SPECIFIC PARAMETERS

| Parameters | Value | Unit |
|---|---|---|
| $L_{max}$ | 20 | $m$ |
| $\sigma$ | 0.25 | $cm$ |
| $\delta$ | 0.60 | $kg/s$ |
| $q_{\lambda_1}$ | $1.3\cdot10^4$ | $J/dm^3$ |
| $q_{\lambda_2}$ | $1.05\cdot10^4$ | $J/dm^3$ |
| $q_{\lambda_3}$ | $1.77\cdot10^4$ | $J/dm^3$ |
| $q$ | $3.6\cdot10^7$ | $J/kg$ |
| $\beta$ | 10 | $^\circ C$ |
| $\mu_{c+1}$ | -15% | - |
| $\mu_{c-1}$ | 15% | - |
| $\mu_{c-2}$ | 30% | - |

Then, the trends of operational parameters changing with road segments are shown in Fig. 8. The spraying algorithm of snow-melting agents of this approach allows for dynamic adjustment of the amount of snow-melting agents sprayed per unit on each segment, even in complex snow conditions, based on the type, thickness of ice and snow, or regional ambient temperature, as shown in Fig. 8(c). Likewise, the operating speed of each segment is dynamically and coordinately adjusted with the amount of snow-melting agents used per unit, as illustrated in Fig. 8(d), to ensure the uniform distribution of the snow-melting agents over the road surface of per unit length. The above diagram indicates that this algorithm can integrate the current and future spatiotemporal regional environmental conditions of each segment of the road, comprehensively consider the real-time accumulation condition of snow on the road surface, and dynamically adjust the amount of snow-melting agents sprayed along the route according to the actual needs of each segment.

Additionally, apart from adaptively adjusting the spraying amount as needed, this approach is also able to change its operation mode to the corresponding lane scenarios, as demonstrated by the left and right sections separated by the solid line in Fig. 8. Combining the proposed design of autonomous driving and automatic spraying, after adjusting to the operation mode in the corresponding lane scenario, uncrewed ice or snow clearance can be realized. Therefore, this approach can apply in areas characterized by harsh environmental conditions and danger, where large-scale manual ice or snow clearance is challenging, yet clearance is necessary.

*C. Economic and environmental analysis*

When applying snow-melting agents for snow and ice clearance, the proposed approach drives the spraying amount design by actual needs to ensure adequate but not excessive snow-melting agents, realizing the concept of environmentally friendly operations. Specifically, in the spraying amount algorithm, we have fully considered the de-icing or snow-melting performance of the snow-melting agents and the differences in snow-melting agents required for different types of ice and snow, such as the differences in the $q$-series parameters shown in Table VI, to obtain the actual snow-melting agents demand for a specific type of per unit volume ice or snow. We have restricted the coverage thickness of ice and snow on each section within a tiny margin of error ($\sigma$) to the average coverage thickness of the segment, combined with specific lane scenarios, and accurately calculated the coverage volume and range of specific types of ice and snow on the road surface. On the basis of this, parameters related to the impact of environmental temperature on ice and snow melting, shown as the $\mu$-series parameters in Table VI, and a pre-spraying model in the light of weather forecast are designed to include both the current environmental temperature of the operational region and the future spatiotemporal snowfall in the adjustment of spraying amount.

This approach subdivides the road covered by ice and snow into continuous grids to fully consider the different actual situations during operation on each road segment, as shown by the dashed and solid line boxes in Fig. 8. Analyzing the various types of requirement items for snow-melting agents in the operational region under different circumstances, as shown in Fig. 9 (the data from the feasibility analysis experiment), enables the adaptive adjustment of the spraying amount along the road under sufficiently considering the combined action of multiple factors, avoiding ineffective excessive spraying.

