# Software Requirements Specification for Bridge Chloride Exposure Predictor (BCEP): A Chloride Exposure Prediction Model

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# Contents

# Revision History

| Date | Version | Notes |
|---|---|---|
| Jan 27, 2024 | 0.0 | Initial release |
| Feb 23, 2024 | 0.1 | Add more details according to feedback from peer review |
| Mar 7, 2024 | 0.2 | Modified according to feedback from Dr. Spence Smith |
| Apr 13, 2024 | 0.3 | Final revision for 741 |
| June 13, 2024 | 0.4 | Revision base on feedback from Dr. Smith |
| July 13, 2024 | 0.5 | Revision after requirement walkthrough meeting |
| July 25, 2024 | 0.6 | Revision after task-based inspection |

# 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 |
| kg | mass | kilogram |
| t | mass | tonne |
| s | time | second |
| day | duration | day |

## 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 that can occur from splash |
| $a_{spray}$ | $kg/m^3$ | maximum deposition rate that can occur from spray |
| $a_{air}$ | $kg/m^3$ | total maximum deposition rate that can occur |
| $b$ | m | tire width |
| $b_{splash}$ | N/A | splash emission rate coefficient |
| $b_{spray}$ | N/A | spray emission rate coefficient |
| $C_s$ | $kg/m^3$ | chloride concentration on the bridge substructure |
| $C_{s_{air}}$ | $kg/m^3$ | chloride concentration sprayed and splashed by all vehicles per winter |
| $\delta_{salt}$ | kg/kg | ratio of mass of salt over mass of water for a unit area of road |
| $d$ | m | distance between road edge and nearby bridge structure |
| $D(x)$ | $kg/m^3$ | total airborne deposition at a certain distance from the road |
| $h_{app}$ | 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 |
| $K$ | m/m | ratio of the tire width that is not a groove to the full tire width |
| $L$ | m | drainage length |
| $lat$ | $\circ$ | latitude |
| $long$ | $\circ$ | longitude |
| $m$ | N/A | the end year for the period that surface chloride concentration is measured |
| $M_{app}$ | $kg/m^2$ | 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 |
| $n$ | N/A | the start year for the period that surface chloride concentration is measured |
| $N_{lane}$ | lane | number of lanes |
| $p$ | N/A | number of decimal of chloride exposure result |
| $r$ | N/A | linear growth rate for AADT and AADTT |

| | | |
|---|---|---|
| $SD_{BW}$ | kg/m$^3$ | spray density by a single tire due to bow |
| $SD_{CA}$ | kg/m$^3$ | spray density by a single tire due to capillary adhesion |
| $SD_{SW}$ | kg/m$^3$ | spray density by a single tire due to side waves |
| $SD_{TP}$ | kg/m$^3$ | spray density by a single tire due to tread pickup |
| $SD_{total}$ | kg/m$^3$ | spray density kicked up by each passing truck |
| $SD_{total\_cl}$ | kg/m$^3$ | 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 |
| $V$ | m/s | truck speed |
| $V_{salt_h}$ | t/cm/km | normalized high salt application rate |
| $V_{salt_l}$ | t/cm/km | normalized low salt application rate |
| $V_{speed}$ | km/h | heavy vehicle speed for calculating mass flow rate |
| $V'$ | miles/h | heavy vehicle speed for calculating spray density |
| $W_{lane}$ | m | lane width |
| $WD$ | m | water depth (thickness) |
| $x$ | m | distance between road and object surface |
| $\rho_{water}$ | kg/m$^3$ | density of water |
| $\Theta$ | 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 |
| AADT | Annual Average Daily Traffic |
| AADTT | Annual Average Daily Truck Traffic |
| ADT | Average Daily Traffic |
| BCEP | Bridge Chloride Exposure Predictor |
| BW | Bow Waves |
| CA | Capillary Adhesion |
| DD | Data Definition |
| GD | General Definition |
| GS | Goal Statement |
| IM | Instance Model |
| LC | Likely Change |
| MFR | Mass Flow Rate |
| NaCl | Sodium Chloride, the main component of deicing salts |
| PS | Physical System Description |
| R | Requirement |
| SRS | Software Requirements Specification |
| SW | Side Waves |
| TM | Theoretical Model |
| TP | Tread Pickup |

## 1.4 Mathematical Notation

| symbol | description |
|---|---|
| $\mathbb{R}$ | Real number |
| $\mathbb{N}$ | Natural number |
| $[x]_t^n$ | A list of values over time period $t$ to $n$ |

## 1.5 Symbolic Parameters

This section includes the symbolic parameters introduced in the report. We use symbolic parameters to represent values that are constant for a specific implementation of BCEP. The value could be modified to create a new instance of BCEP. For instance, JURISDICTION could be changed to provide the tool for a province or state other than Ontario. The values for the symbolic parameters are from [7].

| Symbol | Description | Value | Unit |
|---|---|---|---|
| $b$ | tire width | 0.56 | m |
| $d$ | distance between road edge and bridge substructure | 3.5 | m |
| GRID_SIZE | Minimum area sharing the same climate and traffic data | $25 \times 25$ | - |
| $h_{film}$ | depth of the water film picked up in each rotation | 0.0001 | m |
| JURISDICTION | An geographic area sharing a same set of laws or rules | Ontario | - |
| $K$ | ratio of tire width that is not a groove to tire width | 0.75 | N/A |
| $p$ | number of decimal of chloride exposure result | | N/A |
| $r$ | linear growth rate for AADT and AADTT | 2% | N/A |
| $V$ | speed of vehicle | 62.1371 | miles/h |
| $V_{speed}$ | speed of heavy vehicle | 100 | km/h |
| $V_{salt_h}$ | high salt application rate | 0.07 | t/cm/km |
| $V_{salt_l}$ | low salt application rate | 0.05 | t/cm/km |
| $W_{lane}$ | lane width | 3.75 | m |
| $\rho_{water}$ | water density | 997 | kg/m$^3$ |
| $\theta_{chloride}$ | molar mass ratio of chloride ions over deicing salts | 0.61 | N/A |
| $\Theta$ | ratio of chloride ions sprayed and | | |
| | splashed by trucks over light-duty vehicles | 6 | N/A |

Table 1: Auxiliary Constant

# 2 Introduction

Most of the bridges on highways are made with reinforced concrete decks. Unfortunately, weather conditions and traffic pattern cause bridge surfaces to be damaged by chloride-induced corrosion. Many elements influence the amount of damage, such as the quality of construction materials, and the maintenance practices employed. One of the most important factors is deicing salts. The primary deicing salt used is sodium chloride (rock salt). When the salt melts the snow and is in contact with water, it may have a chemical reaction and release chloride ions. The ions could penetrate the concrete and induce corrosion in the reinforcing steel, thus damaging a bridge's structure and its capacity.
There is a tight connection between chloride exposure, weather conditions and traffic flow. Specifically, the amount of deicing salt 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.
Given the complex relationship between weather, traffic and chloride exposure, and the importance of bridge safety and maintenance, there is a need for a software that can integrate weather and traffic data to predict potential corrosion for the bridges. This document provides specifications for such a software called Bridge Chloride Exposure Predictor (BCEP). The following 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 BCEP. 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 reinforced concrete, or to be more specific, how they influence the chloride exposure.

