SEWRPC Technical Report No. 62

IMPACTS OF CHLORIDE ON THE NATURAL AND BUILT ENVIRONMENT

Chapter 4

IMPACTS OF CHLORIDES ON INFRASTRUCTURE AND THE BUILT ENVIRONMENT

4.1 INTRODUCTION

Chloride salts have wide commercial and industrial uses that result in chloride contamination of the natural and built environment. Major uses contributing chloride to the environment include snow and ice control operations, water softening, water treatment processes, agricultural practices, food processing, and chemical manufacturing. In snow and ice control operations, sodium chloride (NaCl), magnesium chloride (MgCl$_2$), and calcium chloride (CaCl$_2$) are used for deicing roads, sidewalks, parking lots, and driveways. Dissolved chloride salts reduce the freezing temperature of water, which reduces the amount of ice formation. In water softening, NaCl and potassium chloride (KCl) are used to reduce the hardness of water. The salts participate in an ion-exchange process in which calcium and magnesium ions in the water, which contribute to hardness, are replaced with sodium or potassium ions from the salt. In drinking water and wastewater treatment, aluminum chloride (AlCl$_3$) and ferric chloride (FeCl$_3$) are used as coagulants to remove contaminants. In agriculture, potash (KCl) is used in fertilizers to deliver potassium as a nutrient to crops. In food processing, NaCl is used in a wide range of applications such as preserving food, seasoning, coloring, maintaining food texture, and regulating fermentation and chemical reactions. Lastly, various chloride salts are used in many chemical manufacturing processes. In general, NaCl is the most widely used chloride salt across industries due to its lower cost and availability. The disadvantage of using chloride salts in the built environment is that they can induce and accelerate damage to various types of infrastructure and reduce their useful life.

This chapter evaluates mechanisms and impacts of corrosion in metals such as metallic bridges, reinforcing steel in concrete, roadside infrastructure, water supply infrastructure, vehicle metal components, and mechanisms and impacts of deterioration in concrete such as roads, bridges, and buildings. This chapter also briefly discusses impacts to other infrastructure such as power systems and railroads.

4.2 CHORIDE-INDUCED METAL CORROSION MECHANISMS

Corrosion is a natural electrochemical process in which the refined metal is oxidized and is converted into more chemically stable metallic oxide compounds. All metals are subject to similar corrosion mechanisms. Figure 4.1 shows photos of typical corrosion occurring on a bridge, a culvert, and a motor vehicle. In the case of iron and its alloy steel, ferric oxide is formed when the iron is corroded. Corrosion develops when electrochemical reactions occur between the metal, water, and oxygen. Corrosion occurs by means of the flow of electrons in a process similar to what happens in a battery. When water contacts metal, the metal surface provides microscopic sites that act as anodes and cathodes. Electrons flow through the metal between the anodic and cathodic sites.

Figure 4.2 illustrates a typical iron corrosion process. On the figure, metallic iron at the anode is oxidized in the presence of water into iron(II) in the following reaction and is dissolved into solution as ions:

$$Fe \rightarrow Fe^{2+} + 2e^-$$
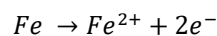
The cathode, often at locations of impurities in the metal, receives the electrons from the iron oxidation. The electrons then reduce oxygen at the cathode. Under acidic conditions, the electrons, oxygen, and hydrogen ions in the water react to produce additional water molecules in the following reaction:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$
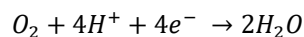
Under neutral or alkaline conditions, the electrons, oxygen, and water react to form hydroxide ions in the following reaction:

$$O_2 + H_2O + 4e^- \rightarrow 4OH^-$$
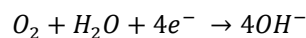
Iron(II) ions from the anode further react with hydroxide ions in the water and are oxidized by oxygen to form iron oxides known as rust. Several chemical reactions can be involved, and different types of rust can result depending on the availability of oxygen and water. Most common types of rust include hydrated ferric oxides ($Fe_2O_3 \cdot nH_2O$) and ferric oxide-hydroxide ($Fe(OH)_3$). In low moisture environments, ferric oxide (Fe_2O_3) may result. In rare cases of a prolonged low oxygen environment, iron(II) may be favored, resulting in magnetite (Fe_3O_4) or ferrous oxide (FeO).

The addition of chloride anions, such as from road salt, greatly increases the rate of metallic corrosion. The primary factor for the higher rate of corrosion is the increased conductivity of the solution. Chloride is a strong electrolyte. The presence of electrolytes in water increases the speed of electron transfer between anode and the cathode. This increases the rate of corrosion.[1] Chloride salts also decrease the freezing point of water which may increase the contact time between the liquid water and the metal surface. This allows the corrosion process to occur over a longer period and a wider range of temperatures.

A wide variety of metals are used in road infrastructure, bridges, and motor vehicles. The most common metals are iron, steel, aluminum alloys, magnesium alloys, copper, and copper alloys. Cast iron is used in motor vehicle engines and drive train components, roadside infrastructure, and bridges. Steel, which includes a wide range of alloy compositions and manufacturing methods, is typically used in concrete reinforcement, steel bridges, and motor vehicle structural components, body panels, fuel tanks, fittings, and tubing. $CaCl_2$ is more corrosive to steel than either NaCl and $MgCl_2$.[2] Aluminum alloys are also used both in motor vehicle components and roadside infrastructure such as guardrails, handrails, and light poles. Magnesium alloys are used for motor vehicle wheels, transmission housings, and various brackets and supports. Copper and cooper alloys are used primarily for electrical wiring and electrical contacts in motor vehicles, roadside infrastructure, and bridges. These diverse metals have different susceptibility to corrosion. In general, iron, steel, and magnesium alloys are highly susceptible to corrosion, while aluminum and copper alloys are less susceptible. When aluminum and copper corrode in air, a protective oxide layer is formed on the surface of the metal. The oxide layer prevents oxygen from contacting the metal atoms underneath and protects the metal from further corrosion.[3]

Corrosion Inhibitors

Due to the corrosive impacts of chloride-based deicers to metal infrastructure, reinforced concrete, and motor vehicles, corrosion inhibitors are often added to deicers. Corrosion inhibitors are chemical substances added in small amounts that reduce or prevent the deterioration of metals in corrosive environments.

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[1] *Levelton Consultants Limited, "Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts," National Cooperative Highway Research Program Report 577, 2007.*

[2] *Massachusetts Department of Transportation, "MassDOT Snow and Ice Control Program 2017 Environmental Status and Planning Report," EEA# 11202, 2017.*

[3] *Levelton Consultants Limited, 2007, op. cit.*

According to a 2014 Idaho Transportation Department research report, the Wisconsin Department of Transportation (WisDOT) uses corrosion inhibitors in 10 to 50 percent of dry salt and salt brine applications.[4]

Several types of corrosion inhibitors exist. Some inhibit the electrochemical reactions that occur at the anode or cathode sites on the metal. Others form a physical barrier on metal surfaces that inhibits corrosion. Anodic inhibitors include phosphates, carbonates, and silicates. These are highly effective at preventing corrosion of iron-based alloys in a laboratory testing. However, when they are present at low concentrations such as when they become diluted, anodic inhibitors may increase rather than inhibit corrosion in localized areas. Cathodic inhibitors include calcium bicarbonate, zinc ions, polyphosphates, and phosphonates. They are generally less effective than anodic inhibitors; however, they are considered safer than anodic inhibitors because they can decrease general corrosion without increasing localized corrosion attacks.[5] Inhibitors that form a physical barrier include organic compounds derived from agricultural biproducts, such as juice from sugar beets. In general, they protect metals by physical adsorption, chemisorption, and film formation on the metal surface.[6]

The formulations of most commercially available inhibitors are proprietary and are generally derived from agricultural byproducts. This makes them difficult to classify or study. It is worth noting that while these commercial inhibitors in deicers reduce corrosion of metal infrastructure, they can have other impacts on the environment. For example, the beet juice used in many commercial inhibitors can increase biochemical oxygen demand and deplete oxygen levels in waterways. Similarly, the phosphorous compounds used in many commercial inhibitors may contribute to eutrophication of surface waterbodies. The sensitivity of receiving waters to these compounds can vary widely. The quantity, type, and application locations of corrosion inhibitors should be adapted based on local conditions. For example, the application of corrosion inhibitors can be reduced or eliminated near waterbodies with algal bloom issues.

