

Software Requirements Specification for Bridge Corrosion: A Chloride Exposure Prediction Model

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Revision History

| Date | Version | Notes |
|--------------|---------|---|
| Jan 27, 2024 | 1.0 | Initial release |
| Feb 23, 2024 | 2.0 | Add more details according to feedback from peer review |

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

Throughout this document SI (Système International d’Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit and the SI name.

| symbol | unit | SI |
|--------|----------|----------|
| m | length | metre |
| mile | distance | mile |
| kg | mass | kilogram |
| s | time | second |
| h | time | hour |

1.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units. The symbols are listed in alphabetical order.

| symbol | unit | description |
|------------------|----------------------------|--|
| a_{splash} | kg/m ³ | maximum deposition rate occur from splash |
| a_{spray} | kg/m ³ | maximum deposition rate occur from spray |
| a_{air} | kg/m ³ | maximum deposition rate |
| b | m | tire width |
| b_{splash} | N/A | splash emission rate coefficient |
| b_{spray} | N/A | spray emission rate coefficient |
| C_s | kg/m ³ /vehicle | chloride on the bridge substructure |
| $C_{s_{air}}$ | kg/m ³ /vehicle | chloride sprayed and splashed per unit air volume per vehicle |
| δ_{salt} | N/A | ratio of salt over water per unit area of road |
| d | m | distance between road edge and nearby bridge structure |
| h_{app} | m | daily water film thickness on the road |
| h_{film} | m | depth of the water film picked up in each rotation |
| h_{total} | m | the total snowfall during a winter season |
| I | m/h | rainfall intensity |
| K | N/A | ratio of the tire width that is not a groove to the tire width |
| L | m | drainage length |
| M_{app} | kg/m ² | deicing salts quantity applied per day |
| M_{total} | kg/m ² | total amount of deicing salts quantity over winter |
| MR_{BW} | kg/s | MFR displaced by a single tire due to bow |
| MR_{CA} | kg/s | MFR displaced by a single tire due to capillary adhesion |
| MR_{SW} | kg/s | MFR displaced by a single tire due to side waves |
| MR_{TP} | kg/s | MFR displaced by a single tire due to tread pickup |
| MR_W | kg/s | general MFR displaced by a single tire due to capillary adhesion |
| N_{lane} | lane | number of lanes |
| ρ_{water} | kg/m ³ | density of water |
| SD_{BW} | kg/m ³ /vehicle | spray density by a single tire due to bow |
| SD_{CA} | kg/m ³ /vehicle | spray density by a single tire due to capillary adhesion |
| SD_{SW} | kg/m ³ /vehicle | spray density by a single tire due to side waves |
| SD_{TP} | kg/m ³ /vehicle | spray density by a single tire due to tread pickup |
| SD_{total} | kg/m ³ /vehicle | spray density kicked up by each passing truck |
| $SD_{total\ cl}$ | kg/m ³ /vehicle | mass of chloride ions per unit air volume |
| S | m/m | slope as a ratio |
| T | mm | profile depth |

| | | |
|---------------------|---------|---|
| t_1 | days | number of days with snowfall |
| t_2 | days | number of days with snow melting |
| t_{snow} | days | number of days with snow |
| V | m/s | truck speed |
| V_{salt} | t/cm/km | normalized salt application rate |
| V_{speed} | km/h | heavy vehicle speed |
| V' | miles/h | heavy vehicle speed |
| W_{lane} | m | lane width |
| WD | m | water depth/thickness |
| x | m | distance between road and object surface |
| Θ | N/A | ratio of chloride ions sprayed and splashed by trucks over those by light duty vehicles |
| $\theta_{chloride}$ | N/A | molar mass ratio of chloride ions over deicing salts |

1.3 Abbreviations and Acronyms

| symbol | description |
|--------|--|
| A | Assumption |
| DD | Data Definition |
| GD | General Definition |
| GS | Goal Statement |
| IM | Instance Model |
| LC | Likely Change |
| PS | Physical System Description |
| R | Requirement |
| SRS | Software Requirements Specification |
| BC | Bridge Corrosion |
| TM | Theoretical Model |
| NaCl | Sodium Chloride, the main component of deicing salts |
| CA | Capillary Adhesion |
| TP | Tread Pickup |
| BW | Bow Waves |
| SW | Side Waves |
| MFR | Mass Flow Rate |
| ADT | Average Daily Traffic |
| AADT | Annual Average Daily Traffic |
| AADTT | Annual Average Daily Truck Traffic |

1.4 Mathematical Notation

| symbol | description |
|------------------|-----------------------|
| \mathbb{R} | Real number |
| $\{\mathbb{R}\}$ | a list of real number |

2 Introduction

In Ontario, most of the bridges in highway are made of Reinforced Concrete decks. However, the bridges may face the chloride-induced corrosion which damage its surface. There are many elements influencing this situation, one of the most important one is deicing salts. The primary used is sodium chloride (rock salt), when they melt the snow and in contact with water, they could have a chemical reaction and release the chloride ions. Those chloride could penetrate the concrete and induce corrosion in the reinforcing steel, then damage the bridges' structure and capacity.

There is a tight connection between chloride exposure, weather conditions and traffic flow. Specifically, the amount of deicing salts applied on the road surface greatly depends on the amount of snowfall, and the amount of water and dissolved chloride ions that end up on nearby objects depends on the traffic patterns.

This section outlines the document's purpose, delineates its scope of requirements, describes the intended audience's characteristics, and provides an overview of the document's organization.