## 2.2 Scope of Requirements

The entire document is written assuming deicing salts are the main source of chlorides attacking concrete structures, and chloride ions are transported from the road to the exterior surface of bridge substructures through vehicle spray and splash mechanisms. The factors that affect bridge chloride exposure are assumed to be limited to salt application practices, climatic conditions, and traffic patterns. Additionally, the scope of the project is limited to provincial highway bridges because these bridges are of significant interest to stakeholders and we have the most comprehensive and reliable data available for these bridges.

### 2.3 Characteristics of Intended Reader

Readers of this documentation are expected to have a understanding of high school mathematics and chemistry. The model utilizes empirical equations developed from computational fluid dynamics (CFD) analysis, but it does not require readers to comprehend basic CFD results. The users of BCEP 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.

## 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

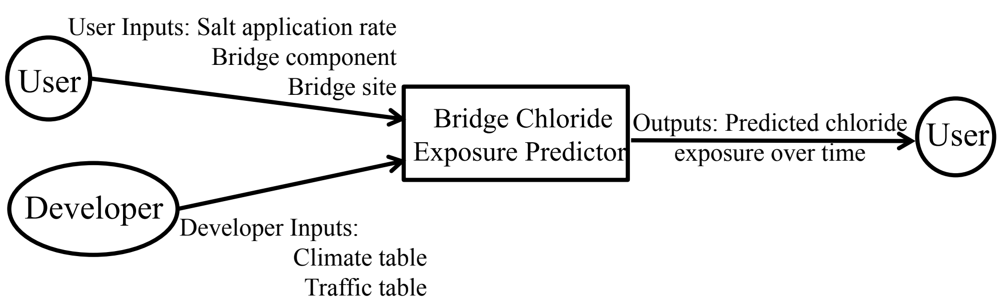


Figure 1: System Context

Figure 1 shows the system context of the software. The user should input a valid salt application rate, bridge component and bridge site (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 assume the following responsibilities:

- User Responsibilities:

  - Provide valid salt application rate, bridge component and bridge site (coordinates) to the software.

- Developer Responsibilities:
  - Provide valid climate table and traffic table to the software.

- BCEP Responsibilities:
  - Build a database storing the chloride exposure data for every GRID_SIZE grid in the past and future.
  - Search and return the chloride exposure trend of the bridge component in given salt application rate at given input bridge site (coordinate).
  - Provide visualization (line graphs and grids) displaying the output data.

## 3.2 User Characteristics

The end user of BCEP should have a high school understanding of geographic coordinates. Additionally, users may benefit from university level of knowledge of bridge components and chloride-induced corrosion to better understand the context and implications of the predicted chloride exposure.

## 3.3 Stakeholders

A stakeholder is a person, group or organization with a vested interest in the project. For BCEP, the stakeholders include:

- Government agency: Government entities need this data for effective bridge management. By identifying bridges with higher corrosion risks, they can allocate budgets more efficiently.

- Bridge engineer: Bridge engineers require the accurate data to use as a reference for planning the road construction of JURISDICTION. For example, they need the data to perform analysis and determining the minimum requirements for a bridge to stand for certain years.

- Researcher: Professionals within the civil engineering field who are concerned with the impacts of climate change on corrosion damage. In particular, this project is conducted in collaboration with Dr. Cancan Yang and Ph.D. candidate Mingsai Xu from the Department of Civil Engineering at McMaster University.

- Developer: Individuals involved in the development, maintenance, and potential future enhancements of the predictive model. This group may include software developers or engineers tasked with inheriting, sustaining, and advancing the model beyond the initial research phase.

- Casual user: People that are interested in the bridge chloride exposure of their area and those interest in the impacts of climate change and traffic pattern.

## 3.4 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 and traffic might impact corrosion-induced damage for reinforced concrete bridges by influencing their 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 (MFR): The amount of water displaced by a single tire. (kg/s)
- 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 referring to the density of water in the air (mass of water per unit volume of air) in the environment. (kg/m$^3$)
- Spray: When water droplets, generally less that 0.5 mm (0.02 inches) in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized.
- Splash: The mechanical action of a vehicle's tire forcing water out of its path. Splash is generally defined as water drops greater than 1.0 mm (0.04 inches) in diameter, which follow a ballistic path away from the tire.
- Airborne deposition: The process of chloride ions moving from the atmosphere to solid surfaces.
- Deposition rate: The rate at which chloride ions are deposited onto a surface over a specific period of time. (kg/m$^3$)

- Drainage: The process by which water or other liquids flow away from an area with excess water.
- AADT: The average daily traffic volume at a given location over an entire year, measured by the number of vehicles.
- AADTT: The average daily truck traffic volume at a given location over an entire year, measured by the number of vehicles.
- Pier: An upright support for a structure or superstructure such as an arch or bridge. A bridge pier is a type of structure that extend to the ground below.
- Deck: The surface of a bridge.

#### 4.1.2 Physical System Description

The key physical system of BCEP, as shown in Figure 2, simulate the situation where a vehicle sprays and splashes 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 vehicle tires.

