

**A PORTABLE METHOD TO DETERMINE CHLORIDE
CONCENTRATION ON ROADWAY PAVEMENTS**

By

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16. Abstract <p>Sodium chloride (NaCl) is by far the most commonly used deicing chemical. More effective use of deicer chemical could result in significant economical and environmental benefits. Studies have shown that the ability to measure the salt concentration on the roadway surface would bring dramatic advances in the effective use of deicer. Concentration measurement devices currently in use are only for point measurement and are dangerous for field measurement personnel because they require manual on site measurement. Our new portable concentration system in this project which is mounted on a truck enables safe and continuous measurement of salt concentration.</p> <p>This study adopts the principle of collecting the tire splash to measure the residual salt concentration on the road surface. A conductivity probe is used to detect salt concentration because it is simple to use and is suitable for rugged field applications. Field test results show that the system was able to continuously detect the salt concentration and distinguish the difference between two areas of different salt concentration under field conditions. We observed delay in the salt concentration detection due to the inflow fluid detained in the snow collection box. However, we developed an analytical method to model this delay and to predict the inflow concentration.</p>			
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**Table for Metric to Imperial Conversion
in This Report**

metric ->		imperial
1 millimetre [mm]		0.0394 in
1 centimetre [cm]	10 mm	0.3937 in
1 metre [m]	100 cm	1.0936 yd
1 kilometre [km]	1000 m	0.6214 mile
1 sq cm [cm ²]	100 mm ²	0.1550 in ²
1 cu cm [cm ³ , ml]		0.0610 in ³
1 kilogram [kg]	1,000 g	2.2046 lb

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1. INTRODUCTION

Sodium chloride (NaCl), often referred to as road salt, is by far the most commonly used deicing chemical for pavements. It is widely used because of its proven effectiveness, its relatively low cost, and its ease of application. It is used to ensure safe and open passage of the road, but it also causes side effects, such as damage to roads, bridges and the environment. Currently about 10 million tons of road salt is used each winter in the United States [1]. It has been estimated that application of ice control chemicals, totaling \$500 million per year [1], accounts for about one-third of highway winter maintenance expenditures in the United States. More effective use of deicer chemical could result in significant economical and environmental benefits.

Application rates for salt reported by many agencies vary because of differences in weather conditions and the expectations of highway users. In order to help agencies make decisions as to the need for the reapplication of salt to road surfaces, it is necessary to be able to measure the actual concentration of salt remaining on the road surface. Existing salt concentration meters permit only point-to-point measurement and are, therefore, not suitable for road management that relies on longitudinally continuous concentration measurement. These existing methods of measurement also require that field personnel stop the vehicle and manually take measurements on the pavement [3]. Thus, this method is not convenient and is also dangerous for field personnel. Therefore, the purpose of our project is to develop a portable method to continuously measure salt concentration on the pavement to support winter road management.

In 1999, we commenced, under the sponsorship of the New England Transportation Consortium, the development of a method for the continuous measure of deicer concentration. This project was divided into two phases. The first phase was conducted during fiscal years 1999 to 2000. The approach adopted in this project was to measure the residual chloride concentration by collecting tire splash. Conductivity was used to detect salt concentration in the tire splash since conductivity probe technology is simple to apply and is suitable for rugged field applications. After the laboratory experiments, a prototype, which could continuously measure conductivity, was designed and manufactured. Field runs were carried out during a snowstorm in February 2000. The test results proved promising in terms of sensitivity of the system to variation in pavement deicer concentration. However, the results of tests to check

for accuracy of the measured conductivity values were not very promising. In the test we found that to get instantaneous values of pavement conductivity reading, the influent should be brought in immediate contact with the probe to reduce the measurement delay. However, the relatively large retention volume of the collection assembly caused a sampling problem. The influent flow inside the box would first mix with the retained fluid before draining out. Thus the conductivity measurement was not for the liquid being collected but for all the liquid in the box at any given instant in time. This mixing effect affected the accuracy and the sensitivity of the conductivity measurement. Tests also showed that the heating arrangement, which used low DC energy, was not sufficient to melt all the slush in the tire spray.

In Phase II our main goal was to address the problems encountered in Phase I in order to come up with more reliable and useful measurements. We found that making modifications to the original prototype equipment would not solve all the design drawbacks. For example, the original collection box could not accommodate the new heating arrangement needed to improve significantly the melting speed of the snow. Thus we decided to redesign the equipment based on the recommendations from Phase I. The collection box was redesigned to minimize the retention volume. The conductivity probe was installed vertically so that the probe could contact the fluid continuously. The heating system was redesigned and temperature control device was introduced to stabilize the snow-melting rate and increase safety. Two field tests of the prototype were conducted in a snowstorm in 2001. The details of design and the results of the tests are given in this report.

This report is arranged as follows.

1. Design of New Prototype: This chapter presents a detailed description of the redesigned system. Thermal and volumetric optimization and related calculations are presented.
2. Description of Tests: This chapter covers two field tests performed during the winter of 2000-2001 for the prototype.
3. Test Results and Analysis: In this chapter the field test results and analysis are presented. A model to calculate the instantaneous reading of conductivity from the measured value is also discussed.
4. Conclusions: The last chapter presents the conclusions drawn from the test results and directions for possible future research.

2. DESIGN OF NEW PROTOTYPE

This chapter, separated into three parts, addresses the redesign of the prototype deicer meter. The first part of this chapter describes the redesigned heating system for the assembly. The second part presents the optimization to minimize the retention volume in the snow collection box. The last part summarizes the layout of the new prototype.

The design of the new deicer system was started in September 2000. The snow collection box was redesigned and manufactured in the Machine Shop in School of Engineering, University of Connecticut and the equipment was assembled during December 2000 to January 2001.

2.1. Thermal Optimization

2.1.1. Power Supply

The power supply of the prototype design in Phase I was a 24 Volt DC battery. The low voltage of the battery resulted in slow melting of snow. In the new design we chose to use an electrical generator in order to provide sufficient voltage. A Homelite Generator, 4300 series was selected. The generator's rated power is 3800Watts and it can work for more than five hours at full load. The generator uses fuel that can be easily obtained at a gas station. Two isolated voltage outputs are used for the heaters and the temperature controller respectively. In this way, the low power temperature controller could be protected from any electrical surge caused by the high power electrical generator. The electrical generator was installed on the back of the truck. Photograph of the electrical generator is shown in Figure 2-1.

2.1.2. Heater

Strip heaters were chosen for the Phase II project instead of the tubular heaters used in Phase I. Strip heaters have larger contact area than tubular heaters for the same power consumption and are thus more efficient for snow melting.

Strip heaters with chrome steel sheath were selected since chrome steel sheath is capable of operating at temperatures of up to 648 °C. We need to avoid losing water to steam which inadvertently concentrating the chloride. The strip heater was clamped to the back of the snow collection plate. A total of five strip heaters were installed. Each heater is 38.7 cm

long and 3.8 cm wide and operates at 500 watts. Therefore, the total output wattage of the heaters in the assembly is 2500 W.



Figure 2-1. Photograph of Power Supply: Electrical Generator

2.1.3. Temperature Controller

A temperature controller was used with electric heaters to control the heating process and to safeguard the electric heaters from any excessive temperature that could damage the heaters. To stabilize snow melting and ensure safety, a type Omega CN9422 Temperature Controller was used. Photograph of the temperature control box is presented in Figure 2-2. This controller was configured as an auto-tune PID temperature controller. The input signal for this controller is generated from a K-type temperature sensor. There are two 5V, 15mA DC pulse outputs for this controller. One pulse output is used to switch a Solid State Relay (SSR) while the other output serves as a standby output in case the first one fails. The DC pulse control signal causes the SSR to switch the AC load ON or OFF in the same way as a conventional mechanical contact switch. The SSR has none of the problems associated with moving contact relays, such as corrosion, pitting and bounce. It is mounted on a Finned Heat Sink to dissipate the heat that it develops.

Figure 2-3 shows the electrical connection diagram for the temperature controller. A solid state relay contact is connected in series with the heater. The relay contact can turn on and shut off the power of the heater to control the temperature.

A K-type Temperature Sensor was chosen to measure the temperature. This type of thermal sensor can measure maximum temperature up to 593 °C. To install this sensor on the surface of the heater, a special glue is used. This glue has high heat conductivity and electrical insulation to minimize the temperature measurement error.

2.1.4. Thawing Speed of Snow

Our main goal of thermal optimization is to improve the melting rate of snow. The faster the snow melt, the more accurate the conductivity reading we can obtain. The melting speed of snow could be significantly increased by optimizing the thermal conditions in the new prototype.

