SUMMARY REPORT
FOR
2020 CORROSION RESEARCH STUDY

Prepared for:

City of Edmonton

Prepared By:
Corrpro Canada, Inc.
Edmonton, AB

Permit to Practice No.:
P05933

2020-10-01

CORRPRO DOCUMENT No.: 0120-4632-CED-CRR-002-0

REV	DATE (DD-MMM-YY)	COMMENTS	ORIGINATOR	REVIEWER	APPROVER
0	01-OCT-20	Final Report	K. Duncan, E.I.T. Corrosion Engineer-in-Training	N. Melendez, P.Eng. Corrosion Engineer	S. Gibson, P.Eng. Project Manager

This document has been prepared by Corrpro Canada, Inc. (Corrpro) and is intended solely for the City of Edmonton (the City). This document and all copies are the property of Corrpro and the City. This document was created specifically for the City's 2020 Corrosion Research Study and any other use is prohibited.

Originated by:

Kristen Duncan, E.I.T.
Corrosion Engineer-in-Training
Email: kduncan@aegion.com

Reviewed by:

Natanael Melendez, M.Sc., P.Eng.
Corrosion Engineer
Email: nmelendez@aegion.com

Approved by:

Stephen Gibson, M.Sc., P.Eng.
Project Manager
Email: sgibson@aegion.com

REVISION LOG

REV	REVISION / CHANGE DESCRIPTION
0	Final Report

EXECUTIVE SUMMARY

The City of Edmonton (the “City”) commissioned Corrpro to conduct a targeted corrosion research study related to the anti-icing/de-icing products used in their winter road maintenance program. This research study involves a field program to investigate the corrosion impacts of the City’s anti-icing/de-icing program on a selection of metals. The metals tested and reasons for inclusion are detailed below:

- Carbon steel (heavily utilized in vehicle, bicycle and municipal infrastructure construction)
- Aluminum (bicycle frames and some vehicles)
- Stainless steel (some vehicle/bicycle components)

The field testing program included the installation and monitoring of corrosion coupons on buses and municipal infrastructure. The coupons were placed in areas where the application of anti-icing/de-icing products are consistently used. After exposure to Edmonton winter conditions (winter 2019/2020) and retrieval from the field, the corrosion effects of the de-icing products were evaluated.

The results of the 2019/2020 field program are compared to the results of the 2018/2019 field program. In winter 2018/2019, the City’s anti-icing pilot program involved the added use of corrosion-inhibited calcium chloride ($CaCl_2$) brine as an anti-icing agent in addition to a de-icing program. The City’s current de-icing program involves the application of a sodium chloride (NaCl) and sand mixture that is pre-wetted with $CaCl_2$ brine before application. For the winter of 2019/2020, the City discontinued its anti-icing program for all areas except select bicycle lanes. This meant that most areas subject to the City’s winter road maintenance program were only exposed to a de-icing program.

The major conclusions and recommendations from the 2019/2020 project are summarized below:

- Anti-icing and de-icing products, including $CaCl_2$, NaCl and other chloride salts, are used globally for winter road maintenance in areas that experience icy conditions.
- Aqueous solutions containing chloride salts, such as NaCl, $CaCl_2$ and $MgCl_2$, are known to contribute to corrosion on various types of metals, including those commonly used for infrastructure and vehicles.
- Research studies and pilot programs have been introduced worldwide to determine the impact of anti-icing and de-icing chemicals on metal infrastructure and vehicles. However, the results of research programs found in literature review have been inconsistent. Both laboratory and field programs are highly dependent on several factors, such as metal type, temperature, humidity, amount of exposure, and many more.
- The results of this study indicate that carbon steel and aluminum can corrode when exposed to typical environmental conditions found in Edmonton. It is recommended that additional corrosion prevention methods be applied to metal surfaces exposed to corrosive environments. Examples methods include limitation of actual exposure to moisture (keeping surfaces dry), the application and maintenance of high-performance corrosion protection coatings (e.g. paint on a car) or lubrication (e.g. for bicycle chains/cassettes).
- The amount/length of exposure to corrosive environments was a major contributing factor to amount of corrosion observed on field coupons. In general, more exposure to corrosive environments leads to more corrosion.
- The amount of corrosion observed varied with coupon material type. The most corrosion was observed on the carbon steel coupons, while a relatively much smaller amount of corrosion was observed on the aluminum coupons. A negligible amount of corrosion was observed on the stainless steel coupons.

- The mass loss observed on the carbon steel and aluminum coupons in 2019/2020 was generally higher as compared to the mass loss observed in 2018/2019.
  - Using statistical analysis, the results indicate that change in winter road maintenance programs from 2018/2019 to 2019/2020 could not be directly associated with the differences in corrosion observed.
  - In the winter of 2019/2020, total chloride applied from both NaCl and $CaCl_2$ were lower than in the winter of 2018/2019 yet the amount of corrosion observed (in general) increased. Based on known corrosive effects of aqueous solutions containing chloride salts, this result is unexpected and indicates the presence of other influencing factors.
  - There are many possible other factors that could have influenced the corrosion observed on the coupons including, but not limited to, amount of exposure to moisture, frequency of vehicle utilization, field exposure time, weather conditions, amount/concentration of anti-icing/de-icing products, amount/speed of traffic on roads and road conditions. Many of these factors (or variables) could not be controlled in this type of study.
- To better understand how different factors influence corrosion of metals, additional testing should be completed utilizing more advanced corrosion monitoring tools/equipment over a longer period of time. A systematic approach over a longer period of time could allow for the impact of different factors to be observed and correlated with corrosion impact. Based on the data obtained to date, it cannot be concluded that the change in municipal anti-icing/de-icing programs from winter 2018/2019 to winter 2019/2020 had a statistically relevant effect on the amount of corrosion observed on the coupons.

Contents

List of Tables

Table of Figures

1.0 INTRODUCTION

1.1 PROJECT HISTORY AND SCOPE

For the 2018/2019 winter season, Corrpro was selected by the City to conduct a targeted corrosion research project related to its winter road maintenance program. Specifically, the City was interested in determining the corrosion effects of an anti-icing pilot program that involved the added use of a corrosion inhibited calcium chloride ($CaCl_2$) brine as an anti-icing agent. This corrosion research project included a laboratory and field portion and the findings were summarized in a report (document number 0119-4632-CED-REN-001-2) and submitted to the City in July of 2019.

For the winter of 2019/2020, the City discontinued its anti-icing program for all areas except select bicycle lanes. This meant that most areas subject to the City's winter road maintenance program were only exposed to a de-icing program. The City's current de-icing program involves the use of a sodium chloride (NaCl) and sand mixture that is "pre-wetted" with calcium chloride ($CaCl_2$) brine before application to road surfaces. This pre-wetted mixture is applied to road surfaces after a snowfall to melt snow and ice. To help to better understand the corrosive effects of the anti-icing program and de-icing programs individually, the City requested that Corrpro repeat the field portion of the 2018/2019 study in the winter of 2019/2020. Specifically, the project involves an investigation into the corrosion impacts of the City's anti-icing and de-icing programs on municipal metals through field-based corrosion testing in the winter of 2019/2020, with comparison of the results to the findings of the 2018/2019 research project.

The project phases and deliverables are listed in 'Table 1'.