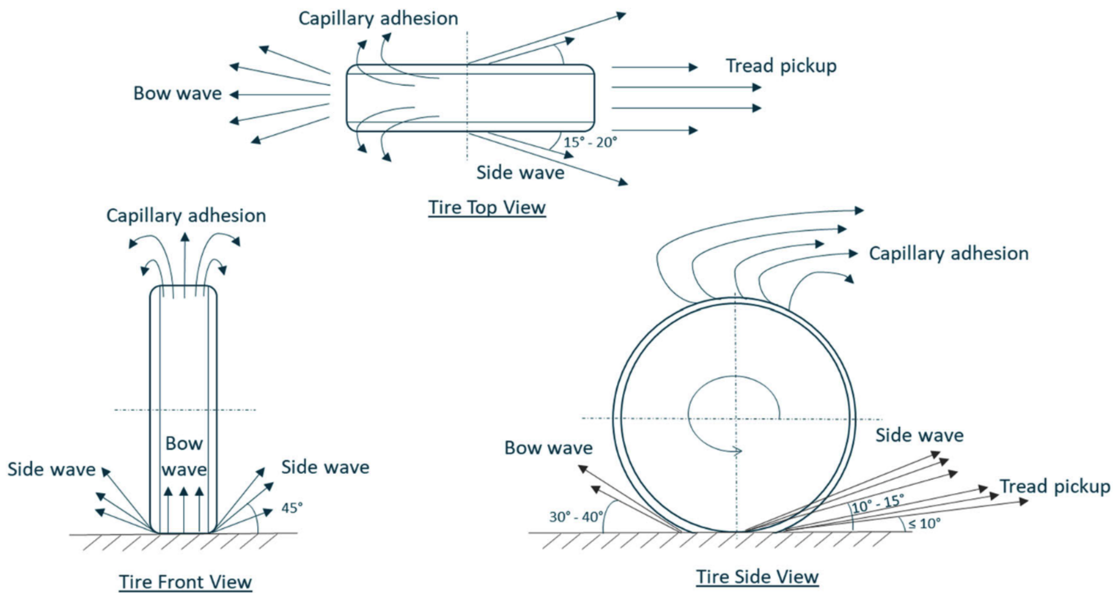


Figure 2: Mechanisms of vehicle spray and splash [4]

#### 4.1.3 Goal Statements

Given the climate data, traffic data, salt application rate, bridge component and geographical coordinates, the goal is to:

GS1: Predict the chloride exposure for bridges in JURISDICTION in the past and future.

### 4.2 Solution Characteristics Specification

Section 4.2.2 begins with reasonable assumptions that simplify the original problem. Section 4.2.3 and Section 4.2.4 present the theoretical models and general definitions being refined by the instance models, respectively. Section 4.2.5 includes the symbols and equations provided for the problem, while Section 4.2.6 describes the instance models that govern this project. A figure showing the relations between Theoretical Model [TM], General Definition [GD], Data Definition [DD], Instance Model [IM] could be found in Figure 3.

#### 4.2.1 Scope Decisions

Only the damage due to the chloride from deicing salt is considered; other sources of damage, like car accident and mechanical wear, are not considered.

#### 4.2.2 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 dissolved in the water on the road surface.

A2: There is no buildup of chloride ions at the surface over multiple seasons.

A3: Only the pier section at the substructure base is affected by the vehicle spray and splash.

A4: All the deicing salts are applied on days with snowfall. (RefBy: DD6)

A5: The lane width for all the roads are the same. (RefBy: DD6, LC1)

A6: The main component of deicing salt is NaCl. (RefBy: DD10)

A7: The tire width for all the vehicles are the same. (RefBy: TM2, GD1 – GD7)

A8: The speed for all the vehicles are the same, taken as the highway speed limit. (RefBy: TM2, GD1 – GD7)

A9: All highway segments has a linear annual growth rate of $r$ AADT and AADTT, with the baseline year being 2006 based on the data from Ontario Ministry of Transportation. (RefBy: DD1, DD2)

A10: The climate and traffic is constant over the entire area of each GRID_SIZE cell. (RefBy: IM3)

A11: The calibration factor $\alpha$ and $\beta$ are assumed to be 0.5, in the calculation for mass flow rate of bowl waves and side waves. (RefBy: GD3)

A12: The deposition of deicing salts along a highway in Sweden is similar to other JURISDICTION. (RefBy: IM1)

A13: The amount of water is enough to activate all four kinds of mechanisms of vehicle spray and splash. (RefBy: GD1, GD2, GD3)

#### 4.2.3 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 | The above equation computes the water film thickness (WD) based on the rainfall intensity and pavement surface properties.<br>• $WD$ is the water depth. (m)<br>• $T$ is the pavement texture. (mm)<br>• $L$ is the pavement drainage length. (m)<br>• $I$ is the rainfall intensity. (m/h)<br>• $S$ 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 | The above equation ($MR_W$) is the general equation for mass flow rate (MFR), which is the maximum amount of water available for splash and spray.<br>• $V$ is the truck speed. (m/s)<br>• $b$ is the tire width. (m)<br>• $WD$ is the water depth/thickness. (m)<br>• $\rho_{water}$ is the density of water. (kg/m$^3$) |
| Note | $b$, the tire width, is assumed to be the same for all vehicles according to A7. $V$, the truck speed, is assumed to be the same for all vehicles, taken as the highway speed limit in Table 1, according to A8. $WD$, the result of TM1, is used as a parameter in this equation. |
| Source | [5] |
| Ref. By | GD1, GD2, GD3 |
| Uses | A7, A8, TM1 |

| | |
|---|---|
| Number | TM3 |
| Label | **Chloride sprayed and splashed** |
| SI Units | kg/m$^3$ |
| Equation | $C_{s_{air}} = (SD_{total\_cl} \times \frac{1}{\Theta} \times \frac{ADT-N}{N_{lane}} + SD_{total\_cl} \times \frac{N}{N_{lane}}) \times t_2$ |
| Description | The above equation computes the mass of chloride ions per unit air volume sprayed and splashed ($C_{s_{air}}$) by all the vehicles passing near the bridge pier every winter, accounting for all the days with snow in a typical winter season.<br><br>• $SD_{total\_cl}$ is the mass of chloride ions per unit air volume, calculated in DD10. (kg/m$^3$)<br>• $\Theta$ is the ratio of chloride ions sprayed and splashed by trucks to light-duty vehicles, it is a constant in Table 1.<br>• $ADT$ is the average daily traffic. (number of vehicles/day)<br>• $N$ is the average number of heavy-duty vehicles per day. (number of vehicles/day)<br>• $N_{lane}$ is the number of lanes.<br>• $t_2$ is the number of days with snow melting. |
| 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, to turn the total traffic for the road into traffic for one lane. |
| Source | [4] |
| Ref. By | GD8 |
| Uses | DD10 |

| Number | TM4 |
| --- | --- |
| Label | **Total airborne deposition at a certain distance** |
| SI Units | kg/m$^3$ |
| Equation | $D(x) = a_{spray} \times e^{-0.05x} + a_{splash} \times e^{-0.5x}$ |
| Description | The above equation describes the total airborne deposition $D$ at a certain distance $x$ from the road.<br>• $a_{spray}$ is the maximum deposition rates that occur from spray. (kg/m$^3$)<br>• $a_{splash}$ is the maximum deposition rates that occur from splash. (kg/m$^3$)<br>• $x$ is the distance between the road and the object. (m) |
| Source | [12] |
| Ref. By | IM1 |

