Software Requirements Specification for Bridge Corrosion Predictor (BCP): 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 for BCP base on feedback from Dr. Smith

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
δ_{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_{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	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
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
AADT	Annual Average Daily Traffic
AADTT	Annual Average Daily Truck Traffic
ADT	Average Daily Traffic
BCP	Bridge Corrosion 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 typically remain constant.

Symbol	Description	Value	Unit
JURISDICTION	An area that share a particular set of laws or rules	Ontario	-
GRID_SIZE	Minimum area sharing the same climate and traffic data	25×25	-
V	speed of vehicle	62.1371	miles/h
V_{speed}	speed of heavy vehicle	100	km/h
b	tire width	0.56	m
d	distance between road edge and bridge substructure	3.5	m
h_{film}	depth of the water film picked up in each rotation	0.0001	m
K	ratio of tire width that is not a groove to tire width	0.75	N/A
ρ_{water}	water density	997	kg/m^3
W_{lane}	lane width	3.75	m
V_{salt_h}	high salt application rate	0.07	t/cm/km
V_{salt_l}	low salt application rate	0.05	t/cm/km
$\theta_{chloride}$	molar mass ratio of chloride ions over deicing salts	0.61	N/A
Θ	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 deiicing 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 Corrosion Predictor (BCP).
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 BCP. 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 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. The factors that affect bridge corrosion are assumed to be limited 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 BCP 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

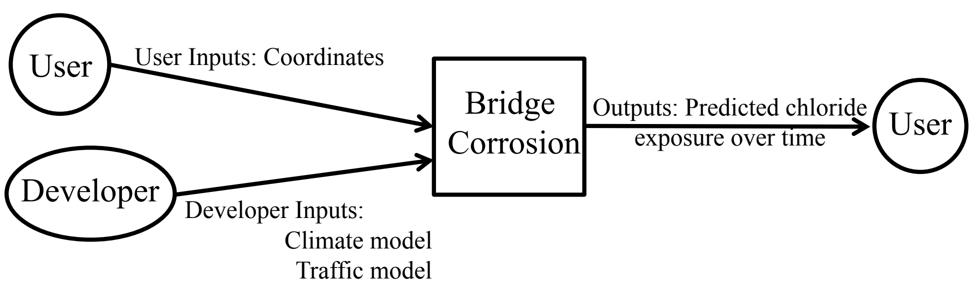

Figure 1: System Context

Figure 1 shows the system context of the software. The user should input a 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 coordinates to the software.
- Developer Responsibilities:
  - Provide valid climate model and traffic model to the software.

- BCP 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 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 BCP should have a 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 Stakeholders

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

- Government: Government entities require the accurate data to use as a reference for planning the road construction of JURISDICTION. For example, they might want to adjust the thickness of the road in certain areas based on the data from this model.
- 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 chloride exposure rate 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 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. (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.

4.1.2 Physical System Description

The key physical system of BCP, 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.