Table 1 - Project Deliverables

Phase	Deliverable
1	Procurement of materials and equipment
2	Installation of field coupons and related equipment
3	Retrieval of field coupons and related equipment
4	Submittal of final report
	Acceptance of final report

1.2 PROJECT BACKGROUND INFORMATION

1.2.1 METALS COMMONLY USED IN MUNICIPAL INFRASTRUCTURE & VEHICLES

Some metals commonly used in municipal infrastructure and vehicles include carbon steel, aluminum, galvanized steel, and stainless steel. Cast iron, titanium and other specialized metals are also used, but in limited quantities. Steel is often used to create the chassis or cage beneath the body of a vehicle, or on door beams, car roofs and body panels. Aluminum is commonly used because of its high strength to weight ratio. In cars, aluminum is typically used in body panels and wheel rims. Additionally, aluminum is used for bicycle frames and street signs. Stainless steel is commonly used in exhaust pipes on cars due to its higher resistance to corrosive environments. Light posts are typically made of galvanized steel.

Most metals used in civil infrastructure and vehicles have a protective coating applied to them, whether it is paint on your car or a galvanized coating on lamp posts. Coatings will increase the lifespan of the metal by acting as a barrier between the metal and corrosive environments. It is important to note that coatings on metals do not last forever; proper maintenance of the coating must be maintained to avoid localized corrosion. Ensure cars are properly coated, regularly cleaned, and the coating is maintained to minimize corrosion.

As requested by the City, the metals tested in this project are the same that were tested in the field program of the 2018/2019 project:

- Carbon steel (heavily utilized in vehicle, bicycle and municipal infrastructure construction)
- Aluminum (bicycle frames and some vehicles)
- Stainless steel (some vehicle/bicycle components)

1.2.2 ANTI-ICING AND DE-ICING PROGRAMS AND CHEMICALS

Anti-icing and de-icing chemicals are commonly used for road maintenance in areas that experience icy winter driving conditions. Anti-icing is a preventative strategy where there is an application of chemicals to roads before snowfall to prevent ice formation. De-icing is the practice of removing snow and ice once it has fallen, therefore; it is a reactive strategy. The process of de-icing generally involves plowing or the application of chemicals or abrasives on roads. In many jurisdictions, these two strategies are used in combination to improve overall effectiveness and economics of winter road maintenance programs. The most common anti-icing and de-icing chemicals used include NaCl, $CaCl_2$, abrasives (sand), magnesium chloride ($MgCl_2$), agricultural-based, and others [1]. Aqueous solutions containing chloride salts such as the ones listed above are known to contribute to corrosion of various types of metal, including those commonly used for infrastructure and vehicles [2].

In the City of Edmonton implemented programs, the following definitions apply:

- De-icing Program – A program in which a NaCl and sand mixture is applied to road surfaces after snow or ice is already present (e.g. after a snowfall). The sand in this mixture is “pre-wetted” by applying a liquid $CaCl_2$ brine to the sand to help reduce clumping, freezing and the amount of back-spray/bounce. Liquid brine pre-wetting also helps to improve the efficacy of the other anti-icing materials through improved road salt activation and decreased dispersion from vehicle traffic [3].

- Anti-icing Program – A pilot program conducted in the 2017/2018 and 2018/2019 winter seasons that involved the added use of $CaCl_2$ brine as an anti-icing agent. The $CaCl_2$ brine was deployed in certain expected temperature ranges *before* anticipated snowfall to assist with goals of overall winter maintenance program [2].

In winter of 2018/2019, the City utilized their anti-icing program on select roadways and bicycle lanes and their de-icing program in all areas. In winter of 2019/2020 the City utilized their anti-icing program on select bicycle lanes and their de-icing program in all areas.

1.2.3 INFLUENCING FACTORS FOR THE CORROSION OF MUNICIPAL INFRASTRUCTURE AND VEHICLES

There are many external factors that can influence the corrosion rates of metals utilized in municipal infrastructure and vehicles. Some external factors included, but are not limited to:

- amount of exposure to moisture,
- field exposure time,
- weather conditions (precipitation, temperature, humidity, etc.),
- amount/concentration of anti-icing/de-icing products applied to the roads,
- amount/speed of traffic on the roads,
- road conditions (drainage, amount of debris, etc.).

2.0 FIELD TESTING PROGRAM FOR 2019/2020

Field testing was conducted to determine the corrosion effects of the City's anti-icing/de-icing programs in Edmonton's weather and traffic conditions. Field testing in Edmonton was important as the corrosion effect of anti-icing/de-icing chemicals can vary significantly based on weather conditions [4]. Corrpro's recommended field program included the installation and monitoring of a number of coupons on buses and metal infrastructure in Edmonton.

A total of 180 field coupons were ordered on January 7, 2020 and received on February 6, 2020. An example photo of the as-received coupons of each metal typed are shown in 'Figure 1'. Each coupon was marked and individually serial numbered for tracking purposes.

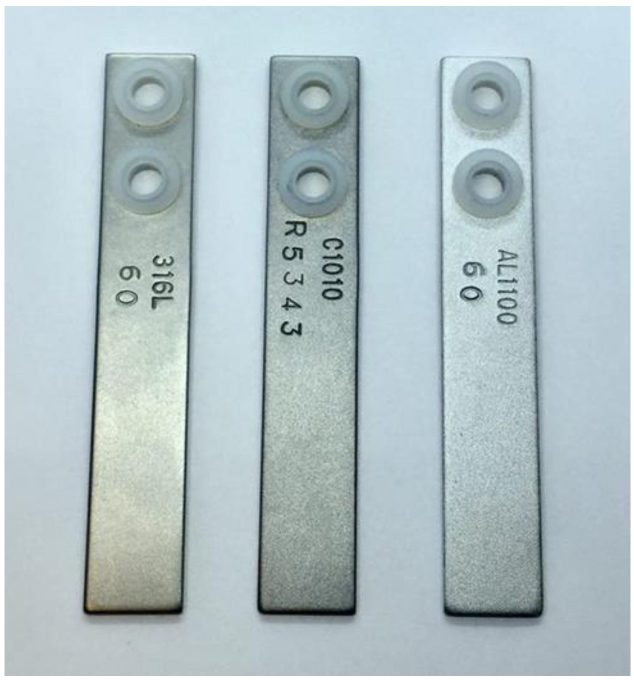

Figure 1 - As Received Field Coupons (Left to Right: Stainless Steel, Carbon Steel and Aluminum)

2.1 FIELD COUPON INSTALLATION

The field coupons were installed on vehicle-related, infrastructure-related, and bicycle-related structures and equipment throughout the City of Edmonton. The breakdown of the number of coupons installed on each structure or equipment type is shown in 'Table 2'.

Table 2 - Installation Areas of Field Coupons

Structure & Equipment	Number of Field Coupons	Percentage
Vehicle-related	72	40%
Infrastructure-related	54	30%
Bicycle-related	36	20%
Environmental Control	3	2%
Extra	15	8%
Total	**180**	**100%**

The locations of the field coupons are shown in the Google Earth map in 'Figure 2'.