#### 4.2.4 General Definitions

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

| Number | GD1 |
| --- | --- |
| Label | **Mass flow rate for capillary adhesion** |
| SI Units | kg/s |
| Equation | $MR_{CA} = V_{speed} \times b \times K \times h_{film} \times \rho_{water}$ |
| Description | This equation compute the contribution to the amount of water displaced by a single tire (MFR) of capillary adhesion mechanism ($MR_{CA}$).<br>• $V_{speed}$ is the heavy vehicle speed, it is a constant in Table 1. (km/h)<br>• $b$ is the tire width, it is a constant in Table 1. (m)<br>• $K$ is the ratio of the tire width that is not a groove to the tire width, it is a constant in Table 1.<br>• $h_{film}$ is the depth of the water film picked up in each rotation, it is a constant in Table 1. (m)<br>• $\rho_{water}$ is the density of water, it is a constant in Table 1. (kg/m$^3$) |
| Notes | This equation is a refinement of TM2, it assumes that all vehicles have the same speed and same tire width, as stated in A7 and A8 |
| Source | [4] |
| Ref. By | GD4 |
| Uses | A7, A8, A13, TM2 |

### Detailed derivation of mass flow rate for capillary adhesion

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

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

| Number | GD2 |
|---|---|
| Label | **Mass flow rate for tread pickup** |
| SI Units | kg/s |
| Equation | $MR_{TP} = V_{speed} \times b \times (1 - K) \times h_{app} \times \rho_{water}$ |
| Description | The above equation computes the contribution to the amount of water displaced by a single tire (MFR) of tread pickup mechanism ($MR_{TP}$).<br>• $V_{speed}$ is the heavy vehicle speed, it is a constant in Table 1. (km/h)<br>• $b$ is the tire width, it is a constant in Table 1. (m)<br>• $K$ is the ratio of the tire width that is not a groove to the tire width, it is a constant in Table 1.<br>• $h_{app}$ is the thickness of melted water per day with snow melting. (m)<br>• $\rho_{water}$ is the density of water, it is a constant in Table 1. (kg/m$^3$) |
| Notes | This equation is a refinement of TM2, it assumes that all vehicle have same speed and tire width, as stated in A7, A8. It also uses $h_{app}$, which is the result calculated from DD7. As stated in A13, this equation will always be activated as the amount of water is enough. |
| Source | [4] |
| Ref. By | GD5 |
| Uses | A7, A8, A13, TM2, DD7 |

**Detailed derivation of mass flow rate for tread pickup**

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 the tire's tread on each rotation multiplied by the density of water:

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

| | |
|---|---|
| Number | GD3 |
| Label | **Mass flow rate for bow waves and side waves** |
| SI Units | kg/s |
| Equation | $MR_{BW} = MR_{SW} = 0.5 \times V_{speed} \times b \times (h_{app} - K \times h_{film} - (1-K) \times h_{app}) \times \rho_{water}$ |
| Description | The above equation computes the contribution to the amount of water displaced by a single tire (MFR) of bow waves mechanism ($MR_{BW}$) and side waves mechanism ($MR_{SW}$).<br>• $V_{speed}$ is the heavy vehicle speed, it is a constant in Table 1. (km/h)<br>• $b$ is the tire width, it is a constant in Table 1. (m)<br>• $K$ is the ratio of the tire width that is not a groove to the tire width, it is a constant in Table 1.<br>• $h_{film}$ is the depth of the water film picked up in each rotation, it is a constant in Table 1. (m)<br>• $h_{app}$ is the thickness of melted water per day with snow melting. (m)<br>• $\rho_{water}$ is the density of water, it is a constant in Table 1. (kg/m$^3$) |
| Notes | This equation is a refinement of TM2, it assumes that all vehicle have same speed and tire width, as stated in A7, A8. It also uses $h_{app}$, which is the result calculated from DD7. The calibration factor $\alpha$ and $\beta$ are assumed to be 0.5, according to A11. As stated in A13, this equation will always be activated as the amount of water is enough. |
| Source | [4] |
| Ref. By | GD6, GD7 |
| Uses | A7, A8, A11, A13, TM2, DD7 |

### Detailed derivation of mass flow rate for bow waves and side waves

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

| Number | GD4 |
| --- | --- |
| Label | **Spray density for capillary adhesion** |
| SI Units | kg/m$^3$ |
| Equation | $SD_{CA} = (-2.69 \times 10^{-5} \times V' + 2.43 \times 10^{-3}) \times MR_{CA}$ |
| Description | 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] .<br>• $V'$ is the heavy vehicle speed according to A8, it is a constant in Table 1 . (miles/h)<br>• $MR_{CA}$ is the mass flow rate for capillary adhesion, calculated by GD1. (kg/s) |
| Source | [4] |
| Ref. By | DD8 |
| Uses | A8, GD1 |

| Number | GD5 |
|---|---|
| Label | **Spray density for tread pickup** |
| SI Units | kg/m$^3$ |
| Equation | $SD_{TP} = (1.16 \times 10^{-5} \times V' - 5.25 \times 10^{-5}) \times MR_{TP}$ |
| Description | 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] .<br><br>• $V'$ is the heavy vehicle speed according to A8, it is a constant in Table 1. (miles/h)<br><br>• $MR_{TP}$ is the mass flow rate for tread pickup, calculated by GD2. (kg/s) |
| Source | [4] |
| Ref. By | DD8 |
| Uses | A8, GD2 |

| Number | GD6 |
|---|---|
| Label | **Spray density for bow waves** |
| SI Units | kg/m$^3$ |
| Equation | $SD_{BW} = (2.67 \times 10^{-5} \times V' - 4.71 \times 10^{-4}) \times MR_{BW}$ |
| Description | 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] .<br><br>• $V'$ is the heavy vehicle speed according to A8, it is a constant in Table 1. (miles/h)<br><br>• $MR_{BW}$ is the mass flow rate for bow waves, calculated by GD3. (kg/s) |
| Source | [4] |
| Ref. By | DD8 |
| Uses | A8, GD3 |

| | |
|---|---|
| Number | GD7 |
| Label | **Spray density for side waves** |
| SI Units | $kg/m^3$ |
| Equation | $SD_{SW} = (1.65 \times 10^{-5} \times V' - 3.99 \times 10^{-4}) \times MR_{SW}$ |
| Description | 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] .<br>• $V'$ is the heavy vehicle speed according to A8, it is a constant in Table 1. (miles/h)<br>• $MR_{SW}$ is the mass flow rate for side waves, calculated by GD3. (kg/s) |
| Source | [4] |
| Ref. By | DD8 |
| Uses | A8, GD3 |

| Number | GD8 |
|---|---|
| Label | **Chloride sprayed and splashed** |
| SI Units | $kg/m^3$ |
| Equation | $C_{s_{air}} = (SD_{total\_cl} \times \frac{1}{\Theta} \times (AADT - AADTT) + SD_{total\_cl} \times AADTT) \times t_2$ |
| Description | This equation refines TM3. 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.<br><br>• $SD_{total\ cl}$ is the mass of chloride ions per unit air volume, it is the result of DD10. ($kg/m^3$)<br>• $\Theta$ is the ratio of chloride ions sprayed and splashed by trucks to light-duty vehicles, it is a constant in Table 1.<br>• $AADT$ is the annual average daily traffic per lane, given by traffic table DD1.<br>• $AADTT$ is the annual average daily truck traffic per lane, given by traffic table DD2.<br>• $t_2$ is the number of days with snow melting, given by climate table in DD5. |
| Sources | [7, 8] |
| Ref. By | IM1 |
| Uses | TM3 , DD1, DD2, DD5, DD10 |

