Implementation of Analysis, Modeling, and Simulation Tools for Road Weather Connected Vehicle Applications

Project Report

November 2020

FHWA-HOP-20-060

U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
FHWA-HOP-20-060</td><td colspan="2">2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="3" rowspan="2">4. Title and Subtitle
Implementation of Analysis, Modeling, and Simulation Tools for Road Weather Connected Vehicle Applications Project Report</td><td colspan="2">5. Report Date
November 2020</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="3">7. Author(s)
Jiaqi Ma; Hani Mahmassani; J. Kyle Garrett; Eunhye Kim; Michelle Neuner</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="3" rowspan="2">9. Performing Organization Name and Address

Leidos Inc.
11251 Roger Bacon Drive
Reston, VA 20190

Synesis Partners LLC
Northwestern University Transportation Center
University of California, Los Angeles</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
DTFH6116D00053L</td></tr>
<tr><td colspan="3" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td colspan="2">13. Type of Report and Period Covered
Project Report
3/26/2018–10/1/2020</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
HOP</td></tr>
<tr><td colspan="5">15. Supplementary Notes
Road Weather Management Program
Task Order Contracting Officer Representative (TOCOR): Jawad Paracha
Acknowledgments: Vince Garcia (Wyoming Department of Transportation); Mohamed M. Ahamed and Guangchuan Yang (University of Wyoming); Yadollah Montazery (Chicago Department of Transportation).</td></tr>
<tr><td colspan="5">16. Abstract
The Federal Highway Administration (FHWA) Road Weather Management Program (RWMP) weather-responsive traffic management (WRTM) initiative focuses on developing actionable strategies for system management and operations in challenging road weather conditions. The study described in this document uses analysis, modeling, and simulation (AMS) tools with connected vehicle (CV) data to assess weather-responsive management strategies (WRMS) for traffic management and winter maintenance. The project team assessed CV data collection and use, WRMS implementations, and AMS modeling among and for State and local transportation agencies. Two agencies and sets of applications were selected for detailed simulation and analysis. An assessment of traveler information messages (TIM), variable speed limits (VSL), and snowplow pre-positioning strategies was conducted for a corridor along Interstate 80 (I–80) in Wyoming. A study of snowplow route optimization to preserve traffic flows was made for a network of freeways and arterial roadways in the Chicago area. The studies conclude that the AMS tools can be used to perform these assessments, and that significant safety, mobility, and operational efficiencies can be achieved with WRMS implemented with CV data.</td></tr>
<tr><td colspan="3">17. Key Words
Prediction; Road Weather Management Program (RWMP); weather-responsive management strategy (WRMS); weather-responsive traffic management (WRTM); traffic modeling; road condition; weather; road weather; Wyoming; Chicago</td><td colspan="2">18. Distribution Statement
No restrictions.</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td colspan="2">20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
104</td><td>22. Price
n/a</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS

ACC	adaptive cruise control
AMS	analysis, modeling, and simulation
API	application programming interface
ASOS	Automated Surface Observing Systems
ATDM	active traffic demand management
AV	automated vehicle
AVL	automated vehicle location
AZ	Arizona
BSM	basic safety message
CA	California
CACC	cooperative adaptive cruise control
CFM	continuous flow metering
CO	Colorado
COM	component object model
ConOps	concept of operations
CV	connected vehicle
CVM	Connected Vehicle Monitor
CVP	connected vehicle pilot
CV–VSL	connected vehicle-based variable speed limit
Cyn	Canyon
DIA	de-icing application
DLL	dynamic linked library
DMA	dynamic mobility application
DN	distress notification
DOT	department of transportation
DPS	department of public safety
DPW	department of public works
DSRC	dedicated short-range communication
DUAP	data use analysis and processing
EDC	Every Day Counts
EJMT	Eisenhower Johnson Memorial Tunnel
ELC	early lane-change
EMDSS	enhanced maintenance decision support system
ESS	environmental sensor station
ESV	Enhanced Safety of Vehicles
FCW	forward collision warning
FHWA	Federal Highway Administration
ft/s	foot per second
GPS	global positioning system
HGV	heavy-goods vehicle
HMI	human-machine interface
I–10	Interstate 10
I–290	Interstate 290
I–290 E	Interstate 290 East
I–290 W	Interstate 290 West

I2V	infrastructure-to-vehicle
I–30	Interstate 30
I–35	Interstate 35
I–70	Interstate 70
I–76	Interstate 76
I–80	Interstate 80
I–90	Interstate 90
I–90 N	Interstate 90 North
I–90 S	Interstate 90 South
I–94	Interstate 94
IA	Iowa
ICAO	International Civil Aviation Organization
IMO	Integrating Mobile Observations
IMRCP	Integrated Modeling for Road Condition Prediction
INFLO	Intelligent Network Flow Optimization
IROS	Intelligent Robots and Systems
iTTC	inverse time-to-collision
km/h	kilometer per hour
KS	Kansas
M–14	Michigan Highway 14
MI	Michigan
m	meter
m/s	meter per second
MADIS	Meteorological Assimilation Data Ingest System
MAW	motorist advisories and warnings
MDSS	maintenance decision support system
mm	mile marker
mph	mile per hour
MPR	market penetration rate
MT–ITS	models and technologies for intelligent transportation systems
MV	maintenance vehicle
NCDC	National Climatic Data Center
NDEX	Nevada Data Exchange
NFD	network-wide fundamental diagram
NGSIM	Next Generation Simulation
NOAA	National Oceanic and Atmospheric Administration
Nov	November
NREL	National Renewable Energy Lab
ns–3	Node Mobility Model
NY	New York
OBU	onboard unit
OD	origin-destination
PC	personal computer
PF	public facility
rad/s	radian per second
RSU	roadside unit

RWCV	road weather connected vehicle
RWIS	road weather information system
RWMP	road weather management program
s	second
SHRP2	Strategic Highway Research Program 2
SPaT	signal phasing and timing
SPR	snowplow routing
STIP	State Transportation Improvement Plan
STOL	Saxton Transportation Operations Lab
SUMO	simulation of urban mobility
SWIW	spot weather impact warning
TC	transportation cabinet
TFHRC	Turner-Fairbank Highway Research Center
TIM	traveler information message
TMC	traffic management center or traffic management system
TrEPS	Traffic Estimation and Prediction Tool
TSMO	transportation systems management and operations
TSR	traffic-smoothing rate
TTC	time-to-collision
UCLA	University of California, Los Angeles
US–23	U.S. Route 23
US–395	U.S. Route 395
USDOT	U.S. Department of Transportation
UT	Utah
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VDT	Vehicle Data Translator
veh/min	vehicle per minute
VMS	variable message sign
VSL	variable speed limit
W.	West
WRMS	weather-responsive management strategy
WRTM	weather-responsive traffic management
WxDE	Weather Data Environment
Wx–TINFO	Weather-Responsive Traveler Information System
WY	Wyoming
WYDOT	Wyoming Department of Transportation

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) Road Weather Management Program (RWMP) weather-responsive traffic management (WRTM) initiative focuses on developing actionable strategies for system management and operations in challenging road weather conditions. Although the potential impacts of using WRTM strategies can be valuable, the strategies can be challenging to implement effectively. They require sufficient information on traffic and weather conditions; development of appropriate strategies, infrastructure, and information systems to support implementation of those strategies; agency operators supportive and knowledgeable of the strategies; and drivers who are aware and responsive. Over the years, the RWMP has addressed these challenges in a variety of programs directed at condition data gathering from fixed and connected vehicle (CV) sensors, strategy development, decision support system development, and support for agency implementations. Analysis, modeling, and simulation (AMS) tools have been used by FHWA and agencies to assess the effectiveness of these data sets, strategies, and methods in improving the operational response.

The objectives of this study are to: (1) evaluate existing AMS tools, (2) survey and partner with agencies that use or plan to use CV data for WRTM and want to be able to evaluate their existing and enhanced practices, (3) apply the AMS tools with those agencies to CV-enabled weather-responsive management strategies (WRMS) for traffic management and winter maintenance, and (4) summarize the results and provide recommendations on these uses of the AMS tools.

Several AMS tools can be used to study the traffic impacts of CV systems and data. Those tools include general-purpose commercially available AMS platforms, in addition to customized research models, developed to answer specific questions related to CV systems. Several studies have assessed the impacts of weather on traffic, depending on the severity of rain, snow, or other conditions, and researchers have already incorporated such weather impacts in analyses using traffic simulation modeling tools. Application of either mesoscopic or microscopic AMS tools requires additional adaptation of those tools. At the meso level, DYNASMART has had the most cumulative experience in road weather applications. Micro-level tools offer flexibility to implement such capabilities through application programming interfaces (API) and other mechanisms. These CV capabilities have been demonstrated with some tools, such as Aimsun® and Vissim®, two widely used platforms.

Site recommendations for assessing the benefits of applying AMS tools to WRMS using CV data depend on the availability of CV data, WRMS in use, and calibrated AMS tools for those sites. Agencies and sites must currently be implementing WRMS, collecting CV or mobile data, and using or interested in using an AMS tool for evaluating their applications. AMS for WRMS analysis must be applicable to those particular strategies and fully implementable on the agency’s transportation network. Given these considerations, sites selected in this project for the application of AMS tools using CV data to simulate WRMS are along the Interstate 80 (I–80) corridor in Wyoming, and on a portion of the road network in the City of Chicago.

The Wyoming case study evaluates three CV-enabled WRMS, including traveler information messages (TIM), CV-based variable speed limits (VSLs), and snowplow pre-positioning along the 402-mile I–80 corridor through the southern part of the State. To improve driver safety along

the corridor, the Wyoming connected vehicle pilot (CVP) uses dedicated short-range communication-based (DSRC) applications that leverage vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity to support a range of services, such as advisories, roadside alerts, and dynamic travel guidance for freight and passenger travel. The three WRMS are evaluated using a framework consisting of a Vissim network module, a simulation manager module, and an API module that determines driver behavior under the CV application scenarios. The simulations demonstrate that CV-based WRMS applications can improve traffic safety performance, as measured by inverse time-to-collision (*iTTC*). The effectiveness is most dramatic under severe weather conditions. TIM can help improve the safety performance of the traffic system by reducing the risk of collisions and the occurrence of pileup crashes near the lane-closure event zones. VSL can provide suitable speed limit advisories under different weather scenarios to keep vehicles driving at safe speeds. Snowplow pre-positioning is an effective strategy for winter surface maintenance that helps to improve operation efficiency, reduce collision risks, and increase the mobility efficiency of the traffic system.

The Chicago case study assesses the potential of using CV data for optimizing snowplow operations to reduce impacts on traffic flow. The Chicago testbed network spans the Chicago Loop, O'Hare International Airport, and Evanston, Illinois, and includes the Kennedy Expressway on Interstate 90 (I–90), Edens Expressway on Interstate 94 (I–94), Eisenhower Expressway on Interstate 290 (I–290), and Lake Shore Drive along Lake Michigan. The snowplow routing optimization application was assessed using the DYNASMART AMS capabilities, with additional modules developed to estimate and predict conditions and capacities of road sections affected by snow accumulation. The network traffic states are estimated and predicted by processing data from simulated CVs operating throughout the network. The Snowplow Command module then uses the information to generate snowplow routes to minimize the weather impact on traffic. Performance of weather-related strategies was quantitatively evaluated with measurements of traffic speed and flow on the network. The performance measures were compared to the results under the two scenarios of (1) doing nothing, and (2) executing a predetermined plan extracted from global positioning system (GPS) data for simulated snowplow routes. Results support the potential benefit of two different types of CV technology in WRMS practice. First, the traffic estimation results verify that data from passenger vehicles with connectivity can be a source of timely disaggregated information on traffic conditions, even with low market penetration rates. Second, local agencies can monitor the current WRMS performance by tracking CVs acting as agents or probes, estimate road surface condition with the executed service plan, and generate real-time service plans for remaining road sections by using incoming information to maximize the WRMS performance.