To get the best results we need to estimate the snow melting speed under the optimized thermal condition. The following is the theoretical estimation of the melting speed of snow.

The heat (Q) required to melt a mass of snow (M) is given by the equation:

$$Q = M * L$$

Where, L is the latent heat of fusion of snow (336000 Joules/kg) (1)

We know that

$$M = \rho * V$$

(2)

Where, ρ is the density of fresh fallen snow (100kg/m³) and V is the volume of snow.
Thus, $Q = \rho * V * L$, so we have:

$$V = \frac{Q}{\rho * L}$$

(3)

Substituting 2500 W for Q, we can get the melting speed of snow $V = 74.2\text{ml/s}$. With only 120 Watts heaters in the old prototype design, the melting speed of snow is only 3.5ml/s. This rate of melting in the old prototype is clearly too low as could be seen by the snow clog in the collection box which blocked the inflow opening. We anticipate that this clog will not occur if we increase the melting speed to the expected value of 74.2ml/s.

2.2. Volumetric Optimization

To get accurate conductivity readings, it was necessary to reduce the retention volume inside the snow collection assembly. The previous collection assembly had a 400ml retention volume. The new design decreases the retention volume to 66 ml. Photographs of the collection device after installation under the truck are presented in Figure 2-4 and Figure 2-5.

Figure 2-6 shows a photograph of the front view of the collection device. To maximize the collection of the snow, the area of the inflow of snow was made 38.7 cm in width and 22.2 cm in height. Thus the inflow area 858 cm² was increased 3 times compared to the previous design (213 cm²). A cover was installed in front of the collection box. This cover can be manually adjusted up and down to control the height of the opening. Thus the inflow rate of snow could be adjusted through this cover. Figure 2-7 provides a photograph of the rear view of the collection device. The conductivity probe is installed vertically in a flow cell. A plastic outlet is connected to the flow cell horizontally. The height of outlet could be manually adjusted to control the outflow rate of the salt water. Figure 2-8 presents the schematic of the front view of the collection device and Figure 2-9 presents the cross-sectional view of the collection device.



Figure 2-2. Photograph of Temperature Control Box

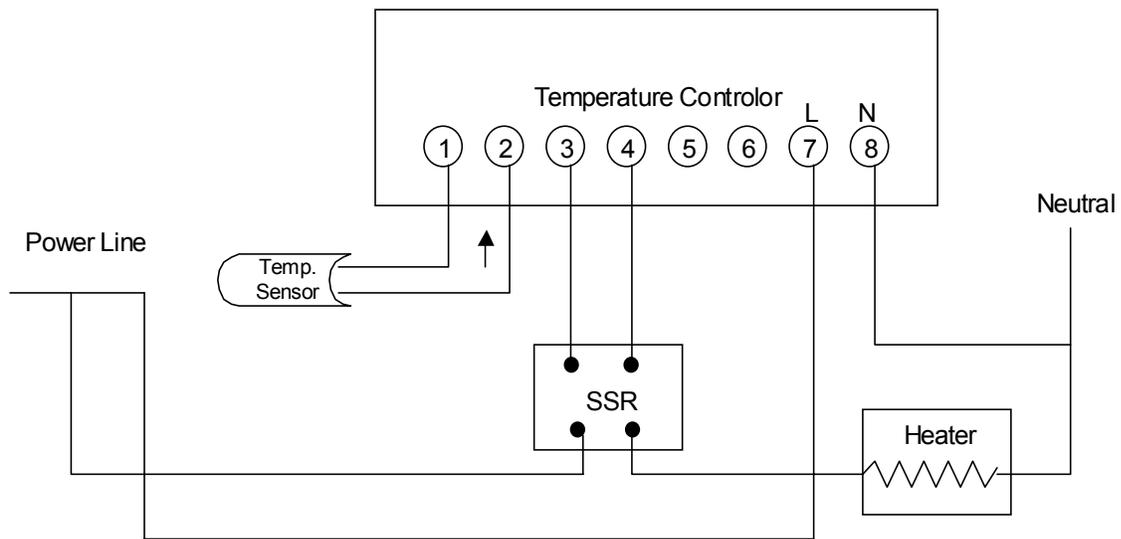


Figure 2-3. Design Diagram

(SSR: Solid State Relay)



Figure 2-4. Photograph of Deicer Collection Box (Front View)



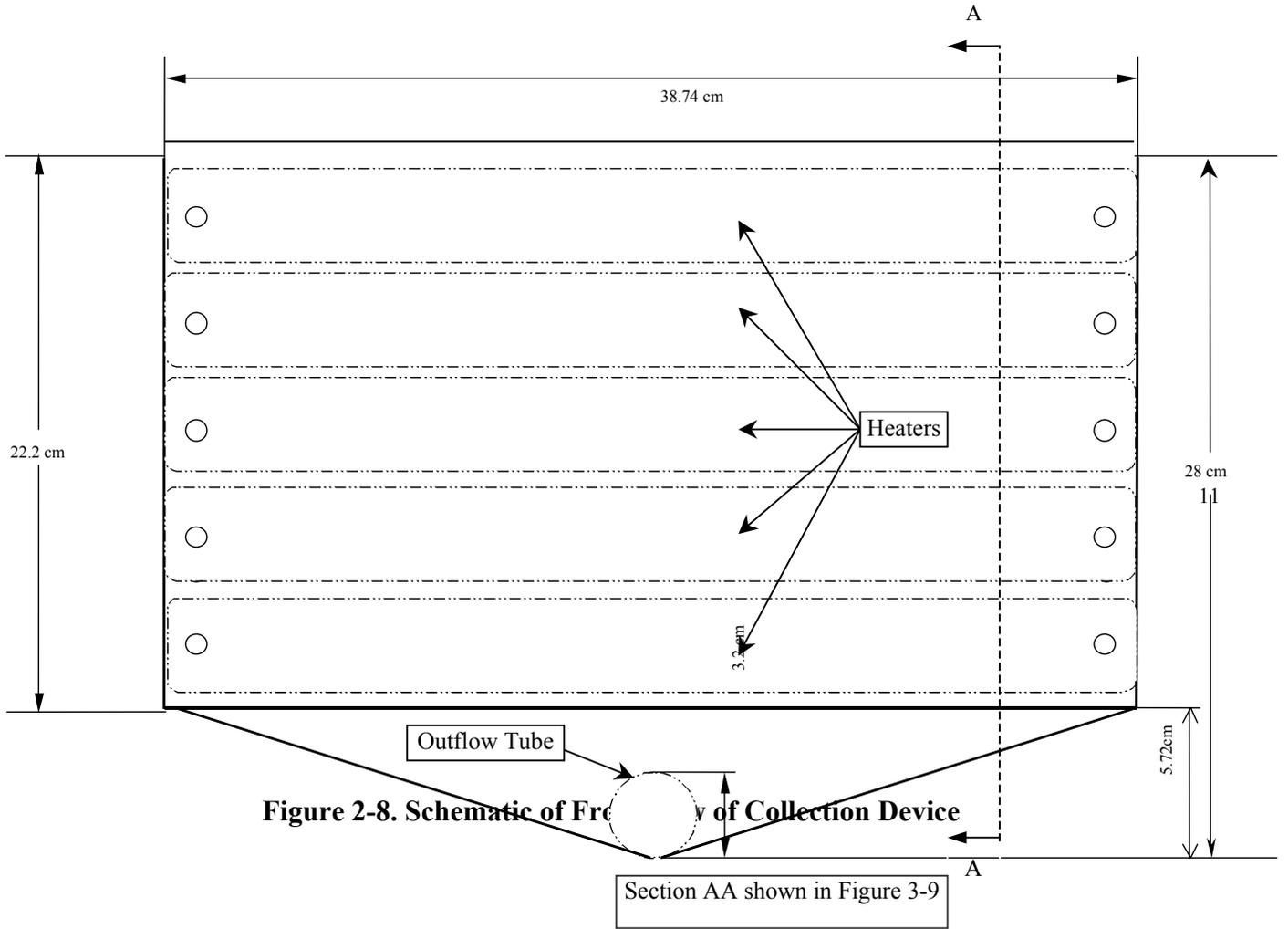
Figure 2-5. Photograph of Deicer Collection Box (Back View)