### 4.2.5 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 | **AADT** |
| Symbol | $AADT$ |
| SI Units | N/A |
| Equation | $AADT : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ |
| Description | $AADT(longitude, latitude)$ is the Annual Average Daily Traffic as a function of position, it is determined from the traffic table by taking two real number (longitude and latitude), and return a real number (AADT). An example of it could be found in Table 4). The traffic data is constant over each GRID_SIZE cell by A10. According to A9, $AADT$ has a linear growth rate of $r$ with the baseline year being 2006. Future $AADT$ values are determined using this growth rate. |
| Sources | [7] |
| Ref. By | GD8, IM2 |
| Uses | A9, A10 |

| Number | DD2 |
|---|---|
| Label | **AADTT** |
| Symbol | $AADTT$ |
| SI Units | N/A |
| Equation | $AADTT : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ |
| Description | $AADTT(longitude, latitude)$ is the Annual Average Daily Truck Traffic as a function of position, it is determined from the traffic table by taking two real number (longitude and latitude), and return a real number (AADTT). An example of it could be found in Table 5). The traffic data is constant over each GRID_SIZE cell by A10. According to A9, $AADTT$ has a linear growth rate of $r$ with the baseline year being 2006. Future $AADTT$ values are determined using this growth rate. |
| Sources | [7] |
| Ref. By | GD8 |
| Uses | A9, A10 |

| Number | DD3 |
|---|---|
| Label | **Total snowfall** |
| Symbol | $h_{total}$ |
| SI Units | m |
| Equation | $h_{total} : \mathbb{R} \times \mathbb{R} \times \mathbb{N} \rightarrow \mathbb{R}$ |
| Description | $h_{total}(longitude, latitude, year)$ is the total snowfall during a winter season, it is determined from the climate table by taking two real number (longitude and latitude) and one natural number (year), and return a real number ($h_{total}$). An example of the $h_{total}$ in climate table could be found in Table 6. |
| Sources | [7] |
| Ref. By | DD6, DD7, IM2 |
| Uses | A10 |

| Number | DD4 |
|---|---|
| Label | **Snowfall days** |
| Symbol | $t_1$ |
| SI Units | day |
| Equation | $t_1 : \mathbb{R} \times \mathbb{R} \times \mathbb{N} \rightarrow \mathbb{N}$ |
| Description | $t_1(longitude, latitude, year)$ is the number of days with snowfall during a winter season, it is determined from the climate table by taking two real number (longitude and latitude) and one natural number (year), and return a real number ($t_1$). An example of the $t_1$ in climate table could be found in Table 7. |
| Sources | [7] |
| Ref. By | DD6 |
| Uses | A10 |

| | |
|---|---|
| Number | DD5 |
| Label | **Snow melting days** |
| Symbol | $t_2$ |
| SI Units | day |
| Equation | $t_2 : \mathbb{R} \times \mathbb{R} \times \mathbb{N} \rightarrow \mathbb{N}$ |
| Description | $t_2(longitude, latitude, year)$ is the number of days with snow melting during a winter season, it is determined from the climate table by taking two real number (longitude and latitude) and one natural number (year), and return a real number ($t_2$). An example of the $t_2$ in climate table could be found in Table 8. |
| Sources | [7] |
| Ref. By | GD8, DD7 |
| Uses | A10 |

| Number | DD6 |
| --- | --- |
| Label | **Deicing salts quantity** |
| Symbol | $M_{app}$ |
| SI Units | kg/m$^2$ |
| Equation | $$M_{app} = \begin{cases} \frac{V_{salt_h} \times h_{total}}{t_1 \times W_{lane}} & \text{for high salt application rate} \\ \frac{V_{salt_l} \times h_{total}}{t_1 \times W_{lane}} & \text{for low salt application rate} \end{cases}$$ |
| Description | The equation determine the quantity of deicing salts applied per day with snowfall, according to A4, that the deicing salts are applied on the days of snowfall. There are two cases of calculating $M_{app}$, one is for high salt application rate, and the other one is low salt application rate, both taken as constant in Table 1.<br><br>• $V_{salt_h}$ is the normalized high salt application rate, it is a constant in Table 1. (t/cm/km)<br>• $V_{salt_l}$ is the normalized low salt application rate, it is a constant in Table 1. (t/cm/km)<br>• $h_{total}$ is the total snowfall during a winter season, given by the climate table DD3. (m)<br>• $t_1$ is the number of days with snowfall, given by the climate table DD4.<br>• $W_{lane}$ is the lane width. According to A5, all the lane has the same width, it is a constant in Table 1. (m). |
| Sources | [4, 7] |
| Ref. By | DD9 |
| Uses | A4, A5, DD3, DD4 |

| | |
|---|---|
| Number | DD7 |
| Label | **Daily water film thickness** |
| Symbol | $h_{app}$ |
| SI Units | m |
| Equation | $h_{app} = h_{total}/t_2$ |
| Description | The equaition above calculates the thickness of melted water per day with snow melting.<br>• $h_{total}$ is the the total snowfall during a winter season, given by the climate table DD3. (m)<br>• $t_2$ is the number of days with snow melting, given by the climate table DD5. |
| Sources | [4, 9] |
| Ref. By | GD2, GD3, DD9 |
| Uses | DD3, DD5 |

| Number | DD8 |
|---|---|
| Label | **Total spray density** |
| SI Units | $kg/m^3$ |
| Equation | $SD_{total} = SD_{CA} + SD_{TP} + SD_{BW} + SD_{SW}$ |
| Description | 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.<br>• $SD_{CA}$ is the spray density due to capillary adhesion, calculated by GD4.<br>• $SD_{TP}$ is the spray density due to tread pickup, calculated by GD5.<br>• $SD_{BW}$ is the spray density due to bow waves, calculated by GD6<br>• $SD_{SW}$ is the spray density due to side waves, calculated by GD7. |
| Source | [4] |
| Ref. By | DD10 |
| Uses | GD4, GD5, GD6, GD7 |