CHAPTER 1. INTRODUCTION

The Federal Highway Administration's (FHWA) Road Weather Management Program (RWMP) has been leading national efforts to mitigate the impacts of weather on roadway infrastructure and operations for many years. The RWMP has sponsored many strategic and developmental initiatives, providing frameworks for data gathering, quality checking, operational response, decision support, information dissemination, performance measurement, technology transfer, and interagency cooperation.

Among these RWMP initiatives, the development of weather-responsive traffic management (WRTM) focuses on actionable strategies for system management and operations. It is potentially the most impactful of RWMP initiatives, since it directly affects the driving public and agency responses to roadway conditions. Although the potential impacts of using WRTM strategies can be valuable, the strategies can be challenging to implement effectively. They require sufficient information on traffic and weather conditions; development of appropriate strategies, infrastructure, and information systems to support implementation of those strategies; agency operators supportive and knowledgeable of the strategies; and drivers who are aware and responsive.

Over the years, the RWMP has addressed these challenges in a variety of programs supportive of technology and strategy developments. Condition data gathering has been developed throughout the Clarus, Integrating Mobile Observations (IMO), Meteorological Assimilation Data Ingest System (MADIS), and Weather Data Environment (WxDE) efforts. It is being expanded through the connected vehicle (CV) data standards in anticipation of widespread mobile observation availability. WRTM strategies for dealing with road weather conditions have been explored in projects investigating winter maintenance with plow routing and anti-icing treatment, variable speed limits (VSL) for low-visibility and weather-degraded pavement conditions, and variable message signs (VMS) to inform drivers of imminent road weather conditions. These strategies are then supported by development of infrastructure and systems, such as fixed and mobile sensors for data gathering and for treatment, the Maintenance Decision Support System (MDSS), Pikalert®, and guidance for message sign use in hazardous weather conditions. FHWA has provided operations support though the Every Day Counts (EDC) initiatives (Rounds 4 and 5), Pathfinder initiative, the Road Weather Management Exchange, road weather management stakeholder meetings, and focused WRTM meetings.

Road weather management application analyses and WRTM efforts have also included foundational studies of the effectiveness of technologies and strategies using analysis, modeling, and simulation (AMS) tools. Most studies of operations strategies with AMS tools have looked more generally at the network or corridor responses to active traffic demand management (ATDM) or control strategies to improve mobility. The RWMP has more specifically invested in studies of the benefits of weather-responsive maintenance activities and traffic management. These have included seminal studies of road weather ATDM and CV dynamic mobility applications (DMA), further studies of traffic signal optimization in degraded-weather conditions, and the study of Integrated Modeling for Road Condition Prediction (IMRCP), which brings together weather and traffic prediction in online, near-real-time forecasts.

The remaining challenge is to bring these research elements into an integrated assessment of CV-enabled weather-responsive management strategies (WRMS). Agencies will then be able to use AMS tools to inform operational decisions for their specific sites, strategies, and conditions. The objectives of this study are to:

- Review and evaluate the existing AMS tools available for road weather management applications, particularly traffic management and winter maintenance activities, that use CV data.
- Identify transportation agencies that currently use or plan to use CV data for traffic management and winter maintenance, and want to be able to evaluate their existing/enhanced practices with CV data.
- Apply and incorporate the AMS tools to the agency's CV-enabled traffic management and winter maintenance strategies.
- Summarize the AMS application results and provide recommendations on the use of the AMS tools for evaluating CV-enabled road weather management strategies.

This report documents the activities and findings of the study.

- **Chapter 1** provides the background, objectives, and overview of this report.
- **Chapter 2** provides a review and evaluation of AMS tools for CV-enabled road weather management strategies.
- **Chapter 3** describes the state of WRMS practice among State and local transportation agencies and the selection of sites for the application of AMS tools for this study.
- **Chapter 4** describes the application of the tools and the WRMS results for a corridor along Interstate 80 (I–80) in Wyoming.
- **Chapter 5** describes the application of the tools and the WRMS results for a network model of the City of Chicago.

CHAPTER 2. EVALUATION OF ANALYSIS, MODELING, AND SIMULATION TOOLS FOR CONNECTED VEHICLE-ENABLED ROAD WEATHER MANAGEMENT STRATEGIES

ASSESSMENT FRAMEWORK

This section presents the assessment framework developed to evaluate existing simulation and modeling tools from the standpoint of connected vehicles (CV) and road weather management applications. Following an overview of existing methodological approaches, functional requirements are identified for the analysis, modeling, and simulation (AMS) tools with regard to these capabilities.

Road weather and CV factors have only been partially addressed in previous studies and in existing tools. Road weather impacts have mostly been captured in mesoscopic tools for which typical detector data can be used for calibration. Road weather impacts on CV performance, including communication capabilities, have not been addressed. The opportunities made available by CVs for better prediction and management are currently under development by researchers. The AMS testbed developed for Chicago is the only one that has sought to integrate road weather and CV factors.

Background on Existing Platforms and Related Features

Model platforms that integrate various components are required to capture interactions related to CVs. Platforms in this context are primarily conceptual analytical constructs embedded in a software tool. They typically entail a collection of models representing interacting agents or processes. Different physics have been used to represent flow processes in these platforms. The main differentiation has been in terms of the detail of representation, with micro, meso, and macro being the main labels for this differentiation. Dynamic traffic assignment (DTA) tools have been developed with all three types of physics; the discussion here primarily applies to particle-based simulation, where individual vehicles/entities are tracked and used in conjunction with either meso- or micro-level physics.

Examples of simulation-based DTA platforms used in research, practice, or both, include DYNASMART–P and DynaMIT–P, which were originally developed for the Federal Highway Administration (FHWA) to support intelligent transportation system (ITS) deployment studies. Both platforms combine particle-based mesoscopic simulators with pathfinding algorithms for traveler route choice decisions; however, certain important details differ, with implications for the ability to represent various aspects of CV deployment. DYNASMART–P and DynaMIT–P have also formed the basis of online Traffic Estimation and Prediction Tools (TrEPS) intended for real-time traffic prediction to support traffic management functions; most notable road weather applications of TrEPS tools include the FHWA-supported deployment in Salt Lake City(1) and the Integrated Modeling for Road Condition Prediction (IMRCP) project in Kansas City.(2) There are several offshoots of the original DYNASMART–P framework, including VISTA, DynusT, DTALite, and DIRECT—all share the same modeling philosophy, though with possibly important differences for weather and CV impact modeling. Of these, only DYNASMART has been configured, calibrated, and deployed to specifically capture the impact of road weather on traffic operations. (See references 2, 3, 4, 5, 6, 7, and 8.)

In addition to university-generated tools, commercial platforms for meso-level DTA have emerged, generally as a complement to static macroscopic assignment tools, or as add-ons to microscopic simulators. Examples include TransModeler® (TransCAD®), Dynameq® (Emme), Cube Voyager, and Visum (related static platforms by the same vendor in parentheses). There is considerable variation across the commercial packages, which can be somewhat opaque in the absence of documented refereed publications describing these tools. This is a limitation for CV-related development, which requires detailed knowledge of and access to specific algorithmic components.

A third category of simulation-based network modeling tools, originally intended as agent-based activity-based demand models, includes the FHWA-funded TRANSIMS and its evolution into MATSim in Switzerland. The latter adopts a non-standard cellular-automata traffic flow representation that is not necessarily consistent with traffic flow theories, but allows fast computation for large networks, albeit when not seeking to reach equilibrium states. It also allows flexibility to route agents and execute elaborate rule-based activity schedules.

In addition to DTA platforms, which have largely supplemented or co-opted static macro network tools for new model investment by agencies, the other category of simulation platforms consists of microscopic simulation tools primarily intended for traffic operational applications. Originating in the 1970s with FHWA-supported NETSIM, which subsequently evolved into the current CORSIM, the domain experienced substantial commercial growth with the advent of ITS and adaptive signal control strategies that required fine-grained representation for design and evaluation. Three commercial platforms used internationally are Vissim, Aimsun, and PARAMICS. Like CORSIM—and NETSIM before it—these are time-based, discrete event, discrete particle simulators with heavy reliance on Monte Carlo methods to generate random variable realizations of a driver's every maneuver. With similar underlying logic (albeit different specific behavioral rules for drivers), the products have sought to differentiate through the quality, look, features, and functionalities of their graphical user interfaces.

Other traffic operational microscopic platforms have also been developed and have gained some traction, usually in specialized markets. These include TransModeler microscopic simulator, which is patterned in part on MITSim, and is built on a TransCAD network; INTEGRATION, which evolved from a mesoscopic version to a microscopic platform; Cube Avenue, and the open-source SUMO (Simulation of Urban MObility) developed at the German DLR Institute of Transportation Systems.

Off-the-shelf commercial packages for either strategic or operational applications are generally not capable of representing the particular aspects of CVs that impact both operational performance and users' behavior. In some instances, modification of certain aspects through application programming interfaces (API) is possible, but control of how the API is used in the overall simulation is generally not available. For this reason, researchers have developed special-purpose tools focused on the particular questions of interest to their scope of the study. These are typically not comprehensive or integrated platforms, but simplified representations in all but those aspects essential to the question of interest.

A key question for developers and agencies interested in developing an AMS capability for CVs is whether to add CV capabilities to existing platforms, thereby taking advantage of graphical user interfaces and other useful components, or whether to integrate a special-purpose tool into a larger, custom-targeted platform built around those capabilities. The simple answer is: it depends on several factors, including the structure and logic of the platform itself, and the degree to which the software could accommodate the desired features. For an agency, tool selection also depends on budget, tool availability, existing models, and staff expertise.

Functional Requirements

To guide the assessment of existing AMS tools for the purpose of this study, the following list of functional requirements was identified:

- Ability to represent weather events
    - Assumes the ability to represent different weather scenarios and impacts thereof in simulation (rain, snow, heavy snow) via built-in capability
- Facility types (freeways, arterials, etc.)
- Road weather management strategies
- Traffic and operational conditions
    - Traffic events such as incidents and work zones
- Weather and traffic parameters
- CV data/deployment parameters
- Transportation system performance measures
- Assumptions (i.e., impacts of CV information/data)
- Calibration and validation requirements
- Computing/programming requirements to use the tool
- Corridors/networks where they have been used and transportation agencies involved
- Applicability/transferability to different corridors/networks
- Availability of the tools for general/public use
- Telecommunication aspects of CVs, and performance under bad weather
- Use of CV data for estimation and prediction
- Ability to use CV data for management strategies

Assessment of Tools against Above Requirements

CV technology is expected to affect the operational performance of transportation systems in different aspects,[9] including safety,[10,11] mobility,[12,13] and sustainability.[14] The technology is expected to improve traffic safety through reduction of accidents caused by human error, increase throughput[15] through driving at higher densities with the help of highly responsive CVs, and improve traffic control[16] at intersections (see references 17, 18, 19, 20, 21, 22, 23, and 24) through wireless communications.

To evaluate those impacts effectively, the distinct behavior of CVs[25] needs to be captured in the AMS tools. Given the required detail at the individual vehicle level, the logical type of methodology consists of traffic microsimulation. Microsimulation provides the highest degree of detail in capturing the characteristics of CVs, including car-following behavior, lane-changing, sensor range, wireless communications,[26] reaction time, etc. Microsimulation is the only type of simulation capable of simulating mixed traffic conditions at different CV market penetrations as each vehicle is simulated individually. Therefore, most of the prior/current studies on the operational performance impacts of CVs relied on microsimulation tools. The main limitation for this type of simulation is the computing power it requires to process and analyze the high amount of detail associated with the simulated vehicles. This can limit the amount of time and the network (area of study) size for which simulations are run.