Figure 2-6. Front View of Collection Device Showing Inlet for Tire Spray



Figure 2-7. Rear View of Collection Device Showing Conductivity Probe



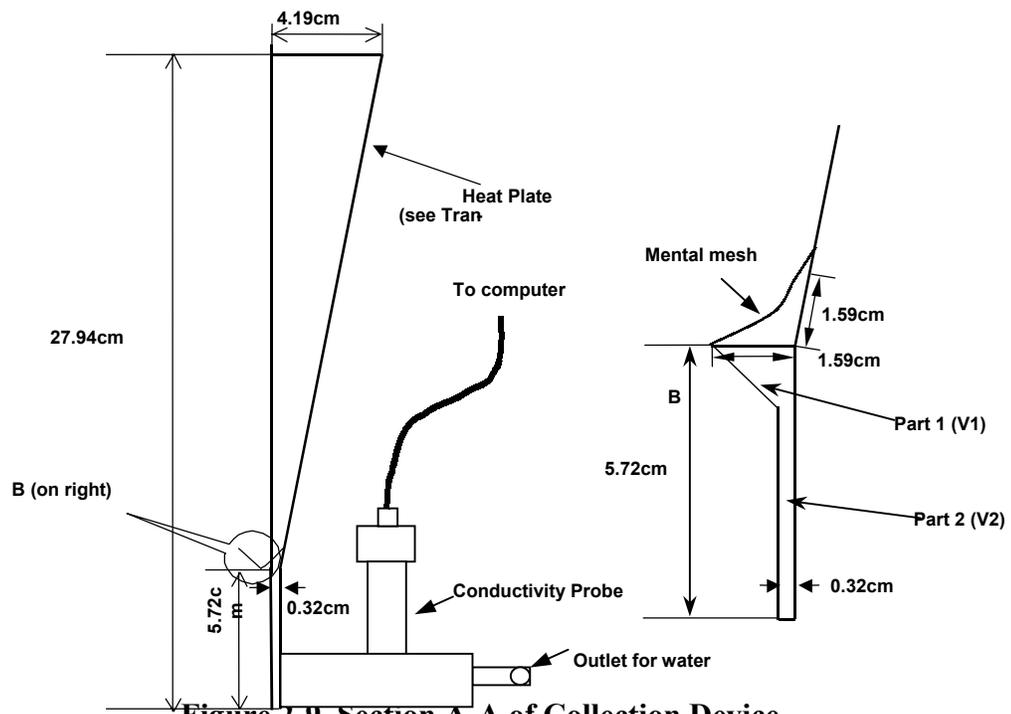


Figure 2-9. Section A-A of Collection Device

The calculation of the retention volume could be obtained by separating the collection box into two parts that are shown on the right of Figure 2-9. The total retention volume is the sum of these two parts. Therefore the total volume is 66ml.

2.3. Equipment Layout

After the deicer collection device was manufactured, the equipment was attached to a truck that belongs to the Connecticut Transportation Institute. The layout of equipment in the truck is shown in Figure 2-10.

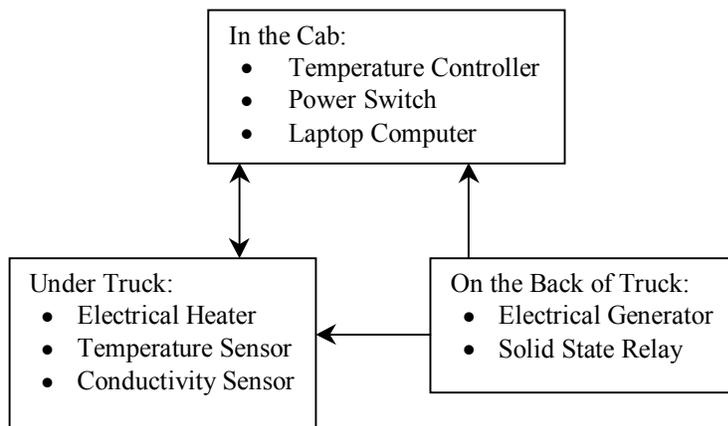


Figure 2-10. Layout of the Deicer Equipment

One temperature controller and two electrical switches are located in the cab. One electrical switch is used to turn on/off the electrical heater. The other switch is used to turn on/off the electrical generator. An operator in the cab can adjust the temperature using the front panel mounted buttons on the temperature controller. A laptop computer is connected to the conductivity probe to collect readings that are sampled every second by the probe. The equipment in the cab was designed so that the operator can easily adjust the temperature and operate the power switch of the outside equipment.

The electrical generator and a terminal box were located on the back of the car. The solid state relay was installed inside the terminal box. It was installed on the back of the cab to better dissipate the heat developed in it.

The heaters and temperature sensor are located under the truck behind the left front wheel.

The conductivity probe was connected directly to the collection box itself. The probe was installed vertically outside the collection box in a flow-through cell that was connected to the bottom of the collection box. This kind of connection ensured a continuous contact between the fluid and the flow-through cell. This design also ensured that all the fluid first come in contact with the probe before draining out.

3. DESCRIPTION OF TEST & RESULTS

Field test runs were conducted during two snowstorms on February 23, 2001 and March 3, 2001. These two tests were carried out under controlled conditions on an unused roadway (Horsebarn Hill Extension Road) on the campus of the University of Connecticut. The first field test was conducted on one section of the road a 400m in length. A sand to salt ratio of 5:1 combination was used in this test. The second field test was conducted on two contiguous sections of the road each of a 400m in length. Two different sand to salt ratio was used: 5:1 on the first section and 10:1 on the second. The average truck speed during testing was about 24 kph.

3.1 February 23, 2001 Test

The purpose of this series of tests was to evaluate the overall performance of the new design under field conditions. For this reason the test was conducted under controlled conditions with a constant salt application over the length of the test section. The test was conducted in four runs of about half an hour each and the average running time of the tests was 63 seconds. The collection box was flushed before the starting of each test run to ensure the same collection condition in the system for each run.

The snowstorm ended in the early morning of February 23 with a total snow accumulation of about 13 cm. Landscaping personnel spread the deicer on our test section after the snowstorm at between 11:00 AM and 11:30 AM, two hours before the first test run. During the test there was no snow and it was bright and sunny. The air temperature was between 5 °C to 10 °C.

The results of several trial runs showed that the temperature of the heaters needs to prevent the snow clogging was at least 200 °C. Therefore, to improve the speed of snow melt and to prevent clogging, the maximum temperature 225 °C was selected for this field test.

3.1.1. Test Results from Feb. 23, 2001

The raw data collected during the four runs is shown in Figure 3-1. Distance was used instead of time on the X axis in order to make sure the conductivity data had the same location reference for each run. The total distance of the test section is about 400 meters as shown in the figure.