4.3 DEICER-INDUCED CONCRETE DETERIORATION MECHANISMS

Concrete structures including roads, buildings, and bridges are susceptible to deterioration caused by deicers. Portland cement concrete is a hardened composite material made from stone and sand aggregates

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[4] *P.C. Casey, C.W. Alwan, C.F. Kline, G.K. Landgraf, and K.R. Linsenmayer, "Impacts of Using Salt and Salt Brine for Roadway Deicing," Idaho Transportation Department Research Report, 2014.*

[5] *Levelton Consultants Limited, 2007,* op. cit.

[6] *Ibid.*

bonded together by hydrated cement paste. In most infrastructure applications concrete is reinforced with steel reinforcement bars (rebar). Examples of infrastructure built with steel-reinforced concrete include bridge decks and abutments, road expansion joints, and building support structures. Based on current research, three primary concrete deterioration mechanisms have been identified which include physical damage caused by salt scaling, chemical reactions between deicers and cement binders, and alkali-aggregate reactions increased by deicers.

Salt Scaling Effect

During winter conditions, freeze-thaw cycles for water in the concrete cement pores produce expansive forces that cause scaling on the concrete surface. This scaling removes the cement paste on the surface layer and successively removes lower cement paste layers. As cement is removed, concrete aggregates and sand are exposed to the environment, encouraging further damage to the concrete. Figure 4.3 shows concrete scaling damage. The rate at which scaling occurs and the magnitude of scaling damage are significantly increased in the presence of deicers. The precise mechanism of salt scaling damage is not well understood. Several mechanisms have been proposed including the following: [7]

- Salt applications increase the frequency of freeze-thaw cycles that cause progressive expansion of the cement paste due to hydraulic pressure in the cement pores

- Salt concentration gradients in the concrete cause water movement in the cement pores that creates osmotic pressure in the concrete during freezing conditions

- Salt in the cement pore solutions create differences in vapor pressure between liquid water and ice that cause water movement in the concrete

- Crystallization of salt can occur as saline water in the concrete freezes

- Glue spall may occur (see Figure 4.4). Ice contracts and expands with temperature change more than concrete. When water freezes over a concrete surface, its contraction and expansion create tensile stress on the concrete surface. When the surface ice fractures under tension, the cracks can penetrate

[7] *J. Cao,* A Study of Effects of a New Agricultural-Based Deicer on the Properties of Pavement Concrete*, Master's Thesis, Iowa State University, Ames, Iowa, 2014.*

the concrete substrate and propagate below the interface causing spalling. Salt can weaken the ice and promote these factures to occur.

Salt scaling likely results from a combination of different processes. Although the mechanism cannot be fully explained, the characteristics of salt scaling and the factors affecting scaling damage are well studied and understood. The water to cement ratio in the concrete, amount of cement in the concrete, amount of air entrained in the concrete, the surface finish of the concrete, and the addition of supplementary cementitious materials like fly ash, slag, and silica fume can be manipulated to improve resistance to salt scaling.[8]

Cement Paste Reactions

Chloride-based deicing chemicals that enter into chemical reactions with Portland cement paste can damage concrete. The reaction with $MgCl_2$ is more destructive to concrete than those with NaCl and $CaCl_2$. The strength of concrete is primarily derived from the reaction between cement and water. During hydration of Portland cement, calcium-silicate-hydrate (C-S-H) is formed. This provides strength and binding capacity in concrete. $MgCl_2$ reacts with C-S-H in the cement paste to produce $CaCl_2$ and a non-cementitious magnesium-silicate hydrate (M-S-H). M-S-H has a very low binding capacity. Its formation causes physical crumbling of the concrete. When $CaCl_2$ deicers are used on concrete containing dolomite aggregates, the $CaCl_2$ accelerates dedolomitization reactions to release magnesium that form additional M-S-H.[9]

During freeze-thaw cycles, chloride reacting with cement paste can cause decalcification of the cement. When calcium bearing minerals in concrete dissolve during freezing, the available calcium hydroxide in the pore solution reacts with chloride ions to form oxychloride crystals. This leads to calcium leaching from the concrete, which weakens it.[10]

Out of the three primary chloride-based deicers (NaCl, $CaCl_2$, and $MgCl_2$), $MgCl_2$ causes the most severe deterioration of concrete by damaging the strength of the cement matrix. NaCl has been shown to cause the least damage to the cement matrix in concrete structures.[11]

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[8] G. Xu and X. Shi, "Impact of Chemical Deicers on Roadway Infrastructure: Risks and Best Management Practices," Chapter 11 in: X. Shi and L. Fu (editors), Sustainable Winter Road Operations, Wiley Blackwell, 2018.

[9] Levelton Consultants Limited, 2007, op. cit.

[10] G. Xu and X. Shi, 2018, op. cit.

[11] Levelton Consultants Limited, 2007, op. cit.

Alkali-Aggregate Reactions

Chloride compounds can also increase the occurrence of two alkali-aggregate reactions within concrete. The two reactions are alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

ASR is caused by chemical interactions between alkalis within the cement and silica in the aggregate. While the overall reaction is a complex process, ASR can result in the production of two gels. These gels are produced when alkali cations interact with reactive silica. An expansive gel can produce internal stresses within concrete that cause cracking. One gel produced in the ASR reaction is a calcium-alkali-silicate-hydrate that is not expansive. The other is an alkali-silica-hydrate that is expansive. Damage to concrete will not occur when only the non-expansive gel is formed; however, formation of both gels can lead to cracking. Exposure of concrete to NaCl can increase the pH of the concrete pore solution which creates more favorable conditions for ASR reactions. $CaCl_2$ and $MgCl_2$ have less effect on ASR reactions because they decrease the pH of the concrete pore solution.

ACR occurs in concrete containing dolomite aggregates. In ACR, brucite ($Mg(OH)_2$) and calcite ($CaCO_3$) crystals are produced as a result of reactions between dolomite in the aggregate and portlandite in the cement. Crystal formation produces internal pressure in the concrete that can lead to fracturing. Exposure of dolomite-containing concrete to $CaCl_2$ and $MgCl_2$ can increase the amount of crystal formation because it makes additional Mg^{2+} and Ca^{2+} ions available to the reactions.[12]

Effects on Reinforcing Steel in Concrete

Steel is used in reinforced concrete to provide tensile and shear strength. Steel is a good material to reinforce concrete with because its rate of expansion with temperature is similar to that of concrete and the cement paste in concrete will conform to the surface of the steel as it dries, allowing stresses to be passed between the concrete and steel. The reinforcement is often accomplished by embedding steel bars (rebar) or meshes in the concrete.

Rebar corrosion caused by deicers compromises the strength and shortens the service life of concrete infrastructure. Under normal circumstances, the concrete cover provides physical and chemical protection for the reinforcing steel. The embedded steel is protected from corrosion by the high pH of the concrete pore solution. This produces an oxide/hydroxide film on the surface of the steel that act as a chemical barrier

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[12] X. Shi, M. Akin, T. Pan, L. Fay, Y. Liu, and Z. Yang, "*Deicer Impacts on Pavement Materials: Introduction and Recent Developments,*" The Open Civil Engineering Journal *3:16–27, 2009.*

to corrosion.[13] Salt scaling, cement paste reaction, and alkali-aggregate reactions can compromise the concrete cover, allowing chloride, oxygen, and water to move through the concrete cover and reach the embedded steel.

Once the concrete has become compromised, chloride-induced steel corrosion discussed in section 4.2 can initiate in the steel rebars. The volume of the rust produced by corrosion is greater than that of the parent steel. Because of this, corrosion increases the internal pressure applied to the concrete by the rebar, eventually resulting in cracking of the concrete. Figure 4.5 shows a photo of a reinforced concrete beam damaged by rebar corrosion and Figure 4.6 illustrates this process.