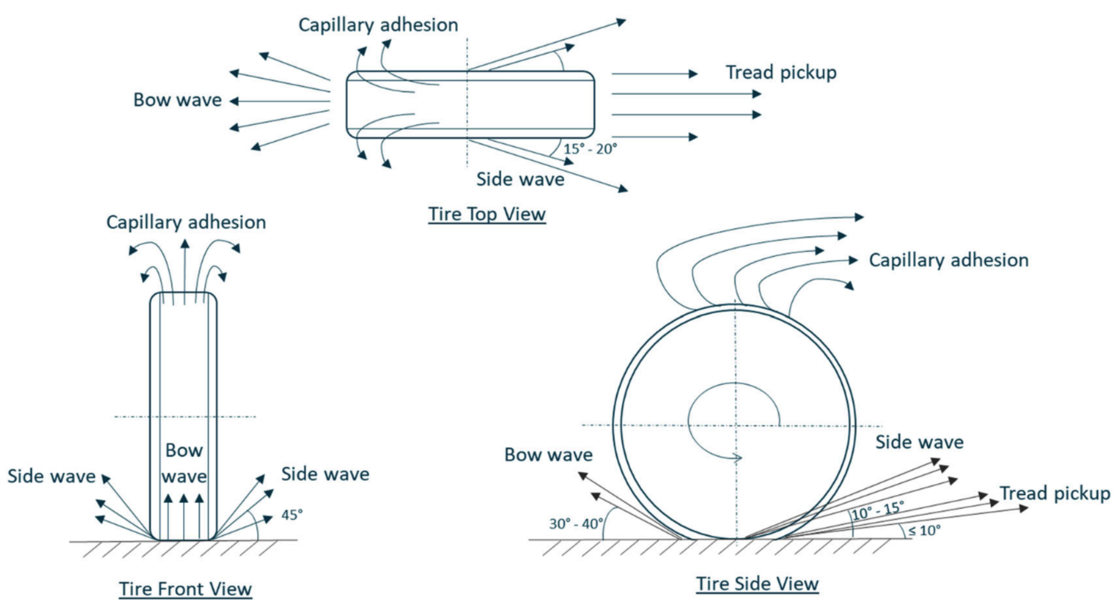

Figure 2: Mechanisms of vehicle spray and splash [4]

4.1.3 Goal Statements

Given the climate data, traffic data and geographical coordinates, the goal statement is:

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.

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 applied on days with snowfall. (RefBy: DD6)

A2: The lane width for all the roads are the same. (RefBy: DD6, LC1)

A3: The main component of deicing salt is NaCl. (RefBy: DD10)

A4: The tire width for all the vehicles are the same. (RefBy: TM2, GD1 - GD7)

A5: The speed for all the vehicles are the same, taken as the highway speed limit. (RefBy: TM2, GD1 - GD7)

A6: All highway segments has a linear annual growth rate of 2% AADT and AADTT. (RefBy: DD1, DD2)

A7: The climate and traffic is constant over the entire area of each GRID_SIZE cell. (RefBy: IM3)

A8: The calibration factor α and β are assumed to be 0.5, in the calculation for mass flow rate of bowl waves and side waves. (RefBy: GD3)

A9: The deposition of deicing salts along a highway in Sweden is similar to other JURISDICTION. (RefBy: IM1)

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. • 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	The above equation is the general equation for mass flow rate (MFR), which is the maximum amount of water available for splash and spray. • 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)
Note	b, the tire width, is assumed to be the same for all vehicles according to A4. V, the truck speed, is assumed to be the same for all vehicles, taken as the highway speed limit in Table 1, according to A5. WD, the result of TM1, is used as a parameter in this equation.
Source	[5]
Ref. By	GD1, GD2, GD3
Uses	A4, A5, 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. • SD_{total_cl} is the mass of chloride ions per unit air volume, calculated in DD10. (kg/m^3) • Θ is the ratio of chloride ions sprayed and splashed by trucks to light-duty vehicles, it is a constant in Table 1. • 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_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 at a certain distance from the road. • 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) • 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}). • V_{speed} is the heavy vehicle speed, it is a constant in Table 1. (km/h) • b is the tire width, it is a constant in Table 1. (m) • K is the ratio of the tire width that is not a groove to the tire width, it is a constant in Table 1. • h_{film} is the depth of the water film picked up in each rotation, it is a constant in Table 1. (m) • ρ_{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 same tire width, as stated in A4, A5
Source	[4]
Ref. By	GD4
Uses	A4, A5, 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}). The tread pickup will be activated only if there is water remaining after the capillarity adhesion • V_{speed} is the heavy vehicle speed, it is a constant in Table 1. (km/h) • b is the tire width, it is a constant in Table 1. (m) • K is the ratio of the tire width that is not a groove to the tire width, it is a constant in Table 1. • h_{app} is the thickness of melted water per day with snow melting. (m) • ρ_{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 A4, A5. It also uses h_{app}, which is the result calculated from DD7.
Source	[4]
Ref. By	GD5
Uses	A4, A5, 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}). This equation will be activated only if there is water remaining after the capillary adhesion and tread pickup. • V_{speed} is the heavy vehicle speed, it is a constant in Table 1. (km/h) • b is the tire width, it is a constant in Table 1. (m) • K is the ratio of the tire width that is not a groove to the tire width, it is a constant in Table 1. • h_{film} is the depth of the water film picked up in each rotation, it is a constant in Table 1. (m) • h_{app} is the thickness of melted water per day with snow melting. (m) • ρ_{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 A4, A5. It also uses h_{app}, which is the result calculated from DD7. The calibration factor α and β are assumed to be 0.5, according to A8.
Source	[4]
Ref. By	GD6, GD7
Uses	A4, A5, A8, 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 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	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] . • V' is the heavy vehicle speed according to A5, it is a constant in Table 1 . (miles/h) • MR_{CA} is the mass flow rate for capillary adhesion, calculated by GD1. (kg/s)
Source	[4]
Ref. By	DD8
Uses	A5, 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] . • V' is the heavy vehicle speed according to A5, it is a constant in Table 1. (miles/h) • MR_{TP} is the mass flow rate for tread pickup, calculated by GD2. (kg/s)
Source	[4]
Ref. By	DD8
Uses	A5, 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] . • V' is the heavy vehicle speed according to A5, it is a constant in Table 1. (miles/h) • MR_{BW} is the mass flow rate for bow waves, calculated by GD3. (kg/s)
Source	[4]
Ref. By	DD8
Uses	A5, 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] . • V' is the heavy vehicle speed according to A5, it is a constant in Table 1. (miles/h) • MR_{SW} is the mass flow rate for side waves, calculated by GD3. (kg/s)
Source	[4]
Ref. By	DD8
Uses	A5, GD3