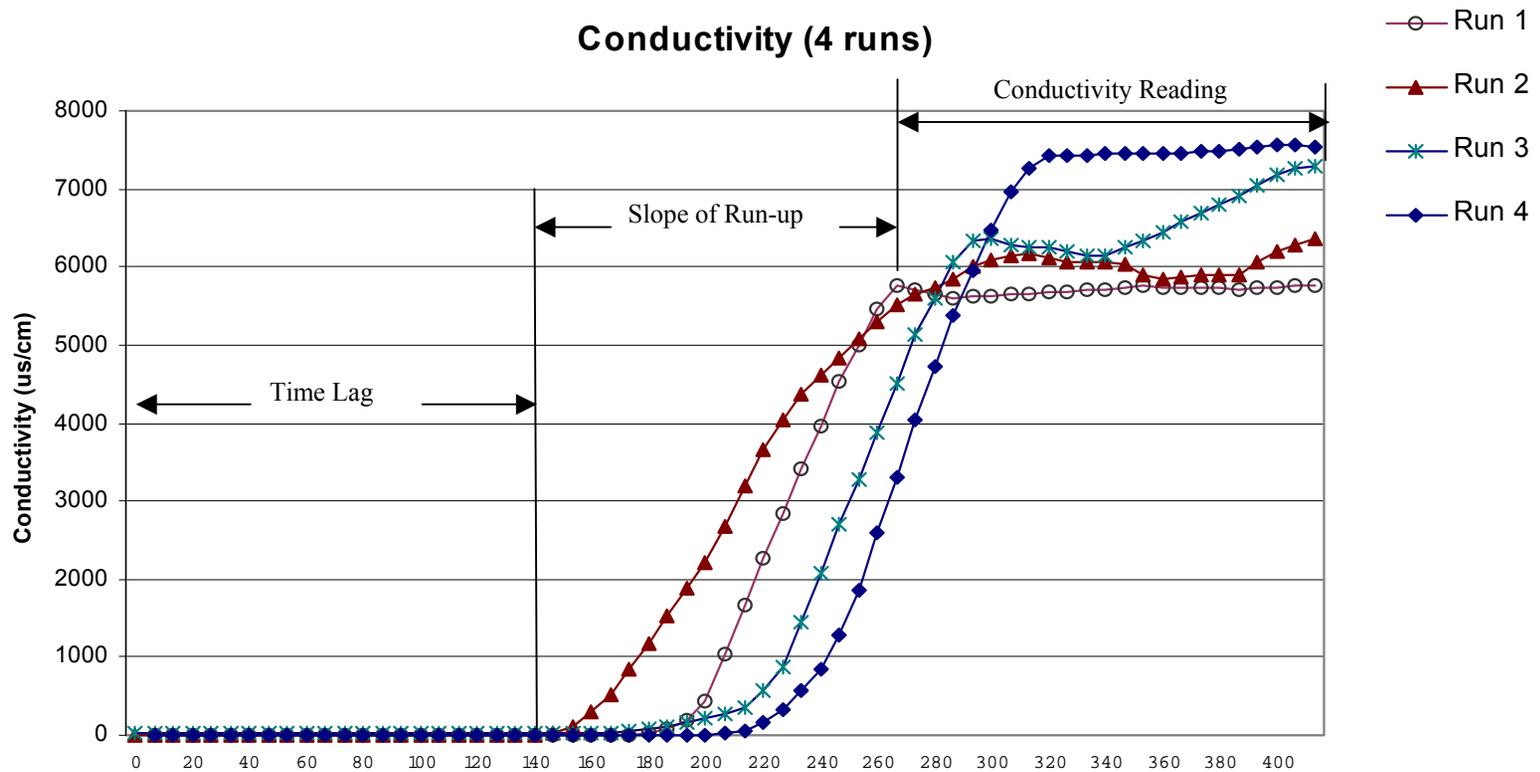


Figure 3-1 shows a period during which the logged conductivity value increases at a roughly constant slope. This time period is referred to as the slope in Figure 3-1 and Figure 3-2. This slope is caused by a steady increase in the area of the probe that is in contact with the fluid. Since the probe was installed vertically, it needed a certain level of fluid to completely cover the detection zone of the conductivity probe. As the melting fluid built up in the collection box, the probe had more contact with the liquid. The end of this slope occurs when the fluid completely covered the surface of the probe.

Table 3-2 shows the slope time for each run and the average for all runs. The average slope time is 15.4 seconds. This slope time is a function of the speed of truck, the size of the opening of the box and the size of the detector. In practical terms this represents an additional delay before the detector is fully functional.

Run No./ Slope Time	Run 1	Run 2	Run 3	Run 4	Total Average
Slope Time	13 sec	16 sec	17 sec	16 sec	15.4

Table 3-2. Slope Time for Four Runs

The time lag and the slope are delays which will have negative effects on the performance of the conductivity meter. To get accurate instantaneous conductivity reading, these delays must be minimized. In this regard, the new prototype performs much better than the old. The duration of the time lag has been reduced from 4 minutes to 26 seconds and the duration of slope has been reduced from 8 minutes to 15 seconds.

(3). Constant Reading

From Figure 3-2 we expect that when the inflow fluid fully covers the detection zone of conductivity probe, we should obtain constant conductivity reading if the salt concentration of the flow fluid is constant. We expect fluctuation to some degree and this is part of the problem. The results in Figure 3-1 show that this was the case. In the Phase I project, we could not obtain constant reading because the fluid would frequently lose contact with the detection zone of the probe. Therefore the logged readings appeared as a series of spikes on the graph. The results show that we have solved this problem by changing from a horizontal to a vertical installation of the probe (see Figure 3-2).

Variation of the deicer conductivity during the duration of the test was examined by comparing the readings from the four runs. Table 3-3 shows the average readings and standard deviations for each run.

Run No.	Avg. of runs	Standard Deviation
Run 1	5700	50
Run 2	6000	130
Run 3	6600	360
Run 4	7500	66
Total Avg.	6400	

Table 3-3. Average readings for each run.

Figure 3-3, which gives a plot of the average readings, shows that there is a steady increase in conductivity level over the course of the test. The conductivity values increased from 5700 to 7470 $\mu\text{s}/\text{cm}$. This variation can be accounted for the fact that the snow melted on the road over the course of the test resulting in an increasing concentration of salt in the snow slush.

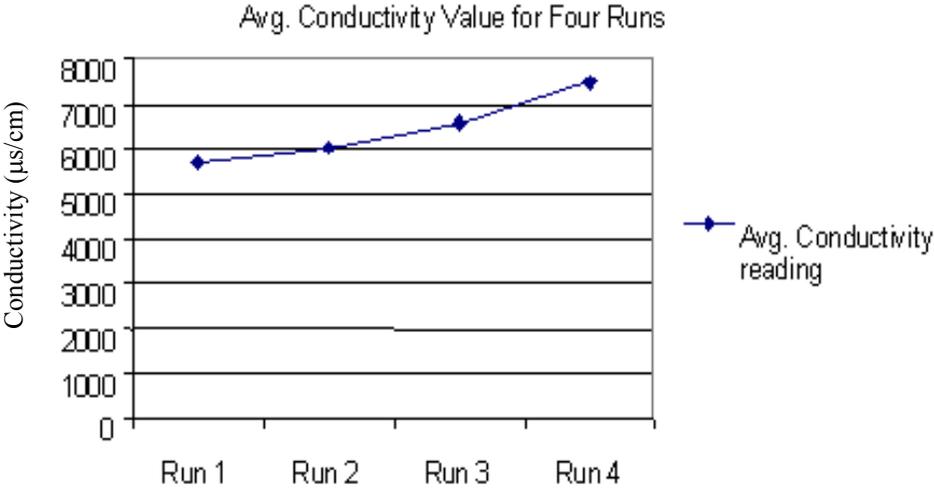


Figure 3-3. Average Value for Four Runs

3.2. March 3, 2001 Test

The overall goal of Phase II is to build on the results of the Phase I study to improve accuracy, applicability and convenience of the deicer detection system. The Feb. 2001 test of the redesigned prototype showed that we had resolved two of the major problems with the Phase I prototype: momentary loss contact of the probe with the influent fluid and insufficient heating. The second field test was conducted to get additional data about the accuracy of the meter under field conditions. This test was again conducted under controlled conditions on an unused roadway on the campus of University of Connecticut. However, in this second series of test the test design was more complicated than in the first test runs. In this case we used different concentration of salt on each of two different sections of the roadway. The goal was to gain more insight about how the system would perform under conditions approaching the real world conditions in which the concentration would change from point to point.

This second field test was conducted on March 3, 2001. Landscaping personnel spread the deicer on the road sections between 11:00 AM and 11:30 AM. About half of the length of the test section was spread with regular sand to salt ratio of 10:1 and the other half was spread with low sand to salt ratio of 5:1 (higher salt concentration). The salt application rates for these two sections were about 40 kg per lane-km and 80 kg per lane-km respectively. The average running time of each test was about 100 seconds and the total length of the road under testing was about 700m. Figure 3-4 shows a picture of the test section.

A total of eight runs were conducted over the three-hour duration of the tests. As in the first test, the collection box was flushed before the start of each run. The running direction of the test was from the area of low salt concentration to the area of high salt concentration.

The weather condition in this test was also different from that of the first test. Compared to sunny conditions for the first field test, the second test was conducted during the snowstorm itself. The snowfall was at a rate of about 5 cm per hour over the three-hour duration of the test. The air temperature was between -5 °C to 0 °C. The temperature of temperature controller was set at 225 °C, the same as for the previous testing.

3.2.1 Test Results from Mar. 3, 2001

The raw data collected during all the eight runs is shown in Figure 3-5. Run 1 to Run 7 were conducted from 12:10 PM to 1:12 PM. The plotted data for these seven runs indicates that section 2 (with sand to salt ratio 5:1) has a higher conductivity value than that in section 1.