Some deicers may cause greater corrosion of steel-reinforcement in concrete than others. $MgCl_2$ and $CaCl_2$ can decrease the pH of the cement paste. Since the embedded steel is chemically protected by the high pH of the concrete, this pH reduction can further increase the rate of rebar corrosion.[14] Additionally, laboratory testing has shown that $MgCl_2$ and $CaCl_2$ diffuse more quickly through concrete than NaCl. For example, the diffusion coefficient of $MgCl_2$ through Portland cement was 3 times greater than that of NaCl.[15,16] This suggests that $MgCl_2$ and $CaCl_2$ pose a greater risk of corrosion to reinforcing steel in concrete than NaCl; however, conflicting results have been reported in literature. A 2013 literature review concluded that most studies reported that $MgCl_2$ causes the greatest amount of damage to reinforced concrete while NaCl causes the least.[17] Conversely, a 2010 study concluded that NaCl causes the most damage to reinforced concrete followed by $CaCl_2$ and then $MgCl_2$.[18] More research may be needed to resolve this point.

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[13] *Levelton Consultants Limited, 2007, op. cit.*

[14] Ibid.

[15] *R. Kondo, M. Satake, and H. Ushiyama, "Diffusion of Various Ions into Hardened Portland Cement," paper presented at 28th General Assembly of the Cement Association of Japan, Tokyo, 1974.*

[16] *J. Deja and G. Loj, "Effects of Cations Occurring in the Chloride Solutions on the Corrosion Resistance of Slag Cementitious Materials," paper presented at Infrastructure Regeneration and Rehabilitation, Improving the Quality of Life Through Better Construction: A Vision for the New Millennium, Sheffield, United Kingdom, 1999.*

[17] *E.S. Sumsion and W.S. Guthrie, "Physical and Chemical Effects of Deicers on Concrete Pavement: Literature Review," Prepared for the Utah Department of Transportation Research Division by Brigham Young University, Department of Civil and Environmental Engineering, 2013.*

[18] *X. Shi, Y. Liu, M. Mooney, M. Berry, B. Hubbard, and T.A. Nguyen, "Laboratory Investigation and Neural Networks Modeling of Deicer Ingress into Portland Cement Concrete and its Corrosion Implications,"* Corrosion Reviews*, 28:105– 154, 2010.*

Some concrete manufacturing techniques have been shown to improve concrete durability in the presence of deicers. Additives to the concrete mix such as fly ash and silica fume have been shown to reduce the permeability of concrete.[19] Reducing the water-to-cement ratio to below 0.4 has been shown to increase concrete strength.[20] Greater than 3 percent air entrainment has been shown to increase its resistance to frost damage.[21] Regular washing programs can also help to increase the life of concrete structures.

Effects on Asphalt Concrete

Asphalt concrete (asphalt) and Portland cement concrete (concrete) differ mainly in the binding material used: bitumen and Portland cement, respectively. Bitumen is a complex hydrocarbon material produced from petroleum production. It is an excellent binding material in asphalt because of its inherent adhesive properties. Portland cement is a fine powder material made from processing a mixture of limestone and clay. When Portland cement reacts with water, it hardens and becomes the binding material in concrete. Both asphalt and concrete are used in road and pavement construction. Asphalt is not used for constructing load-bearing members due to the viscosity of bitumen. This causes asphalt to undergo time dependent deformation under load especially at high temperatures.

As with concrete, asphalt can be affected by deicers; however, due to the physical and chemical differences described above, the mechanisms are different from those that affect concrete. The effects of salt on asphalt are very complex and not fully understood. In general, studies show that at low temperatures deicers compromise its fatigue resistance properties and reduce its rutting resistance by decreasing the stiffness of asphalt.[22,23] In particular, chloride-based deicers can weaken the bond between bitumen and aggregate, shortening the service life of the asphalt pavement.[24]

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[19] *Massachusetts Department of Transportation, 2017,* op. cit.

[20] *Levelton Consultants Limited, 2007,* op. cit.

[21] *G. Xu and X. Shi, 2018,* op. cit.

[22] *X. Yu, Y. Wang, Y. Luo, and L. Yin, "The Effects of Salt on Rheological Properties of Asphalt after Long-term Aging,"* The Scientific World Journal*, pages 1–10, 2013.*

[23] *L. Wang, Y. Cui, Z. Liu, and W. Huang, "Influence of Salt Freezing on Asphalt Mortar's Stiffness Modulus," paper presented at the International Conference on Transportation Engineering, American Society of Civil Engineers, Chengdu, China, 2013.*

[24] *D. Feng, J. Yi, D. Wang, and L. Chen, 2010,* op. cit.

Alternative Non-Chloride Deicers

Other non-chloride-based deicer compounds also exist. These include calcium magnesium acetate (CMA), potassium acetate, potassium formate, sodium acetate, sodium formate, and urea. These are widely used as alternatives to chloride-based deicers in airports because of their reduced risk of corrosion to aircraft parts; however, their higher costs limit their use on roadways.[25] Acetates and organic deicers have been shown to cause deterioration of concrete pavements through different mechanisms than chloride-based deicers.[26] They can also contribute biochemical oxygen demand to receiving waters which can affect water quality.[27] Non-chloride deicers are not the focus on this study and will not be discussed in detail in this report. For further discussion on these and other non-chloride deicers, see SEWRPC Technical Report No. 66, *State of the Art of Chloride Management* (in development).

4.4 CHORIDE IMPACTS TO MOTOR VEHICLES AND INFRASTRUCTURE

Motor vehicle and infrastructure corrosion and deterioration induced by chloride road salts have been widely observed and documented since road salt use became widespread during the 1960s. Due to growing concerns over the impacts of deicing salt usage, the mechanisms through which chloride causes corrosion of infrastructure and motor vehicles have been extensively researched. While the quantitative impacts of deicers to infrastructure and the built environment are difficult to estimate, several studies have attempted to estimate the economic costs of damages caused by deicers. The results of these studies are summarized below. It is worth noting, however, that due to the age of some of these studies and the difficulty in accurately estimating specific costs associated with damages caused by road salt, the values presented should be interpreted with care.

Impacts to Motor Vehicles

The impact of corrosion on motor vehicles is one of the better studied topics. Several major studies have been conducted to estimate the total costs from vehicle corrosion and a few studies have attempted to estimate those costs attributable to roadway deicing only. The economic costs are first presented as stated in the original studies. These costs are then compared after computing the per vehicle unit costs and

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[25] *Levelton Consultants Limited, 2007,* op. cit.

[26] *G. Xu and X. Shi, 2018,* op. cit.

[27] *National Academies of Sciences, Engineering, and Medicine, "Formulations for Aircraft and Airfield Deicing and Anti-Icing: Aquatic Toxicity and Biochemical Oxygen Demand," Washington D.C., The National Academies Press, 2009.*

adjusting them for inflation to June 2021 dollars. When possible, the estimated total costs for the Region are also presented.

Impacts from All Sources of Corrosion

Table 4.1 shows nationwide estimated costs of corrosion from two studies. In a 1978 study conducted for the National Bureau of Standards (NBS), Battelle Columbus Laboratories (BCL) estimated the total direct and indirect annual cost of metallic corrosion across all industries in the U.S. to be $82 billion.[28] These costs accounted for 4.9 percent of the U.S. Gross National Product (GNP) in 1975. The study attributed about $31 billion of these costs to the automotive industry. More specifically, the annual cost of corrosion protection for new privately-owned vehicles was estimated to be $937 million nationwide. The costs of corrosion-related maintenance and repairs to privately-owned vehicles was estimated to be $5 billion per year. These estimates were all given in 1975 dollars.

The BCL/NBS study was updated in 1995 (see Table 4.1).[29] The update attempted to account for the significant improvements to anticorrosion technology and practices that had occurred since the original study was published, particularly those in the automotive industry. Implementation of stainless steel, coated metal, and protective finishes in many industries had reduced the costs due to corrosion in the U.S. The study noted though that certain corrosion costs had increased due to expanded regulations. It cited regulations prohibiting the use of certain methods of corrosion protection that were implemented due to their negative impacts to public safety and the environment. The updated study estimated metallic corrosion costs in 1995 to be $296 billion per year across all industries. This amount accounted for economic growth in the U.S. and represented about 4.2 percent of GNP in 1995. Approximately $94 billion or 32 percent of the costs were attributed to motor vehicle corrosion.[30] The 1995 study update also found that 35 percent of total metallic corrosion costs could be avoided through broader application of corrosion-resistant materials and best practices. This was lower than the 40 percent that was estimated in the original 1978 study.