For strategic-level CV analyses of large regional networks, detailed microsimulation of all traffic maneuvers is unnecessary and impractical. Developing macroscopic relations for either facilities or networks requires observation of actual systems at different penetration levels of the technologies, which is not possible under the current situation because these technologies remain in very early stages of test deployment. It is possible to rely on microsimulation experiments conducted for facilities and subnetworks to produce macroscopic fundamental diagrams that could then be used in mesoscopic simulation-based network modeling tools. Mesoscopic models provide a fidelity that is in between microscopic and macroscopic models. A recent example of incorporating the market penetration of CVs in a mesoscopic tool was illustrated by Mittal et al.;[(27)] the input speed-density parameters were generated using a special-purpose microsimulation tool. Trajectories obtained from the network simulations then formed the basis for calibrating link-level as well as networkwide fundamental diagrams (NFD).

In addition to modeling mixed flow impacts of CV systems, modeling emerging traffic control and management strategies enabled by the new technology is also challenging.[(28)] An important aspect of emerging control algorithms is wireless telecommunications. However, most AMS tools lack an abstract representation of telecommunications, its performance, and its impacts on driving behavior in their models. Microsimulation is also used in this case for modeling those strategies, as it provides enough details to capture the interactions between the vehicle's control devices (or lack of them) and the infrastructure.

Commercially available simulation tools, such as Vissim and Aimsun, recently introduced the capability to model CV systems, and also have means to enable users to code their own models; this is the primary mechanism used by researchers to evaluate CV alternatives with these tools. However, the parameters for these models would still need to be assumed, as the data required to calibrate them remain difficult to obtain.

In addition to coding special CV characteristics into existing tools, some researchers have developed simulation platforms specifically designed to model mixed traffic with CV systems. The tools included are those that meet certain thresholds of usability and responsiveness to the main considerations in this project (road weather, CVs). The review will describe how these tools address the functional capabilities.

The assessment of simulation tools involves two major aspects: (1) modeling connected environments and their impact on overall system's operational performance and (2) adverse weather-related behavior and management strategies. To the best of the authors' knowledge, table 1 assesses all mesoscopic simulation tools, and table 2 assesses all microscopic tools.

The functional requirements in chapter 2 are grouped into three categories reflecting the study objectives:

1. Weather event modeling and related management strategies
2. Capabilities pertaining to modeling CVs and connected environments
3. General simulation capabilities and features

Each category corresponds to a block of rows in table 1 and table 2, with specific functionalities corresponding to individual rows within each block.

Table 1. Mesoscopic simulation tools assessment based on identified requirements.

Capability/Requirement	General Platforms	DYNASMART (P, X)	DynaMIT (P, X)	DTALite	MEZZO	DynusT	Dynameq®
CATEGORY: WEATHER							
Represent weather events (rain, snow, heavy snow)—system integrates external operational conditions and simulates effects on transportation system performance under different scenarios.	**NO**	**YES**	**YES***	**NO**	**NO**	**NO**	**NO**
Represent road weather management strategies—system has built-in capability to model and execute management strategies: • *Variable message signs (VMS)* • *Variable speed limits (VSL)* • *Snowplow routing (SPR)* • *De-icing application (DIA)*	**NO**	**YES (VMS, VSL, SPR)** **PARTIAL (DIA)**	**NO**	**PARTIAL (VMS, VSL); not road-weather specific** **NO (SPR, DIA)**	**NO**	**PARTIAL (VMS, VSL); not road-weather specific** **NO (SPR, DIA)**	**NO**
Represent weather with respect to traffic parameters.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

* requires extensive external calibration of parameters. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. PC = personal computer. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 1. Mesoscopic simulation tools assessment based on identified requirements. (continuation)

Capability/Requirement	General Platforms	DYNASMART (P, X)	DynaMIT (P, X)	DTALite	MEZZO	DynusT	Dynameq®
CATEGORY: CV ENVIRONMENT							
Model different effects of telecommunication technologies on connected drivers.	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommunica-tions in current versions	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions
Model sensor performance and reliability aspects that directly influence vehicle performance.	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Integrate information flow through V2I/V2V/V2X communications within AMS system.	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Use new data sources from CV systems, and traditional data sources, (e.g., loop detectors) for traffic estimation and prediction.	**NO**	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing
Use new data sources from CV systems, traditional data sources (loop detectors), or management strategies. Calibrate/ recalibrate model parameters of connected-manual driving as actual trajectories are available.	**NO**	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing

* requires extensive external calibration of parameters. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. PC = personal computer. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 1. Mesoscopic simulation tools assessment based on identified requirements. (continuation)

Capability/Requirement	General Platforms	DYNASMART (P, X)	DynaMIT (P, X)	DTALite	MEZZO	DynusT	Dynameq®
CATEGORY: GENERAL							
Model different facility types (freeways, arterials, etc.).	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Model various traffic and operational conditions—system enables users to define different operational scenarios to be simulated.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Retrieve transportation system performance measures.	Scenario comparison (highway networks, public transit services & socioeconomic), transport performance statistics, matrix histograms, environmental analyses (noise, emissions), accident data analysis*	Network-, link-, and vehicle-level performance indicators	Travel guidance: departure time, travel mode, and route; network/link performance indicators: including travel time, flows, speeds, and densities	Network/link-level average values of traffic measurements: flows, densities, speeds, travel times, vehicle counts, and queues	Link-level average speed, inflow/outflow, densities and queue length; vehicle-level travel time, distance traveled, and route switched; OD pair summary statistics (vehicle generated, arrived, total travel time, and distance travelled)	Link/lane-level and path-level average values of traffic measurements: flows, densities, speeds, travel times, vehicle counts, and queues	Link/lane-level and path-level average values of traffic measurements: flows, densities, speeds, travel times, vehicle counts, and queues
Post-processing of outputs.	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable

* requires extensive external calibration of parameters. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. PC = personal computer. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 1. Mesoscopic simulation tools assessment based on identified requirements. (continuation)

Capability/Requirement	General Platforms	DYNASMART (P, X)	DynaMIT (P, X)	DTALite	MEZZO	DynusT	Dynameq®
CATEGORY: GENERAL							
Calibration and validation requirements.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Applicability/ transferability to different corridors/networks.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Corridors/networks where they have been used, and transportation agencies involved.	**Various**	**Various**	**Various**	**Various**	**Various**	**Various**	**Various**
Availability of the tools for general/public use (open source).	**NO**	**YES**	**NO**	**YES**	**YES**	**YES**	**NO**
Ability to modify or build on source code (API available).	Can be modified via scripting language (in most cases)	Codes can be modified	Codes can be modified	Open source; codes can be modified	Open source; codes can be modified	Open source; codes can be modified	Using a Python®-based API to implement advanced strategies
Cost to modify API.	**High**	**High**	**High**	**High**	**High**	**High**	**High**
Computational power (runs on regular PC).	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size

* requires extensive external calibration of parameters. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. PC = personal computer. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 2. Microscopic simulation tools assessment based on identified requirements.

Capability/ Requirement	Vissim®	Aimsun®	PARAMICS	Trans-Modeler®	NUTC Platform	FHWA–STOL/ UCLA Platform	PATH Platform	ECO–CACC Integration
Category: Weather								
Represent weather events (rain, snow, heavy snow)—system integrates external operational conditions and simulates effects on transportation system performance under different scenarios.	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Represent road weather management strategies – system has built-in capability to model and execute various management strategies: • *Variable message signs (VMS)* • *Variable speed limits (VSL)* • *Snowplow routing (SPR)* • *De-icing application (DIA)*	**PARTIAL (VSL); not road-weather specific** **NO (VMS, SPR, DIA)**	**PARTIAL (VSL); not road-weather specific** **NO (VMS, SPR, DIA)**	**PARTIAL (VMS, VSL); not road-weather specific** **NO (SPR, DIA)**	**NO**	**PARTIAL (VSL); not road-weather specific** **NO (VMS, SPR, DIA)**	**NO**	**NO**	**NO**
Represent weather with respect to traffic parameters.	**YES**	**YES**	**YES**	**YES**	**NO**	**YES**	**NO**	**NO**

* requires extensive external calibration of parameters. — = not assessed. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. FHWA = Federal Highway Administration. PC = personal computer. STOL = Saxton Transportation Operations Lab. UCLA = University of California, Los Angeles. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 2. Microscopic simulation tools assessment based on identified requirements. (continuation)

Capability/ Requirement	Vissim®	Aimsun®	PARAMICS	Trans-Modeler®	NUTC Platform	FHWA–STOL/ UCLA Platform	PATH Platform	ECO–CACC Integration
CATEGORY: CV ENVIRONMENT								
Model different effects of telecommunication technologies on connected drivers.	**NO**	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions	**YES; V2I and V2V**	**YES; V2I and V2V**	No representation of wireless telecommuni-cations in current versions	No representation of wireless telecommuni-cations in current versions
Model sensor performance and reliability aspects that directly influence vehicle performance.	**NO**	**NO**	**NO**	**NO**	**YES**	**NO**	**NO**	**NO**
Integrate information flow through V2I/V2V/V2X communications within the AMS system.	**NO**	**NO**	**NO**	**NO**	**YES**	**NO**	**NO**	**NO**
Use new data sources from CV systems, and traditional data sources (e.g., loop detectors), for estimation and prediction.	**NO**	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing

* requires extensive external calibration of parameters. — = not assessed. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. FHWA = Federal Highway Administration. PC = personal computer. STOL = Saxton Transportation Operations Lab. UCLA = University of California, Los Angeles. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 2. Microscopic simulation tools assessment based on identified requirements. (continuation)

Capability/ Requirement	Vissim®	Aimsun®	PARAMICS	Trans-Modeler®	NUTC Platform	FHWA–STOL/ UCLA Platform	PATH Platform	ECO–CACC Integration
Use new data sources from CV systems, and traditional data sources (e.g., loop detectors) or management strategies. Calibrate/recalibrate model parameters of connected-manual driving as actual trajectories become available.	**NO**	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing	Yes; might need pre-processing
CATEGORY: GENERAL								
Model different facility types (freeways, arterials, etc.).	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Model various traffic and operational conditions – users define different operational scenarios to be simulated.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

* requires extensive external calibration of parameters. — = not assessed. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. FHWA = Federal Highway Administration. PC = personal computer. STOL = Saxton Transportation Operations Lab. UCLA = University of California, Los Angeles. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 2. Microscopic simulation tools assessment based on identified requirements. (continuation)

Capability/ Requirement	Vissim®	Aimsun®	PARAMICS	Trans-Modeler®	NUTC Platform	FHWA–STOL/ UCLA Platform	PATH Platform	ECO–CACC Integration
Retrieve transportation system performance measures.	Scenario comparison statistics of transport performance, matrix histograms, environmental analyses (noise, emissions), crash data*	Network-, link-, and vehicle-level performance indicators	Travel guidance: departure time, travel mode, and route; network/link performance indicators including travel time, flow, speeds, and densities	Network/link-level average values of traffic measurements: flows, densities, speeds, travel times, vehicle counts, and queues	Link-level average speed, inflow/ outflow, densities, and queue length; vehicle-level travel time, distance traveled, and route switched; OD pair summary statistics	Link/lane-level and path-level average values of traffic measure-ments: flows, densities, speeds, travel times, vehicle counts, and queues	Link/lane-level and path-level average values of traffic measure-ments: flows, densities, speeds, travel times, vehicle counts, and queues	Link/lane-level and path-level average values of traffic measure-ments: flows, densities, speeds, travel times, vehicle counts, and queues
Post-processing of outputs required.	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable	YES, if outputs not configurable
Calibration and validation requirements.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

* requires extensive external calibration of parameters. — = not assessed. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. FHWA = Federal Highway Administration. PC = personal computer. STOL = Saxton Transportation Operations Lab. UCLA = University of California, Los Angeles. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 2. Microscopic simulation tools assessment based on identified requirements. (continuation)