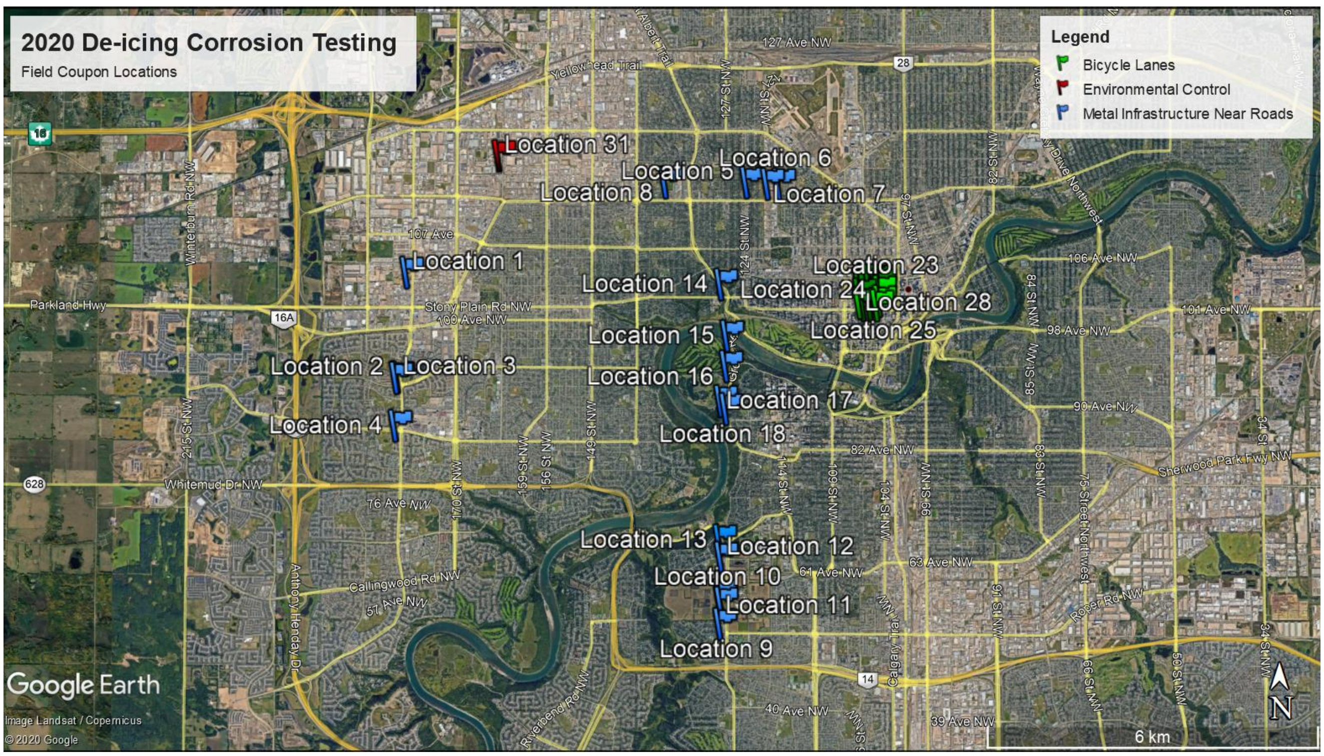

Figure 2 - Field Coupon Locations

2.1.1 VEHICLE-RELATED

All of coupons were installed on the City of Edmonton and Spruce Grove buses by March 6, 2020. There were two sets of each metal coupon on each bus for the field program. All coupons were installed on the curbside of the bus near the rear wheel well, as this area typically is the most severely corroded. One set of coupons were installed behind the wheel well, and the other one on the mud flap. ‘Figure 3’ indicates the areas on the bus where the coupons are mounted (circled).

Figure 3 - Mounting Locations of Field Coupons on Buses

‘Figure 4’ shows the coupons behind the wheel wells were hung from wiring on the bottom of the bus. Heavy duty plastic cable ties were used to hang the coupons with the goal of securing the coupons while eliminating any metal-to-metal contact.

Figure 4 - Field Coupons Installed on Wiring Behind Wheel Well

Another set of coupons was installed on the mud flaps, as shown in 'Figure 5'. The coupons exposed to the spray on the mud flap are in the highest exposure area; therefore, these coupons should see the most significant corrosion. The coupons are secured directly on to the mud flap with bolts and lock nuts. However, there is a nylon insulator between the bolts and the coupons to eliminate metal-to-metal contact.

Figure 5 - Field Coupons Installed on Mud Flaps

'Table 3' indicates the bus numbers of the City of Edmonton and Spruce Grove buses that were used for this field program.

Table 3 - City of Edmonton and Spruce Grove Buses Used in Program

City of Edmonton Buses	Spruce Grove Buses
7031	6900
4536	6901
4366	6902
4543	6903
4374	6904
4916	6905

2.1.2 INFRASTRUCTURE-RELATED

Installation of the infrastructure and bicycle-related field coupons was completed on February 13, 2020. The infrastructure-related structures used in this field program were mounted on specified routes in the city. The routes the coupons were installed on are as follows:

- 122nd Street, between 51st Street and 62nd Avenue
- Groat Road, between 87th Avenue and Groat Bridge
- 178th Street, between Stony Plain Road and Whitemud Drive
- 111th Avenue, between Groat Road and 120th Street

The coupons were mounted to a neoprene sheet with nylon bolts, washers and nuts. Holes were drilled into the neoprene to allow for heavy duty cable ties to secure the apparatus to metal infrastructure. 'Figure 6' shows the field coupon mounting apparatus and examples of how the coupon apparatuses were mounted to various metal infrastructure on the specified routes.

Figure 6 - Field Coupons Installed on Metal Infrastructure Near Roadways

2.1.3 BICYCLE-RELATED

Instead of attaching the coupons directly to bicycles, the coupons were mounted in areas around the city with designated bike lanes. The coupons were mounted to signs, posts, barriers, etc. that are near the designated bike lanes in the city. The coupons were installed on bicycle lanes in downtown Edmonton, as shown in 'Figure 7'.

Figure 7 - Field Coupons Installed on Bicycle-Related Structures

For the bicycle-related structures, the coupons were mounted downtown on the streets with designated bike lanes; the routes are as follows:

- 106th Street
- 102nd Avenue
- 103rd Street
- 100th Avenue

2.1.4 ENVIRONMENTAL CONTROL

An additional mounting apparatus with a set of coupons was placed outside the Corrpro office. This set of coupons was not in contact with any anti-icing/de-icing products, therefore; it served as a control to see the amount of corrosion based solely on the weather/environment.

2.2 RETRIEVAL OF FIELD COUPONS

The infrastructure and bicycle-related field coupons were retrieved the week of June 1-5, 2020. The bus related coupon retrieval was dispersed over a longer period of time because of scheduling conflicts caused by the COVID-19 crisis. The bus coupons were retrieved at varied times between June 15, 2020 and July 17, 2020. The varied exposure times have been considered in regard to the corrosion analysis of the coupons.

2.2.1 VEHICLE-RELATED

An example photo of the retrieved field coupons installed on buses are shown in 'Figure 8'. The coupons are slightly covered in dirt; however, it is still visible that the carbon steel coupons corroded the most, aluminum coupons had minimal corrosion, and the stainless steel coupons did not visibly corrode.