Number	GD8
Label	**Chloride sprayed and splashed**
SI Units	kg/m^3
Equation	$C_{s_{air}} = (SD_{total\_cl} \times \frac{1}{\Theta} \times (AADT\ per\ lane - AADTT\ per\ lane) + SD_{total\_cl} \times AADTT\ per\ lane) \times t_2$
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. • $SD_{total\ cl}$ is the mass of chloride ions per unit air volume, it is the result of DD10. (kg/m^3) • Θ is the ratio of chloride ions sprayed and splashed by trucks to light-duty vehicles, it is a constant in Table 1. • $AADT\ per\ lane$ is the annual average daily traffic per lane, given by traffic model DD1. • $AADTT\ per\ lane$ is the annual average daily truck traffic per lane, given by traffic model DD2. • t_2 is the number of days with snow melting, given by climate model 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	$long : \mathbb{R} \times lat : \mathbb{R} \rightarrow AADT : \mathbb{R}$
Description	$AADT$ is the Annual Average Daily Truck Traffic, it is given by the traffic model. The $AADT$ for each GRID_SIZE grid could be found by inputing the coordinate. According to A6, $AADT$ has a linear growth rate of 2%, so the future $AADT$ values are determined using this growth rate. An example of the $AADT$ in traffic model could be found in Table 4.
Sources	[7]
Ref. By	GD8, IM2
Uses	A6

Number	DD2
Label	**AADTT**
Symbol	$AADTT$
SI Units	N/A
Equation	$long : \mathbb{R} \times lat : \mathbb{R} \rightarrow AADTT : \mathbb{R}$
Description	$AADTT$ is the Annual Average Daily Truck Traffic, it is given by the traffic model. The $AADTT$ for each GRID_SIZE grid could be found by inputing the coordinate. According to A6, $AADTT$ has a linear growth rate of 2%, so the future $AADTT$ values are determined using this growth rate. An example of the $AADTT$ in traffic model could be found in Table 5.
Sources	[7]
Ref. By	GD8
Uses	A6

Number	DD3
Label	**Total snowfall**
Symbol	h_{total}
SI Units	m
Equation	$long : \mathbb{R} \times lat : \mathbb{R} \times year : \mathbb{N} \rightarrow h_{total} : \mathbb{R}$
Description	h_{total} is the total snowfall during a winter season, it is given by the climate model. The h_{total} for each GRID_SIZE grid could be found by inputing the coordinate and the year. An example of the h_{total} in climate model could be found in Table 6.
Sources	[7]
Ref. By	DD6, DD7, IM2

Number	DD4
Label	**Snowfall days**
Symbol	t_1
SI Units	day
Equation	$long : \mathbb{R} \times lat : \mathbb{R} \times year : \mathbb{N} \rightarrow t_1 : \mathbb{N}$
Description	t_1 is the number of days with snowfall during a winter season, it is given by the climate model. The t_1 for each GRID_SIZE grid could be found by inputing the coordinate and the year. An example of the t_1 in climate model could be found in Table 7.
Sources	[7]
Ref. By	DD6