Capability/ Requirement	Vissim®	Aimsun®	PARAMICS	Trans-Modeler®	NUTC Platform	FHWA–STOL/ UCLA Platform	PATH Platform	ECO–CACC Integration
CATEGORY: GENERAL								
Applicability and transferability to different corridors/ networks.	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
Corridors/networks where they have been used, and transportation agencies involved.	**Various**	**Various**	**Various**	**Various**	**Various**	**Various**	**Various**	**Various**
Availability of the tools for general/public use (open source).	**NO**	**NO**	**NO**	**YES**	**YES**	**YES**	**YES**	**NO**
Ability to modify or build on source code (API available).	Can use API via Python®, Microsoft® Visual Basic, C, C++, and others to implement advanced strategies/ Vissim–COM program-ming	Can use Aimsun micro API to implement advanced strategies/ applications	Can use script language or API to implement advanced strategies	Open source; codes can be modified	Open source; codes can be modified	Can use API via Python, Microsoft Visual Basic, C, C++, and others to implement advanced strategies/ Vissim–COM program-ming	—	—

* requires extensive external calibration of parameters. — = not assessed. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. FHWA = Federal Highway Administration. PC = personal computer. STOL = Saxton Transportation Operations Lab. UCLA = University of California, Los Angeles. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

Table 2. Microscopic simulation tools assessment based on identified requirements. (continuation)

Capability/ Requirement	Vissim®	Aimsun®	PARAMICS	Trans-Modeler®	NUTC Platform	FHWA–STOL/ UCLA Platform	PATH Platform	ECO–CACC Integration
Cost to modify API.	**Moderate**	**Moderate**	**Moderate**	**High**	**High**	**High**	**High**	**High**
Computational power (runs on regular PC).	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size	x-server, depending on model size

* requires extensive external calibration of parameters. — = not assessed. AMS = analysis, modeling, and simulation. API = application programming interface. CV = connected vehicle. OD = origin-destination. FHWA = Federal Highway Administration. PC = personal computer. STOL = Saxton Transportation Operations Lab. UCLA = University of California, Los Angeles. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle. V2X = vehicle-to-everything.

The following conclusions emerged from the assessment of available capabilities against the functional requirements identified for AMS to support use of CVs for road weather management:

1. The majority of mesoscopic tools are not weather-ready, except for DYNASMART– (P, X), which has been applied in several road-weather related studies, and, to some degree, DYNAMIT, which has been used with limited calibration in one previous weather-related study. However, virtually all existing mesoscopic tools offer the possibility of specifying traffic model parameter values that have been calibrated to weather conditions as input values.

2. Virtually all off-the-shelf microscopic simulation tools are not explicitly weather-ready. However, they all allow users to specify parameter values for the driver behavior models that reflect adverse weather. For example, the Federal Highway Administration-Saxton Transportation Operations Lab/University of California, Los Angeles (FHWA–STOL/UCLA) tool has adopted calibrated driver behavioral models using naturalistic driving data to reflect various weather features.

3. Representation of road weather management strategies is available only partially to the mesoscopic simulation user, except for DYNASMART, which has been applied in previous studies to analyze the impact of road-weather related variable message signs (VMS), variable speed limits (VSL), snowplow routing (SPR) and de-icing application (DIA). Most models offer some form of VMS with limited integration of specific behavior related to road weather messaging.

4. Microscopic simulation tools offer VMS and VSL modeling capability at the individual vehicle level, with road-weather features modeled through driver behavioral parameters. SPR and DIA capabilities have not been evaluated through microscopic tools in the literature, though similar approaches as used for VMS/VSL can be applied for small networkwide SPR and DIA.

5. CV features are beginning to emerge for both microscopic and mesoscopic simulation approaches. However, calibration remains limited. Most development has taken place through modification to microscopic simulation tools, particularly the car-following rules and lane-changing mechanisms that govern human drivers.

6. For mesoscopic tools, one application has relied on microscopic simulation to generate performance profiles under different CV market penetration rates, which serve as fundamental diagrams relating speed to density in the meso model.

7. There remain gaps in simulation of CV capabilities with respect to data collection and weather-related management; at the microscopic levels, we can expect availability of such features to take place over time, though the absence of data for calibration of the micro level remains a limitation.

In summary, application of either mesoscopic or microscopic AMS tools requires additional adaptation of the tools in question. At the meso level, DYNASMART has extensive cumulative experience in road weather applications. At the micro level, most off-the-shelf tools are not configured for the combined impact of CVs and road weather, but they offer flexibility to implement such capabilities through APIs and other mechanisms. The recent FHWA–STOL/UCLA platform has developed customized functions for CV and weather features and has been used for CV/automated vehicle (AV) applications.

REVIEW OF SELECTED ANALYSIS, MODELING, AND SIMULATION TOOLS

Describing and predicting roadway conditions and events that may impact travel across a road network require a broad range of data and analytical tools. These data and tools span multiple scientific and engineering disciplines. The assessment in the previous section addressed the most commonly available mesoscopic and microscopic modeling tools. This section only includes recent special-purpose tools developed specifically to capture CV system features and/or weather road traffic management.

Traffic condition and network performance models describe and predict the operational state of the traffic system, and its future evolution over time and space. The traffic state characteristics typically of interest consist of the traffic volume (flow), traffic density, speed along the different parts of the network, and the variation of these characteristics over time.

Modeling and prediction of traffic condition may be performed at the single link, freeway system, major arterials, corridor, and network (or subnetwork) levels over the short term, such as a 15-minute prediction, or they may extend to medium and longer terms on the order of hours or possibly days. Traffic condition and network performance models usually combine current traffic state observations (from sensors) with historical traffic data to generate more accurate predictions than would be possible with either current observations or historical information alone. Traffic system performance is not merely a repeat of past occurrences, but is influenced by the unique situations and prevailing events that day or at any given time. However, history can be a guide and starting point from which to pivot and adjust prediction to reflect the measured state of the system and unfolding events.

Given the role and recurrence of historical patterns, data-driven approaches based on statistical models and artificial intelligence methods play a role in data mining and pattern recognition and matching. However, without sufficient data coverage and—more importantly—when the identified patterns are disrupted by exogenous factors and events (e.g., severe weather, occurrence of one of more crashes in a given location), it is necessary to go back to the underlying systematic effects and relations rooted in traffic physics and behavioral modeling to predict the evolution of traffic flows in the system under consideration. Hence the rationale for prediction approaches based on traffic modeling and simulation, used as a basis for control actions and predictive interventions to mitigate the negative impact of these events. The integration of statistical and data-driven models with simulation-based approaches has recently emerged as a direction for development.

Special Purpose Tools and Platforms

Integrated Wireless Telecommunication Traffic Simulation – NUTC

The integrated wireless telecommunication traffic simulation platform developed by Talebpour et al.[29] is a special-purpose tool for simulating mixed traffic conditions on freeways in a connected environment. The platform integrates three different driving behaviors: regular (non-connected and non-automated) vehicles, CVs, and AVs, in addition to modeling vehicle-to-infrastructure (V2I)/vehicle-to-vehicle (V2V) wireless telecommunications. For regular vehicles, the platform uses a stochastic car-following model introduced by Hamdar et al.(30) and extended by Talebpour et al.(31) The model is based on the Prospect Theory(32) and captures drivers' crash-avoiding behavior while maintaining a desired speed. For modeling CVs, the platform relies on a deterministic car-following model introduced by Kesting et al.(15) Finally, for AVs, the platform uses a car-following model based on the previous simulation studies by Van Arem et al.(33) and Reece and Shafer.(34) For lane-changing, the platform uses a game-theoretical approach that endogenously captures the effects of additional information through wireless communications on lane-changing decisions.

With respect to modeling wireless telecommunications, the Node Mobility Model (ns–3) was integrated with the microscopic vehicular traffic simulation framework. Thus, the positions of the vehicles are governed by the micro rules in the simulator, including whatever messages may be received, as transmitted by ns–3 to the vehicles in their evolving positions. Thus, the integrated simulation tool addresses some of the limitations of general platforms by explicitly modeling wireless telecommunications and its impact on the driving behavior of CVs. The tool is restricted to modeling freeway sections, which limits its capability of evaluating CV impacts on arterials or urban networks.

FHWA–STOL/UCLA CAV Simulation Tool – STOL/UCLA

FHWA–STOL has developed a series of Vissim driver model APIs (and component object model [COM] codes) for modeling different CAV applications, such as cooperative adaptive cruise control (CACC), signalized intersection approach and departure, cooperative merge, and speed harmonization. This platform was originally developed as an FHWA simulation CV/AV simulation guidebook, and has been gradually enhanced to address the following needs:

- Modeling AV behavior: calibrated using available field experiment data; cooperative automation considers collaborative behavior between vehicles, e.g., platooning, cooperative merge, and eco-approach for departure at signalized intersections.
- Modeling wireless communication for CV applications to consider potential communication performance (package delay, drops): communication model calibration using the data collected at FHWA–STOL and Michigan Safety Pilot, and considers communication performance under various conditions.
- Reflecting weather conditions through calibrated driver behavioral parameters: recent research at the University of Wyoming and Turner-Fairbank Highway Research Center (TFHRC) used Strategic Highway Research Program 2 (SHRP2) Naturalistic Driving Study data(35) to capture driving behavior in a variety of weather conditions. The calibrated Wiedemann 1999 car-following model has been incorporated into the tool.

Connected Vehicle Traffic Simulation Tool – PATH

The CACC traffic simulation tool developed by PATH(36) is a microsimulation model implemented using the Aimsun API and Micro–SDK. It represents multilane freeway traffic operations with varying levels of market penetration of vehicles equipped with adaptive cruise control (ACC), CACC, and close-formation platoon capabilities. The major components of the microscopic traffic model include the vehicle dispatching model, human driver model, and ACC/CACC model. The vehicle dispatching model determines how a modeled vehicle enters the simulation network and the distribution of different types of vehicles across the multilane highway. It is intended to generate very high volumes of vehicles at the source section, under steady state conditions, as it is essential for simulating CACC strings that have much shorter time gaps between consecutive vehicles.

The human driver model is built upon the basic framework of the Next Generation Simulation (NGSIM) oversaturated flow model proposed by Yeo et al.,(37) which partitions the driver's car-following and lane-changing behavior into multiple fundamental driving modes. The ACC/CACC driving behavior models in the tool are based on empirical models developed by Milanes and Shladover,(38) in which CACC-equipped vehicles can form strings with short gaps. Drivers of CACC-equipped vehicles can also exit their closely coupled string and switch off CACC to make lane changes or exit the freeway. Although the CACC system implementation relies on information received from the leading vehicle in the CACC string as well as from the immediately preceding vehicle, the empirical models used in the simulation provide a simplified description of the closed-loop vehicle-following dynamics.

ECO–CACC Traffic Simulation Tool (Extension of INTEGRATION) – Virginia Tech

The ECO–CACC traffic simulation tool is an extension(39) of the microsimulation tool INTEGRATION that was developed by Rakha et al.(40,41) The objective of the implemented ECO–CACC system is to reduce fuel consumption of CACC vehicles driving through multiple intersections. It uses traffic signal phasing and timing (SPaT) data transmitted through V2I communications and vehicle queue predictions to estimate fuel-optimal speed limits. The advisory speed limits are then sent to CACC vehicles via V2I communications to prevent them from completely stopping at intersections.

The general INTEGRATION platform is a microscopic traffic assignment and simulation tool(40) that allows detailed analysis of vehicle movements and lane-changing maneuvers on a network. Its main capabilities include detailed estimation of vehicle fuel consumption and emissions and the expected number of crashes using a time series model. The traffic assignment module within the platform uses different heuristics to assign vehicles to links on the network. The cruise control behavior emulated by ECO–CACC is different from typical CACC systems. Rather than vehicles communicating to form platoons, ECO–CACC vehicles communicate only with traffic signals when driving near intersections through V2I technology. This limits the tool's usefulness to evaluate general CACC systems. The tool also lacks the capability to model the information flow through wireless telecommunications and its effect on driving behavior.