2.1 Purpose of Document

This document details the requirements of the software Bridge Corrosion. The responsibilities of the user and software are laid out and the requirements that the software must satisfy are explicitly detailed. This document provides the software requirements specification (SRS) for a project to investigate how the climate and traffic could have impact on the corrosion-induced damage for the reinforced concrete, or to be more specific, how they influence the chloride exposure.

2.2 Scope of Requirements

The entire document is written assuming chloride is the main source of corrosion damage to the reinforced concrete, and chloride ions are transported from the road to the exterior surface of bridge substructures through vehicle spray and splash mechanisms. Another scope of the document is the factors that affect bridge corrosion is limit to chloride levels, climatic conditions, and traffic patterns.

2.3 Characteristics of Intended Reader

Readers of this documentation are expected to have a understanding of high school mathematics and chemistry, and the ability to comprehend basic results generated through computational fluid dynamics. The users of Bridge Corrosion may exhibit diverse levels of expertise, as further detailed in [Section 3.2](#).

2.4 Organization of Document

The organization of this document follows the template for an SRS for scientific computing software proposed by Smith et al. [1, 2, 3]. Starting with the reference material including units, symbols and abbreviations, this document next introduce the system that we are going to build from general to specific, including the problem, goal, assumptions, theoretical model and instance models. It also talks about the functional and nonfunctional requirements for this project, which could be referred to in process of development.

3 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics and lists the system constraints.

3.1 System Context

Figure 1 shows the system context of the software. The user should input a coordinates to the software, and the software will return the predicted chloride exposure in the past and future to the user. The user and the software also assume the following responsibilities.

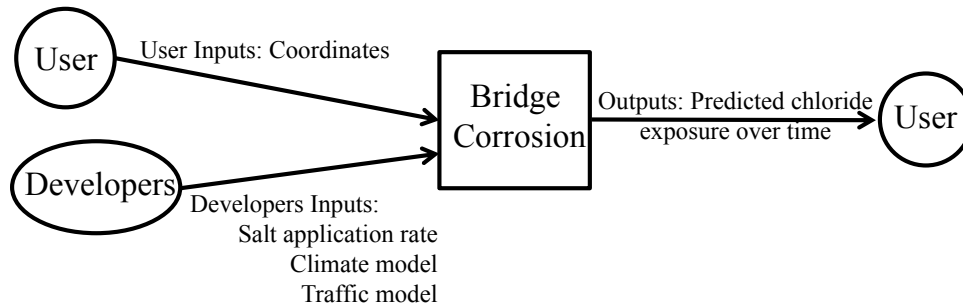


Figure 1: System Context

- User Responsibilities:
 - Provide valid coordinates to the software.
- Bridge Corrosion Responsibilities:
 - Build a database storing the chloride exposure data for every 25 km in the past and future.
 - Search and return the chloride exposure trend at given input coordinate.
 - Provide visualization of the output, such as histograms, line graphs, or grids displaying the data.

3.2 User Characteristics

The end user of Bridge Corrosion should have the high school understanding of geographic coordinates. Additionally, users may benefit from university level of knowledge of bridge construction or civil engineering principles to better understand the context and implications of the predicted chloride exposure.

3.3 System Constraints

There is no system constraints for this software.

4 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved. This is followed by the solution characteristics specification, which presents the assumptions, theories, definitions and finally the instance models.

4.1 Problem Description

This project is intended to investigate how climate, traffic might impact corrosion-induced damage for reinforced concrete bridges by influencing the chloride exposure.

4.1.1 Terminology and Definitions

This subsection provides a list of terms that are used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements:

- Mass Flow Rate: The amount of water displaced by a single tire.
- Spray density: Spray density is the measure of how closely packed the droplets or particles are within the spray plume. It quantifies the amount of material dispersed per unit area. In this document, it is referred to the density of water in the air (mass of water per unit air volume) in the environment.
- Airborne deposition: The process of particles moving from the atmosphere to the earth's surface.
- Deposition rate: The rate at which a substance is deposited onto a surface over a specific period of time.
- Drainage: The removal of a surface's water from an area with excess water.

4.1.2 Physical System Description

The key physical system of Bridge Corrosion, as shown in Figure 2 provided by [4], simulate the situation that a vehicle spray and splash the water, it includes the following elements:

- PS1: Capillary adhesion: The absorption of water (present on the road surface) by the tires through surface tension.
- PS2: Tread pickup: Water within the grooves of a tire being sprayed and splashed behind the tire by turbulent flow in the grooves.
- PS3: Bow wave: Water sent towards the front of the tire because of the physical displacement of water from the road surface due to the vehicle tires.
- PS4: Side wave: Water sent in the direction perpendicular to the traffic because of the physical displacement of water from the road surface due to the the vehicle tires.