**Figure 3-4. Photograph Showing Test Section.
(Black Line Separates the Areas of Different Concentration)**

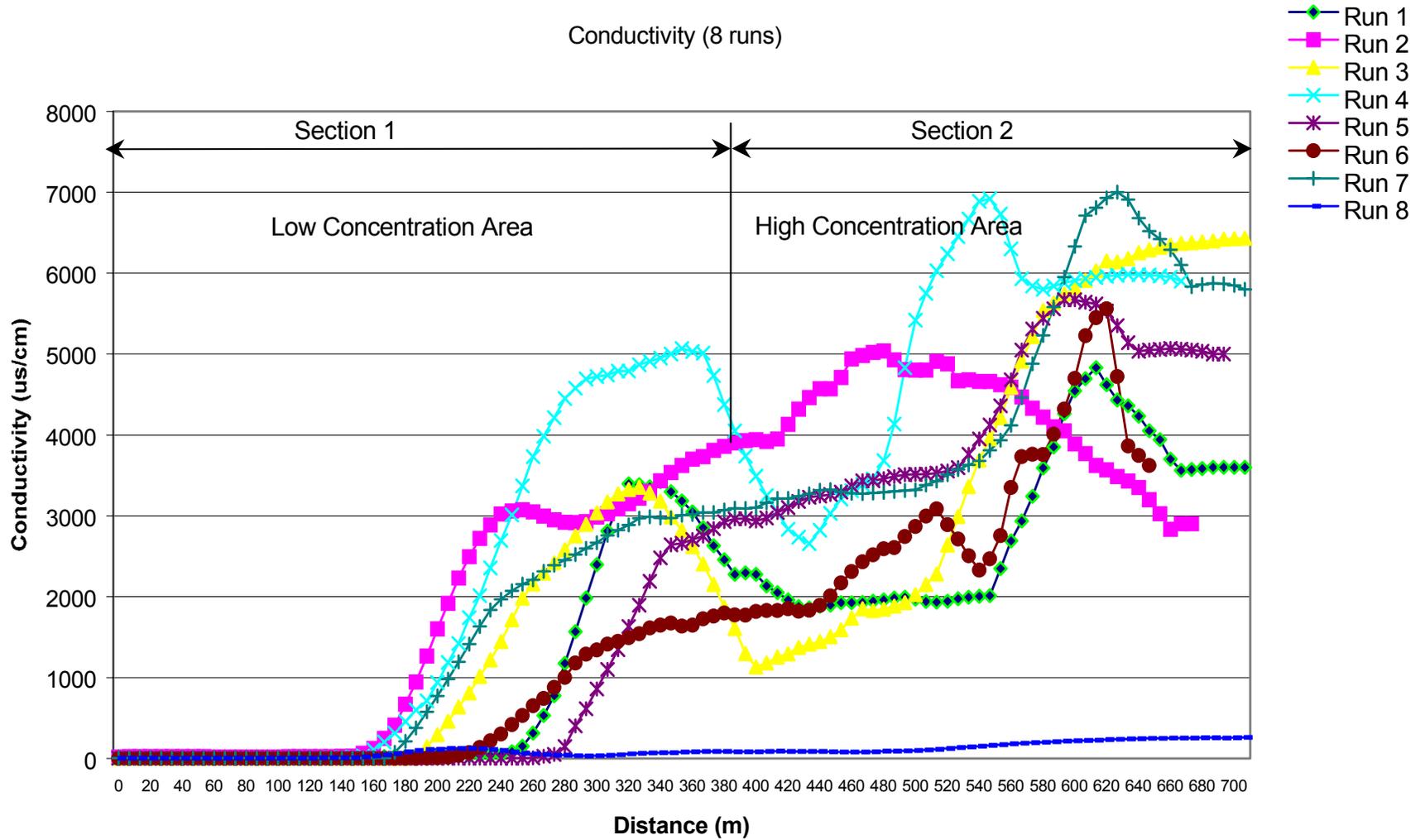


Figure 3-5. Conductivity Readings for Eight Runs During Snowstorm of March 3,2001

Run 8 was conducted considerably later than the other runs at 4:43 PM. By the time this eighth and last run got started, a layer of snow had accumulated on the test road. Therefore, the deicer on the pavement was diluted by the cover of additional snow which caused a decrease in the salt concentration. The conductivity values measured in this run were all below 300 $\mu\text{s}/\text{cm}$. Because of the unusual conditions during this run, run 8 was not considered in the analysis that follows.

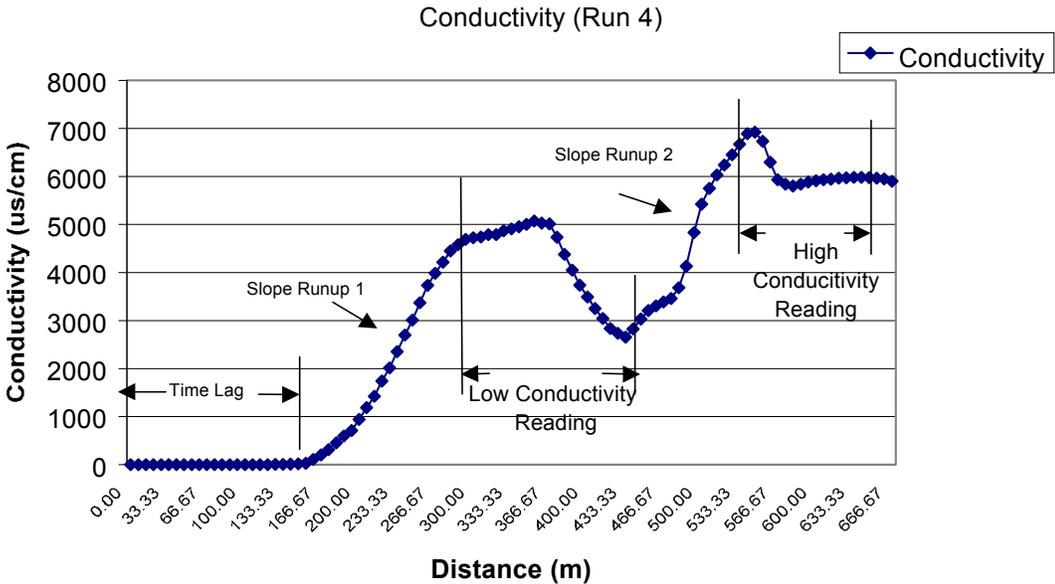


Figure 3-6. Typical Run Result

Figure 3-6 shows the typical pattern that was observed for each run of the seven applicable runs. From Figure 3-6, we can identify five segments that are similar to the pattern found for the first field test. We labeled these five segments as follows: time lag, first slope, low conductivity reading, second slope and high conductivity reading. The interpretation of this pattern is given below.

(1). Time Lag

There is a time lag at the beginning of the test similar to that in the first test. As we explained previously, this time lag is caused by the liquid not making contact with the probe because there isn't enough fluid in the system. Table 3-4 shows the time lag for each run and

the average time lag for all runs. The average delay time is 26.4 seconds. This value is virtually identical to the average time lag 26.5 seconds for the first field testing.

Run No./Time Lag	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Total Average
Time Lag	24 sec	22 sec	28 sec	23 sec	31 sec	31 sec	26 sec	26.4

Table 3-4. Time Lag for Seven Runs

(2). First Slope

As there are two different conductivity values in the pavement, there are two periods during which the logged conductivity value increases at a roughly constant slope. These two periods are referred to as first slope and second slope which are marked in Figure 3-6. The first slope occurred before the low conductivity reading area. As we discussed before, this slope is caused by a steadily increasing area of the conductivity-measuring probe that is in contact with the fluid. Table 3-5 shows the time of this first slope for each run and the average for all runs. The average duration of the slope is 16.5 seconds. This value is similar to the 15.4 seconds for the first field testing.

Run No./Slope Time	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Total Average
Slope Time	13 sec	16 sec	20 sec	18 sec	13 sec	15 sec	21 sec	16.5

Table 3-5. First Slope Time for Seven Runs

The fact that the duration of time lag and first slope are essentially identical in two tests under different weather conditions are important for data analysis and modeling which will be discussed in the next chapter. These delays are determined by the retention volume of the collection box, the speed of the truck and the melting speed of the collection box. The retention volume and the speed of the truck are same in these two tests. Thus we could infer that the melting speed of snow is also the same. This shows that the temperature controller was effective at controlling the melting speed of snow during our test.

(3). Low Conductivity Reading

After the first slope, the inflow fluid has totally covered the conductivity probe. Since the influent liquid has constant concentration of salt we maintain a constant reading during this

period. The range of low conductivity reading is marked in Figure 3-6. The conductivity reading for this segment is measured starting from the end of the first slope and ends at the beginning of the second slope.

(4). Second Slope

After the truck passed into the area of high salt concentration, the conductivity meter begins to collect fluid which has a higher salt concentration. There is a period of time that the low salt concentration fluid needs to completely drain out of the system and be replaced by high salt concentration fluid. This period of time is referred to as the second slope which is marked in Figure 3-6. This slope is not caused by the degree of contact of fluid with the conductivity probe since the melting fluid has already covered the probe. It is instead caused by the change of salt concentration in the fluid and represents the mixing effect of the two different fluids in the collection box.

The second slope is more important for our study because this situation will frequently happen during the measurement since the concentration of deicer on the pavement will change constantly. The first slope only happens after the collection box is cleaned. The time of the second slope represents the mixing time of two fluids that have different concentration. Table 3-6 shows the time of the slope for each run and the average for all runs. In the next chapter, we will discuss this mixing effect in detail and from that, we will provide an analytical approach for predicting the inflow conductivity from the measured outflow conductivity.