| Number | DD9 |
|---|---|
| Label | **Ratio of salt over water** |
| SI Units | none |
| Equation | $\delta_{salt} = \frac{M_{app}}{h_{app} \times \rho_{water}}$ |
| Description | 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.<br>• $M_{app}$ is the quantity of deicing salts applied per day, calculated by DD6. ($kg/m^2$)<br>• $h_{app}$ is the thickness of melted water per day, calcualted by DD7. (m)<br>• $\rho_{water}$ is the density of water, it is a constant in Table 1. ($kg/m^3$) |
| Source | [4] |
| Ref. By | DD10 |
| Uses | DD6, DD7 |

| Number | DD10 |
|---|---|
| Label | **Mass of chloride ions** |
| SI Units | $kg/m^3$ |
| Equation | $SD_{total\_cl} = SD_{total} \times \delta_{salt} \times \theta_{chloride}$ |
| Description | This equation computes the mass of chloride ions per unit air volume kicked up by each truck, where we assume the chloride ions are from NaCl (A6). <br>• $\theta_{chloride}$ is the molar mass ratio of chloride to deicing salts, it is a constant in Table 1. (ratio) <br>• $SD_{total}$ is the mass of water per unit air volume, calculated by DD8. ($kg/m^3$) <br>• $\delta_{salt}$ is the salt-to-water mass ratio per unit area of road, calculated by DD9. (ratio) |
| Source | [4, 7] |
| Ref. By | TM3, GD8 |
| Uses | A6, DD8, DD9 |

### 4.2.6 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 4.2.5 to replace the abstract symbols in the models identified in Sections 4.2.3 and 4.2.4.

The goal GS1 is solved by IM1, IM2, IM3.

| Number | IM1 |
|---|---|
| Label | **Chloride on the pier** |
| Input | $C_{s_{air}}, d$ |
| 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 | The above equation is a refinement of TM4, it is assumed that the situation in Sweden is similar to other JURISDICTION, so theories in [11, 12] could be applied. This 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.<br>• $C_{s_{air}}$ is the result from GD8, which is the cumulative mass of chloride ions per unit air volume sprayed and splashed by all the vehicles passing near the bridge pier. ($\text{kg/m}^3$)<br>• $d$ is the distance between the road edge and nearby bridge structure, it is a constant in Table 1. (m) |
| Sources | [7, 10, 11, 12] |
| Ref. By | IM3, LC2 |
| Uses | A12, TM4, GD8 |

**Detailed derivation of chloride on the surface**

In TM4, it is mentioned that

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

Given the distance between road edge and nearby bridge structure is $d$, 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, where $a_{air}$ could be substituted as $C_{s_{air}}$, the total maximum chloride deposition rate that can occur:

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

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

then 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 | **Chloride on the deck** |
| Input | $h_{total}, AADT$ |
| Output | $C_s$ |
| Equation | $C_s = 0.11 \times h_{total} - 0.000189 \times AADT + 3.349$ |
| Description | The above equation computes the chloride ions deposition on bridge decks. It is based on a linear regression model by [6], that characterize the relationship between the surface chloride concentration on bridge decks and two key factors: the annual snowfall amount ($h_{total}$) and the AADT<br><br>• $h_{total}$ is the total snowfall during a winter season, given by climate table in DD3. (m)<br><br>• $AADT$ is the annual average daily traffic, given by traffic table in DD1. |
| Sources | [6, 7] |
| Ref. By | IM3 |
| Uses | DD1, DD3 |

| | |
|---|---|
| Number | IM3 |
| Label | **Search data for specific coordinate** |
| Input | $long : \mathbb{R}, lat : \mathbb{R}$ |
| Output | $[C_s]_n^m$ |
| Description | This instance model get the longitude and latitude as input, and return a list of surface chloride concentration, over the time periods $n$ to $m$ as output, which is the result of IM1 and IM2. The searching process is conducted using coding logic. This is the model that the end user of this software will encounter.<br>• $(long, lat)$ is the coordinate of a location. (°, °)<br>• $[C_s]_n^m$ is a list of chloride exposure data over the time periods $n$ to $m$. ([kg/m$^3$])<br>• $n$ is the start year (an integer) for the period, based on the availability of data in the climate and traffic tables.<br>• $m$ is the end year (an integer) for the period, based on the availability of data in the climate and traffic tables. |
| Uses | A10, IM1, IM2 |

### 4.2.7 Input Data Constraints

Table 2 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 for typical values lists the most frequent occurrences in the traffic and climate table. 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 BCEP project, we talk about not only the input variables mentioned in instance models, but also include those in other models that the instance models use. The physical constraints are purposed by [4]. Beside those, the input of the software need to be coordinates inside JURISDICTION. This will be done by input checking algorithm later.
The specification parameters in Table 2 are listed in Table 1.

Table 2: Input Variables

| Var | Physical Constraints | Software Constraints | Typical Value | Uncertainty |
|---|---|---|---|---|
| $AADT$ | $AADT \geq 0$ | $AADT \geq 0$ | 559 | 10% |
| $AADTT$ | $AADTT \geq 0$ | $AADTT \geq 0$ | 103 | 10% |
| $h_{total}$ | $h_{total} \geq 0$ | $h_{total} \geq 0$ | 70 | 10% |
| $lat$ | $-90 \leq lat \leq 90$ | $-90 \leq lat \leq 90$ | 48.0863 | 10% |
| $long$ | $0 \leq long \leq 360$ | $0 \leq long \leq 360$ | 275.0678 | 10% |
| $t_1$ | $0 \leq t_1 \leq 365$ | $0 \leq t_1 \leq 365$ | 90 | 10% |
| $t_2$ | $0 \leq t_2 \leq 365$ | $0 \leq t_2 \leq 365$ | 70 | 10% |

#### 4.2.8 Properties of a Correct Solution

A correct solution must exhibit the chloride exposure values that does not exceed the solubility limits of chloride ions, which is according to the property of sodium chloride.

Table 3: Output Variables

| Var | Physical Constraints |
|---|---|
| $C_s$ | $C_s < 360\ kg/m^3$ |

# 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 climate table should be processed by domain expert, originally from the CanRCM4.

R2: The traffic table should be processed by domain expert, originally from the AASHTOWare Pavement ME Design Traffic Map.

R3: The software should have a map of JURISDICTION that users can click to provide the input coordinate (longitude & latitude).

R4: The software should only accept coordinate that are inside JURISDICTION. (By IM3)

R5: The software should have an option for user to select parameters for the two bridge components: pier and deck. For chloride on pier (IM1) consider the different salt application rate (DD6), while the chloride on deck (IM2) is not related to salt application rate.

R6: The result list of surface chloride concentration should be of $p$ decimal data, showing the trend of chloride exposure from 2006 to 2100 at the input location. (By IM3)

R7: The result list of surface chloride concentration should have an visualization of line graph and table.