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[28] *Battelle Columbus Laboratories, "Economic Effects of Metallic Corrosion in the United States," Appendix B, NBS Special Publication 511-2, SD Stock No. SN-003-003-01926-5, 1978.*

[29] *Battelle Columbus Laboratories, "Economic Effects on Metallic Corrosion in the United States-Update," 1995.*

[30] *J.R. Davis, "The Effect and Economic Impact of Corrosion," Chapter 1 in: J.R. Davis,* Corrosion: Understanding the Basics, *ASM International, January 2000.*

A few other studies attempted to obtain more detailed estimates of costs associated with motor vehicle corrosion. In 1991, the Transportation Research Board (TRB) published a study that estimated corrosion protection costs in newly manufactured vehicles. The cost estimates ranged between $3.8 billion and $12.3 billion with an average of $7.7 billion (1989 dollars).[31] In 1998, an amendment to the Transportation Equity Act of the 21st Century mandated that a comprehensive study of the economic cost of corrosion be conducted. The Federal Highway Administration (FHWA) completed the required study in 2002.[32] This study estimated that the total annual direct cost of corrosion across all industry sectors of the U.S. economy was $276 billion, representing 3.1 percent of the 1998 U.S. Gross Domestic Product (GDP). The portion of this cost attributable to corrosion of motor vehicles was estimated to be $23.4 billion (1999 dollars). This cost consisted of $2.5 billion for new vehicle corrosion protection materials, $6.5 billion for repairs and maintenance to vehicles due to corrosion, and $14.4 billion for vehicle depreciation related to corrosion.[33,34]

To facilitate comparisons among the studies above, the costs were expressed as per vehicle costs and adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index (CPI). Table 4.2 summarizes the corrosion per vehicle costs. The estimated per vehicle unit costs for both new vehicle corrosion protection and used vehicle repairs and maintenance were lower in the 2002 FWHA study than those from the two earlier studies. The difference was attributed to the successful implementation of corrosion management strategies and the application of new anticorrosion technologies in the automotive industry.[35] However, it is worth noting that the studies differ in methodology and that any corrosion cost comparisons should be used with care.

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[31] *Transportation Research Board, "Highway Deicing: Comparing Salt and Calcium Magnesium Acetate," National Research Council, Washington D.C., 1991.*

[32] *G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, "Corrosion Cost and Preventative Strategies in the United States," U.S. Department of Transportation, Federal Highway Administration, NACE International, Report FHWA-RD-01-156, 2002.*

[33] *J.T. Johnson, "Corrosion Costs of Motor Vehicles," Appendix N in: G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, "Corrosion Cost and Preventative Strategies in the United States," U.S. Department of Transportation, Federal Highway Administration, NACE International, Report FHWA-RD-01-156, 2002.*

[34] *The motor vehicle numbers used in the study include automobiles and trucks, and do not include motorcycles and trailers.*

[35] *G. Koch, J. Varney, N. Thompson, O. Moghissi, N. Gould, J. Payer, "International Measures of Prevention, Application, and Economics of Corrosion Technologies Study," NACE International IMPACT, 2016.*

There are approximately 1.5 million[36] available automobiles and trucks registered in the seven counties served by SEWRPC (Region). Using the estimated figures from the 2002 FHWA study, the annual total cost of vehicle repairs and maintenance due to corrosion would be $79 million (2021 dollars), and the annual cost of vehicle depreciation due to corrosion would be $268 million (2021 dollars) in the Region.

Impacts from Corrosion Due to Roadway Deicing

The studies discussed in the previous section examined the cost of vehicle corrosion from all sources. In a literature review of studies that were conducted in the late 1960s and early 1970s, Jones and Jeffery concluded that approximately 50 percent of vehicle corrosion can be attributed to the use of road salt in snow impacted regions.[37] Based on the findings of the 2002 FHWA study, this would suggest that the total annual direct cost of vehicle corrosion including protection, repairs, and depreciation in the U.S. due to road deicing could be approximately $120 per vehicle (2021 dollars).[38] The estimated total annual cost for the Southeastern Wisconsin Region could be on the order of $180 million (2021 dollars).

Several studies have attempted to estimate the costs of vehicle depreciation resulting from corrosion caused by road salt (see Table 4.3). An early study carried out for the U.S. Environmental Protection Agency (USEPA) in 1976 estimated that the annual cost of vehicle depreciation due to road salt was approximately $1.4 billion or $14 per vehicle nationwide (1973 dollars).[39] A 1991 study by Menzies estimated the annual deprecation cost due to road salt by comparing vehicle deprecation in regions affected by both marine environments and road deicing to regions only affected by marine environments.[40] This study estimated that the annual per vehicle cost of depreciation due to road salt was $17 (1991 dollars). The 2002 FHWA study by Johnson employed a method similar to the study by Menzies. This study estimated an annual per

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[36] *2021 Wisconsin DOT Vehicle Registration information and SEWRPC estimates.*

[37] *P.H. Jones and B.A. Jeffrey, "Environmental Impact of Road De-icing," in F.M. D'Itri (editor),* Chemical Deicers and the Environment*, Boca Raton, Florida: Lewis Publishing, pages 1-97, 1992.*

[38] *Calculation used the estimate from the 2002 FHWA study that 60 percent of approximately 200 million vehicles in the U.S. at the time of publication were in the snow impacted regions of the U.S. The U.S. Bureau of Labor Statistics Consumer Price Index for June of each year was also used to adjust for inflation.*

[39] *D.M. Murray and W.F.W. Ernst, "An Economic Analysis of the Environmental Impact of Highway Deicing," United States Environmental Protection Agency, EPA-600/2-76-105, 1976.*

[40] *T.R. Menzies, "National Cost of Motor Vehicle Corrosion from Deicing Salts," Corrosion 91/399, Houston TX, NACE International, 1991.*

vehicle depreciation cost due to road salt of $32 (1999 dollars).[41,42] Based on this estimate, the total vehicle depreciation cost due to road salting in the U.S. in 1999 would have been $3.8 billion per year.[43] Based on the estimated cost in given in the 2002 FHWA study, the total annual vehicle deprecation cost due to road salt in the Southeastern Wisconsin Region could be approximately $78 million (2021 dollars).

The TRB study published in 1991 also estimated the per vehicle cost of corrosion protection as a direct response to road salt.[44] Based on survey of vehicle manufacturers, the estimate was between $125 and $250 per new vehicle (1989 dollars). When adjusted for inflation, this cost is between $274 and $547 per new vehicle (2021 dollars). Since vehicle registration data for newly manufactured vehicles are not available for the Region, the costs of corrosion protection due to roadway deicing for the Study area were not estimated.

Summary of Impacts to Motor Vehicles

National interest in quantifying the economic impacts of corrosion from all sources and corrosion due to road salt has led to several studies being done since the 1960s with the latest comprehensive study being completed in 2002. These studies concluded that corrosion affecting all industries carries a significant cost to the U.S. economy, which is equivalent to several percentage points of U.S. GDP. Nevertheless, costs due to corrosion have noticeably decreased, particularly in the automotive industry. Between 1975 and 1999 costs of new vehicle corrosion protection and used vehicle corrosion repair and maintenance from all sources of corrosion decreased by a factor of more than three (see Table 4.2). Similarly, between 1973 and 1999 vehicle depreciation costs due to corrosion from road salt also saw a significant reduction (see Table 4.3). These cost reductions can be attributed to improvements in the corrosion management techniques and implementation of anticorrosion technology in the automotive industry. Despite these improvements, the costs of motor vehicle corrosion from road salting are still appreciable. Based on the 2002 FHWA study and the 1992 Jones and Jeffery estimate, the total annual direct cost of vehicle corrosion due to road salt in the Southeastern Wisconsin Region is on the order of $180 million (2021 dollars). This estimate is based on studies conducted over 20 years ago. New corrosion protection technologies have likely been implemented

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[41] *J.T. Johnson, 2002,* op. cit.