Figure 8 - Corroded Bus Coupons Installed on Spruce Grove Bus (Left to Right: Carbon Steel, Aluminum And Stainless Steel)

2.2.2 INFRASTRUCTURE-RELATED

An example photo of retrieved field coupons installed on infrastructure near roadways are shown in 'Figure 9'. The coupons shown in this figure was installed in an area exposed to the de-icing chemicals used in Edmonton's winter road maintenance program.

Figure 9 - Corroded Field Coupons Installed On 178 Street (Left to Right: Carbon Steel, Stainless Steel and Aluminum)

2.2.3 BICYCLE-RELATED

'Figure 10' shows a set of coupons installed on infrastructure near bicycle lanes after exposure to conditions in Edmonton during winter 2019/2020.

Figure 10 - Corroded Coupons Installed on Bicycle Lanes (Left to Right: Carbon Steel, Stainless Steel and Aluminum)

2.2.4 ENVIRONMENTAL CONTROL

A photo of the environmental control field coupons is shown in 'Figure 11'. The coupons shown in this figure were installed in an area not exposed to the City's winter road maintenance program.

Figure 11 – Corroded Environmental Control Field Coupons Installed Near Corrpro Office (Left to Right: Carbon Steel, Stainless Steel and Aluminum)

The corrosion observed on the environmental control coupons shown in 'Figure 11' is visibly less than the corrosion observed on the infrastructure related coupons in 'Figure 9', which is most evident on the carbon steel coupons.

2.3 FIELD PROGRAM ANALYSIS

2.3.1 VEHICLE-RELATED

The carbon steel coupons showed the most significant surface corrosion (approx. 100% of surface corroded), the aluminum coupons showed only some visible corrosion (approx. 20-30% of surface corroded), and the stainless steel showed no observed corrosion (approx. 0% of surface corroded).

Significant corrosion typically occurred near the holes where the coupons were secured with the bolts. This localized corrosion is likely caused by the crevice between the nylon insulators and the coupon (crevice corrosion). 'Figure 12' shows a closer view of the corrosion near the mounting holes in the coupons.

Figure 12 - Crevice corrosion on carbon steel coupon

The corrosion products were removed from the coupons according to the ASTM standard [5]. The average mass change of each metal coupon installed on the buses was recorded, the results are shown in 'Table 4'.

Table 4 - Average Measured Change in Mass On Bus Coupons

Bus Route	Location on Bus	Carbon Steel		Stainless Steel		Aluminum	
		Average Measured Change in Mass (g)	Total Coupon Mass Change (%)	Average Measured Change in Mass (g)	Total Coupon Mass Change (%)	Average Measured Change in Mass (g)	Total Coupon Mass Change (%)
Spruce Grove Buses	Mud Flap	-0.11	-1.20	0.00	-0.01	-0.01	-0.34
	Wheel Well	-0.10	-1.01	0.00	-0.01	-0.01	-0.26
	Combined	-0.11	-1.11	0.00	-0.01	-0.01	-0.30
City of Edmonton Buses	Mud Flap	-0.31	-3.25	0.00	-0.02	-0.02	-0.66
	Wheel Well	-0.28	-2.92	0.00	-0.01	-0.01	-0.33
	Combined	-0.30	-3.19	0.00	-0.02	-0.02	-0.49

As seen from the table above, the carbon steel coupons showed the most significant mass loss, followed by the aluminum coupons, and then the stainless steel coupons which showed very minimal to no mass loss. The coupons attached to the mud flaps generally experienced greater mass loss, likely due to higher exposure. There were scratches on the mud flap coupons compared to the coupons attached to the wheel well, likely due to rocks and debris impacting the coupons while in service.

For carbon steel coupons, the City of Edmonton buses show significantly higher mass losses as compared to Spruce Grove buses. Due to the COVID-19 pandemic, the Spruce Grove buses were not in operation starting from the end of March, onwards. The Spruce Grove buses did not have safety shields installed to protect the drivers and were therefore put out of service during the crisis. Whereas, the City of Edmonton buses remained in full operation through the duration of the pandemic [6]. This may be why the results demonstrate that the Edmonton buses have higher mass losses for carbon steel coupons than Spruce Grove buses.

2.3.2 INFRASTRUCTURE-RELATED

The average mass change of each metal coupon installed on the metal infrastructure near roadways was recorded, the results are shown in 'Table 5'.

Table 5 - Average Measured Change in Mass On Infrastructure-Related Coupons

Infrastructure/ Equipment	Location	Carbon Steel		Stainless Steel		Aluminum	
		Average Measured Change in Mass (g)	Total Coupon Mass Change (%)	Average Measured Change in Mass (g)	Total Coupon Mass Change (%)	Average Measured Change in Mass (g)	Total Coupon Mass Change (%)
Metal Infrastructure Near Roadways	178th Street	-0.19	-1.99	0.00	-0.01	-0.02	-0.47
	111th Avenue	-0.19	-2.03	0.00	-0.02	-0.03	-0.73
	122nd Street	-0.18	-1.87	0.00	-0.01	-0.03	-0.75
	Groat Road	-0.16	-1.70	0.00	-0.01	-0.02	-0.49

As with the bus-mounted coupons, no mass loss was measured for the stainless steel coupons installed on metal infrastructure. As expected, the carbon steel coupons experienced the largest mass loss. The aluminum coupons installed on metal infrastructure showed minimal mass loss. The mass change measurements agree with the visual observations of the corrosion after retrieving the coupons.

All routes were exposed to the City's de-icing program; therefore, the main difference affecting the corrosion rate would be this amount of exposure. There was not a significant difference in the measured mass losses for any of the metal types tested regardless of the location they were exposed to. This infers that the amount of exposure was relatively similar in all routes where the coupons were installed. The amount of exposure is a very significant factor that can affect the extent of corrosion on the coupons. Exposure can be affected by the amount of splashing on the coupons, distance from the road, traffic conditions, duration of test, etc.

2.3.3 BICYCLE-RELATED

'Table 6' shows the average mass changes related to the coupons installed on bicycle lanes in downtown Edmonton.

Table 6 - Average Measured Change in Mass On Bicycle-Related Coupons

Infrastructure/ Equipment	Location	Carbon Steel		Stainless Steel		Aluminum	
		Average Measured Change in Mass (g)	Total Coupon Mass Change (%)	Average Measured Change in Mass (g)	Total Coupon Mass Change (%)	Average Measured Change in Mass (g)	Total Coupon Mass Change (%)
Bicycle Lanes	Downtown	-0.10	-1.04	0.00	0.01	-0.02	-0.65

The mass change for the carbon steel coupons attached to the bicycle lanes was lower as compared to the coupon attached to metal infrastructure. The stainless steel and aluminum coupons attached to bicycle lanes experienced similar mass loss to those attached to metal infrastructure.

Bicycle lanes are typically less utilized compared to roads in Edmonton during the winter due to weather condition. As well, bicycles do not generate as much splash on these coupons compared to cars because of their smaller size and reduced speed. Therefore, bicycle-related coupons would have significantly less exposure to splash and anti-icing/de-icing chemicals as compared to the metal infrastructure and vehicle-related coupons.

2.3.4 ENVIRONMENTAL CONTROL

'Table 7' shows the mass change related to the environmental control coupons installed outside the Corrpro office.