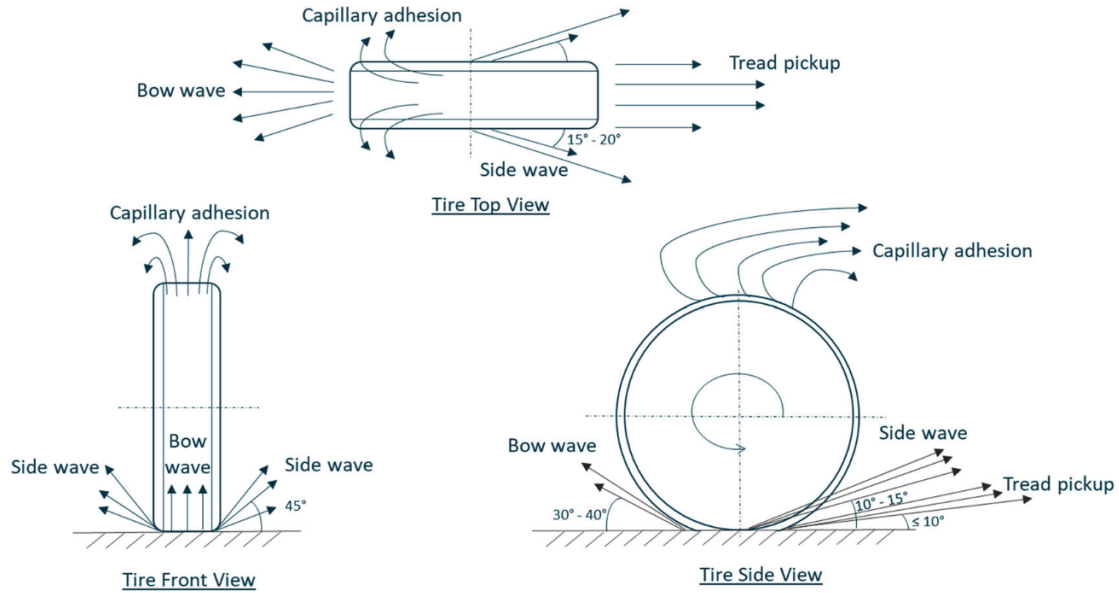


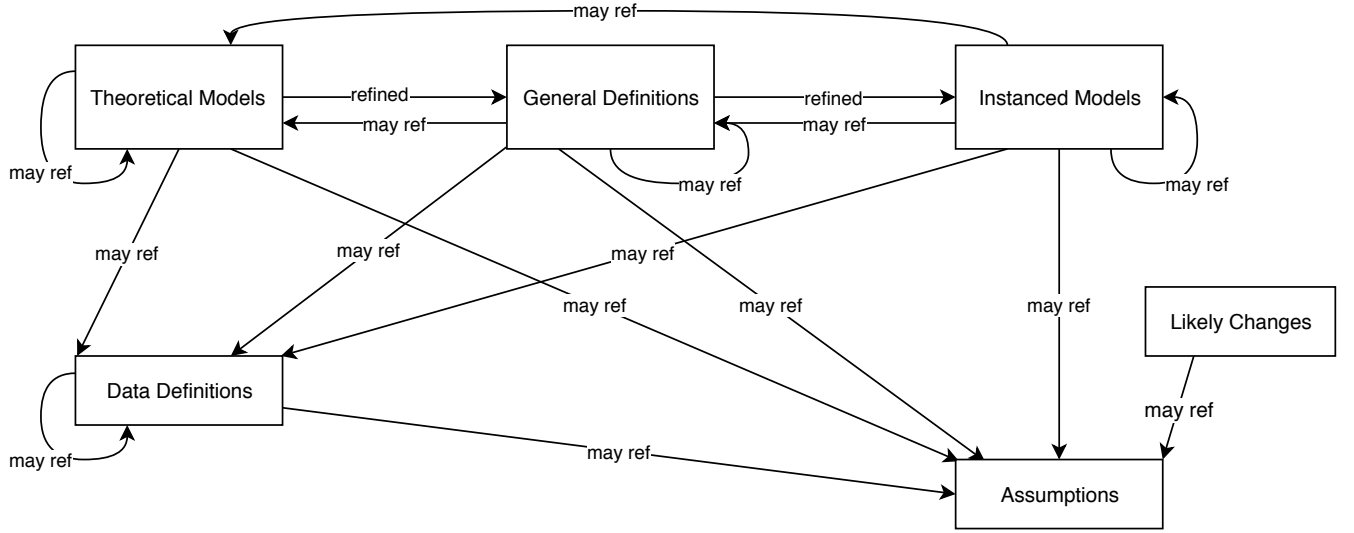
Figure 2: Mechanisms of vehicle spray and splash

4.1.3 Goal Statements

Given the salt application data, climate data, traffic data and coordinate across different regions and time period, the goal statements are:

GS1: Predict the chloride exposure for bridges in Ontario in the past and future, allow user to input coordinate and return the prediction for that location.

4.2 Solution Characteristics Specification



The instance models that govern this project are presented in Subsection 4.4.5. The information to understand the meaning of the instance models and their derivation is also presented, so that the instance models can be verified.

4.2.1 Types

Input:

- User input:
 - longitude = \mathbb{R}
 - latitude = \mathbb{R}
- Dataset input:
 - climate model
 - * annual snowfall $h_{total} = \mathbb{R}^+$
 - * annual number of days with snowfall $t_1 = \mathbb{R}^+$

- * annual number of days with snow melting $t_2 = \mathbb{R}^+$
- traffic model
 - * AADT per lane $AADT = \mathbb{R}^+$
 - * AADTT per lane $AADTT = \mathbb{R}^+$
 - * lane width $W_{lane} = \mathbb{R}^+$
 - * the distance between roadway edge and bridge substructures $d = \mathbb{R}^+$
- salt application rate $M_{total} = \mathbb{R}^+$

Output:

- predictedChlorideExposure = $\{\mathbb{R}\}$

4.3 Scope Decisions

- The surface chloride exposure data is in a 25-km grid resolution. This is because the climate data extracted from the CanRCM4 model ([13]) is at a resolution of 25×25 km.
- If the input coordinate does not have a bridge on it, it would return the value of the nearest bridge.