Number	DD5
Label	**Snow melting days**
Symbol	t_2
SI Units	day
Equation	$long : \mathbb{R} \times lat : \mathbb{R} \times year : \mathbb{N} \rightarrow t_2 : \mathbb{N}$
Description	t_2 is the number of days with snow melting during a winter season, it is given by the climate model. The t_2 for each GRID_SIZE grid could be found by inputing the coordinate and the year. An example of the t_2 in climate model could be found in Table 8.
Sources	[7]
Ref. By	GD8, DD7

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 A1, 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. • V_{salt_h} is the normalized high salt application rate, it is a constant in Table 1. (t/cm/km) • V_{salt_l} is the normalized low salt application rate, it is a constant in Table 1. (t/cm/km) • h_{total} is the total snowfall during a winter season, given by the climate model DD3. (m) • t_1 is the number of days with snowfall, given by the climate model DD4. • W_{lane} is the lane width. According to A2, all the lane has the same width, it is a constant in Table 1. (m).
Sources	[4, 7]
Ref. By	DD9
Uses	A1, A2, 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. • h_{total} is the the total snowfall during a winter season, given by the climate model DD3. (m) • t_2 is the number of days with snow melting, given by the climate model 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. • SD_{CA} is the spray density due to capillary adhesion, calculated by GD4. • SD_{TP} is the spray density due to tread pickup, calculated by GD5. • SD_{BW} is the spray density due to bow waves, calculated by GD6 • 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. • M_{app} is the quantity of deicing salts applied per day, calculated by DD6. (kg/m^2) • h_{app} is the thickness of melted water per day, calcualted by DD7. (m) • ρ_{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 (A3). • $\theta_{chloride}$ is the molar mass ratio of chloride to deicing salts, it is a constant in Table 1. (ratio) • SD_{total} is the mass of water per unit air volume, calculated by DD8. (kg/m^3) • δ_{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	A3, 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. • $C_{s_{air}}$ 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. (kg/m^3) • 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	A9, 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, that is, a_{air} is 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	$C_s = 0.11 \times h_{total} - 0.000189 \times AADT\ per\ lane + 3.349$
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 • h_{total} is the total snowfall during a winter season, given by climate model in DD3. (m) • $AADT$ is the annual average daily traffic, given by traffic model 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	$[C_s]_t^n$
Description	This instance model get the longitude and latitude as input, and return a list of chloride exposure rate, over the time periods t to n 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. • $(long, lat)$ is the coordinate of a location. (°, °) • $[C_s]_t^n$ is a list of chloride exposure data over the time periods t to n. ([kg/m^3]) • t is the start time for the period. • n is the end time for the period.
Uses	A7, 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 model. 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 BCP 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.

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 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%

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 software should have a map of JURISDICTION that users could click on as approach of input.

R2: The software should only accept coordinate that is inside JURISDICTION. (By IM3)

R3: The software should have an option for user to select the different concerned parameter: 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.

R4: The result list of chloride exposure rate should be visualized in the map using color scheme to represent the severity of chloride exposure data across different regions.

R5: The result list of chloride exposure rate should be of two decimal data [TODO ask how many decimal they want —Author], showing the trend of chloride exposure from 2006 to 2100 at the input location. (By IM1, IM3)

R6: The result list of chloride exposure rate should have an visualization of line graph and histogram. [TODO ask which they prefer —Author]

R7: The result list of chloride exposure rate [(and the visualization?TODO ask) —Author] should be able to be downloaded by users to their local machine.

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 input coordinates and look at the predicted chloride exposure 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 A1, the deicing salts need to be applied on the roads in time to ensure safe driving conditions during winter weather.
- A2, A4 and A5 simplify the model by standardizing the lane width, tire width and vehicle speed, which streamlines the analysis and allows for consistent calculations.
- A3 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 has been observed that the traffic volume across Ontario experiences an annual growth rate of about 2% 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 2% was applied to both AADT and AADTT for all highway segments in A6.
- A7 is assumed following the resolution of the CanRCM4 model ([13]), where the climate data are extracted from.
- A8 The calibration factor α and β are assumed to be 0.5, in the calculation for mass flow rate of bowl waves and side waves.

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 A2 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.

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 Sample Tables for Climate Model and Traffic Model

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.