Table 7 - Measured Change in Mass On Environmental Control Coupons

Infrastructure/ Equipment	Location	Carbon Steel		Stainless Steel		Aluminum	
		Measured Change in Mass (g)	Coupon Mass Change (%)	Measured Change in Mass (g)	Coupon Mass Change (%)	Measured Change in Mass (g)	Coupon Mass Change (%)
Environmental Control	Outside Corrpro Office	-0.02	-0.19	0.00	-0.01	-0.01	-0.28

Compared with the coupons installed on city infrastructure near roadways and on buses, less corrosion was observed and measured on the environmental control coupons. Based on the installation location, these coupons would not have experienced any splashing from roadways and would have received minimal exposure to anti-icing/de-icing chemicals. Consequently, the corrosion would have been due to regular environmental conditions in Edmonton (snow, rain, wind, fluctuating temperatures, etc.). This highlights the corrosive nature of the local environments found around roadways in Edmonton.

2.4 SUMMARY OF RESULTS

'Figure 13' and 'Figure 14' show the graphical representation of the average mass loss measured on the carbon steel coupons and aluminum coupons, respectively, exposed to the various infrastructure/equipment analyzed during this field program. There is no graph for the stainless steel coupons because the mass loss experienced by the stainless steel coupons was too low to be able to accurately distinguish the values from actual mass loss or measurement error.

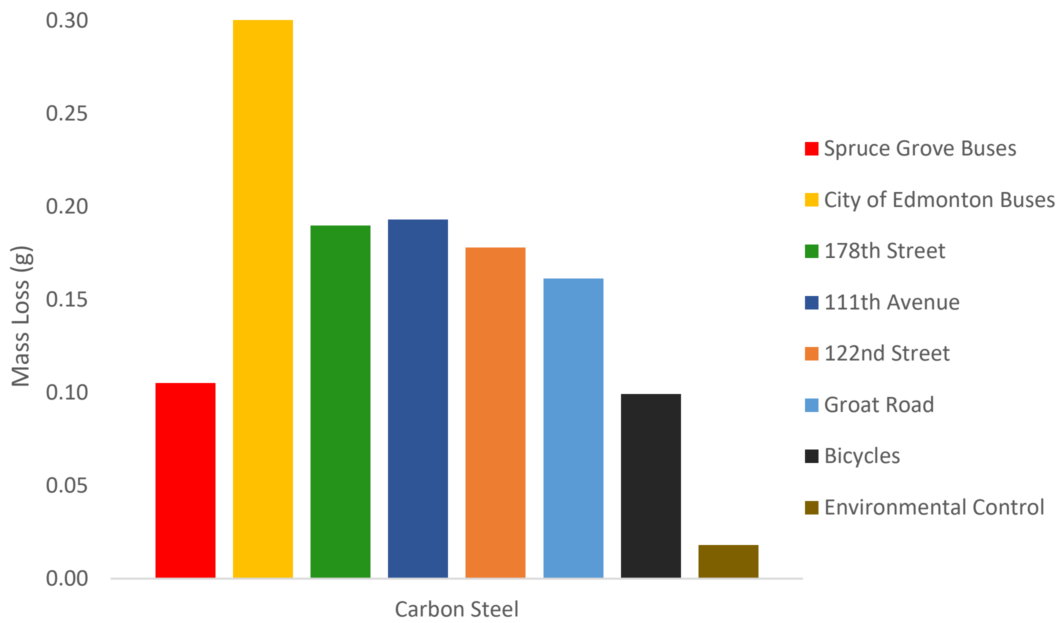

Figure 13 - Average Mass Loss of Carbon Steel Coupons

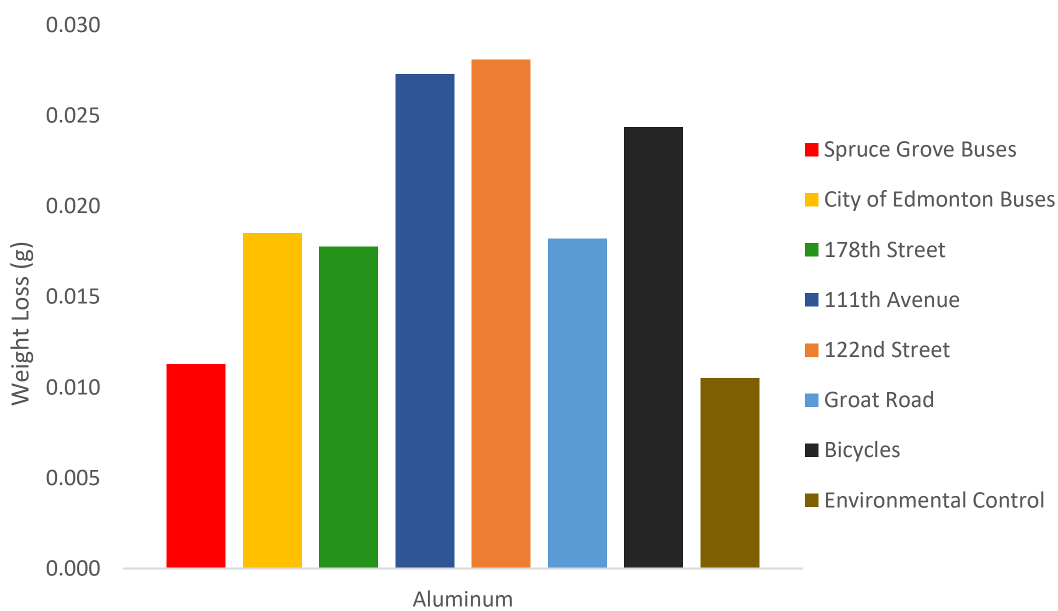

Figure 14 - Average Mass Loss of Aluminum Coupons

For the carbon steel coupons, the amount of corrosion observed varied based on coupon location. More corrosion was observed on coupons installed on bus mud flaps versus coupons installed further away from the road and wheel (on cabling behind the wheel well). More corrosion was observed on coupons installed on City of Edmonton buses versus coupons installed on municipal infrastructure. Additionally, more corrosion was observed on coupons installed on municipal infrastructure near to major roadways (car traffic) versus coupons installed near bicycle lanes. The least corrosion was observed on the carbon steel coupons installed on municipal infrastructure located further away from roadways (environmental control) because there is less probability of splash exposure from vehicles.

The aluminum coupons showed significantly less mass loss as compared to the carbon steel coupons. However, the aluminum coupons did not corrode similar to carbon steel coupons in the sense that areas with the highest amount of exposure to splash did not always show the highest amount of mass loss. An influencing factor could be the amount of anti-icing/de-icing products that were applied in each corresponding area. Literature shows that aluminum is very susceptible to corrosion in environments that contain high amounts of chlorides [7] [8] [9]. The areas where the coupons are showing higher mass losses (111th Avenue, 122nd Street, and bicycle lanes downtown), could have had a higher amount of anti-icing/de-icing applications or build-up on the roads compared to the other areas tested. In the winters of 2018/2019 and 2019/2020, the studied bicycle lanes were subject to multiple applications of both anti-icing and de-icing materials [3] [10].

As seen in both graphs, the coupons attached to the City of Edmonton buses had significantly higher mass losses as compared to the coupons attached to the Spruce Grove buses. This is likely due to the Spruce Grove buses being out of service for a period of the testing time (reduced exposure to corrosive environment).