4.4 Modelling Decisions

4.4.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [TM], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

- A1: All the deicing salts are applied on days with snowfall. (RefBy: TM3, GD3, DD1, DD2)
- A2: The lane width for all the roads are the same. (RefBy: DD1, LC1)
- A3: The main component of deicing salt is NaCl. (RefBy: DD3, DD6)
- A4: Same class of the road over which the bridge spans has the same AADT. (RefBy: GD3, LC2)

4.4.2 Theoretical Models

This section focuses on the general equations and laws the project is based on.

| | |
|-------------|--|
| Number | TM1 |
| Label | Water film thickness |
| SI Units | m |
| Equation | $WD = 6 \times 10^{-4} \cdot T^{0.09}(L \cdot I)^{0.6} \cdot S^{-0.33}$ |
| Description | <p>The above equation compute the water film thickness based on the rainfall intensity and pavement surface properties.</p> <ul style="list-style-type: none">• WD is the water depth. (m)• T is the pavement texture. (mm)• L is the pavement drainage length. (m)• I is the rainfall intensity. (m/h)• S is the slope. (m/m) |
| Source | [5] |
| Ref. By | TM2 |

| | |
|-------------|--|
| Number | TM2 |
| Label | Max flow rate general |
| SI Units | kg/s |
| Equation | $MR_W = V \cdot b \cdot WD \cdot \rho_{water}$ |
| Description | <p>The above equation is the general equation for mass flow rate, which is the maximum amount of water available for splash and spray.</p> <ul style="list-style-type: none"> • V is the truck speed. (m/s) • b is the tire width. (m) • WD is the water depth/thickness. (m) • ρ_{water} is the density of water. (kg/m^3) |
| Source | [5] |
| Ref. By | GD1 |
| Use | TM1 |

| | |
|-------------|---|
| Number | TM3 |
| Label | Chloride sprayed and splashed |
| SI Units | kg/m ³ /vehicle |
| Equation | $C_{s_{air}} = (SD_{totalcl} \times \frac{1}{\Theta} \times \frac{ADT-N}{N_{lane}} + SD_{total\ cl} \times \frac{N}{N_{lane}}) \times t_{snow}$ |
| Description | <p>The above equation computes the mass of chloride ions per unit air volume sprayed and splashed by all the vehicles passing near the bridge pier every winter, accounting for all the days with snow in a typical winter season.</p> <ul style="list-style-type: none"> • $SD_{total\ cl}$ is the mass of chloride ions per unit air volume. ($kg/m^3/vehicle$) • Θ is the ratio of chloride ions sprayed and splashed by trucks to light-duty vehicles. (ratio) • ADT is the average daily traffic. (number of vehicles/day) • N is the average number of heavy-duty vehicles per day. (number of vehicles/day) • N_{lane} is the number of lanes. • t_{snow} is the number of days with snow. |
| Notes | The first part in the parentheses calculate the chloride exposure by light-duty vehicle, and the second part is for heavy-duty vehicles. The calculation focus on the road lane that is closest to the bridge component, so N_{lane} is included in the denominator. |
| Source | [4] |
| Ref. By | GD3 |
| Use | A1, DD6 |

| | |
|-------------|---|
| Number | TM4 |
| Label | Total airborne deposition at a certain distance |
| SI Units | kg/m ³ |
| Equation | $D(x) = a_{spray} \times e^{b_{spray} x} + a_{splash} \times e^{b_{splash} x}$ |
| Description | <p>The above equation describes the total airborne deposition at a certain distance from the road.</p> <ul style="list-style-type: none"> • a_{spray} is the maximum deposition rates that occur from spray. (kg/m^3) • a_{splash} is the maximum deposition rates that occur from splash. (kg/m^3) • b_{spray} is the spray emission rate coefficient. • b_{splash} is the splash emission rate coefficient. • x is the distance between the road and the object. (m) • e is the base of natural logarithm. |
| Source | [12] |
| Ref. By | IM1 |

4.4.3 General Definitions

This section collects the laws and equations that will be used in building the instance models.

| | |
|-------------|---|
| Number | GD1 |
| Label | Mass flow rate |
| SI Units | kg/s |
| Equation | $\begin{cases} MR_{CA} = V_{speed} \times b \times K \times h_{film} \times \rho_{water} & \text{for } CA \\ MR_{TP} = V_{speed} \times b \times (1 - K) \times h_{app} \times \rho_{water} & \text{for } TP \\ MR_{BW} = MR_{SW} = 0.5 \times V_{speed} \times b \times (h_{app} \\ - K \times h_{film} - (1 - K) \times h_{app}) \times \rho_{water} & \text{for } BW \text{ and } SW \end{cases}$ |
| Description | <p>The above equations compute the contribution to the amount of water displaced by a single tire (also called MFR) of each splash and spray mechanism, using the following equations in the order presented until the total amount of available water is exhausted. $MR_{CA}, MR_{TP}, MR_{BW}, MR_{SW}$ stands for capillary adhesion, tread pickup, bow waves and side waves correspondingly.</p> <ul style="list-style-type: none"> • V_{speed} is the heavy vehicle speed. (km/h) • b is the tire width. (m) • K is the ratio of the tire width that is not a groove to the tire width. (ratio) • h_{film} is the depth of the water film picked up in each rotation. (m) • h_{app} is the thickness of melted water per day with snow melting. (m) • ρ_{water} is the density of water. (kg/m^3) <p>The tread pickup will be activated only if there is water remaining after the capillarity adhesion, and the bow and side waves will be activated only if there is water remaining after the capillary adhesion and tread pickup.</p> |
| Source | [4] |
| Ref. By | GD2 |
| Use | TM2, DD2 |

Detailed derivation of mass flow rate

The following derivation is based on the theories purposed in [4].