[42] *These estimates do not consider the economic differences between the different regions of the U.S. being compared nor do they consider the possible movement of vehicles between regions at the point of sale.*

[43] *Johnson estimated 60 percent of approximately 200 million vehicles in the U.S. at the time of his study publication are in the snow impacted regions of the U.S., therefore $32/vehicle x 60% x 200 million vehicles = $3.8 billion.*

[44] *Transportation Research Board, 1991* op. cit.

since that time and now, the cost of vehicle corrosion may be lower. New studies would be needed to assess the current state of motor vehicle corrosion due to road salt with greater accuracy.

Impacts to Bridges

Two major studies have been conducted to evaluate the cost of corrosion damages to highway bridges in the U.S. The 2002 FHWA study previously discussed included estimated bridge costs from all sources of corrosion, and the previously discussed 1991 TRB study estimated bridge damage costs due to road salt.[45,46] Costs from both studies are first presented as stated in the original studies. Following this, the total estimated cost of damages to highway bridges in the Region due to road salt is presented in 2021 dollars.

Impacts from All Sources of Corrosion

According to the 2022 National Bridge Inventory (NBI) dataset,[47] there are currently over 620,000 highway bridges in the United States. Reinforced concrete bridges, including conventional and prestressed concrete, account for 428,000 or 69 percent of these bridges. Metal bridges, including those made from steel, aluminum, or iron account for 175,000 or 28 percent of the highway bridges in the U.S. Approximately 11 percent of all highway bridges are in poor structural condition.[48] Structural damages are primarily attributed to corrosion of metal and metal reinforcement in concrete.[49] As part of the 2002 FHWA study on the economics of corrosion, Yunovich estimated the annual direct cost of corrosion of highway bridges to be between $6.4 billion and $10.2 billion (1999 dollars).[50] These costs included the costs of replacing structurally deficient bridges ($3.8 billion), replacing and maintaining concrete bridge decks ($1.1 billion to $2.9 billion), replacing and maintaining concrete substructures and superstructures ($1.1 billion to $2.9 billion), and painting metal bridges ($0.5 billion). Additionally, life-cycle analyses estimated that the indirect costs of bridge corrosion due to lost productivity and traffic delays are more than 10 times that of the direct

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[45] *G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, 2002,* op. cit.

[46] *Transportation Research Board, 1991,* op. cit.

[47] *U.S. Federal Highway Administration, National Bridge Inventory, U.S. Department of Transportation, www.fhwa.dot.gov/bridge/nbi/ascii.cfm, accessed on July 28, 2022.*

[48] *Structural Evaluation rating of 4 or lower within the NBI dataset.*

[49] *G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, 2002,* op. cit.

[50] *M. Yunovich, N.G. Thompson, T. Balvanyos, and L. Lave, "Corrosion Costs of Highway Bridges," Appendix D in: G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Prayer, "Corrosion Cost and Preventative Strategies in the United States," U.S. Department of Transportation, Federal Highway Administration, NACE International, Report FHWA-RD-01-156, 2002.*

cost of corrosion. In the past two decades, progress has been made to improve the percentage of deficient bridge structures in the U.S. In year 2000, 18 percent of highway bridges were rated as being in poor or worse condition. Today, that number has dropped to 11 percent.[51] The median age of bridges in the U.S continues to increase. Between 2000 and 2022, the median age of American highway bridges increased from 35 years to 44 years. As the bridge infrastructure continues to age, additional bridge deterioration would be expected. In addition, the costs of repairing and replacing deteriorating bridge infrastructure will increase in the future.

Impacts from Corrosion Due to Roadway Deicing

Not all damage to bridges can be attributed to road salting; however, the effects of salt on bridge infrastructure are well known. During the 1950s and 1960s, many newly constructed bridge decks on Interstate highways used steel reinforcement positioned two inches below the concrete surface. Due to the shallow depth of the embedded steel, corrosion was observed soon after construction in regions where road salt was used. A few studies have attempted to estimate the costs of bridge damage associated with road salting. The 1991 TRB study previously discussed made the most recent comprehensive assessment of bridge damage costs.[52] This study estimated the total annual direct costs of bridge damage from road salt in the U.S. as being between $250 million and $650 million (1991 dollars). Half of the total cost were attributed to salt damage to bridge decks. Localized damage such as potholes often form after a portion of the bridge deck has been critically contaminated with chloride. While patching is commonly used to repair localized damage to decks, deterioration could continue after this type of damage despite patching repairs or discontinued use of road salt. It is estimated that in regions with heavy road salt use, decks unprotected by special waterproofing or sealants will reach a critical chloride contamination level within 10 to 15 years after construction.[53] Since 1984, the FHWA has required that corrosion protection be installed on all new bridges constructed with Federal assistance in states where road salt is used. Today, most bridges built in snow impacted regions use corrosion protection such as epoxy-coated reinforcing steel, waterproofing membranes, concrete covers or overlays, or catalytic protection. It should be noted that nearly 60 percent of all highway bridges in the U.S. in use today were built prior to 1984. Some of those bridges have already had their decks replaced, but a significant portion of them still require deck replacement.[54] The 1991 TRB study estimated that the total annual nationwide cost of repairing salt damage to bridge decks would be

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[51] *Calculated based on the U.S. Federal Highway Administration National Bridge Inventory dataset from 2000 and 2022.*

[52] *Transportation Research Board, 1991,* op. cit.

[53] Ibid.

[54] *U.S. Federal Highway Administration, 2022,* op. cit.

between $50 million and $200 million.[55] This study also estimated that the annual nationwide cost of providing deck protection to bridges would be between $75 million and $125 million. The TRB study committee also estimated that the annual costs of repairing other bridge components in the U.S. including grid decks, joints, drainage systems, and structural components such as bearings, steel framing and supports, and concrete support structures fall within the same range as repairing bridge decks, about $125 million to $325 million per year.

According to the 2022 NBI dataset, southeastern Wisconsin contains about 2,000 highway bridges.[56] Bridge conditions in the Region are generally better than the nationwide average. Only about 6 percent of bridges in the region have structural conditions rated poor or worse. The median age of highway bridges in southeastern Wisconsin is approximately 40 years. Based on the 1991 TRB study, the annual direct cost of damage to highway bridges due to road salt use in the Region would be between approximately $800,000 to $2.1 million (1991 dollars). When adjusted for inflation, the annual damage estimate range becomes $2.4 million to $6.3 million (2021 dollars).[57]

Summary of Impacts to Bridges

Since only a few studies have attempted to estimate road salt damage costs to bridges, no temporal trend can be determined. Two competing factors impact bridge damage trends: implementation of anticorrosion measures and the aging bridge infrastructure in the U.S. The implementation of corrosion protection techniques and technologies are extending the useful life of bridges. Advances in concrete construction, use of anticorrosion materials, and implementation of washing programs all potentially reduce damage due to road salt. By contrast, the current average ages of highway bridges in the U.S. and southeastern Wisconsin are 44 years and 40 years, respectively. These average bridge ages have also increased over time. As bridge infrastructure deterioration increases due to aging, bridges will become more susceptible to damage from road salt. Based on the 1991 TRB study, the total annual damages to highway bridges in the Region are estimated to be between $2.4 million and $6.3 million (2021 dollars). This estimate is based on studies conducted over 30 years ago. New studies are needed to assess the current state of bridge infrastructure damage with greater accuracy.

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[55] *Transportation Research Board, 1991,* op. cit.

[56] *U.S. Federal Highway Administration, 2022,* op. cit.