3.0 COMPARISON BETWEEN 2018/2019 & 2019/2020 FIELD PROGRAMS

The environmental and road use conditions of the two winter seasons being analyzed were not the same (and no winter seasons will ever exactly be the same). Additionally, road and bus usages were heavily impacted by restrictions/changes due to the COVID-19 pandemic. The environmental conditions that may affect the corrosion effects on metal used in municipal infrastructure could include but is not limited to, amount of traffic on the roads (influencing the amount of splash on the coupons and concentration of salt on the road), amount of anti-icing/de-icing products applied to the roads, frequency of bus utilization, and exposure time.

'Table 8' shows an overview of the anti-icing/de-icing chemical that each area, equipment, or metal infrastructure was exposed to in the winters of 2018/2019 and 2019/2020.

Table 8 – Anti-Icing and De-Icing Program Exposure

Infrastructure/ Equipment	2018/2019 Program(s)	2019/2020 Program(s)
Spruce Grove Buses	De-icing	De-icing
City of Edmonton Buses	De-icing & Anti-icing	De-icing
178th Street	De-icing & Anti-icing	De-icing
122nd Street	De-icing	De-icing
111th Avenue	De-icing & Anti-icing	De-icing
Groat Road	De-icing	De-icing
Bicycle Lanes	De-icing & Anti-icing	De-icing & Anti-icing
Environmental Control	None	None

The results of the 2019/2020 program were compared to the 2018/2019 program to attempt to identify significant differences in corrosion. 'Figure 15' and 'Figure 16' show graphical representations comparing the corrosive effect of the winter road maintenance programs used the last two winter seasons in Edmonton. The graphs show the average mass loss of carbon steel coupons and aluminum coupons, respectively. The mass loss of the stainless steel coupons was not graphed as they showed minimal to no mass loss.

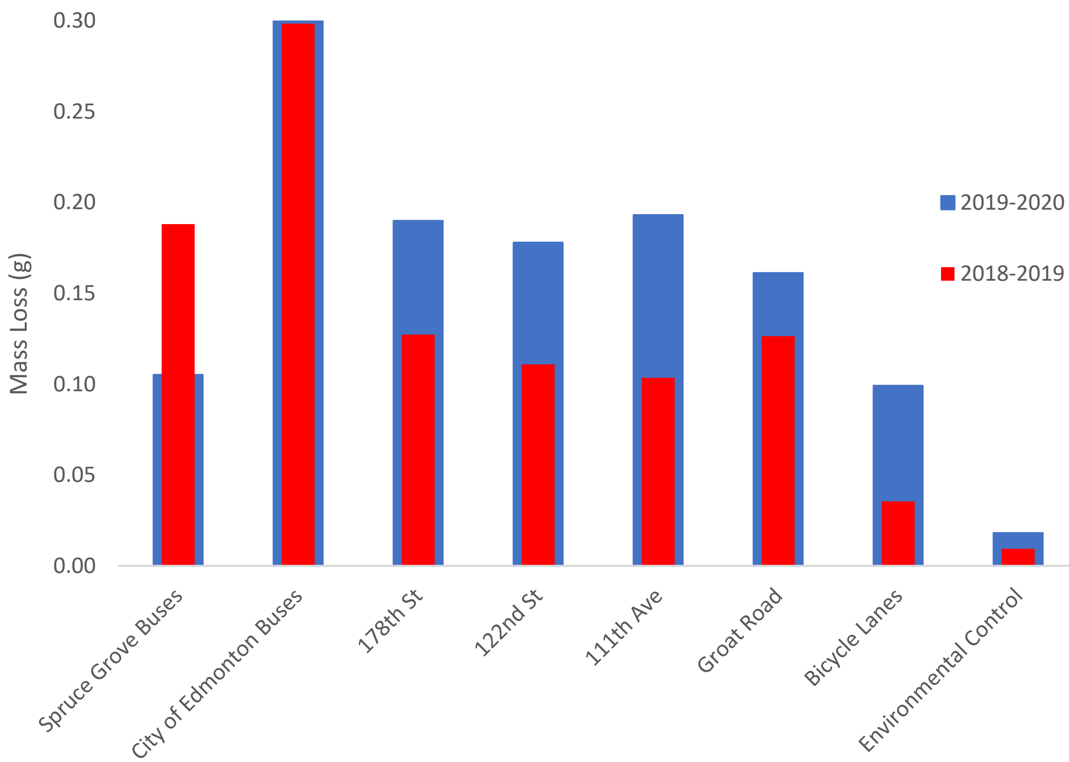

Figure 15 - Comparison of Average Mass Loss of Carbon Steel Coupons Between 2018/2019 And 2019/2020

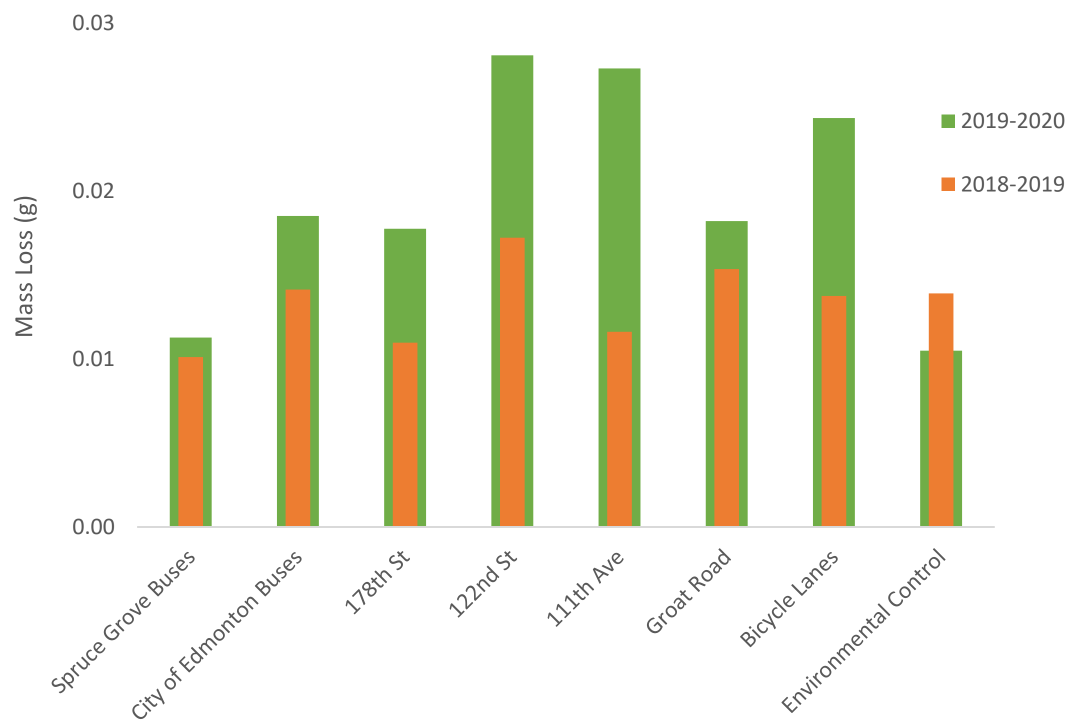

Figure 16 - Comparison of Average Mass Loss of Aluminum Coupons Between 2018/2019 and 2019/2020

As seen from the graphs, the majority of coupons experienced higher amounts of mass loss in 2019/2020 as compared to 2018/2019 for all metal types. The only exception being the carbon steel coupons on the Spruce Grove buses, which experienced higher weight loss averages in 2018/2019 as compared to 2019/2020. This could be primarily due to reduced environmental exposure for the coupons on the Spruce Grove buses due to the buses being out of service due to COVID-19 safety concerns for the last few months of the testing period.