The maximum mass flow rate associated with capillary adhesion (MR_{CA}) is estimated as the number of tire rotations per second multiplied by the volume of water dispersed on each tire rotation multiplied by the density of water, or

$$MR_{CA} = \left[\frac{V_{speed}}{2\pi R} \right] \cdot [2\pi R \times b \times K \times h_{film}] \times \rho_{water} = [V_{speed} \times b \times K \times h_{film}] \times \rho_{water}$$

After capillary action, the tire is able to displace a volume of water within its tread. The maximum flow rate for this mechanism (MR_{TP}) will occur when all the water contained in the tread volume is flung out of the tread during each tire rotation. Thus, it can be computed as the number of tire rotations per second multiplied by the capacity of tire's tread on each rotation multiplied by the density of water:

$$MR_{TP} = V_{speed} \times b \times (1 - K) \times h_{app} \times \rho_{water}$$

Any remaining water for which there is no capacity either underneath the tire contact area or within the tire tread must be displaced to the front of the tire or to the side, causing the bow wave and side wave, respectively. So, the total mass flow rate that can be attributed to bow and side wave mechanisms can be written as:

$$MR_{BW} + MR_{SW} = \rho_{water} \times b \times V_{speed} \times (h_{app} - K \times h_{film} - (1 - K) \times h_{app})$$

So, MR_{BW} and MR_{SW} can be estimated separately as:

$$MR_{BW} = \alpha \times \rho_{water} \times b \times V_{speed} \times (h_{app} - K \times h_{film} - (1 - K) \times h_{app})$$

$$MR_{SW} = \beta \times \rho_{water} \times b \times V_{speed} \times (h_{app} - K \times h_{film} - (1 - K) \times h_{app})$$

where α and β are calibration factors that satisfy $\alpha + \beta = 1$. Until other evidence is available, it will be assumed that $\alpha = \beta = 0.5$.

| | |
|-------------|--|
| Number | GD2 |
| Label | Spray density |
| SI Units | kg/m ³ /vehicle |
| Equation | $\begin{cases} SD_{CA} = (-2.69 \times 10^{-5} \times V' + 2.43 \times 10^{-3}) \times MR_{CA} & \text{for } CA \\ SD_{TP} = (1.16 \times 10^{-5} \times V' - 5.25 \times 10^{-5}) \times MR_{TP} & \text{for } TP \\ SD_{BW} = (2.67 \times 10^{-5} \times V' - 4.71 \times 10^{-4}) \times MR_{BW} & \text{for } BW \\ SD_{SW} = (1.65 \times 10^{-5} \times V' - 3.99 \times 10^{-4}) \times MR_{SW} & \text{for } SW \end{cases}$ |
| Description | <p>Spray density is derived by conducting regression analysis to develop relationship between spray density, mass flow rate and vehicle speed, to compute the concentration of water kicked up to the environment. The detailed process could be found in section 6.6.1 in [4] .</p> <ul style="list-style-type: none"> • V' is the heavy vehicle speed. (<i>miles/h</i>) • $MR_{CA}, MR_{TP}, MR_{BW}, MR_{SW}$ is the mass flow rate for capillary adhesion, tread pickup, bow waves and side waves correspondingly. (<i>kg/s</i>) |
| Source | [4] |
| Ref. By | DD4 |
| Use | GD1 |

| | |
|-------------|---|
| Number | GD3 |
| Label | Chloride sprayed and splashed |
| SI Units | kg/m ³ /vehicle |
| Equation | $C_{s_{air}} = (SD_{totalcl} \times \frac{1}{\Theta} \times (AADT \text{ per lane} - AADTT \text{ per lane}) + SD_{total \text{ cl}} \times AADTT \text{ per lane}) \times t_2$ |
| Description | <p>The cumulative mass of chloride ions per unit air volume sprayed and splashed by all vehicles every winter, can be calculated by first finding the mass of chloride ions per unit air volume sprayed and splashed by all the vehicles per day, and times with the number of days with snow melting.</p> <ul style="list-style-type: none"> • $SD_{total \text{ cl}}$ is the mass of chloride ions per unit air volume. ($kg/m^3/vehicle$) • Θ is the ratio of chloride ions sprayed and splashed by trucks to light-duty vehicles. • $AADT \text{ per lane}$ is the annual average daily traffic per lane. • $AADTT \text{ per lane}$ is the annual average daily truck traffic per lane. • t_2 is the number of days with snow melting. |
| Notes | This equation simplified TM3 by using AADT and AADTT that are generated from existing database for calculation for light traffic and heavy-duty traffic. |
| Sources | [7, 8] |
| Ref. By | IM1 |
| Use | A1, A4, DD6, TM3 |

4.4.4 Data Definitions

This section collects and defines all the data needed to build the instance models. The dimension of each quantity is also given.