[57] *Inflation adjustment was based on the Engineering News-Record Construction Cost Index of 1991 and 2021.*

Impacts to Other Highway Components

The largest component of highway infrastructure is roadway pavement. Pavement damage caused by salt scaling during freeze-thaw cycles is perhaps the most well-known impact of road salt on roadways. Poor quality pavement produced by improper curing, finish, air entrainment, or water content have in the past caused rapid deterioration of roadways in northern states. In recent decades, the effects of road salt on concrete and asphalt have become better understood. Pavement damage caused by road salting is no longer as serious a concern as it once was.[58] Today, quality control of pavement construction has vastly improved. Improved practices like the use of air entrainment, the reduction of water to cement ratios, the use of sealants, and the use of additives such as fly ash and silica fume have resulted in more durable pavement in snow impacted regions.[59] The durability of concrete expansion joints remains a concern for concrete pavement. Premature deterioration has been observed at the joints where the pavement is more accessible to moisture, debris, and chlorides. More frequent maintenance and the use of sealants have been proposed to mitigate this concern.[60]

The 1991 TRB study also assessed salting impacts to highway drainage systems, highway fixtures and accessories, and sidewalks and driveways. The study concluded that salt was not a significant factor affecting the durability of these highway components. Other factors such as traffic stress, normal wear, erosion, and soil settlement had the greatest effect on the deterioration of these roadway components.

Based on limited available information, the 1991 TRB committee concluded that road salt is not a major factor for damage to pavements and other highway components. The TRB roughly estimated a total annual nationwide cost of $100 million (1991 dollars).[61]

Impacts to Buildings

Road salt can cause deterioration of buildings through the same mechanisms as those through which it impacts bridges and roads. The lower portions of buildings located along high traffic roads where road salts are applied may be particularly vulnerable. Their exteriors can deteriorate with long term exposure to road

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[58] *Transportation Research Board, 1991,* op. cit.

[59] *Massachusetts Department of Transportation, 2017,* op. cit.

[60] *P. Suraneni, J. Monical, E. Unal, Y. Farnam, C. Villani, T.J. Barrett, and W.J. Weiss, "Performance of Concrete Pavement in the Presence of Deicing Salts and Deicing Salt Cocktails," Indiana Department of Transportation and Purdue University, Report FHWA/IN/JTRP-2016/25, 2016.*

[61] *Transportation Research Board, 1991,* op. cit.

salt. Normal vehicle traffic and winter snow and ice control vehicles can splash water and salt onto building walls, initiating chloride induced damage to building structures. It is likely that this kind of damage is uncommon in the U.S. Most municipalities have minimum building setback ordinances that prevent buildings from being constructed immediately next to roadways. Building damage caused by deicing operations might occur in some densely developed city centers. The extent of such damage is largely unknown, and no estimates are available that quantify the costs of this sort of damage in the U.S. It is likely that the costs related to this type of damage from road salt are relatively small.

Road salt impacts to parking structures, however, may be more significant in regions where deicing is prevalent. During snow seasons, vehicles can transport snow and salt into parking structures. The water and chlorides from melted snow can reach exposed metal components and seep into cracks in the reinforced concrete and the deterioration process would be similar to that of bridges. When poorly maintained, parking structures can quickly lose their serviceability. The 1991 TRB study previously discussed estimated that between 50 and 150 parking structures in the U.S. would require rehabilitation annually due to salt damage.[62] The annual cost of this would be between $50 million and $150 million (1991 dollars). This figure might be lower today as more parking structures are being built with protective systems against chloride degradation such as sealants, membranes, coated reinforcing steel, and better drainage systems. The TRB estimated that the nationwide cost of including salt corrosion protection on the approximately 200 new parking garages built each year would be approximately $25 million per year (1991 dollars).

Impacts to Water Supply Infrastructure

Elevated levels of chloride in drinking water have the potential to corrode water distribution systems, reducing the life of drinking water infrastructure, causing leaks, and degrading drinking water quality. Specifically, the release of lead and copper resulting from the corrosion of water distribution pipes is of major concern. Several studies have found links between high chloride concentrations in finished drinking water and the corrosion of water mains and service lines.[63,64,65] During the 2014 Flint, Michigan water utility

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[62] *Transportation Research Board, 1991,* op. cit.

[63] *American Water Works Association,* Internal Corrosion of Water Distribution Systems*, Second edition, AWWA Research Foundation/DVGW-TZW, Denver, CO, 1996.*

[64] *M. Edwards and S. Triantafyllidou, "Chloride-to-Sulfate Mass Ratio and Lead Leaching to Water,"* Journal of the American Water Works Association, *99:86-109, 2007.*

[65] *C.K. Nguyen, B.N. Clark, K.R. Stone, and M.A. Edwards, "Role of Chloride, Sulfate, and Alkalinity on Galvanic Lead Corrosion,"* Corrosion*, 67, doi: 10.5006/1.3600449, 2011.*

crisis where high lead levels were found in the distribution system, elevated chloride concentrations and chloride-sulfate mass ratio (CSMR) were also observed. [66]

In a 2018 paper, researchers examined trends in chloride concentrations and CSMR in surface waters across the continental U.S.[67] The study found that during the period 1992 through 2012, both chloride concentrations and CSMR increased. The trend was especially strong for urban areas in cold-weather months, suggesting that road salt use could be the main contributor of chloride. Since typical drinking water treatments do not remove chlorides, high chloride concentrations in the source water would be retained in the finished water. In the study, the researchers also found an association between the chloride levels and exceedances of the lead action level (ALEs) in drinking water system monitoring samples. Statistical correlation was observed between the increase in surface water CSMR and the increase in the occurrences of lead ALEs, leading to a potential connection between the quality of the source water and corrosion of water distribution systems.

Another paper examined the extent of chloride concentrations in groundwater and its impact on private well infrastructure in the State of New York.[68] Using data from citizen science sampling, the study found that chloride concentrations in private wells were highest downgradient of road salt storage facilities and within 30 meters (100 feet) of major roadways. Using bench-scale testing, the study found that increased chloride levels in synthetic well water increased galvanic corrosion of wells and home plumbing. Private wells are especially susceptible to this type of corrosion since galvanized iron is still commonly used in well construction. Based on modeling results, the study suggested that potentially two percent of the private wells in the State of New York could be impacted by road salt storage facilities and 24 percent could be impacted by road salt applications.

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[66] *K.J. Pieper, M. Tang, and M.A. Edwards, "Flint Water Crisis Caused by Interrupted Corrosion Control: Investigating "Ground Zero" Home,"* Environmental Science and Technology, *51, 2007–2014, 2017.*

[67] *E. G. Stets, C. J. Lee, D. A. Lytle, and M. R. Schock. "Increasing Chloride in Rivers of the Conterminous U.S. and Linkages to Potential Corrosivity and Lead Action Level Exceedances in Drinking Water,"* Science of the Total Environment, *613–614:1,498–1,509, 2018.*

[68] *K.J. Pieper, M. Tang, C.N. Jones, S. Weiss, A. Greene, H. Mohsin, J. Parks, and M.A. Edwards, "Impact of Road Salt on Drinking Water Quality and Infrastructure Corrosion in Private Wells,"* Environmental Science & Technology, *52, 14,078-14,087, 2018*

Chloride impacts to water supply infrastructure is an emerging area of study. The extent of the impact is still not fully understood. More research is needed on the effects of chloride on both private wells and municipal water supply infrastructure.

Chlorine and Chloride Distinctions in Drinking Water Supply

In the context of water supply infrastructure, it is important to clarify the distinction between chlorine and chloride. Chlorine is a chemical used in drinking water treatment plants to disinfect drinking water by killing harmful parasites, bacteria, and viruses. Chlorine is often introduced to drinking water as sodium hypochlorite (NaClO). When NaClO is dissolved in water, chlorine is released. The use of chlorine in water treatment is an important step to provide safe drinking water. After the initial chlorination of drinking water at the treatment plant, a low level of residual chlorine is typically maintained in the drinking water distribution system to safeguard against water contamination in route to the end user. The residual chlorine present in water distribution system is chemically very different from chloride. Chloride, which is the negatively charged ionic form of chlorine, enters the drinking water distribution system due to the dissolution of chloride salts in the environment. While chloride ions corrode water distribution pipes and promote the release of lead and copper that are harmful to human health, chlorine residuals do not.