Run No./Slope Time	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Total Average
Slope Time	11 sec	10 sec	17 sec	12 sec	16 sec	13 sec	16 sec	13.6 sec

Table 3-6. Second Slope Time for Seven Runs

(5). High Conductivity Reading

After the low conductivity fluid has completely drained from the collection box and has been replaced by the high concentration fluid, the deicer meter is able to fully register the high conductivity reading. The high conductivity reading area is marked in Figure 3-6. The conductivity reading for this area is measured starting from the end of the second slope. Table 3-7 shows the average reading and the standard deviation for this reading.

The overall average of high salt is 1.8 times that of the overall average for the area of low salt. This is close to the expected value of 2 since the sand to salt ratio of section 1 is twice of that of section 2. This confirms that the meter is accurate at differentiating different levels of concentration under the controlled environments of our test. Figure 3-7 shows the different conductivity values for the high and low concentration areas. Standard deviation for each run is also plotted on this figure.

Run No.	Avg. of Section 1	Standard Deviation	Avg. of Section 2	Standard Deviation
Run 1	2300	520	4000	438
Run 2	3400	400	4600	362
Run 3	2000	700	6200	446
Run 4	4800	190	6100	572
Run 5	3200	370	5300	207
Run 6	2100	500	4300	650
Run 7	3100	180	6300	494
Total Avg.	3000		5200	

Table 3-7. Average reading for each run.

From Figure 3-7, we can observe that the average low and high conductivity reading for each run varies during the test period but does not show any observable pattern. This is different from the result in the first field test in which we found an increase of conductivity over time. The different temporal variation in the two tests is attributed to the different weather conditions. The second test was conducted during the snowstorm in which the snow continued to accumulate and the low air temperature slowed any melting of the snow. Conversely, the first test was conducted during sunny weather and higher temperature, which accelerated the snow melting and resulted in an increasing salt concentration and dilution over the course of the testing.

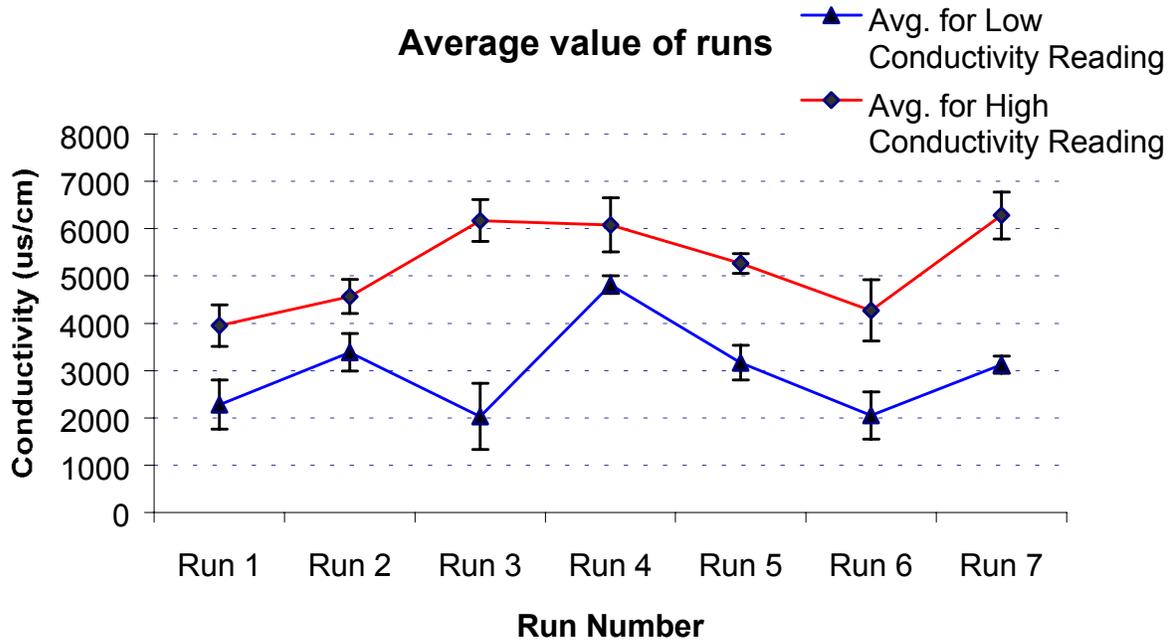


Figure 3-7. Average Value for Seven Runs

As described in this chapter, the results of the tests show that the deicer meter is able to accurately differentiate different salt concentrations on pavement. We also observe that the readings obtained are not the instantaneous reading of the fluid entering the system. There are basically two different factors that must be accounted for if we are to obtain an instantaneous reading of the fluid entering the system. The first factor is due to the time need for the fluid to completely cover the detector. This is only a problem at the beginning of the test when there is no fluid in the system. We have reduced the significance of this type of delay by reducing the volume of the system and thus the time associated with the delay. The second factor that negates an instantaneous result in our system is the delay caused by the mixing effect of fluid in the system. This means that the reading at any given time is the concentration of all the fluid in the system and the fluid collected at that instance. In the next chapter we will provide an analytical approach for predicting the concentration of the inflow at any given instance from the measured concentration value.

4. ANALYSIS OF RESULTS

The conductivity reading obtained from the meter is a measure of the conductivity of all the fluid in the chamber of the collection box. Ideally what we need is a measure of the conductivity of the fluid that is collected directly from the pavement at a given instant in time. This is impossible since the collected snow must first be melted and then sent into the chamber. However, the concentration of the inflow into the chamber is a closer approximation to the actual pavement condition. In this chapter we will develop a procedure for estimating the inflow concentration based on measuring the concentration of the fluid in the chamber. This procedure requires the use of an analytical model of the mixing effect of fluids in the chamber. The development and calibration of the model is discussed in this chapter.

4.1. Model for Calibrating Mixing Effect

Mass balance equation (4), which is shown in equation 4, is used to model the mixing inside the collection box. In Phase I project, Anandram et al [2] developed a single compartment transport model. A schematic of single compartment model is shown in Figure 4-1.

$$\text{Change in mass in the box} = \text{Inflow concentration} - \text{Outflow mass} \tag{4}$$

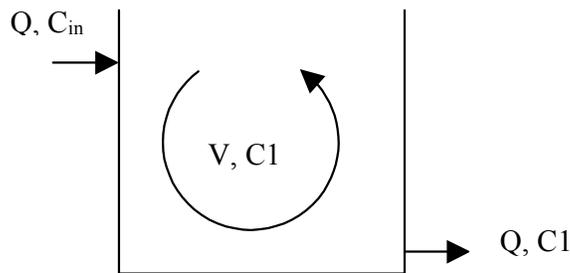


Figure 4-1. A Schematic of Single Compartment Model

Mathematically, the balance equation can be written as:

$$\frac{d(VC_1)}{dt} = QC_{in} - QC_1$$

(5)

Where,

C_{in} = Conductivity of the influent ($\mu\text{s/cm}$)

C_1 = Conductivity of the fluid in the box and that of the effluent ($\mu\text{s/cm}$)

V = Volume of the fluid inside the box (ml)

Q = Volumetric inflow rate, which is equal to the volumetric outflow rate (ml/min)

t = Time (seconds).

Solving the above equation we can get:

$$C_1 = C_{in}(1 - e^{-tQ/V})$$

(6)

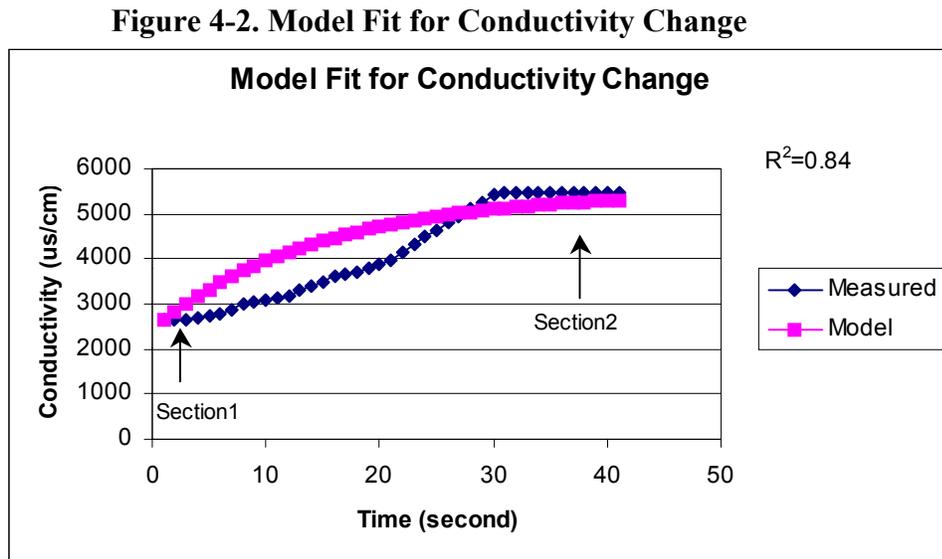
The output of this model [2] is the conductivity C_1 of outflow fluid which is calculated based on the inflow fluid with conductivity C_{in} . In this model, the initial conductivity C_0 of the outflow fluid in the box is assumed to be zero. The mean hydraulic detention time τ , the duration for which the fluid is retained inside the box, is given by the ratio of V/Q . This model treats the collection device as an ideal, completely mixed system. Equation 6 was calibrated by changing the assumed inflow rate (Q) until the model fitted the measured data. The best-fit model was obtained for a Q value of 120ml/min or 2ml/second. So the detention time, τ , is calculated as follows: $V/Q = 400\text{ml}/120\text{ml/min} = 3.33$ minutes. This Phase I result is not suitable to analyze the conductivity change in Phase II since the initial conductivity is not zero in Phase II.