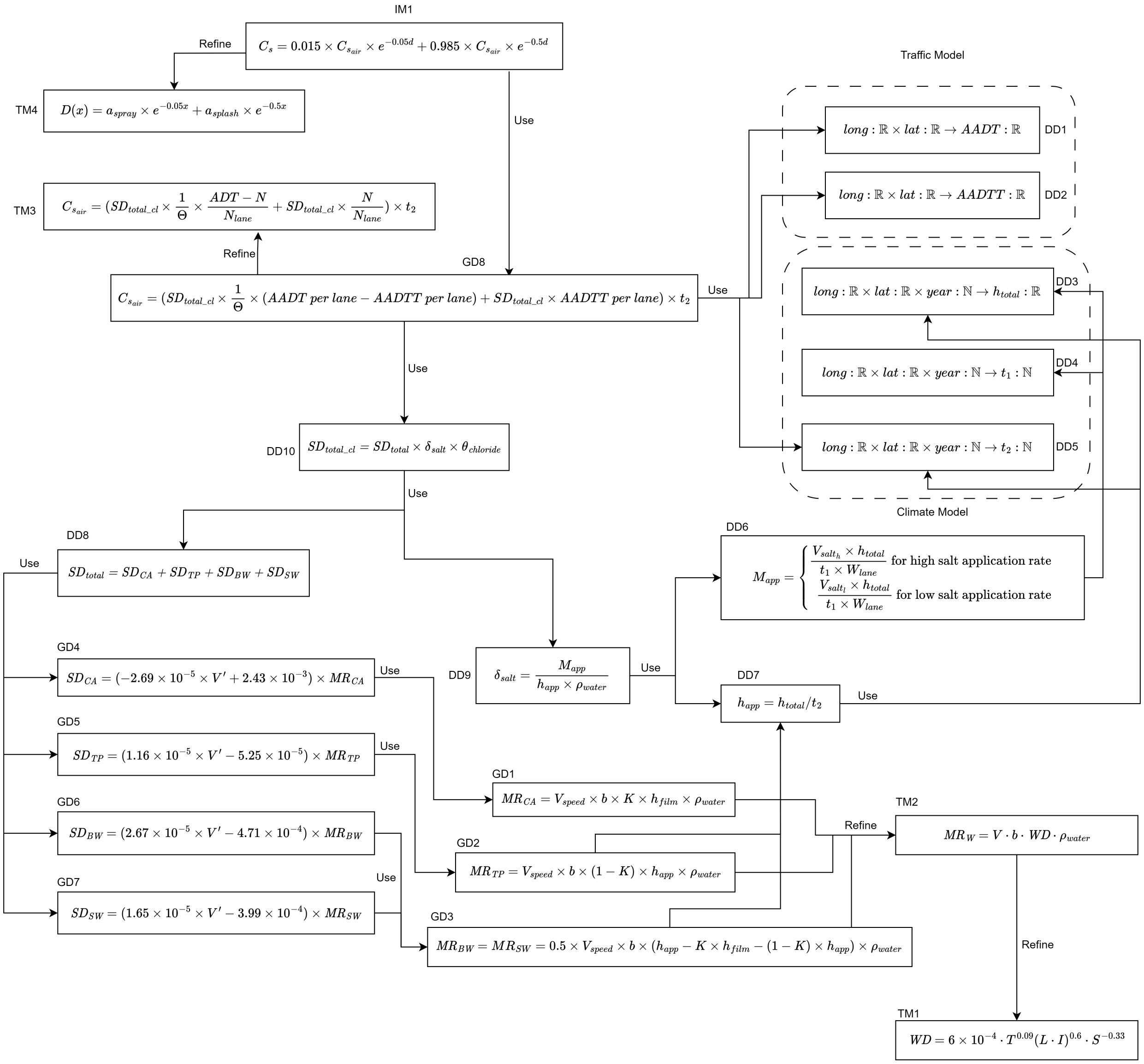

Figure 3: Traceability Between Models

9.1 Traceability Between Models

	A1	A2	A3	A4	A5	A6	A7	A8
TM1								
TM2				X	X			
TM3								
TM4								
GD1				X	X			
GD2				X	X			
GD3				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								
IM2								
IM3							X	
LC1		X						
LC2								
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
R2			X
R3	X	X	
R4			X
R5	X	X	
R6			X
R7			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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