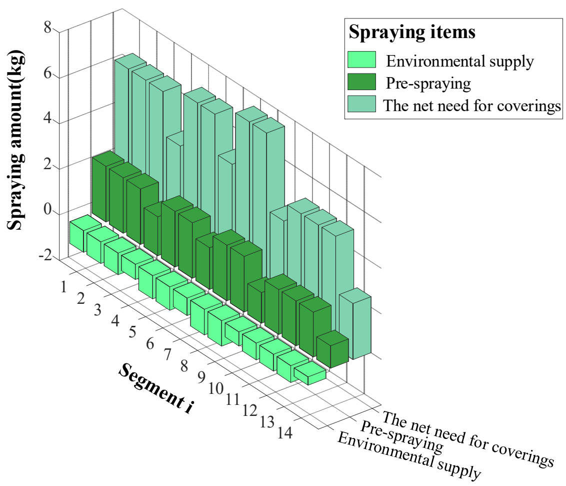



Fig. 9 The precise example of spraying items.

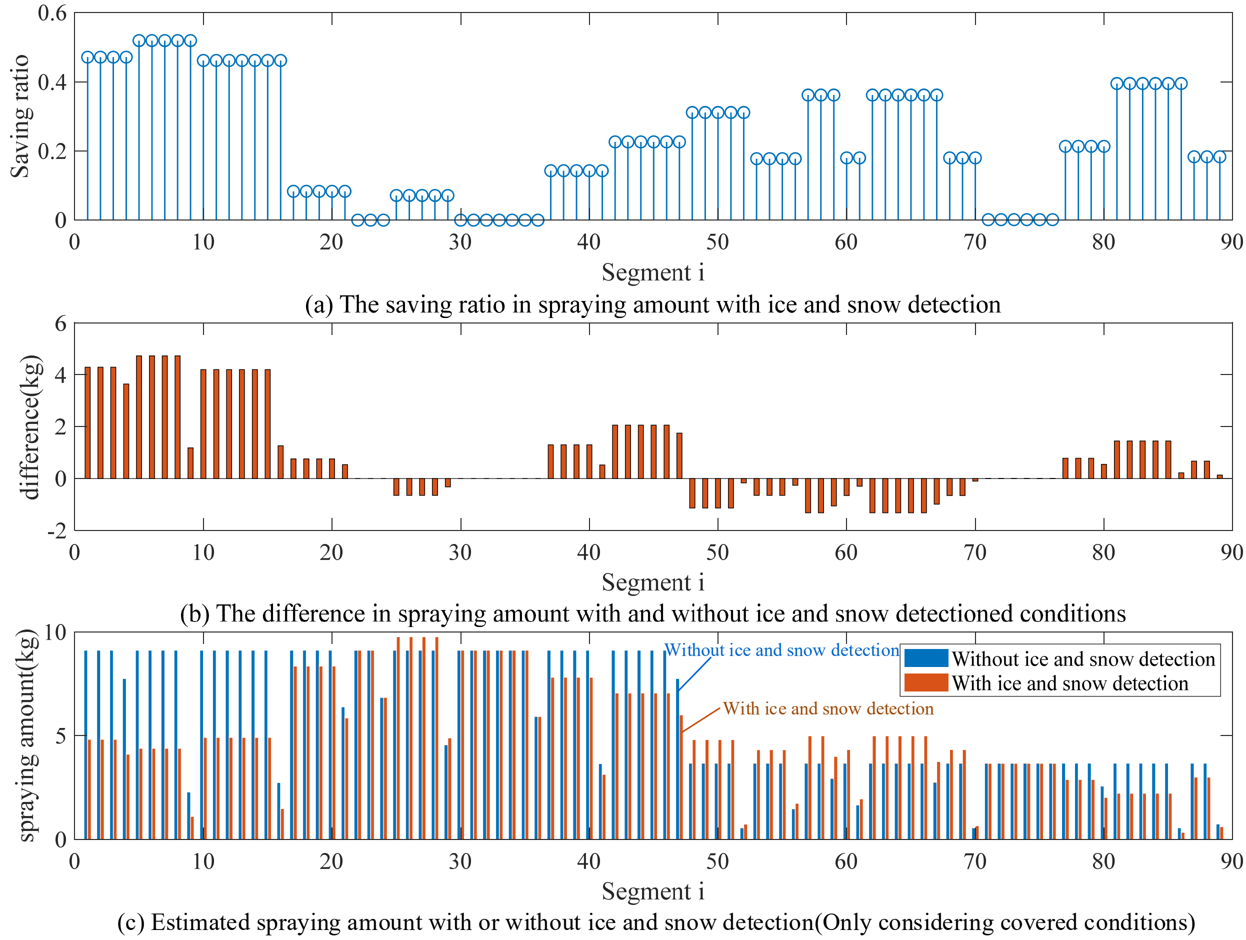



Fig. 10 The spraying amount difference in two types of operation approach.