| | |
|-------------|--|
| Number | DD1 |
| Label | Deicing salts quantity |
| Symbol | M_{app} |
| SI Units | kg/m^2 |
| Equation | $\begin{cases} M_{app} = M_{total}/t_1 \\ M_{app} = \frac{V_{salt} \times h_{total}}{t_1 \times W_{lane}} \end{cases}$ |
| Description | <p>The equation determine the quantity of deicing salts applied per day with snowfall, with A1. In some case there is absence of the data of M_{total}, the second equation is used.</p> <ul style="list-style-type: none"> • M_{total} is the total amount of deicing salts applied on the road during the winter season. (kg/m^2) • t_1 is the number of days with snowfall. • V_{salt} is the normalized salt application rate. ($t/cm/km$) • h_{total} is the total snowfall during a winter season. (m) • W_{lane} is the lane width according to A2. (m). |
| Sources | [4, 7] |
| Ref. By | DD5 |
| Use | A1, A2 |

| | |
|-------------|--|
| Number | DD2 |
| Label | Daily water film thickness |
| Symbol | h_{app} |
| SI Units | m |
| Equation | $h_{app} = h_{total}/t_{snow}$ |
| Description | <p>The equation above calculates the thickness of melted water per day with snow melting.</p> <ul style="list-style-type: none"> • h_{total} is the the total snowfall during a winter season, given by the climate model. (m) • t_{snow} is the number of days with snow melting. |
| Sources | [4, 9] |
| Ref. By | GD1, DD5 |
| Use | A1 |
| Number | DD3 |
| Label | Ratio of chloride in deicing salts |
| SI Units | none |
| Equation | $\theta_{chloride} = \frac{\text{mass of } Cl^{-}}{\text{mass of } NaCl}$ |
| Description | <p>This equation computes the molar mass ratio of chloride to deicing salts, where we assume the main component of deicing salts is NaCl.</p> <ul style="list-style-type: none"> • Cl^{-} is the chloride ions whose exposure we want to investigate. • $NaCl$ is the most commonly used salt. |
| Source | Mass Ratio Calculation |
| Ref. By | DD6 |
| Use | A3 |

| | |
|-------------|--|
| Number | DD4 |
| Label | Total spray density |
| SI Units | kg/m ³ /vehicle |
| Equation | $SD_{total} = SD_{CA} + SD_{TP} + SD_{BW} + SD_{SW}$ |
| Description | <p>The spray density (i.e. mass of water per unit air volume kicked up by each passing truck), is the sum of the four mechanism.</p> <ul style="list-style-type: none"> • SD_{CA} is the spray density due to capillary adhesion. • SD_{TP} is the spray density due to tread pickup. • SD_{BW} is the spray density due to bow waves. • SD_{SW} is the spray density due to side waves. |
| Source | [4] |
| Ref. By | DD6 |
| Use | GD2 |
| Number | DD5 |
| Label | Ratio of salt over water |
| SI Units | none |
| Equation | $\delta_{salt} = \frac{M_{app}}{h_{app} \times \rho_{water}}$ |
| Description | <p>This equation computes the ratio of the mass of salt applied per unit area of road to the mass of water per unit area of road.</p> <ul style="list-style-type: none"> • M_{app} is the quantity of deicing salts applied per day. (kg/m^2) • h_{app} is the thickness of melted water per day. (m) • ρ_{water} is the density of water. (kg/m^3) |
| Source | [4] |
| Ref. By | DD6 |
| Use | DD1, DD2 |

| | |
|-------------|---|
| Number | DD6 |
| Label | Mass of chloride ions |
| SI Units | kg/m ³ /vehicle |
| Equation | $SD_{totalcl} = SD_{total} \times \delta_{salt} \times \theta_{chloride}$ |
| Description | <p>This equation computes the mass of chloride ions per unit air volume kicked up by each truck.</p> <ul style="list-style-type: none"> • SD_{total} is the mass of water per unit air volume. ($kg/m^3/vehicle$) • δ_{salt} is the salt-to-water mass ratio per unit area of road. (ratio) • $\theta_{chloride}$ is the molar mass ratio of chloride to deicing salts. (ratio) |
| Source | [4, 7] |
| Ref. By | TM3, GD3 |
| Use | A3, DD3, DD4, DD5 |

4.4.5 Instance Models

This section transforms the problem defined in Section 4.1 into one which is expressed in mathematical terms. It uses concrete symbols defined in Section 4.4.4 to replace the abstract symbols in the models identified in Sections 4.4.2 and 4.4.3.

The goal GS1 is solved by IM1, IM2.

| | |
|-------------|---|
| Number | IM1 |
| Label | Chloride on the surface |
| Input | $C_{s_{air}}, e, d$ |
| Output | C_s |
| Equation | $C_s = 0.015 \times C_{s_{air}} \times e^{-0.05d} + 0.985 \times C_{s_{air}} \times e^{-0.5d}$ |
| Description | <p>The above equation computes the chloride ions deposition on bridge substructure, taking into account the distance between the edge of the road near the bridge substructure and the bridge substructure.</p> <ul style="list-style-type: none"> • $C_{s_{air}}$ is the cumulative mass of chloride ions per unit air volume sprayed and splashed by all the vehicles passing near the bridge pier. (kg/m^3) • d is the distance between the road edge and nearby bridge structure. (m) • e is the base of natural logarithm. |
| Sources | [7, 10, 11, 12] |
| Ref. By | IM2, LC3 |
| Use | TM4, GD3 |