The results from the second field test, which have two different conductivity readings, are used in developing a suitable mathematical model. The initial conductivity was set at C_0 at time $t = 0$. Thus the equation of single transport model is changed to:

$$C_1 = C_0 e^{-t/\tau} + C_{in} (1 - e^{-t/\tau}) \tag{7}$$

In above equation, C_0 , C_{in} are constant. C_0 is the average value of section one of the seven runs. C_{in} is the average value of section two of seven runs. They are $3000\mu\text{s/cm}$ and $5200\mu\text{s/cm}$ respectively.

Using the above equation, the conductivity curve of second field test was modeled (shown in Figure 4-2) for various values of Q . The best-fit model as shown in Figure 4-2 was obtained for a Q value of 4.7ml/second . The retention volume of the collection box (V) is 66ml in Phase II. Therefore the detention time τ (V/Q) is 14 seconds. It should be noted that this calibrated detention time is about the same as the measured duration of the second slope discussed in Chapter 3. This suggests we are accurately modeling the field test conditions.



For the average test speed of 24 kph, this calibrated detention time τ translates to a mean detention distance (D) of $14 * 24 \text{ kilometer}/3600\text{second} = 0.093$ kilometer (93m). This means that the influent material would be retained inside the box for a distance of 93 meter before it drains out.

The calibrated Q value 4.7ml/second in this model is significantly higher than the Q value 2ml/second (2) which was calibrated in Phase I project. The higher inflow rate of fluid can be attributed to the higher melting rate of the snow. In addition, the detention time has been decreased from 3.3 minutes to 14 seconds. In other words, the detention distance has been decreased from 2.7 kilometers [2] to 93 meters.

From Figure 4-2, we observe that the single compartment model does not accurately represent the conductivity change for different salt concentration. The single compartment model overestimates conductivity values in the slope of the curve. The error in estimation can be attributed to that the fluid in the chamber is not truly a completely mixed system. To find a model that better fits the conductivity change, models based on multiple compartments were investigated. The assumption in using multiple compartment models is that the collection box is behaving as if it is segmented into several equal-volume, complete mixed compartments. As with the single compartment model, this approach is based on the mass balance around each compartment. We illustrate the concept using a two-compartment model. A schematic of two-compartment model is illustrated in Figure 4-3.

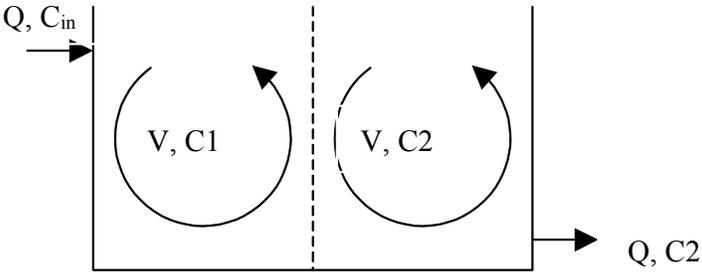


Figure 4-3. A Schematic of Two-compartment Model

The mass balance for the first compartment gives

$$\frac{d(VC_1)}{dt} = QC_{in} - QC_1$$

(8)

Solving the above equation we can get

$$C_1 = C_0 e^{-t/\tau} + C_{in} (1 - e^{-t/\tau}) \quad (9)$$

For the second compartment, the mass balance yields

$$\frac{d(VC_2)}{dt} = QC_1 - QC_2 \quad (10)$$

Solving for C2, we can get:

$$C_2 = C_0 e^{-t/\tau} + C_{in} (1 - e^{-t/\tau}) - \left(\frac{C_{in} - C_0}{\tau}\right) t e^{-t/\tau} \quad (11)$$

The detention time τ in equation 9 is equal to V/Q , where V is equal to one half of the total retention volume of the collection box.

Similarly, we can get the model for three compartments. The equation of three-compartment model is:

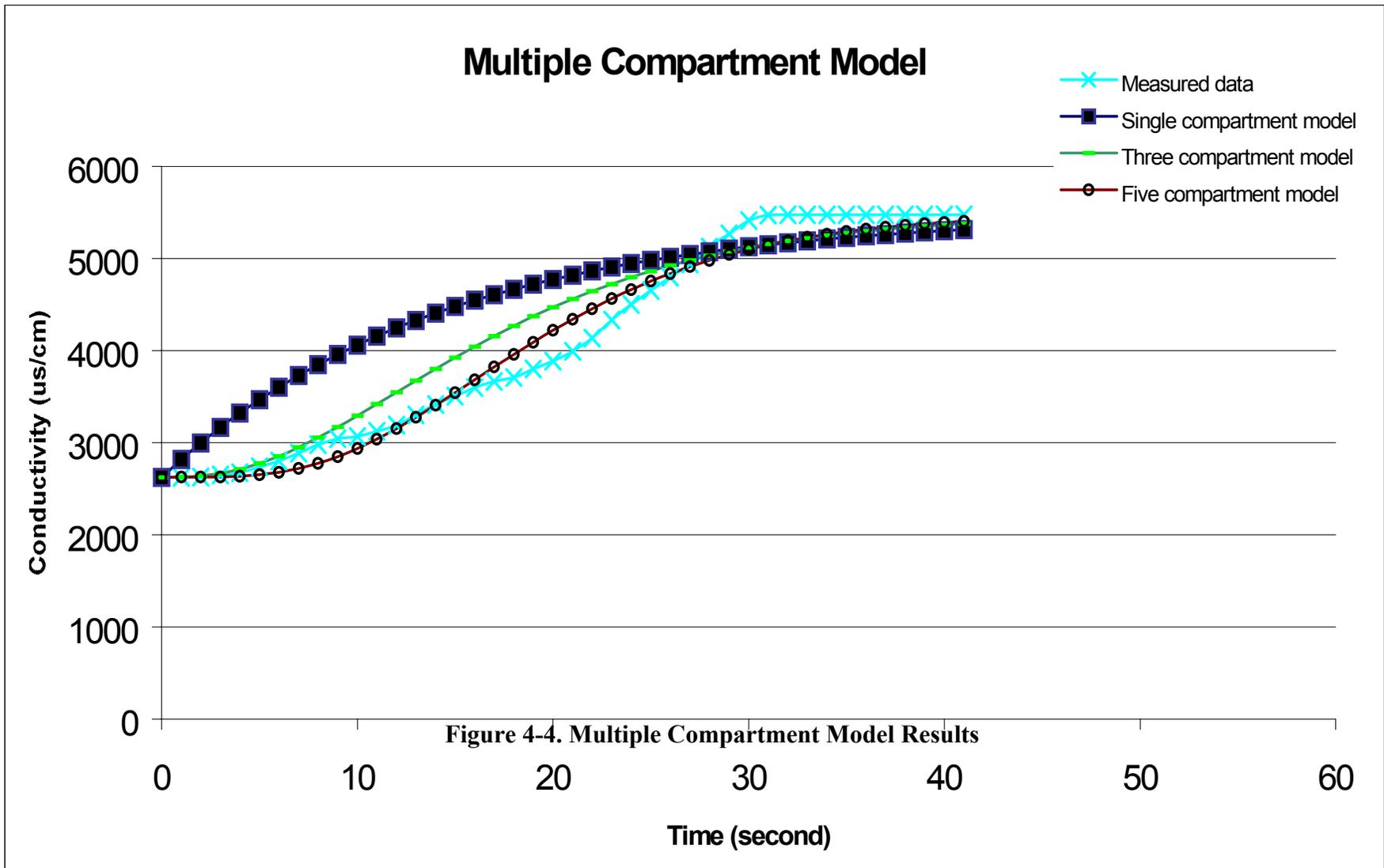
$$C_2 = C_0 e^{-t/\tau} + C_{in} (1 - e^{-t/\tau}) - \left(\frac{C_{in} - C_0}{\tau}\right) t e^{-t/\tau} \left(1 + \frac{t}{2\tau}\right) \quad (12)$$

In the same way, we can derive the four and five-compartment models. Figure 4-4 shows the best-fit curves for single, three and five-compartment models. From Figure 4-4 we can observe that as the number of the compartment increases, we get a better fit with our model. But when the number of compartment is over five, we start to overestimate the conductivity values at the beginning of the slope of the curve. Table 4-1 shows the R^2 values for these five models. From Table 4-1 we can observe that the R^2 value increases as the number of compartments increases; as we increase the number of compartments, the rate of

improvement decreases. It is also important to note that as the number of compartments increases, the model becomes more complex and requiring a greater computational effort.