Impacts to Power Distribution Systems

Some anecdotal information suggests that road salt can degrade insulators surrounding electrical wiring and equipment. When road salt is used, some salt can become airborne (see Chapter 2 of this report). This salt can be deposited and accumulate on electrical structures and suspended wiring. As the chlorides degrade the insulators around the electrical equipment, the insulators can become slightly conductive resulting in current leaks that can cause current disruption, shorting of transmission lines, and fires on wooden electric poles.[69] In 2001, Wisconsin Electric in Milwaukee indicated that during the 2000 winter season, about 15 pole fires and many power outages occurred after the salting of roads.[70] More recently, power outages in Nova Scotia, Canada were also blamed on salt contamination both from sea water and from road salt.[71]

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[69] *Levelton Consultants Limited, 2007,* op. cit.

[70] *Pure Power, "Road Salt Causes Power Outages," March 1, 2001, www.csemag.com/articles/road-salt-causes-power-outages/, accessed September 12, 2022.*

[71] *Canada Broadcasting Corporation, "The Science Behind the Salty Towers Causing Nova Scotia Power Outages," January 13, 2018, www.cbc.ca/news/canada/nova-scotia/salt-air-power-lines-nova-scotia-electricity-1.4483369, accessed September 12, 2022.*

Concerns have also been expressed about potential impacts of chloride salts on underground utility lines and electric power equipment. Several power utilities in the U.S. have claimed that high chloride contamination of soil from road salts have caused short circuits and burnouts of underground electric power transformers, switches, and service cables.[72] The Electric Power Research Institute, however, has stated that the likelihood of corrosion damage to underground electrical utilities due to high salt concentrations is low since most buried service cables are well insulated.[73] It should be noted, though, that issues can arise in older electrical systems that are not well insulated.[74]

No formal studies exist regarding road salt impacts to power distribution systems. All the available information is anecdotal. More research is needed to determine the frequency, mechanism, and magnitude of the potential issue.

Impacts to Railway Traffic Control Signaling

Anecdotal information is also available regarding the impact of road salt on railroad traffic control devices. Train detection on modern railways often relies on transmission of electrical signals through the rails. The presence of trains interrupts electric circuits established on different sections of rail tracks. This information is used to detect the locations and speeds of trains. When a train is detected, traffic warning signals and gates are activated. Signal transmission through the rails can be impacted by ionic salt solutions due to their effect on electrical conductivity. Triggering of train signals without the presence of a train and early initiation of train signals has been attributed to the presence of road salt at railroad crossings.[75] Some cases of train signals failing to activate have also been attributed to road salt usage. In 2011, two vehicles collided with a stopped train in Chicago resulting in serious injuries because the warning signals and gates were not activated. The incident was attributed to an electrical shorting caused by road salt.[76]

The extent and severity of the impacts of road salt on railway traffic signaling is currently unknown. Only cases with extremely high concentrations of road salt solution have been observed to affect railway traffic

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[72] *Transportation Research Board, 1991,* op, cit.

[73] Ibid.

[74] Ibid.

[75] *Levelton Consultants Limited, 2007,* op. cit.

[76] CBS News Chicago, "Road Salt to Blame for Railroad Gate Failure?," February 15, 2011, *www.cbsnews.com/chicago/news/road-salt-to-blame-for-railroad-gate-failure/, accessed September 12, 2022.*

control signaling. Some limited field tests conducted by state departments of transportation have failed to reproduce the observed traffic signaling issues.[77]

Cost-Benefit of Road Salting

Road salting for snow and ice maintenance provides significant benefits to roadway safety and prevents economic losses from road closures. In a 1992 study by Marquette University, researchers analyzed accident statistics and economic costs related to snow and ice operations in the states of New York, Illinois, Minnesota, and Wisconsin.[78] The study compared accidents during winter storm events before and after road salt was applied. It found that after road salt was applied, injuries caused by accidents and the associated costs were reduced by 88 percent for two-lane highways and 85 percent for freeways. The average cost of an accident after road salt was applied was reduced by 10 percent for two-lane highways, and by 30 percent for freeways. The study estimated that $1 spent on direct winter maintenance operation can provide $7 in direct economic benefits for two-lane highways and $4 for freeways. It should be noted that the observed reduction in accidents should not be fully attributed to winter maintenance operations. The reduction in traffic volume as winter storms progress can explain some of the reduction in accidents. Later studies documented that the economic benefits of road salt usage can be much more complex than was presented in the Marquette study. In a 2006 snowstorm crash analysis study, the authors noted that the benefits of road salting can vary significantly depending on the type and severity of winter storms, driver behavior, pavement conditions, visibility, vehicle types, and the timing of deployment of snowplows and salt spreaders.[79] For example, it was concluded that early deployment of winter maintenance operations can improve crash prevention and that delays between salting and snowplowing can result in more crashes. More research is required to better quantify the benefits of road salting.

Regarding the costs of road salting, WisDOT reported that in the winter of 2019/2020, the average cost of road salt purchased was $80 per ton and accounted for 35 percent of the total winter maintenance costs.[80] Based on this figure, the cost of labor and equipment for winter maintenance during the 2019/2020 winter season would have been approximately $150 per ton of road salt used. These figures are similar to what

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[77] *Levelton Consultants Limited, 2007,* op. cit.

[78] *D.A. Kuemmel and R.M. Hanbali, "Accident Analysis of Ice Control Operations," Transportation Research Center, Marquette University, 1992.*

[79] *X. Qin, D.A. Noyce, C. Lee, and J.R. Kinar, "Snowstorm Event-Based Crash Analysis,"* Transportation Research Record*, 1948: 134-141, 2006.*

[80] *Wisconsin Department of Transportation, "Annual Winter Maintenance Report 2020/2021", 2021.*

was reported by several Minnesota studies. [81,82] As discussed in previous sections, the costs of salt usage are not the only costs associated with road salting. Costs also include motor vehicle, infrastructure, and environmental damage caused by its usage. In 1976, an USEPA study estimated that the national cost of salt-related damages to vehicles and infrastructure was 15 times higher than the cost to purchase and apply road salt.[83] Applying this estimate to the WisDOT reported road salt costs yields $3,450 of damages per ton of road salt used. In a later 1992 study, $803 of vehicle and infrastructure damages per ton of road salt applied was estimated.[84] After adjusting for inflation, that damage estimate would be approximately $1,550 per ton of road salt used (2021 dollars). Based on these estimates, $1 spent on direct winter maintenance operation can cause between $7 and $15 of damages to motor vehicles and infrastructure.

Based on the studies mentioned above, the lower estimate of damages is approximately equal to the higher estimate of economic benefits of road salting.[85] In terms of accident economics, it can be roughly concluded that the costs of road salting may be equal to but is likely greater than the benefits of road salting. However, the estimated benefits of road salting were purely in terms of accident economics and do not factor in the value of commerce, human life, and transportation safety. When those are accounted for, the benefits most likely outweigh the costs of road salting. Nevertheless, value can be gained from reducing the usage of road salt. The quantity and strategy of road salt applications can be optimized to provide roadway safety benefits while reducing damages to the natural and built environment. A further discussion on the state-of-the-art road salt usage, application strategies, and alternatives can be found in SEWRPC Technical Report No. 66, *State of the Art of Chloride Management* (in development).

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[81] *C. Dindorf, C. Fortin, B. Asleson, and J. Erdmann, "The Real Cost of Salt Use for Winter Maintenance in the Twin Cities Metropolitan Area," Fortin Consulting, Inc. and Minnesota Pollution Control Agency, 2014.*

[82] *H. Stefan, E. Novotny, A. Sander, and O. Mohseni, "Study of Environmental Effects of De-icing Salt on Water Quality in the Twin Cities Metro Area, Minnesota," Minnesota Department of Transportation, Local Road Research Board, Report 2008-42, 2008.*

[83] *D.M. Murray and U.F. Ernst, 1976,* op. cit.