Detailed derivation of chloride on the surface

According to [12], the spray emission rate coefficient and splash emission rate coefficient could be taken as -0.05 and -0.5, and the distance between road edge and nearby bridge structure is d , so we have:

$$C_s = a_{spray} \times e^{-0.05d} + a_{splash} \times e^{-0.5d}$$

According to [11, 12] which measured the deposition of deicing salts along a highway in Sweden to define the relation between the mass of deicing salts per unit area and distance from roadside, and used nonlinear fitting techniques to determine the proportions of sprayed and splashed chloride ions:

$$a_{spray} = a_{air} \times 0.015$$

$$a_{splash} = a_{air} \times 0.985$$

Combining the above equation in the scenario of chloride, we have:

$$C_s = 0.015 \times C_{s_{air}} \times e^{-0.05d} + 0.985 \times C_{s_{air}} \times e^{-0.5d}$$

| | |
|-------------|--|
| Number | IM2 |
| Label | Search data for specific coordinate |
| Input | $(longitude, latitude)$ |
| Output | $\{C_{s_1}, C_{s_2}, \dots, C_{s_n}\}$ |
| Description | <p>This instance model get the longitude and latitude as input, and return a series of the amount of chloride exposure as output. This is the model that the end user of this software will encounter.</p> <ul style="list-style-type: none"> • $\{C_{s_1}, C_{s_2}, \dots, C_{s_n}\}$ is a list of chloride exposure data. ($\{kg/m^3\}$) • $(longitude, latitude)$ is the coordinate of a location. ($^\circ, ^\circ$) |

4.4.6 Input Data Constraints

Table 1 shows the data constraints on the input output variables. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable. The column for software constraints restricts the range of inputs to reasonable values. The software constraints will be helpful in the design stage for picking suitable algorithms. The constraints are conservative, to give the user of the model the flexibility to experiment with unusual situations. The column of typical values is intended to provide a feel for a common scenario. The uncertainty column provides an estimate of the confidence with which the physical quantities can be measured. This information would be part of the input if one were performing an uncertainty quantification exercise. In the Bridge Corrosion project, I would talk about not only the input variables mentioned in instance models, but also include those in other models that the software need to process. The physical constraints are purposed by [4]. Beside those, the input of the software need to be coordinates inside Ontario. This will be done by input checking algorithm later. The specification parameters in Table 1 are listed in Table 6.

4.4.7 Properties of a Correct Solution

A correct solution must exhibit the chloride exposure values that does not exceed the solubility limits of chloride ions.

Table 1: Input Variables

| Var | Physical Constraints | Software Constraints | Typical Value | Uncertainty |
|-------------|------------------------------|---|---------------|-------------|
| b | $0.2 \leq b \leq 0.71$ | $b_{min} \leq b \leq b_{max}$ | 0.56 m | 10% |
| d | $d > 0$ | $d > 0$ | 3 m | 10% |
| h_{film} | $h_{film} > 0$ | $h_{film} > 0$ | 0.0001 m | 10% |
| K | $0 \leq K \leq 1$ | $b_{min} \leq K \leq b_{max}$ | 0.75 | 10% |
| t_2 | $0 \leq t_2 \leq 365$ | $t_{snow} \leq t_2 \leq 365$ | 70 days | 10% |
| t_{snow} | $0 \leq t_{snow} \leq 365$ | $0 \leq t_{snow} \leq 365$ | 65 days | 10% |
| V' | $37 \leq V' \leq 65$ | $V'_{min} \leq V' \leq V'_{max}$ | 65 miles/h | 10% |
| V_{speed} | $60 \leq V_{speed} \leq 105$ | $V_{speed_{min}} \leq V_{speed} \leq V_{speed_{max}}$ | 105 km/h | 10% |
| Θ | $0 \leq \theta < 1$ | $0 \leq \theta < 1$ | 0.61 | 10% |

Table 2: Output Variables

| Var | Physical Constraints |
|-------|--|
| C_s | $C_s < 357kg/m^3$ (by Water Quality Guidelines) |

5 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

5.1 Functional Requirements

- R1: The user input need to be a coordinate within Ontario (By IM2).
- R2: The output need to be a series of data showing the trend of chloride exposure in the past and future at the input location (By IM2).
- R3: During the calculation, the software should be capable of handling situations where units do not match in between steps as the developers or users are not able to interrupt/modify the data manually during the calculation.
- R4: The output from the previous year should be verifiable against real-world data.
- R5: The output should be in two decimal points, showing the mass of chloride ions per unit air volume (By IM1).

5.2 Nonfunctional Requirements

- NFR1: **Reliability:** The predictions generated by the software should be accurate and reliable, reflecting real-world conditions and factors influencing chloride exposure.
- NFR2: **Usability:** The software interface should be intuitive and user-friendly, allowing users in the section 3.2 to easily input coordinates and look at the predicted chloride exposure in the past and future.
- NFR3: **Maintainability:** The code for this software should be designed and structured in a way that it could be easily comprehended and modified by other potential developers.
- NFR4: **Portability:** This software should be able to run on recent versions of Google Chrome, Firefox, MS Edge and Safari. The operating system include Windows 7+ and Mac OS X 10.7+.
- NFR5: **Scalability:** The software should be scalable to accommodate potential future expansions or updates, ensuring its continued usefulness as new data or techniques become available.