R8: The result list of surface chloride concentration and the visualization should be able to be downloaded by users to their local machine in csv.

## 5.2 Nonfunctional Requirements

NFR1: **Reliability**: The reliability is measured and verified in the VnVplan.

NFR2: **Usability**: The software interface should be intuitive and easy to use, allowing users in the section 3.2 to easily choose salt application levels and concerned bridge components, input coordinates or click on the map, look at the predicted chloride exposure, and download the input data and the results of chloride exposure at that specific location in no more than five minutes. More measurements about usability could be found in VnVplan.

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, taking only 10% of the origin develop time.

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 to more JURISDICTION, support concurrent users while maintaining a quick response time.

## 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 A4, the deicing salts need to be applied on the roads in time to ensure safe driving conditions during winter weather.
- A5, A7 and A8 simplify the model by standardizing the lane width, tire width and vehicle speed, which streamlines the analysis and allows for consistent calculations.
- A6 simplifies the model while still capturing the essence of typical deicing salt compositions, as NaCl is one of the most widely used deicing salts due to its effectiveness and affordability.
- It is important to note that the traffic data of the Pavement ME Design Traffic Map was collected in the year of 2006. However, It has been observed that the traffic volume across Ontario experiences an annual growth rate of about $r$ on average, so to account for the time-variant nature of traffic volume and its impact on chloride exposure, a linear annual growth rate of $r$ was applied to both AADT and AADTT for all highway segments in A9.
- A10 is assumed following the resolution of the CanRCM4 model ([13]), where the climate data are extracted from.

The constraints in Table 2 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 A5 is likely to be changed.

LC2: 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.

LC3: Deicing salt is typically not used in the northern provinces. However, due to climate change, these provinces are now experiencing temperatures as low as -15 degrees. This may necessitate the use of deicing salt, which could lead to changes in adaptation strategies for those JURISDICTION. Further research is needed to fully understand these implications.

LC4: The application rate of deicing salt varies across different provinces due to differing policies, so the values $V_{salt_h}$ and $V_{salt_l}$ in Section 1.5 might change based on those variations.

LC5: Currently, the resolution is limited to 25 km due to the constraints of the CanRCM4 model. If higher-resolution data becomes available in the future, the GRID_SIZE in Section 1.5 can be adjusted accordingly.

LC6: Th model used in IM2 demonstrated a correlation coefficient of 0.76. It is likely that it could be improved substa ntially if the composite chloride profiles were to be based on a much larger sampling in the future.

# 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 A4 is unlikely to change.

ULC2: A6 is also unlikely to change, as the main component of deicing salt remain consistent.

# 8 Examples for Climate Table and Traffic Table

This section includes the sample tables for climate table and traffic table. The longitude and latitude are the center coordinate of each grid. The method to determine which grid the input coordinate belongs to is to find the pair of longitude and latitude in the table with closest distance.

| long | lat | AADT |
|---|---|---|
| 277.9257 | 46.40717 | 559 |
| 278.0479 | 46.8391 | 559 |
| 279.4862 | 43.03779 | 2489 |

Table 4: AADT - Anuual Average Daily Traffic

| long | lat | AADTT |
|---|---|---|
| 277.9257 | 46.40717 | 103 |
| 278.0479 | 46.8391 | 103 |
| 279.4862 | 43.03779 | 433 |

Table 5: AADTT - Anuual Average Daily Truck Traffic

| long | lat | 2006 | 2007 | 2008 | ... | 2100 |
|---|---|---|---|---|---|---|
| 277.9257 | 46.40717 | 128.2556 | 177.2936 | 131.0888 | ... | 84.54496 |
| 278.0479 | 46.8391 | 103.0215 | 58.72967 | 45.85082 | ... | 53.21502 |
| 279.4862 | 43.03779 | 114.4002 | 55.12466 | 42.80479 | ... | 52.90405 |

Table 6: $h_{total}$ - Total Snowfall during a Winter

| long | lat | 2006 | 2007 | 2008 | ... | 2100 |
|---|---|---|---|---|---|---|
| 277.9257 | 46.40717 | 99 | 113 | 83 | ... | 65 |
| 278.0479 | 46.8391 | 70 | 75 | 59 | ... | 44 |
| 279.4862 | 43.03779 | 73 | 74 | 59 | ... | 46 |

Table 7: $t_1$ - Number of Days with Snowfall

| long | lat | 2006 | 2007 | 2008 | ... | 2100 |
|---|---|---|---|---|---|---|
| 277.9257 | 46.40717 | 89 | 84 | 81 | ... | 84 |
| 278.0479 | 46.8391 | 89 | 79 | 69 | ... | 53 |
| 279.4862 | 43.03779 | 89 | 65 | 70 | ... | 52 |

Table 8: $t_2$ - Number of Days with Snow Melting

# 9 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. Figure 3 shows how IM1 is determined using the other models.
Table 9 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions. Table 10 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 11 shows the dependencies of instance models, requirements, and data constraints on each other. 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.