DYNASMART Integrated Platform

DYNASMART is a (meso) simulation-based intelligent transportation network planning tool. The model can be configured to run offline or online. The offline model (DYNASMART–P) includes dynamic network analysis and evaluation, and the online model (DYNASMART–X) provides short-term and long-term prediction. DYNASMART–P models the evolution of traffic flows in a traffic network resulting from the travel decisions of individual drivers. It is designed for use in urban areas of various sizes and is scalable, in terms of the geometric size of the network, with minimal degradation in performance. DYNASMART–P can also model the fine details of transportation networks such as zones, intersections, links, origins, and destinations. Inheriting the core simulation components from DYNASMART–P, the primary feature of the online operational tool (DYNASMART–X) is the capability of interacting with multiple sources of information and providing estimates of network traffic conditions and predictions of network flow patterns.

In a previous active traffic demand management (ATMD)/dynamic mobility application (DMA) project,(3) DYNASMART was used to model, test, and evaluate weather-responsive operations and several potential strategies in the Chicago testbed. During inclement weather events, traffic flow pattern and behaviors had changed, and thus initial strategies and applications for normal weather should have also been modified to mitigate weather impact on traffic. The system supports operators' decision-making in deploying alternative strategies given specific operational conditions. Various potential strategies were designed and tested, with particular focus on snowplow routing and speed harmonization.

ANALYSIS, MODELING, AND SIMULATION TOOLS SUMMARY

Several AMS tools have been proposed to study the traffic impacts of CV systems. Those tools include general-purpose, commercially available AMS platforms in addition to customized research models developed to answer specific questions related to CV systems. There has been particular growth in the latter category.

Weather impacts on traffic depend on the severity of rain, snow, or other conditions. Researchers have already incorporated or have begun to include weather impacts in analyses using traffic simulation modeling tools. Adjustable weather factors allow these models to simulate realistic traffic situations in inclement weather. Furthermore, weather databases provide adequate weather data to deploy the weather module for traffic operations and management. Micro-level simulation platforms Aimsun and Vissim are also modeling and capturing the effect of adverse weather conditions by adjusting car-following and lane-changing behavior of vehicles. Such efforts require extensive site- and configuration-specific parameter calibration.

Microsimulation tools are the dominant methodology for evaluating CV operational impacts; researchers have either sought to extend general-purpose platforms through programming interfaces and development kits or have built their own prototype simulation tools. Most of the existing microsimulation tools with CV capabilities can model mixed traffic flows and CV related policies/controls; however, several other key features remain lacking relative to modeling of weather impacts on CVs.

CV features are beginning to emerge for both microscopic and mesoscopic simulation approaches. However, calibration remains limited. Most development has taken place through modification to microscopic simulation tools, particularly the car-following rules and lane-changing mechanisms that govern human drivers. There remain important gaps facing simulation of CV capabilities, with respect to data collection and weather-related management; at the microscopic levels, we can expect availability of such features to take place over time, though the absence of data for calibration of the micro level remains a major limitation.

In summary, application of either mesoscopic or microscopic AMS tools requires additional adaptation of those tools. Several promising examples have been identified to provide a starting point for an AMS capability to support CV-enabled road weather application. These require varying degrees of modification, adaptation, and calibration for effective deployment to support agency decision-making in adverse weather conditions.

CHAPTER 3. STATE OF THE PRACTICE AND DEMONSTRATION SITE SELECTION

Describing the state of practice for the use of connected vehicle (CV) data in modeling of weather-responsive management strategy (WRMS) using analysis, modeling, and simulation (AMS) tools requires looking at each aspect in turn, and identifying agencies and locations in common. The analysis proceeds from the broadest to the most specific cases, starting with agencies collecting weather-related CV data. It moves to agencies using those data for WRMS, and then to online AMS model deployments, and finally to opportunities for simulation of WRMS with AMS tools using weather-related CV data.

CONNECTED VEHICLE DATA COLLECTION

CV data collection is most common with agency maintenance fleet automated vehicle location (AVL) deployments. CV data collection practices can vary in what data are collected and by what means. They minimally collect vehicle location for dispatch and shift reporting purposes. The most complete deployments may provide detailed information on vehicle location, road condition, and road treatment operation. The Wyoming Department of Transportation (WYDOT) enables its drivers to provide data on events and conditions beyond those specifically associated with winter maintenance, such as rock falls and debris on the roadway.(42) CV data systems may also be used in non-winter applications, such as herbicide application.

CV data, more specifically, has been deployed in integrated mobile observations (IMO) projects and the Wyoming connected vehicle pilot (CVP) sponsored by the U.S. Department of Transportation (USDOT). The IMO projects were developed in three phases of increasing sophistication with the Minnesota, Michigan, and Nevada departments of transportation (DOT).(43) Although the details of the objectives and deployments varied among the three, phase 1 deployments generally demonstrated AVL capabilities for staffing and reporting, followed in phase 2 by more specific weather-related data gathering for winter maintenance activities, and in phase 3 by expanded data gathering over more vehicles, data types, and communications media, including dedicated short-range communications (DSRC). The Wyoming CVP incorporated many of the IMO lessons in the development and deployment of a complete CV solution that addressed applications including spot weather warnings.(44) Information from connected snowplow trucks is blended with road weather information system (RWIS) and weather forecast information to generate alerts for travelers along the Interstate 80 (I–80) corridor through Wyoming.

Table 3 describes the state of practice of CV weather data collection among selected State and local transportation agencies. Data types included in the CV collection are all linked to the vehicle location and time at which they were observed by the vehicle's sensor systems. The data may include observations of environmental conditions such as ambient air and pavement temperatures and relative humidity; the status of pavement treatment equipment such as the plow and material spreader; other vehicle-sourced weather-related information such as wiper status, wheel speed, and brake status; and, in some cases, camera images. Practices vary substantially among agencies.

Agencies generally get CV data from their own fleet vehicles, particularly from snowplow trucks. Data may be routed, however, through third-party data networks, particularly in the case of AVL deployments. These may be solutions operating directly through a cellular service provider, or a more customized AVL solution operating over any of the commercial cellular data networks. Alternatively, agencies may use their own data radio networks on channels typically shared with voice communications. Agencies may also collect the data over a Wi-Fi connection at their maintenance facilities at the end of a vehicle's route. While not providing real-time data collection, this enables downloading the data for maintenance management and road condition reporting. The IMO agencies and WYDOT, as part of the CVP deployment, have demonstrated and continue to get CV road weather data through their DSRC deployments. The literature review did not find any agencies getting CV road weather data from third parties at this time.

Data originating on CVs may be processed at any of several opportunities before they become available to WRMS applications. Although no specific examples were identified in the literature survey, an AVL service provider could modify the data stream, for example, to bucket the data into uniform time intervals rather than provide precise observation times or to insert data to fill gaps. Agencies receiving the data, whether through a third party or their own network, may use intermediate or aggregated data stores to provide common access for multiple applications. Nevada DOT's Nevada Data Exchange (NDEX) and Michigan DOT's Data Use Analysis and Processing (DUAP) capture road weather data in this manner. In the Wyoming CVP, the weather data were extensively processed at each step of the data trail from acquisition at the vehicle to the Operational Data Environment, and on into the Pikalert system. Beyond these specific examples, the most common CV weather data processing comes in the various forms of a maintenance decision support system (MDSS), to be discussed more in the context of WRMS.

Table 3. Agency connected vehicle weather data collection state of practice.

Agency	Data Types	Data Sources (maintenance vehicles [MV])	Communications Channel	Processing
Alaska Department of Transportation and Public Facilities (DOT&PF)	Position, time, plow up/down, material	1,000 MV	Cellular	—
Arizona Department of Transportation (DOT)	Position, time, speed, plow position, spreader status, spreader setting, pre-wet status, pre-wet setting, material type, distance spread, road temperature	>75 percent of MV fleet	Cellular	Web-based supervisory tools
Maricopa County, Arizona	Position, time, and other SAE J2735™ data, depending on application	Anthem, Arizona, testbed for test dedicated short-range communication (DSRC) vehicles	DSRC	—
City of Bozeman, Montana	Position, time, plow up/down	11 MV	Cellular	—
City of Dubuque, Iowa	Position, time, plow up/down, material, pavement temperature, air temperature	18 MV	Cellular	—
City of Goshen, Indiana	Position, time, plow up/down, other	20 MV	Radio	—
Colorado DOT	Position, time, plow up/down, material, pavement temperature, air temperature, humidity, surface friction, dashboard camera (dash cam), engine diagnostics	1,200 heavy-fleet vehicles, 890 light vehicles	Cellular, Wi-Fi, satellite	Maintenance decision support system (MDSS)

Date of data collection: 2019.
— = not applicable.

Table 3. Agency connected vehicle weather data collection state of practice. (continuation)

Agency	Data Types	Data Sources (maintenance vehicles [MV])	Communications Channel	Processing
Idaho Transportation Department	Position, time, plow up/down, material, pavement temperature, air temperature	236 MV	Wi-Fi	—
Illinois DOT	Position, time, plow up/down	40 MV	Radio	—
Indiana DOT	Position, time, pavement temperature, air temperature		Cellular	MDSS
Iowa DOT	Position, time, plow up/down, material, pavement temperature, air temperature, dash cam	902 MV	Cellular, Wi-Fi	—
Kentucky Transportation Cabinet	Position, time, plow up/down, material, pavement temperature, air temperature, other	1,430 MV	Cellular, satellite	MDSS
Maine DOT	Position, time, pavement temperature, air temperature, other	125	Wi-Fi	—
Michigan DOT	Position, time, accelerometry, speed, surface temperature, air temperature, humidity/dew point, images, wheel speed, CAN bus, spray flow meter, images, engine state	15 Integrating Mobile Observations (IMO) Ford® F150s, 340 plow trucks; VIDAS, IMO, automated vehicle location (AVL), basic safety message (BSM); 30 trucks doing herbicide application	Cellular, Wi-Fi, DSRC	Weather-Responsive Traveler Information System (Wx–TINFO), Data Use Analysis and Processing (DUAP), MDSS, Vehicle Data Translator (VDT), Motorist Advisories and Warnings (MAW), ArcGIS®-Collector application (app)

Date of data collection: 2019.
— = not applicable.

Table 3. Agency connected vehicle weather data collection state of practice. (continuation)

Agency	Data Types	Data Sources (maintenance vehicles [MV])	Communications Channel	Processing
Minneapolis, Minnesota	Position, time	200 MV	Cellular	—
Minnesota DOT	Position, time, air temperature, relative humidity, surface temperature, surface condition, friction, spreader control information, wiper status, brake status, dash cam images	850 plow trucks, 25 light-duty vehicles, 35 mower tractors with AmeriTrak AVL	Cellular, DSRC	WebMDSS, 511
Missouri DOT	Position, time, plow up/down, material, pavement temperature, air temperature	20 MV	Cellular	—
Montana DOT	Position, time, plow up/down	5 MV	Wi-Fi	—
Nebraska DOT	Position, time, pavement temperature, air temperature, dash cam images, engine diagnostics	675 MV	Cellular	MDSS
Nevada DOT	Position, time, air temperature (two sensors), ambient pressure, humidity, surface temperature, spreader rate, spreader material, wiper rate	Nine plow trucks, one service patrol	Cellular, DSRC, radio, Wi-Fi	Nevada Data Exchange (NDEX), Pikalert® VDT/enhanced maintenance decision support system (EMDSS)/MAW
New York State DOT	Position, time	1,600 MV	Cellular	—

Date of data collection: 2019.
— = not applicable.