5.3 Rationale

The assumptions made in this document are based on practical considerations to simplify and quantify the data required in the model. In A1, the deicing salts need to be applied on the roads in time to ensure safe driving conditions during winter weather. In A2, it simplifies the model by assuming a standardized lane width across all roads. While lane widths can vary depending on road type and location, assuming a uniform lane width streamlines the analysis and allows for consistent calculations. Additionally, a lane width of 3 meters is commonly used in many road design standards and provides a reasonable approximation for

modeling purposes. Similarly, NaCl is one of the most widely used deicing salts due to its effectiveness and affordability, so A3 simplifies the model while still capturing the essence of typical deicing salt compositions. Lastly, AADT is an important parameter for assessing traffic volume on roads and is typically used to classify roads into different categories based on their traffic intensity, A4 simplifies the analysis by providing a standardized measure of traffic volume. By incorporating these assumptions, the model can effectively simulate real-world scenarios and provide valuable insights into the factors influencing bridge corrosion. The constraints in Table 1 are defined considering real-world scenarios. For example, the speed constraints adhere to established speed limits, ensuring a realistic representation of vehicle speeds. Similarly, the constraints associated with the variable about days are confined within the bounds of the annual calendar, reflecting a practical consideration of time duration within a given year.

6 Likely Changes

- LC1: The lane width in some area might not be fixed, and the lane width standards might change in the future, so A2 is likely to be changed.
- LC2: A4 might be changed with the population density, urbanization, or transportation preferences in different area, which all may influence traffic volume and distribution.
- LC3: The proportions(0.015 and 0.985) in IM1 might change with the site characteristics of a bridge, such as the roadside environment (forested or urban), traffic characteristics (direction and volume), wind direction, and road surface condition.

7 Unlikely Changes

- ULC1: The deicing salt need to be applied on days with snowfall to effectively mitigate the formation of ice and ensure safe road conditions, so A1 is unlikely to change.
- ULC2: A3 is also unlikely to change, as the main component of deicing salt remain consistent.

8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an “X” may have to be modified as well. Table 3 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions. Table 4 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 5 shows the dependencies of instance models, requirements, and data constraints on each other.

| | A1 | A2 | A3 | A4 |
|------|----|----|----|----|
| TM1 | | | | |
| TM2 | | | | |
| TM3 | X | | | |
| TM4 | | | | |
| GD1 | | | | |
| GD2 | | | | |
| GD3 | X | | | X |
| DD1 | X | X | | |
| DD2 | X | | | |
| DD3 | | | X | |
| DD4 | | | | |
| DD5 | | | | |
| DD6 | | | X | |
| IM1 | | | | |
| IM2 | | | | |
| LC1 | | X | | |
| LC2 | | | | X |
| LC3 | | | | |
| ULC1 | X | | | |
| ULC2 | | | X | |

Table 3: Traceability Matrix Showing the Connections Between Assumptions and Other Items

| | TM1 | TM2 | TM3 | TM4 | GD1 | GD2 | GD3 | DD1 | DD2 | DD3 | DD4 | DD5 | DD6 | IM1 | IM2 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| TM1 | | X | | | | | | | | | | | | | |
| TM2 | | | | | X | | | | | | | | | | |
| TM3 | | | | | | | X | | | | | | | | |
| TM4 | | | | | | | | | | | | | | X | |
| GD1 | | | | | | X | | | | | | | | | |
| GD2 | | | | | | | | | | | X | | | | |
| GD3 | | | | | | | | | | | | | | X | |
| DD1 | | | | | | | | | | | | X | | | |
| DD2 | | | | | X | | | | | | | X | | | |
| DD3 | | | | | | | | | | | | | X | | |
| DD4 | | | | | | | | | | | | | X | | |
| DD5 | | | | | | | | | | | | | X | | |
| DD6 | | | X | | | | X | | | | | | | | |
| IM1 | | | | | | | | | | | | | | | X |
| IM2 | | | | | | | | | | | | | | | |

Table 4: Traceability Matrix Showing the Connections Between Items of Different Sections

| | IM1 | IM2 | R1 | R2 | R3 | R4 | R5 | NFR1 | NFR2 | NFR3 | NFR4 | NFR5 |
|------|-----|-----|----|----|----|----|----|------|------|------|------|------|
| IM1 | | | | | | | X | | | | | |
| IM2 | | | X | X | | | | | X | | X | |
| R1 | | X | | | X | | | | | X | | |
| R2 | | | | | | X | X | X | | | | |
| R3 | | | X | | | | | | | | | X |
| R4 | | | | X | | | | X | | | | |
| R5 | | | | X | | | | | | | | |
| NFR1 | | X | | | | X | | | | | | |
| NFR2 | | X | | X | | | | | | | | |
| NFR3 | | | | | | | | | | | | X |
| NFR4 | | | | | | | | | | | | |
| NFR5 | | | | | | | | | | X | | |

Table 5: Traceability Matrix Showing the Connections Between Requirements and Instance Models

9 Values of Auxiliary Constants

| Symbol | Description | Value | Unit |
|-------------------|---|-------|---------|
| V'_{min} | minimum speed of heavy vehicle | 37 | miles/h |
| V'_{max} | maximum speed of heavy vehicle | 65 | miles/h |
| $V_{speed_{min}}$ | minimum speed of heavy vehicle | 60 | km/h |
| $V_{speed_{max}}$ | maximum speed of heavy vehicle | 105 | km/h |
| b_{min} | minimum tire width | 0.2 | m |
| b_{max} | maximum tire width | 0.71 | m |
| b_{spray} | spray emission rate coefficient | -0.05 | N/A |
| b_{splash} | splash emission rate coefficient | -0.5 | N/A |
| W_{lane} | lane width | 3 | m |
| V_{salt} | salt application rate | 0.06 | t/cm/km |
| Θ | ratio of chloride ions sprayed and splashed by trucks over light-duty vehicles | 6 | N/A |

Table 6: Auxiliary Constant

Reference

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