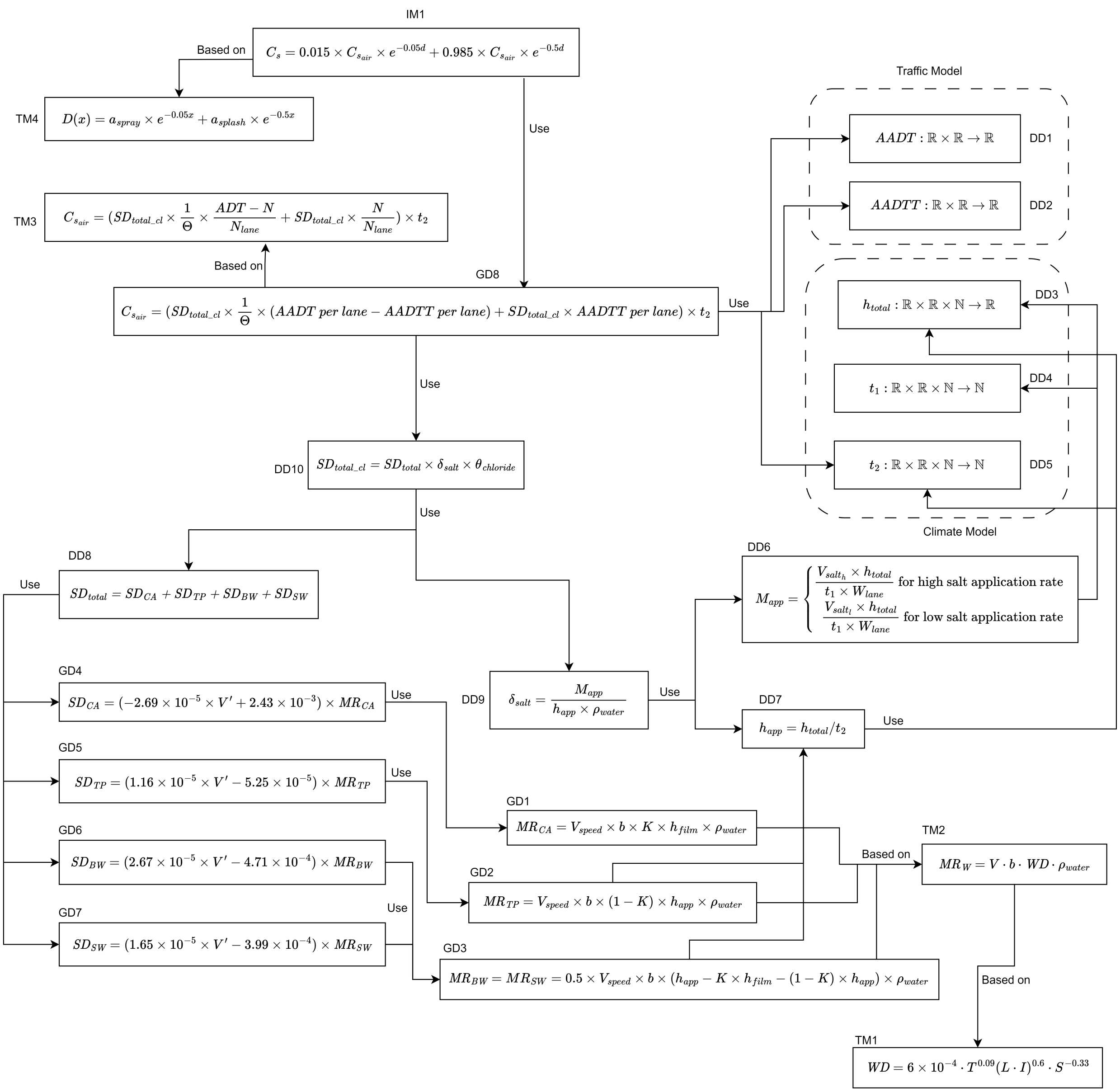


Figure 3: Traceability Between Models

## 9.1 Traceability Between Models

| | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TM1 | | | | | | | | | | | | | |
| TM2 | | | | | | | X | X | | | | | |
| TM3 | | | | | | | | | | | | | |
| TM4 | | | | | | | | | | | | | |
| GD1 | | | | | | | X | X | | | | | X |
| GD2 | | | | | | | X | X | | | | | X |
| GD3 | | | | | | | X | X | | | X | | X |
| GD4 | | | | | | | | X | | | | | |
| GD5 | | | | | | | | X | | | | | |
| GD6 | | | | | | | | X | | | | | |
| GD7 | | | | | | | | X | | | | | |
| GD8 | | | | | | | | | | | | | |
| DD1 | | | | | | | | | X | | | | |
| DD2 | | | | | | | | | X | | | | |
| DD3 | | | | | | | | | | | | | |
| DD4 | | | | | | | | | | | | | |
| DD5 | | | | | | | | | | | | | |
| DD6 | | | | X | X | | | | | | | | |
| DD7 | | | | | | | | | | | | | |
| DD8 | | | | | | | | | | | | | |
| DD9 | | | | | | | | | | | | | |
| DD10 | | | | | | X | | | | | | | |
| IM1 | | | | | | | | | | | | X | |
| IM2 | | | | | | | | | | | | | |
| IM3 | | | | | | | | | | X | | | |
| LC1 | | | | | X | | | | | | | | |
| LC2 | | | | | | | | | | | | | |
| LC3 | X | | | | | | | | | | | | |
| LC4 | | | | | | | | | | | | | |
| LC5 | | | | | | | | | | X | | | |
| LC6 | | | | | | | | | | | | | |
| ULC1 | | | | X | | | | | | | | | |
| ULC2 | | | | | | X | | | | | | | |

Table 9: Traceability Matrix Showing the Connections Between Assumptions and Other Items

| | TM1 | TM2 | TM3 | TM4 | GD1 | GD2 | GD3 | GD4 | GD5 | GD6 | GD7 | GD8 | DD6 | DD7 | DD8 | DD9 | DD10 | IM1 | IM2 | IM3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TM1 | | X | | | | | | | | | | | | | | | | | | |
| TM2 | X | | | | X | X | X | | | | | | | | | | | | | |
| TM3 | | | | | | | | | | | | X | | | | | X | | | |
| TM4 | | | | | | | | | | | | | | | | | | X | | |
| GD1 | | X | | | | | | X | | | | | | | | | | | | |
| GD2 | | X | | | | | | | X | | | | | X | | | | | | |
| GD3 | | X | | | | | | | | X | X | | | X | | | | | | |
| GD4 | | | | | X | | | | | | | | | | X | | | | | |
| GD5 | | | | | | X | | | | | | | | | X | | | | | |
| GD6 | | | | | | | X | | | | | | | | X | | | | | |
| GD7 | | | | | | | X | | | | | | | | X | | | | | |
| GD8 | | | X | | | | | | | | | | | | | | X | X | | |
| DD1 | | | | | | | | | | | | X | | | | | | | X | |
| DD2 | | | | | | | | | | | | X | | | | | | | | |
| DD3 | | | | | | | | | | | | | X | X | | | | | X | |
| DD4 | | | | | | | | | | | | | X | | | | | | | |
| DD5 | | | | | | | | | | | | X | | X | | | | | | |
| DD6 | | | | | | | | | | | | | | | | X | | | | |
| DD7 | | | | | | X | X | | | | | | | | | X | | | | |
| DD8 | | | | | | | | X | X | X | X | | | | | | X | | | |
| DD9 | | | | | | | | | | | | | X | X | | | X | | | |
| DD10 | | | X | | | | | | | | | X | | | X | X | | | | |
| IM1 | | | | X | | | | | | | | X | | | | | | | | X |
| IM2 | | | | | | | | | | | | | | | | | | | | X |
| IM3 | | | | | | | | | | | | | | | | | | X | X | |

Table 10: Traceability Matrix Showing the Connections Between Items of Different Sections

| | IM1 | IM2 | IM3 |
|---|---|---|---|
| R1 | X | X | X |
| R2 | X | X | X |
| R3 | | | X |
| R4 | | | X |
| R5 | X | X | |
| R6 | X | X | |
| R7 | | | X |
| R8 | | | X |
| NFR1 | X | X | X |
| NFR2 | | | X |
| NFR3 | | | X |
| NFR4 | | | X |
| NFR5 | | | X |

Table 11: Traceability Matrix Showing the Connections Between Requirements and Instance Models

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