Furthermore, in terms of economic feasibility, this approach has the potential to be proven to minimize the spraying amount of snow-melting agents and reduce the operational costs as much as possible. Generally, when real-time ice and snow detection is not available, melting operations with snow-melting agents typically estimate the volume of ice and snow as the criterion for the amount to be spread. Therefore, depending on the data from the aforementioned adaptive analysis experiment, the thickness of ice and snow in rough operation can be assumed to be approximately equal to the mode among the actual detected thickness in all segments; there is no distinction between ice and snow types and all being considered as fresh snow. By comparing and analyzing the melting approach based on real-time ice and snow detection proposed in this paper with the general rough operation approach, the differences in the snow-melting agents spraying amount for each operational segment along a 1600-meter road, and the total saved mass can be obtained, as shown in Fig. 10 and Table VII.

TABLE VII
THE DIFFERENT TOTAL SPRAYING MASSES IN TWO TYPES OF OPERATION APPROACH

| Operation approach | The total spraying mass of the road (kg) |
|---|---|
| Without ice and snow detection | 527.94 |
| With ice and snow detection | 455.27 |

Obviously, the traditional operation approach without ice and snow detection can not gain the potential snow-melting agent savings generated by accurate and on-demand calculation. Even more worth mentioning is that when the environmental heat supply is quantified in the approach, it can lead to additional savings in spraying amount. On the other hand, it reduced the operational costs resulting from the reduced number of operations due to pre-spraying. The economic viability of this approach is unquestionable. Then, the more economical application of snow-melting agents will inevitably shine brightly on eco-environmental protection and sustainability.

## VII. Conclusions

To address the issue of uncrewed operations of de-icing and snow-melting, this study elucidates the mechanisms of interaction between snow-melting agents and ice and snow, as well as the differentiation in the process of various types of ice and snow when interacting with snow-melting agents. Then, based on the first law of thermodynamics, a dynamic approach to applying snow-melting agents is proposed, which integrates current and future spatial-temporal ice and snow status and the micro-regional environment. According to the melting performance of snow-melting agents, the spraying amount of snow-melting agents is customized according to the demands of various types of ice and snow in different environments. It advocates the deployment of integrated melting autonomous vehicles for cooperative spraying operations at coordinated speeds. Following verification and analysis, the proposed approach can adaptively adjust the spraying amount of snow-melting agents along the road according to actual demands, enabling comprehensive and uniform melting that is more cost-effective. It also supports large-scale, all-weather melting operations in harsh environments and complex and remote areas, enhancing operating efficiency and effectively addressing the de-icing and snow-melting challenges of high risk, high difficulty, high intensity, and environmental impacts.

The highlights of this study lie in the following:

1) Introducing a pioneering method for delineating work regions based on emerging detection technologies, innovatively realizing the concept of spraying amount design driven by actual conditions.

2) An approach for dynamically adjusting spraying amount and operational speed in a coordinated and adaptive manner is proposed based on the melting mechanism of snow-melting agents and the actual needs in continuous spatiotemporal environmental regions.

3) Innovative application of autonomous driving in uncrewed operations with the goal of ice or snow clearance.

However, this approach relies on precisely identifying ice and snow, posing higher demands on sensors for ice and snow status. Moreover, for complex situations such as multi-layered different types of ice and snow accumulation, diversion and merging ramp areas, and the comprehensive effects of various meteorological elements like rain, wind, and snow, the mechanism of de-icing and snow-melting requires further discussion. Future research will continue to explore these aspects.

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