Table 3. Agency connected vehicle weather data collection state of practice. (continuation)

Agency	Data Types	Data Sources (maintenance vehicles [MV])	Communications Channel	Processing
North Dakota DOT	Position, time, plow up/down, material, pavement temperature, air temperature, other	33 MV	Cellular	MDSS
Ohio DOT	Position, time, material, other	170 MV	Cellular	—
Oregon DOT	Position, time, plow up/down, material, pavement temperature	29 MV	Cellular	—
Pennsylvania DOT	Position, time, material, pavement temperature, air temperature	2,250 MV	Cellular	MDSS
Rhode Island DOT	Position, time, pavement temperature, air temperature, other	86 MV	Cellular	—
South Dakota DOT	Position, time, plow up/down, material, pavement temperature, air temperature, other	125 MV	Cellular	MDSS
St. Joseph County, Indiana	Position, time, plow up/down, material	10 MV	Cellular	MDSS
Utah DOT	Position, time, plow up/down, road conditions, weather conditions, other	505 MV; also, citizen reporters using mobile app, used for 140 roadway segments	Cellular	—
Vermont DOT	Position, time, plow up/down, material, pavement temperature, air temperature	250 MV	Cellular	—

Date of data collection: 2019.
— = not applicable.

Table 3. Agency connected vehicle weather data collection state of practice. (continuation)

Agency	Data Types	Data Sources (maintenance vehicles [MV])	Communications Channel	Processing
Virginia DOT	Position, time	11,000 MV	Cellular	MDSS
Washington State DOT	Position, time, plow up/down, material, pavement temperature, air temperature	500 MV	Cellular, data radio	—
West Des Moines, Iowa	Position, time, plow up/down, material, friction, pavement temperature	16 MV	Cellular	MDSS
Wisconsin DOT	Position, time, plow up/down, material, pavement temperature, air temperature, engine diagnostics	754 MV	Cellular, Wi-Fi	MDSS
Wyoming Department of Transportation (WYDOT)	Road conditions, weather conditions, incidents, alerts, rock fall, location, variable speed limit (VSL) recommendations, damage report, messages	328 plow trucks using WYDOT tablet app and CompassCom® AVL	WyoLink (statewide digital trunked VHF P–25 radio)	—
WDOT	Position, location, BSM Part 1, weather data from WeatherCloud sensors (per Section 5.5.1 of the Wyoming Connected Vehicle [CV] Pilot Interface Control Document)	—	—	Pikalert

Date of data collection: 2019.
— = not applicable.

CONNECTED VEHICLE DATA USE IN WEATHER-RESPONSIVE MANAGEMENT STRATEGIES

Most agencies using CV (AVL) data appear to be focused on non-WRMS applications. The most common use appears to be in staffing and winter maintenance reporting based on snowplow truck locations. AVL data feeds with information on plow and spreader equipment enable agencies to use the data in winter maintenance material management applications. The location data, and any additional vehicle and engine data, may be used in fleet management applications.

A significant number of agencies use the CV data with cameras in those vehicles to inform and support traveler information, 511, and plow camera websites. This use is apparently separate from but not inconsistent with the more fully developed weather-responsive traffic management strategies (WRTM).

Agencies that collect and use mobile and CV data for WRMS are a small subset of agencies that may collect and use mobile and CV data, or may have implemented similar transportation systems management and operations (TSMO) strategies based on non-weather-responsive criteria. For example, many agencies use variable message signs (VMS) for (non-weather-related) incident notification and general traveler information. A smaller subset has access to CV data and uses their VMS for specific WRMS applications. Table 4 identifies agencies that have implemented WRMS applications based on CV data.

Among the WRTM strategies, VSL corridors have been deployed in relatively few locations. VSL has been more generally used for speed harmonization and queue warning systems—for example, on Pennsylvania's Interstate 76 (I–76) Schuylkill Expressway. Oregon DOT has deployed VSL in several locations, but the speed limits are advisory and not tied to any CV data sources. Utah DOT has deployed VSL signage on its I–80 Parley Canyon, specifically for weather-responsive strategies, but it is not tied to any CV data sources. Speed limits on this I–80 section in Utah are recommended by traffic management center (TMC) or highway patrol staff, based on measured speeds and perceived travel conditions, and are not automated. WYDOT has similarly implemented VSL on the Elk Mountain corridor on I–80 between Laramie and Rawlins. Requests for speed limit changes can be initiated by plow truck drivers, the highway patrol, or the TMC. Unlike the Utah location, the Wyoming CVP has enabled CV data from agency vehicles to be explicitly considered in monitoring for conditions meriting a reduced speed limit.

The use of VMS is widespread for relaying roadside traveler information, including weather-related messaging. It is less common to find VMS specifically associated with CV road weather data. The Wyoming CVP has generated enough experience with CV data that it is considering posting relevant messages in conjunction with its VSL postings. Michigan DOT is exploring what messages could be automated, based on which data feeds, in its TMC.

Table 4. Agency connected vehicle road weather-responsive management strategies state of practice.

Agency	Variable Speed Limit (VSL) Deployment Basis	Variable Message Sign (VMS) Deployment Basis	Plow Routing Deployment Basis	Anti-Icing Deployment Basis	Other
Alabama Department of Transportation (DOT)	24 VSL on Interstate 10 (I–10) near Mobile, Alabama, for low-visibility and fog conditions	—	—	—	—
Alaska Department of Transportation and Public Facilities (DOT&PF)	—	—	Routing decision	—	Materials management, reports, operational analysis, vehicle diagnostics
Arizona DOT	—	Dust storm warnings on I–10, not currently using connected vehicle (CV) data	—	—	Risk management, performance monitoring, event reconstruction, operational analysis, materials reporting
City of Bozeman, Montana	—	—	Routing	—	Materials management
City of Dubuque, Iowa	—	—	—	—	Traveler info, road weather reports
City of Goshen, Indiana	—	—	Routing	—	Traveler info, reports, other

Date of data collection: 2019.
— = not applicable.

Table 4. Agency connected vehicle road weather-responsive management strategies state of practice. (continuation)

Agency	Variable Speed Limit (VSL) Deployment Basis	Variable Message Sign (VMS) Deployment Basis	Plow Routing Deployment Basis	Anti-Icing Deployment Basis	Other
Colorado DOT	2018–2019 installing road weather-responsive management strategies (WRMS) VSL on Interstate 70 (I–70) Glenwood Canyon	2018–2019 installing WRMS VMS on I–70 Glenwood Canyon	Route planning, plow locations on website	Maintenance decision support system (MDSS)	Automated vehicle location (AVL) for fuel tracking, road weather info, operational analysis, vehicle diagnostics
Idaho Transportation Department	—	—	—	—	Reports, materials management
Illinois DOT	—	—	—	—	Reports, materials management
Indiana DOT	—	—	—	MDSS	Materials management
Iowa DOT	—	—	Route review	—	Traveler info, reports, materials management, operational analysis, vehicle diagnostics
Kentucky Transportation Cabinet (TC)	—	—	Route optimization (ArcGIS®)	MDSS	Traveler info, reports, materials management
Maine DOT	—	—	—	—	Reports
Michigan DOT	—	Exploring what messages to automate in traffic management system (TMC)	—	MDSS	Herbicide application, operational analysis, vehicle diagnostics, material usage

Date of data collection: 2019.
— = not applicable.

Table 4. Agency connected vehicle road weather-responsive management strategies state of practice. (continuation)

Agency	Variable Speed Limit (VSL) Deployment Basis	Variable Message Sign (VMS) Deployment Basis	Plow Routing Deployment Basis	Anti-Icing Deployment Basis	Other
Minneapolis, Minnesota	—	—	Routing	—	Vehicle diagnostics, staffing
Minnesota DOT	—	—	—	Treatment recommendations through WebMDSS	Motorist Advisories and Warnings (MAW), 511 with plow location, fleet management, vehicle maintenance, materials management
Missouri DOT	—	—	—	—	Reports, materials management
Nebraska DOT	—	—	—	MDSS	Material usage, operational analysis, vehicle diagnostics, road weather
Nevada DOT	On U.S. Route 395 (US–395), triggered by wind gust >30 miles per hour (mph) measured by either of two environmental sensor stations (ESS)	—	—	Treatment recommendations, material usage: per Federal Highway Administration (FHWA)/Nevada DOT practice guidelines	MAW traveler info, data sharing Weather Data Environment (WxDE)
New York State DOT	—	—	—	—	Staffing, vehicle diagnostics, info sharing, operational analysis

Date of data collection: 2019.
— = not applicable.

Table 4. Agency connected vehicle road weather-responsive management strategies state of practice. (continuation)

Agency	Variable Speed Limit (VSL) Deployment Basis	Variable Message Sign (VMS) Deployment Basis	Plow Routing Deployment Basis	Anti-Icing Deployment Basis	Other
North Dakota DOT	—	—	Routing	MDSS	Materials management
Ohio DOT	—	—	Routing	—	Materials management
Oregon DOT	Advisory speeds in several locations, primarily for advanced traffic management applications in corridors	—	—	—	Reports, traveler info, materials management
Pennsylvania DOT	—	—	Route review	MDSS	Reports, material usage, operational analysis
Rhode Island DOT	—	—	Routing	—	Reports materials management
South Dakota DOT	—	—	—	MDSS	Traveler info, reports, materials management
St. Joseph County, Indiana	—	—	Routing	MDSS	Traveler info, other
Utah DOT	Interstate 80 (I–80) Parley Canyon speed limits: highway patrol or TMC recommendations based on traffic speed and road conditions	—	Route optimization (ArcGIS)	—	Traveler info for Utah DOT traffic website/application, 511, vehicle diagnostics

Date of data collection: 2019.
— = not applicable.

Table 4. Agency connected vehicle road weather-responsive management strategies state of practice. (continuation)

Agency	Variable Speed Limit (VSL) Deployment Basis	Variable Message Sign (VMS) Deployment Basis	Plow Routing Deployment Basis	Anti-Icing Deployment Basis	Other
Vermont DOT	—	—	Route optimization (TransCAD®)	—	Traveler info, reports, materials management
Virginia DOT	—	—	—	MDSS	Staffing, info sharing
Washington State DOT	Snoqualmie Mountain Pass on Interstate 90 (I–90)	Snoqualmie Mountain Pass on I–90	—	—	Reports, materials management, road weather reports, operational analysis
West Des Moines, Iowa	—	—	Turn-by-turn real-time routing	MDSS	Materials management, contractor management

Date of data collection: 2019.
— = not applicable.

Winter maintenance strategies have been more broadly deployed, primarily because of their direct association with AVL systems and with MDSS. Many agencies with AVL systems include snowplow routing among applications using that location data. It is less clear how many of those are providing real-time routing based on current vehicle location, as opposed to keeping vehicles on planned routes or planning future routes based on prior routing experience. Routing is a component of MDSS operations for some agencies, though not all.

A few agencies are using route optimization tools to improve efficiency of their plow routes. According to a 2017 Clear Roads Pooled Fund Study report,(45) tools used for this purpose include C2Logix's FleetRoute™, Caliper® Corporation's TransCAD, and Esri® ArcGIS. Use of these tools appears to be offline for planning purposes, and none of these tools appear to explicitly consider impacts of traffic-variable travel time on routing.

Like plow routing, anti-icing strategies can be implemented by standard agency practices based on weather forecasts, or by more interactive MDSS analyses. In either case, data from vehicles can be used alongside forecast data to focus the application timing and locations. Among agencies for which information is provided in the literature, both Nevada(46) and Minnesota(47) explicitly describe using CV data with their MDSS to support treatment decisions.