3.1 STATISTICAL ANALYSIS OF MASS LOSS DIFFERENCES

Using the built-in data analysis tools in Excel, a 't-Test: Two-Sample Assuming Equal Variances' was conducted to determine if the difference in weight loss between the two winter seasons was statistically significant.

Statistical significance is the likelihood that the results in the data are not explainable by chance alone, and thus are caused by an external factor [11]. If the mass loss data is found not to be statistically significant, the data is likely following a trend related to the typical corrosive environments found around roadways in Edmonton. If the mass loss data comparing the winter seasons is determined to be statistically significant; however, an external factor is likely influencing the data. Some external factors that could influence the mass loss data could include, but is not limited to, utilization of the anti-icing versus de-icing chemicals, exposure time, amount of splash, traffic conditions, weather conditions, amount of precipitation, ambient temperatures, and amount/concentration of de-icing chemicals used on roads.

When using the t-Test to compare two sets of data, a p-value is determined. A p-value is the probability of obtaining an effect that is at least as extreme as the results actually observed in the data, assuming the null hypothesis is correct. A smaller p-value ($p < 0.05$) means there is stronger evidence that the alternative hypothesis is correct [11]. In the context of this study, the null hypothesis is that there is not a significant influence of the external factors on the corrosion of the coupons (i.e. the mass loss data) between the winter seasons for each infrastructure/equipment. Therefore, the alternative hypothesis is that external factors are affecting the corrosion of the coupons between the winter seasons for each infrastructure/equipment. ‘Table 9’ and ‘Table 10’ show the results of the t-Test for the mass loss data of the carbon steel coupons and aluminum coupons, respectively. A t-Test was not conducted for the mass loss data of the stainless steel coupons because the mass loss observed was negligible.

In summary, statistical analysis is used to determine if differences between the 2018/2019 and 2019/2020 data sets are significant (probably caused by an actual change/external factor) or just random differences (within normal statistical variance). It should be noted that only two sets of data and the smaller number of data points in each data set leaves a lot of room for statistical uncertainty. More frequent data over a longer period of time would be beneficial in monitoring change in corrosion rates and determining contributing external factors. The effect of weather conditions, such as precipitation and temperature, on the corrosion rate of metal used in municipal infrastructure could be analyzed in greater detail with continuous monitoring as the corrosion rate could be monitored on a day-to-day basis.

Table 9 - Statistical Analysis of Mass Loss Data for Carbon Steel Coupons

Infrastructure/Equipment	Statistical Significance (2018/2019 vs. 2019/2020)
Spruce Grove Buses	STATISTICALLY SIGNIFICANT
City of Edmonton Buses	NOT SIGNIFICANT
178th Street	NOT SIGNIFICANT
122nd Street	NOT SIGNIFICANT
111th Avenue	NOT SIGNIFICANT
Groat Road	NOT SIGNIFICANT
All Metal Infrastructure Near Roadways	STATISTICALLY SIGNIFICANT
Routes with Anti-icing vs. De-icing Chemicals (178th St vs 111th Ave)	NOT SIGNIFICANT
De-icing Chemical Routes (122nd St & Groat Road)	STATISTICALLY SIGNIFICANT
Bicycle Lanes	STATISTICALLY SIGNIFICANT
Environmental Control	NOT SIGNIFICANT

Table 10 - Statistical Analysis of Mass Loss Data for Aluminum Coupons

Infrastructure/Equipment	Statistical Significance (2018/2019 vs. 2019/2020)
Spruce Grove Buses	NOT SIGNIFICANT
City of Edmonton Buses	NOT SIGNIFICANT
178th Street	NOT SIGNIFICANT
122nd Street	NOT SIGNIFICANT
111th Avenue	NOT SIGNIFICANT
Groat Road	NOT SIGNIFICANT
All Metal Infrastructure Near Roadways	STATISTICALLY SIGNIFICANT
Routes with Anti-icing vs. De-icing Chemicals (178th St vs 111th Ave)	NOT SIGNIFICANT
De-icing Chemical Routes (122nd St & Groat Road)	STATISTICALLY SIGNIFICANT
Bicycle Lanes	STATISTICALLY SIGNIFICANT
Environmental Control	NOT SIGNIFICANT

3.1.1 STATISTICAL DISCUSSION FOR VEHICLE RELATED COUPONS (BUSES)

For the carbon steel coupons, the higher weight loss averages observed for coupons attached to Spruce Grove buses in 2018/2019 as compared to 2019/2020 is considered statistically significant. Likely, this is due to the Spruce Grove buses being out of service due to COVID-19 safety concerns for the last few months of the testing period in 2020. Therefore, the external factor affecting the corrosion on the carbon steel coupons is likely exposure time and amount of splash.

Since the city of Edmonton buses were fully operational during the COVID-19 pandemic, it can be assumed that the exposure time for 2018/2019 and 2019/2020 were approximately the same. Therefore, one differentiating external factor between the two seasons is the change from anti-icing chemicals to de-icing chemicals. The results of the t-Test showed that mass loss data comparing 2018/2019 versus 2019/2020 for all coupons attached to the City of Edmonton bus was not significant. This indicates that the addition of the anti-icing program may not have been an influencing external factor affecting the corrosion of the coupons attached to buses. Precipitation, amount of splash, and outside temperatures also could have impacted the corrosion effect on these coupons. Additional testing will be required to better understand influencing external factors.

3.1.2 STATISTICAL DISCUSSION FOR INFRASTRUCTURE RELATED COUPONS

When comparing the various routes where the coupons were attached to metal infrastructure, the differences observed for individual routes were deemed statistically insignificant. When comparing the metal infrastructure routes all together; however, the mass loss data between the winter seasons is statistically significant. Therefore, there is likely an external factor, or combination of external factors influencing the corrosion of the coupons. Factors like the exposure time, amount of splash, traffic conditions, or the amount/concentration of de-icing chemical used on roads could have caused the mass loss observed on the carbon steel and aluminum coupons in 2019/2020 to be higher as compared to 2018/2019.

When comparing the routes that were exposed to the anti-icing and de-icing programs in 2018/2019 and only the de-icing program in 2019/2020 (178th Street & 111th Avenue), the results were not statistically significant. When comparing the routes that used only de-icing chemicals in both years (122nd Street & Groat Road), the results were statistically significant. This infers that the change from the anti-icing to de-icing chemicals may not have been an influencing external factor affecting the corrosion of the coupons attached to metal infrastructure near roadways.