[84] *D.F. Vitaliano, "An Economic Assessment of the Social Costs of Highway Salting and the Efficiency of Substituting a New Deicing Material,"* Journal of Policy Analysis and Management*, 11(3): 397-418, 1992.*

[85] *It should be noted that these estimates are highly approximate and should be used with caution.*

Chapter 4

IMPACTS OF CHLORIDES ON INFRASTRUCTURE AND THE BUILT ENVIRONMENT

TABLES

Table 4.1
**Cost Estimates of Metallic Corrosion
in the United States**

	Annual Direct and Indirect Cost of Corrosion (billion dollars)	
	1978 BCL Study[a]	1995 BCL Update[b]
All Industries		
Total	82.0	296.0
Avoidable	33.0	104.0
Automotive Industry		
Total	31.4	94.0
Avoidable	23.1	65.0

[a] *Reported in 1975 dollars*

[b] *Reported in 1995 dollars*

Source: Battelle Columbus Laboratories, Economic Effects of Metallic Corrosion in the United States, 1978 and Update, 1995

Table 4.2
Annual Cost Estimates of Vehicle Corrosion from All Sources

	Annual Cost Per Vehicle (dollars)					
	1978 BCL Study		1991 TRB Study		2002 FHWA Study	
	1975 dollars	2021 dollars[a]	1989 dollars	2021 dollars[a]	1999 dollars	2021 dollars[a]
New Vehicle Corrosion Protection	140 to 210	710 to 1,064	250 to 800	547 to 1,751	150	245
Used Vehicle Corrosion Repairs and Maintenance	46	236	--	--	32	53

[a] *Adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index for June of each year*

Source: Battelle Columbus Laboratories, Economic Effects of Metallic Corrosion in the United States, 1978; Transportation Research Board, Comparing Salt and Calcium Magnesium Acetate, 1991; Federal Highway Administration, Corrosion Cost and Preventative Strategies in the United States, 2002

Table 4.3
Annual Cost Estimates of Vehicle Deprecation Due to Corrosion by Road Salt

	Annual Cost Per Vehicle (dollars)					
	1976 EPA Study		1991 Menzies Study		2002 FHWA Study	
	1973 dollars	2021 dollars[a]	1991 dollars	2021 dollars[a]	1999 dollars	2021 dollars[a]
Depreciation Due to Corrosion by Road Salt	14	86	17	34	32	52

[a] *Adjusted for inflation using the U.S. Bureau of Labor Statistics Consumer Price Index for June of each year*

Source: Environmental Protection Agency, An Economic Analysis of the Environmental Impact of Highway Deicing, 1976; Menzies T.R., National Cost of Motor Vehicle Corrosion from Deicing Salts, 1991; Federal Highway Administration, Corrosion Cost and Preventative Strategies in the United States, 2002.

Chapter 4

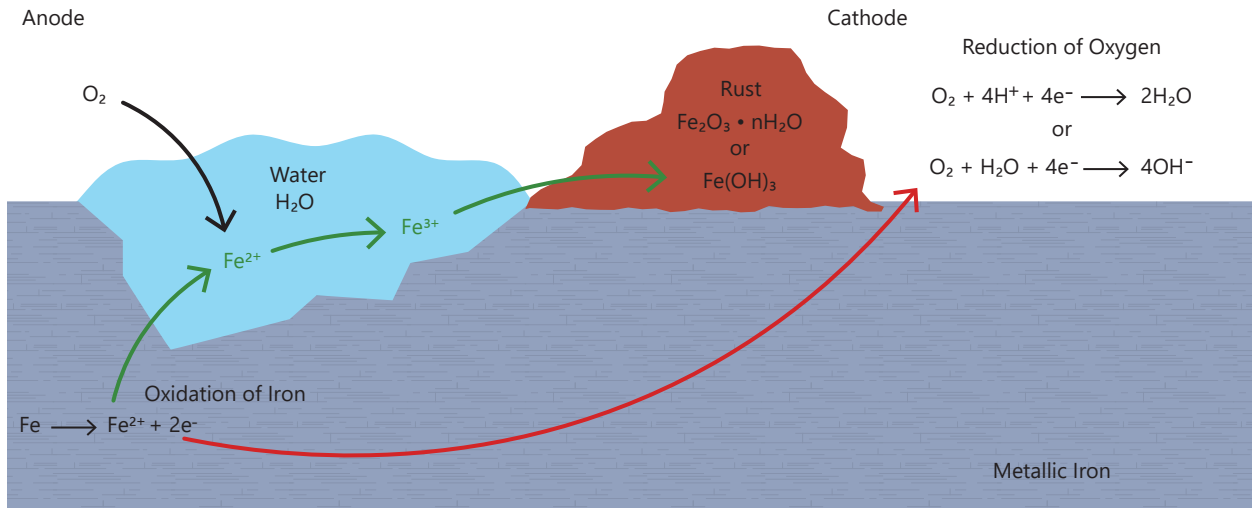# IMPACTS OF CHLORIDES ON INFRASTRUCTURE AND THE BUILT ENVIRONMENT

FIGURES

**Figure 4.1
Metallic Corrosion on a Bridge,
Culvert, and Motor Vehicle**

Source: WisDOT and SEWRPC
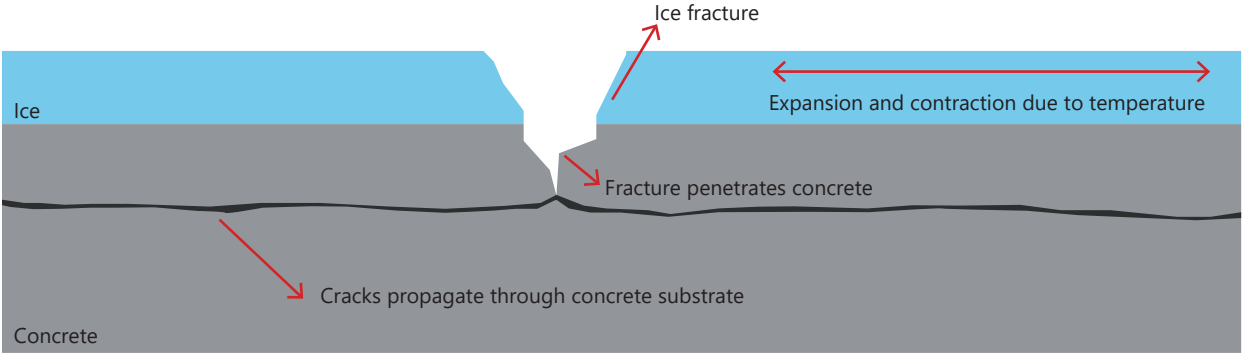
Figure 4.2
Typical Iron Corrosion Process

Anode

O_2

Water
H_2O

Fe^{2+}

Fe^{3+}

Oxidation of Iron

Fe $\longrightarrow$ Fe^{2+} + 2e⁻

Cathode

Rust
$Fe_2O_3 \cdot nH_2O$
or
$Fe(OH)_3$

Reduction of Oxygen

$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$

or

$O_2 + H_2O + 4e^- \longrightarrow 4OH^-$

Metallic Iron

Figure 4.3
Concrete Scaling Damage

Source: SEWRPC

Figure 4.4
Glue Spall Mechanism

Ice fracture

Ice

Expansion and contraction due to temperature

Fracture penetrates concrete

Cracks propagate through concrete substrate

Concrete

Source: SEWRPC

Figure 4.5
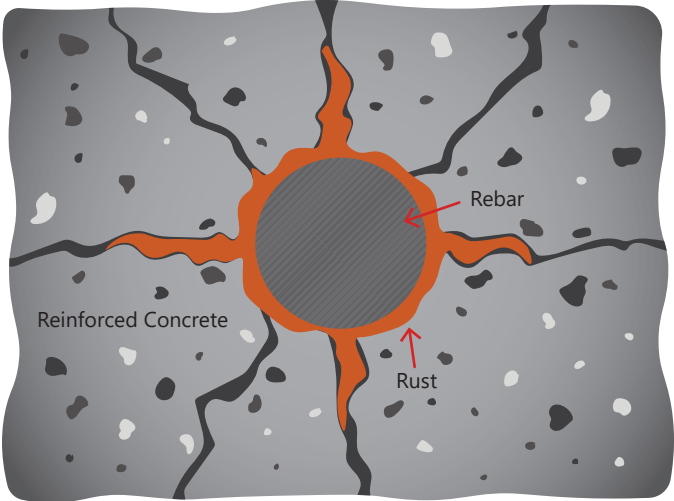**Reinforced Concrete BeamDamaged**
by Rebar Corrosion

Source: WisDOT

Figure 4.6
Steel Reinforcement Corrosion
Causing Concrete Damage

Source: SEWRPC