ANALYSIS, MODELING, AND SIMULATION TOOLS AND WEATHER-RESPONSIVE MANAGEMENT STRATEGIES

The purpose of this state-of-the-practice summary is to identify candidates for modeling of the use of CV data in WRMS using AMS tools. The review of AMS tools describes the basis for and application of AMS tools to assess WRMS. The review also describes several specific assessments of WRMS using those AMS tools. Among those prior analyses, there was limited experience with modeling CV in conjunction with WRMS. There were slightly more cases investigating WRMS applications, but without the CV influence. A broader pool of candidates might be drawn from the collective experience with AMS tools being applied to active traffic demand management (ATDM) and dynamic mobility applications (DMA), but many of these are in areas without significant winter weather conditions. An alternative approach would be to look at other analyses using AMS tools that could be adapted to the CV WRMS cases. The following brief descriptions identify relevant models for inclusion among candidate sites for CV WRMS analysis and deployment.

Colorado. A model of the Eisenhower-Johnson Memorial Tunnel corridor on Interstate 70 (I–70) in Colorado, built to study flow metering techniques,(48) could conceivably be repurposed to investigate CV WRMS. That corridor has been CV-enabled as part of the Colorado DOT RoadX project and could provide a robust testbed for WRMS.

Illinois. The AMS testbed for Chicago is the only known case that has integrated CV and weather into its analyses. A DYNASMART model of the Chicago area was used in both corridor and network studies to assess ATDM and DMA applications related to the impact of weather conditions, including anti-icing and snowplow routing.(3)

Kansas. A Vissim model of a 10-mile segment of Interstate 35 (I–35) in suburban Kansas City has been built and calibrated by Kansas DOT and applied to evaluate multiple operational strategies, including ramp metering. This model can be adapted to account for weather events and CV applications by utilizing driver behavioral parameters and CV Vissim packages developed by the research team.

Kansas/Missouri. A Traffic Estimation and Prediction Tools (TrEPS)/DYNASMART model of a portion of the Kansas City metropolitan area roadway network was developed as part of a Federal Highway Administration (FHWA) project investigating Integrated Modeling for Road Condition Prediction (IMRCP).(2) This online model included effects of weather conditions, incidents, and work zones, but did not explicitly model WRMS strategies to mitigate the impacts of those events.

Minnesota. An AMS model in Minneapolis using DynusT was developed for analysis of various integrated corridor management strategies, including messaging on dynamic message signs.(49) The analysis did not include any weather effects or CV data, but did offer a case of another AMS tool being used in a weather-affected location, with potential for repurposing of that model. Additionally, microscopic models may be available upon request from the Minnesota DOT and University of Minnesota.

Utah. A TrEPS/DYNASMART model of the Salt Lake City network was built to assess "demand management, variable speed limit, VMS, and weather-responsive incident management using VMS."(50) An arterial corridor extract of that TrEPS model of Salt Lake City was used to investigate weather-responsive traffic signal operations.(1) Neither analysis addressed the use of CV data in traffic or weather data gathering.

Wyoming. A significant section of I–80 in Wyoming has been modeled in Vissim for a safety performance evaluation as part of the WYDOT CVP.(51) The model has already had significant calibrations and is intended for further analysis in later phases of the CVP.

SITE ANALYSIS AND SELECTION

Site recommendations for assessing the benefits of applying AMS tools to WRMS using CV data depend on availability of CV data, WRMS in use, and calibrated AMS tools for those sites. Recognizing there is no perfect fit, recommendations aim to balance technological fit of data and systems with the resources required to deploy the models and availability of agencies to assist in development and implement the results.

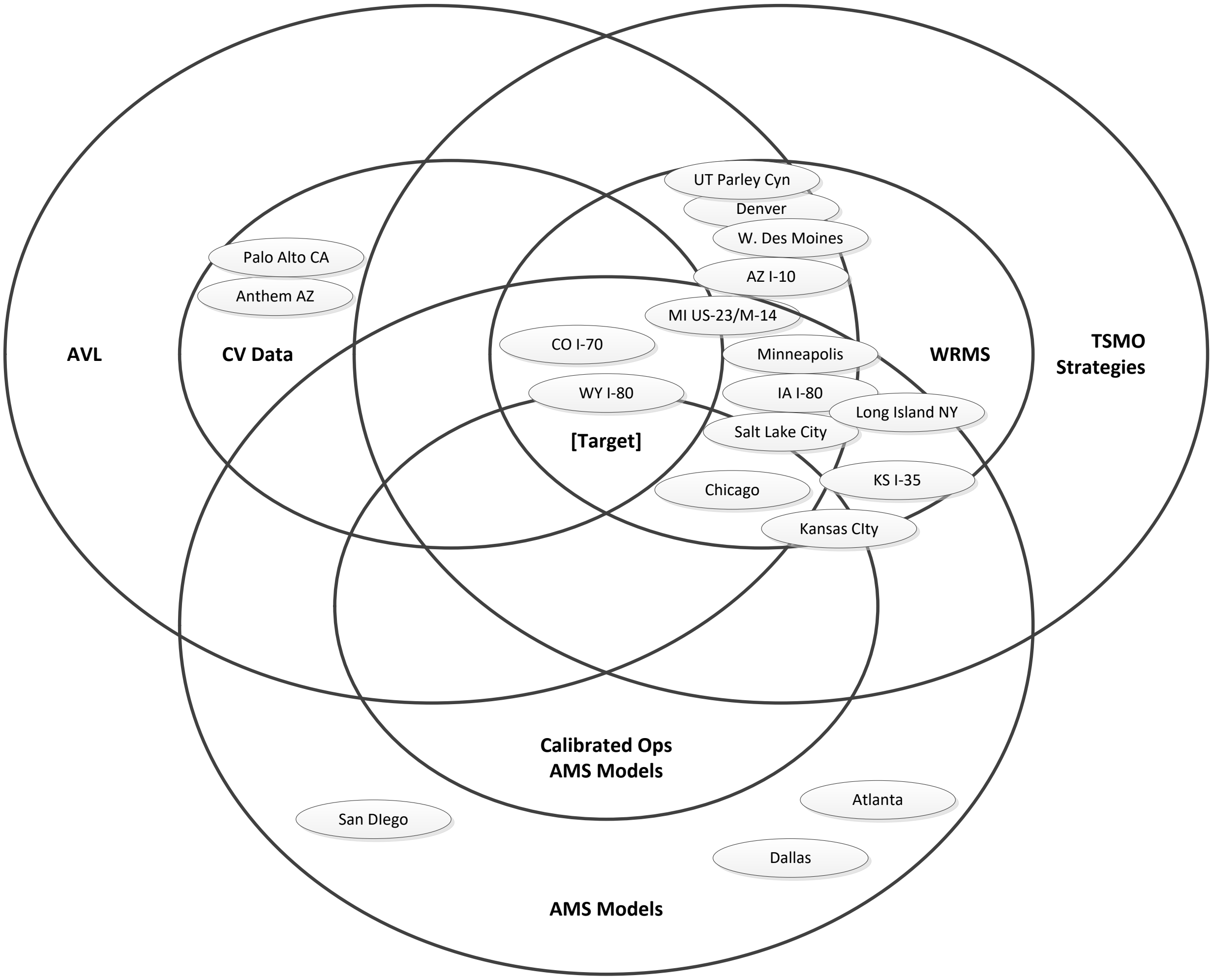
Agencies and sites to be considered must be currently implementing WRMS. The implementation need not be longstanding or fully mature, but committed to development and deployment in its operations. Priority is given to sites looking to expand deployments of WRMS to new operational contexts, whether geographical, modal, or technological. The area of operations has to regularly experience weather conditions such that the WRMS are valuable and provide opportunities for evaluation.

Agencies and sites to be considered must be currently collecting, or intend to collect, CV or mobile data. The data collection could be from an existing or developing AVL or CV environment. Priority is given to those currently collecting vehicle location and road weather data for use in WRMS applications.

Agencies and sites to be considered must be currently using, or interested in using, an AMS tool for evaluating their CV-enabled WRMS applications. Development of traffic models with the AMS tools requires substantial interaction with the infrastructure owner-operator to configure the network model and secure data feeds from network sensors, operations, and controls. Priority is given to agencies and models that have already demonstrated application of models for WRMS application assessment, with or without CV data.

AMS tools to be considered for use in WRMS analysis must be applicable to those particular strategies, and fully implementable on the agency's transportation network. The number of AMS tools applicable to analysis of WRMS with CV data is constrained by the lack of support for weather input to the models, limited support for CV data integration, and scarcity of data with which to calibrate models accordingly.

Figure 1 maps the potential agency sites for applying AMS tools to CV WRMS to the key analysis needs—CV data, WRMS application, and AMS tool models. The most appropriate alternatives from that mapping are summarized in table 5. The sites selected for the application of AMS tools using CV data to simulate WRMS are in the City of Chicago and along the I–80 corridor in Wyoming.



AMS = analysis, modeling, and simulation. AVL = automated vehicle location. AZ = Arizona. CA = California. CO = Colorado. CV = connected vehicle. Cyn = Canyon. I–10 = Interstate 10. I–35 = Interstate 35. I–70 = Interstate 70. I–80 = Interstate 80. IA = Iowa. KS = Kansas. M–14 = Michigan Highway 14. MI = Michigan. NY = New York. TSMO = transportation systems management and operations. US–23 = U.S. Route 23. UT = Utah. W = West. WRMS = weather-responsive management strategy. WY = Wyoming.

Source: FHWA.

Figure 1. Diagram. Mapping of potential evaluation sites to selection criteria.

Table 5. Site analysis summary.

Site	CV DATA: Agency	CV DATA: Probes	AMS TOOL: Network	AMS TOOL: Corridor	WRMS: Anti-Icing	WRMS: Plow Routing	WRMS: VSL	WRMS: VMS (TI)
Chicago	✓	—	✓	✓	—	✓	✓	✓
Kansas City	?	—	✓	✓	—	—	—	✓
Salt Lake City	✓	—	✓	✓	✓	✓	✓	✓
Minneapolis	✓	—	—	✓	✓	✓	—	✓
I–80, Wyoming	✓	✓	—	✓	✓	—	✓	✓
I–70, Colorado	✓	—	—	✓	✓	✓	✓	✓
I–35, Kansas	—	—	—	✓	—	—	—	✓

✓ = meets the analysis need. ? = may meet the analysis need. — = does not meet the analysis need. AMS = analysis, modeling, and simulation. CV = connected vehicle. I–30 = Interstate 30. I–70 = Interstate 70. I–80 = Interstate 80. TI = traveler information. VMS = variable message sign. VSL = variable speed limit. WRMS = weather-responsive management strategies.

CHAPTER 4. WYOMING INTERSTATE 80 TESTBED CASE STUDY

This chapter describes development and application of a customized analysis, modeling, and simulation (AMS) tool for evaluating three selected connected vehicle (CV) weather-responsive management strategies (WRMS) applications: traveler information messages (TIM), CV-based variable speed limit (VSL), and snowplow pre-positioning.