# of Compartment	R ² Value
Single Comp.	0.829
Two Comp.	0.897
Three Comp.	0.942
Four Comp.	0.971
Five Comp.	0.978

Table 4-1. R² Value for Compartment Model



4.2. Method to Determine Instantaneous Reading

Our goal in developing the deicer meter is to be able to determine the instantaneous reading of salt concentration on the pavement surface. The inflow concentration (C_{in}) is a closer approximation to the instantaneous reading than the outflow concentration. This section discusses an approach to calculate C_{in} based on the calibrated model of the mixing effect in the box.

From the modeling of the mixing effect in the collection box discussed in the previous section, the detention time τ can be calibrated. This detention time is determined by the retention volume (V) of the collection box and inflow rate of the snow (Q). The inflow rate of snow is determined by the speed of the truck, the area of the opening of the collection box and melting rate of slush. To estimate the instantaneous reading of the conductivity of the pavement section, the collection device was treated as an ideal, completely mixed system. The measured data we sampled into computer is the average conductivity reading of the entire chamber. We can use mass balance equation to predict the inflow conductivity after calibration for the compartment model.

The two-compartment model is used here as an example to calculate the inflow conductivity C_{in} in real time. The results from the second tests are used. As discussed previously, we need to get the best-fit two-compartment model in order to obtain the calibrated inflow rate (Q). Then we calculate the change of the measured conductivity (C_2) at one second interval. This is referred to as ΔC_2 . According to the mass balance equation: $\frac{d(VC_2)}{dt} = QC_1 - QC_2$, we use ΔC_2 to approximate the dC_2/dt . Substitute for

dC_2/dt with ΔC_2 in the equation, we can obtain $C_1 = C_2 + \Delta C_2 * \tau$. Then we calculate the ΔC_1 . According to the mass balance equation: $\frac{d(VC_1)}{dt} = QC_{in} - QC_1$, substitute for

dC_1/dt with ΔC_1 , we can get $C_{in} = C_1 + \Delta C_1 * \tau$. Therefore C_{in} is the predicted inflow conductivity.

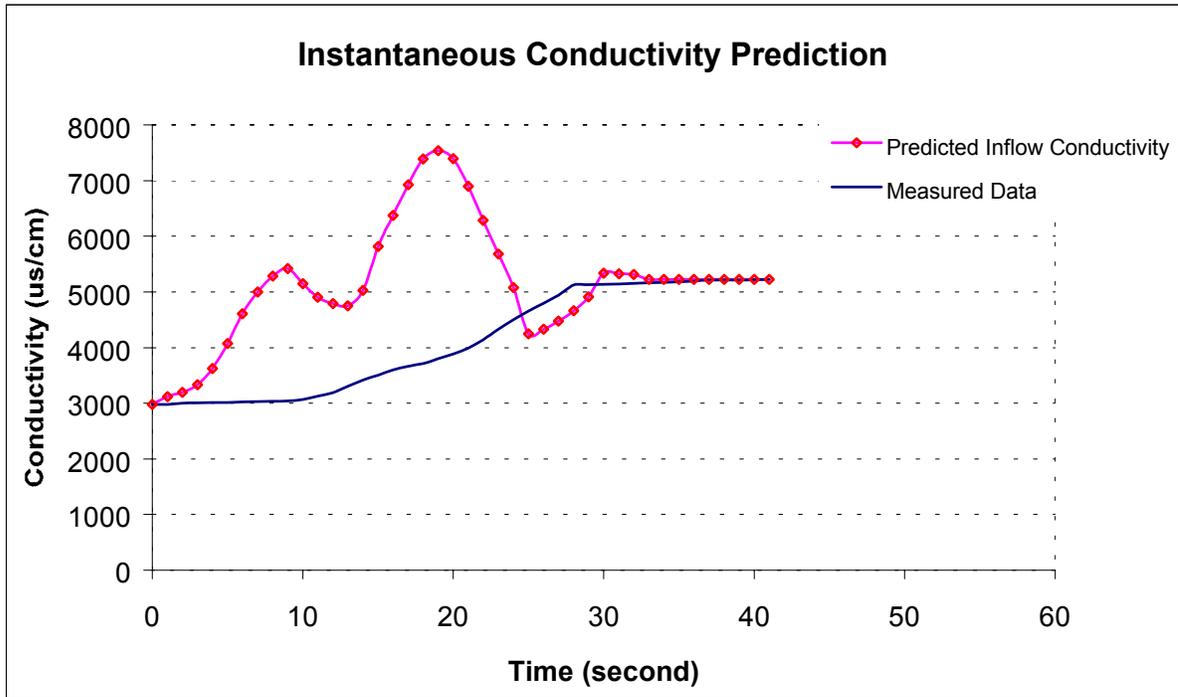


Figure 4-5. Instantaneous Conductivity Prediction

Figure 4-5 shows the instantaneous conductivity prediction for C_{in} . The measured data is the conductivity C_2 which is measured by the conductivity meter. The predicted inflow conductivity is the inflow conductivity value (C_{in}) which is calculated based on the procedure discussed in the previous paragraph.

5. CONCLUSIONS

Snow and ice control on roadways requires accurate prediction of the ever-changing road surface conditions. In the spreading of deicing chemicals, timing is the key. Therefore, the ability to accurately obtain the salt concentration on the surface in real time is especially important for the determination of deicer chemical reapplication for winter roadway management.

The objective of this project was to develop a continuous deicer concentration meter to measure pavement conditions. In Phase I, prototype equipment was manufactured and tested in the field. In Phase II, we addressed problems found in the Phase I prototype design and redesigned and tested the new prototype in the field. Some inspiration in redesigning the prototype was taken from the recommendations of Phase I project.

The first part of work of Phase II project was to redesign the prototype and in particular the heating equipment and collection assembly to improve heating efficiency and reduce the volume of the box. In addition, the loss of contact problem identified in Phase I was addressed by installing the conductivity probe vertically.

By using 220V AC output electrical generator and 2500 Watts stripe heaters, the heat efficiency was greatly improved. Therefore, the melting rate of the snow has been significantly increased. Temperature control in the new design also improved the safety of the heater and stabilized the snow melt. With the smaller retention volume of the collection box, the delay time in measuring conductivity changes has decreased from 3.3 minutes to 14 seconds.

The test results on the re-designed system proved promising in terms of its ability to continuously measure the salt concentration. The system is able to distinguish the difference between two areas of different salt concentration. However, we still observe delay caused by the mixing effect when the salt concentration changes from point to point. A multiple-compartment model was developed to fit the field data for modeling the mixing effect. This model was used to estimate conductivity of the inflow fluid.

The tests also showed that sand accumulation is a potential problem in the system. Although sand does not affect the conductivity reading, it prevents fluid flowing into the collection box after a certain period of time. It would be useful to flush the collection

box at frequent time intervals, such as when coming to a stop signal or moving to a new road.

The tests we conducted in the field show the potential of this technology for measuring salt concentration. However, we believe a much more intensive testing program is needed to work out all the bugs in the system before this device is ready for routine use in the field.

We also believe that the system can be further optimized in three ways:

- 1) Use a more compact conductivity probe to reduce the retention volume thus minimizing the mixing effect.
- 2) Use a gate controller to adjust the opening of the collection box automatically. The objective is to control the inflow snow rate. Adjustments would be made to prevent high snow rate that would cause a clog problem in the collection box. If the inflow rate can be controlled, the detention time could be kept constant under changing vehicle speed and snow accumulation on the pavement. This value could then be calibrated once and used for the prediction of inflow conductivity value.
- 3) Use mass outflow controller to match the outflow rate to the inflow rate. This would prevent overflow or drainage when the inflow rate is higher or lower than the outflow rate.

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