3.1.3 STATISTICAL DISCUSSION FOR BICYCLE RELATED COUPONS (BICYCLE LANES)

For both the carbon steel and aluminum coupons, the mass loss data for the coupons attached to bicycle lanes was considered to be statistically significant. Therefore, the higher mass loss observed in 2019/2020 as compared to 2018/2019 is large enough to be considered out of the margin of reasonable error. According to data obtained from the City of Edmonton, the bicycle lanes in the winters of 2018/2019 and 2019/2020 were subject to multiple applications of both anti-icing and de-icing materials [3] [10]. As the bicycle lanes were subject to the anti-icing program in both winters, it is hypothesized that other factors (besides simply the presence of an the anti-icing program) played a more influencing role in the difference in corrosion observed between the two winter seasons. Other factors could be the total amounts of anti-icing/de-icing products applied to bicycle lanes, concentration of salt on bicycle lanes, weather conditions (amount of precipitation), and bicycle traffic (resulting in different amounts of splash/exposure).

3.2 COMPARISON OF YEARLY ANTI-ICING/DE-ICING PROGRAM SALT USAGE

In an attempt to assess some of the differences in corrosion observed and the effect of $CaCl_2$, the total chlorides applied to City of Edmonton roads were compared year over year. Table 11 displays the source and amounts of applied chlorides. It can be seen that the majority of chloride applied is from NaCl salt. It should also be noted that the percentage chloride from $CaCl_2$ brine decreased from 2017/2018 to 2018/2019, even though both winter seasons were part of the anti-icing pilot program.

Table 11 - Source and Amounts of Applied Chlorides [12]

Source of Chloride	Chloride Applied		
	2017/2018*	2018/2019*	2019/2020
Total chloride applied from NaCl salt + $CaCl_2$ brine (tonnes)	23,317	25,660	21,063
Chloride from $CaCl_2$ brine (tonnes)	1000	132	22
Chloride from $CaCl_2$ brine (%)	4.3%	0.5%	0.1%

*Anti-icing pilot program years

One would expect that a year in which more chlorides were applied, more corrosion would be observed. However, more corrosion (in general) was observed on field coupons in 2019/2020 compared to 2018/2019. As both the total chloride applied and chloride from $CaCl_2$ brine were lower in 2019/2020 compared to 2018/2019, it is clear that the corrosion observed is not solely based on the amounts of chlorides applied (i.e. there must be other influencing external factors).

4.0 CONCLUSIONS

The main conclusions and recommendations are summarized below:

- Anti-icing and de-icing products, including $CaCl_2$, NaCl and other chloride salts, are used globally for winter road maintenance in areas that experience icy conditions.
- Aqueous solutions containing chloride salts, such as NaCl, $CaCl_2$ and $MgCl_2$, are known to contribute to corrosion on various types of metals, including those commonly used for infrastructure and vehicles.
- Research studies and pilot programs have been introduced worldwide to determine the impact of anti-icing and de-icing chemicals on metal infrastructure and vehicles. However, the results of research programs found in literature review have been inconsistent. Both laboratory and field programs are highly dependent on several factors, such as metal type, temperature, humidity, amount of exposure, and many more.
- The results of this study indicate that carbon steel and aluminum can corrode when exposed to common environmental conditions found in Edmonton. It is recommended that additional corrosion prevention methods be applied to metal surfaces exposed to

corrosive environments. Examples methods include limitation of actual exposure to moisture (keeping surfaces dry), the application and maintenance of high-performance corrosion protection coatings (e.g. paint on a car) or lubrication (e.g. for bicycle chains/cassettes).

- The amount/length of exposure to corrosive solutions and environments was a major contributing factor to amount of corrosion observed on field coupons. In general, more exposure to corrosive environments leads to more corrosion.
- The amount of corrosion observed varied with coupon material type. The most corrosion was observed on the carbon steel coupons, while a relatively much smaller amount of corrosion was observed on the aluminum coupons. A negligible amount of corrosion was observed on the stainless steel coupons.
- The mass loss observed on the carbon steel and aluminum coupons in 2019/2020 was generally higher as compared to the mass loss observed in 2018/2019.
    - Using statistical analysis, the results indicate that change in winter road maintenance programs from 2018/2019 to 2019/2020 could not be directly associated with the differences in corrosion observed.
    - In the winter of 2019/2020, total chloride applied from both NaCl and $CaCl_2$ were lower than in the winter of 2018/2019 yet the amount of corrosion observed (in general) increased. Based on known corrosive effects of aqueous solutions containing chloride salts, this result is unexpected and indicates the presence of other influencing factors.
    - There are many possible other factors that could have influenced the corrosion observed on the coupons including, but not limited to, amount of exposure to moisture, frequency of vehicle utilization, field exposure time, weather conditions, amount/concentration of anti-icing/de-icing products, amount/speed of traffic on roads and road conditions. Many of these factors (or variables) could not be controlled in this type of study.

- To better understand how different factors influence corrosion of metals, additional testing should be completed utilizing more advanced corrosion monitoring tools/equipment over a longer period of time. A systematic approach over a longer period of time could allow for the impact of different factors to be observed and correlated with corrosion impact. Based on the data obtained to date, it cannot be concluded that the change in municipal anti-icing/de-icing programs from winter 2018/2019 to winter 2019/2020 had a statistically relevant effect on the amount of corrosion observed on the coupons.

5.0 REFERENCES

[1] Pacific Northwest Snowfighters, *Snow and Ice Control Chemical Products,* PNS Assocation, 2010.

[2] K. Duncan and S. Gibson, "Summary Report for Brine Corrosion Research Study," Edmonton, 2019.

[3] C. Stuart, Interviewee, *Environmental Scientist, City of Edmonton.* [Interview]. 14 August 2020.

[4] X. Shi, L. Fay, C. Gallaway, K. Volkening, M. M. Peterson, T. Pan, A. Creighton, C. Lawlor, S. Mumma, Y. Liu and T. A. Nguyen, "EVALUATION OF ALTERNATIVE ANTI-ICING AND DEICING COMPOUNDS USING SODIUM CHLORIDE AND MAGNESIUM CHLORIDE AS BASELINE DESICERS - PHASE I," Colorado Department of Transportation, 2009.

[5] ASTM International, *ASTM G1 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens,* 2017.

[6] D. Mah, Interviewee, *Engineering Technologist, Fleet Engineering, City of Edmonton.* [Interview]. 31 March 2020.

[7] Total Materia, "Corrosion of Aluminum and Its Alloys: Forms of Corrosion," 2008. [Online]. Available: https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=187#:~:text=nd%20October%202020-,Corrosion%20of%20Aluminum%20and%20Its%20Alloys%3A%20Forms%20of%20Corrosion,is%20also%20a%20passive%20metal.. [Accessed 1 September 2020].

[8] P. R. Roberge, Corrosion Basics: An Introduction, 3rd Edition, NACE International, 2018.

[9] S. A. Bradford, Corrosion Control, CASTI Publishing, 2001.

[10] W. Goulden, "Anti-icing Brine Pilot Project; Environmental Monitoring and Metrics Report," City of Edmonton - Integrated Infrastructure Services, Edmonton, 2017-2018.

[11] W. Kenton, "Statistical Significance," Investopedia, 27 January 2020. [Online]. Available: https://www.investopedia.com/terms/s/statistically_significant.asp. [Accessed 22 July 2020].

[12] J. Tolsma and C. Stuart, "SNIC Monitoring Program PRELIMINARY Surface Water Loadings Evaluation 2019-2020," City of Edmonton Integrated Infrastructure Services Business Planning and Support Engineering Services, 2020.

END OF REPORT