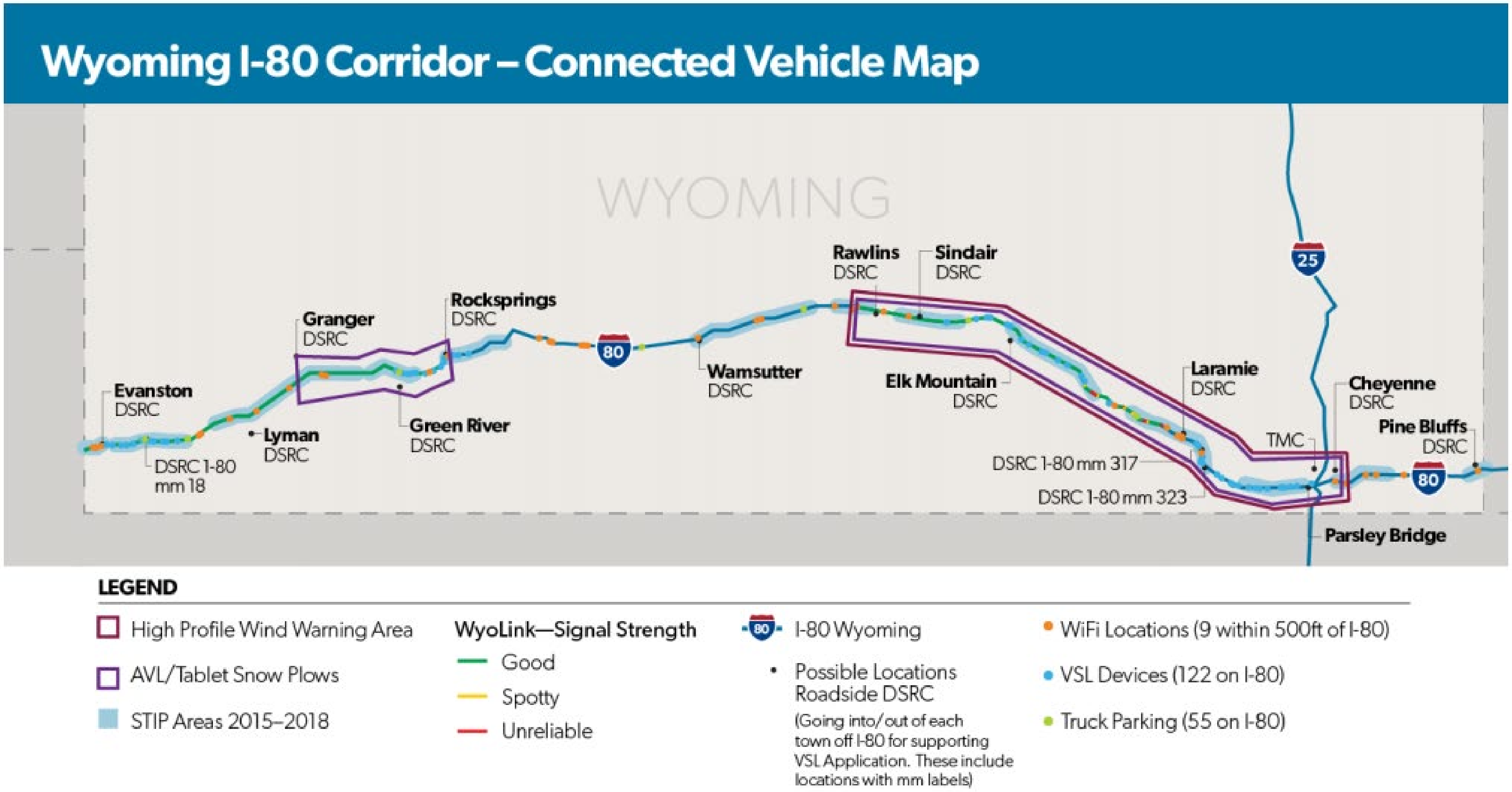
TESTBED REVIEW

Interstate–80 (I–80) runs 402 miles along the southern edge of Wyoming. It is an east-west connector for freight and passenger travel in the country, as shown in figure 2. The corridor averages more than 32 million tons of freight per year (at 16 tons per truck). The truck volume is 30–55 percent of the total annual traffic stream and comprises as much as 70 percent of the seasonal traffic stream. Several crashes, affecting both commercial and private vehicles, have occurred along I–80 in Wyoming that resulted in fatalities, extended closures, and economic loss. To improve driver safety along the corridor, the Wyoming connected vehicle pilot (CVP) uses dedicated short-range communication-based (DSRC) applications that leverage vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity to support advisories, roadside alerts, and dynamic travel guidance for freight and passenger travel.

The test network in this case study is a portion of the Wyoming CVP corridor on I–80 between Cheyenne and Laramie (mileposts 317–340). The total length of the test network is about 23 miles in each direction. V2V and V2I applications will enable communication with drivers for alerts and advisories regarding various road and weather conditions. Information from the V2V and V2I applications is made available directly to vehicles equipped to receive the messages, or through the Wyoming Department of Transportation's (WYDOT) existing traveler information sources.

In the CVP, WYDOT uses V2V, V2I, and infrastructure-to-vehicle (I2V) connectivity to improve monitoring and reporting of road conditions to and from vehicles on I–80. Five CV applications have been highlighted: forward collision warning (FCW), I2V situational awareness, work zone warning, spot weather impact warning (SWIW), and distress notification (DN).

The Wyoming CVP has deployed significant CV and road weather resources to demonstrate CV applications, including spot weather warnings of potentially hazardous travel conditions. Wyoming already uses information from its snowplow vehicles as input to its VSL analysis process and VSL deployment along sections of I–80. It provided an exceptionally functional testbed for the corridor-specific traffic management strategies investigated in this study. An AMS model built for the safety assessment of the CVP applications provided a basis for the integration of the offline and real-time operations of AMS tools.



AVL = automated vehicle location. DSRC = dedicated short-range communications. mm = mile marker. STIP = State Transportation Improvement Plan. VSL = variable speed limit.

Source: Wyoming Department of Transportation.

Figure 2. Map. Wyoming Interstate 80 corridor – connected vehicle pilot map.

WEATHER-RESPONSIVE MANAGEMENT STRATEGIES

This case study evaluated three WRMS, which included two traffic management strategies (TIMs and CV-based VSL) and one winter maintenance strategy (snowplow pre-positioning). The three WRMS were identified as the most beneficial to the testbed corridor, and of the most interest to WYDOT. The CV applications in the CVP, which are all enabled by CV TIMs, are of interest to this project from the traveler information perspective (e.g., real-time information on crashes or work zones). VSL can be communicated through TIMs or on VSL signs that have been installed along I–80. Any CV data related to weather conditions can be used to support the VSL decision-making. Snowplow pre-positioning not only can help clear the road to reduce safety risks, but also provide additional real-time weather data back to the traffic management center or traffic management system (TMC), benefiting other WRMS.

Traveler Information Messages

Traveler information is designed to enable advisory message broadcasting to the vehicle driver based on location and relevant situations. Messages are prioritized, both for delivery and presentation, according to the type of the advisory. Message presentation may be text, graphics, or audio cues. Examples include traveler advisories (traffic information, traffic incidents, major events, evacuations, etc.) and road signs. In this case study, the TIM system is applied in the form of a CV-based weather-responsive application. The TMC delivers the message through the CV roadside unit (RSU) to onboard units (OBU) installed on CVs. The in-vehicle applications parse TIMs from the infrastructure and combine them with vehicle-specific parameters to warn the drivers, if appropriate.

In this case study, TIMs are designed to include necessary information, such as vehicle status, weather parameters, event (e.g., work zone, crashes) information, and static speed limits/VSLs. Therefore, TIMs simulated in this case study can technically enable all of the following five applications in the Wyoming CV testbed. TIM transmission is realized through V2I and V2V communications. Four RSUs are distributed along the corridor, according to the WYDOT Connected Vehicle Monitor (CVM).

Connected Vehicle-Based Variable Speed Limit

Compared with the sign-based VSL, the connected vehicle-based variable speed limit (CV–VSL) provides more options for CV drivers to access VSL information apart from reading VSL signs.(52) In the Wyoming CV testbed, the CV–VSL aims to provide commercial truck drivers with real-time regulatory and advisory speed limits to help them better manage driving speeds under adverse weather conditions and reduce potential speed variances that may cause crashes. Through I2V communication (e.g., DSRC or satellites(53)), drivers can be immediately informed of the dynamic speed limits through in-vehicle devices. For the Wyoming testbed, Yang(54) conducted a driving simulator study to assess the impact of the Wyoming CV–VSL application on truck drivers' behavior under adverse weather conditions. Simulation results showed that when the advisory speed limits were lower than 55 miles per hour (mph), participants generally followed the VSLs displayed on the CV human-machine interface (HMI).(55) Additionally, traffic flows utilizing CV–VSL technology tend to exhibit lower average speeds and speed variances compared with baseline scenarios, indicating a level of influence of CV behavior on the non-CV behavior. These effects of CV–VSL warnings can potentially bring safety benefits (i.e., reduced average speeds and speed variances, and therefore, reduced risk of crashes) under adverse weather conditions. The influence of CV behavior on non-CV traffic (i.e., smoothing the following traffic, and therefore, reducing speed differences in the traffic stream) is also reported in other studies.[56,57] This implies that even under relatively low market penetration, slowing down a certain portion of vehicles can effectively impact a larger number of vehicles in a traffic stream positively.

Snowplow Pre-positioning

During winter months, snow and ice control is a priority for snow-State departments of transportation (DOT) (e.g., I–80 corridor in this case study). The safety of the traveling public, response times of emergency services, and ongoing access to goods and services all depend on the effectiveness of winter maintenance operations. Routing and positioning of snowplow trucks along the freeways include a variety of decisions. The snowplow pre-positioning strategy optimizes the routes of a fleet of snowplow vehicles, subject to roadway entry and exit constraints. This strategy aims to find the optimal locations for snowplow positions before the weather events, for two purposes: (1) clearing the road to improve roadway conditions and (2) providing additional CV data on weather and other events through weather sensors on the snowplow trucks for TMCs to implement optimal strategies.

In this case study, snowplow pre-positioning is the process of creating a set of snow and ice control routes through pre-positioning to minimize the cost of snow and ice control operations and maximize the safety and mobility performance of the traffic system. Well-designed snowplow pre-positioning strategies can result in more effective and more cost efficient snow and ice control services, because roads are cleared more rapidly. Since the route length remains the same in the test network, costs may be measured in terms of operation times (i.e., the required times to clear the roads), safety, and mobility performance.

SIMULATION NETWORK CALIBRATION

Simulation modeling of a segment of Wyoming I–80 CVP corridor has been completed as part of the Wyoming CVP, and has been accessed by the research team. The study network is a portion of the Wyoming CVP corridor on I–80 between Cheyenne and Laramie (mileposts 317–340) developed as a VSL. The corridor presents challenging traffic situations, such as high altitude, high adverse weather events, and steep vertical curves.[51]

PTV Group has multiresolution traffic modeling platforms that include macroscopic, mesoscopic, microscopic, and hybrid mesoscopic-microscopic modeling engines.[52] The microscopic simulator PTV Vissim was used for the I–80 testbed. The research team considered the microscopic tool as the optimal option for the safety analysis in the I–80 case study. In this analysis, traffic congestion (and related performance measures, such as delay) was not of concern. The testbed focused on safety analysis and the effectiveness of the three selected WRMS in reducing crashes or safety risks. The evaluation of safety risks required detailed individual vehicle space-time trajectories at the subsecond level, which could have only been generated through microscopic simulation tools.

The Vissim model, built for the Cheyenne-Laramie VSL corridor, provides the foundation for the WRMS analysis. The basic corridor network was uploaded from the standard map data in

Vissim. The roadway geometric data, including the number of lanes, roadway segment lengths, and grades; the location of lane additions and drops; and locations of rest areas and parking areas have been manually coded in Vissim. The comparison between the specific real-world network and the Vissim model is shown in figure 3. Additional detailed traffic control parameters have been incorporated into the Vissim network to better reflect existing operational conditions. Key traffic parameters include traffic composition, vehicle dynamics data, posted speed limits, and the presence of work zones (including location, length, lane-closure condition, etc.), among others. The car-following behaviors in Vissim under different weather scenarios were also taken into consideration.[51] Calibration and validation results of basic Vissim driver behavior model parameters in response to normal or adverse weather conditions are documented in Gopalakrishna et al.[53] and those are adopted directly in this study. Driver behavior in response to CV applications under investigation are modeled separately in this study and detailed in this chapter.

Source: Wyoming Department of Transportation.

A. Map. Real-world road segment.

Source: FHWA.

B. Map. Vissim simulation road segment.

Figure 3. Maps. Comparison between the real-world and the Vissim network of Interstate 80, Wyoming connected vehicle pilot corridor.

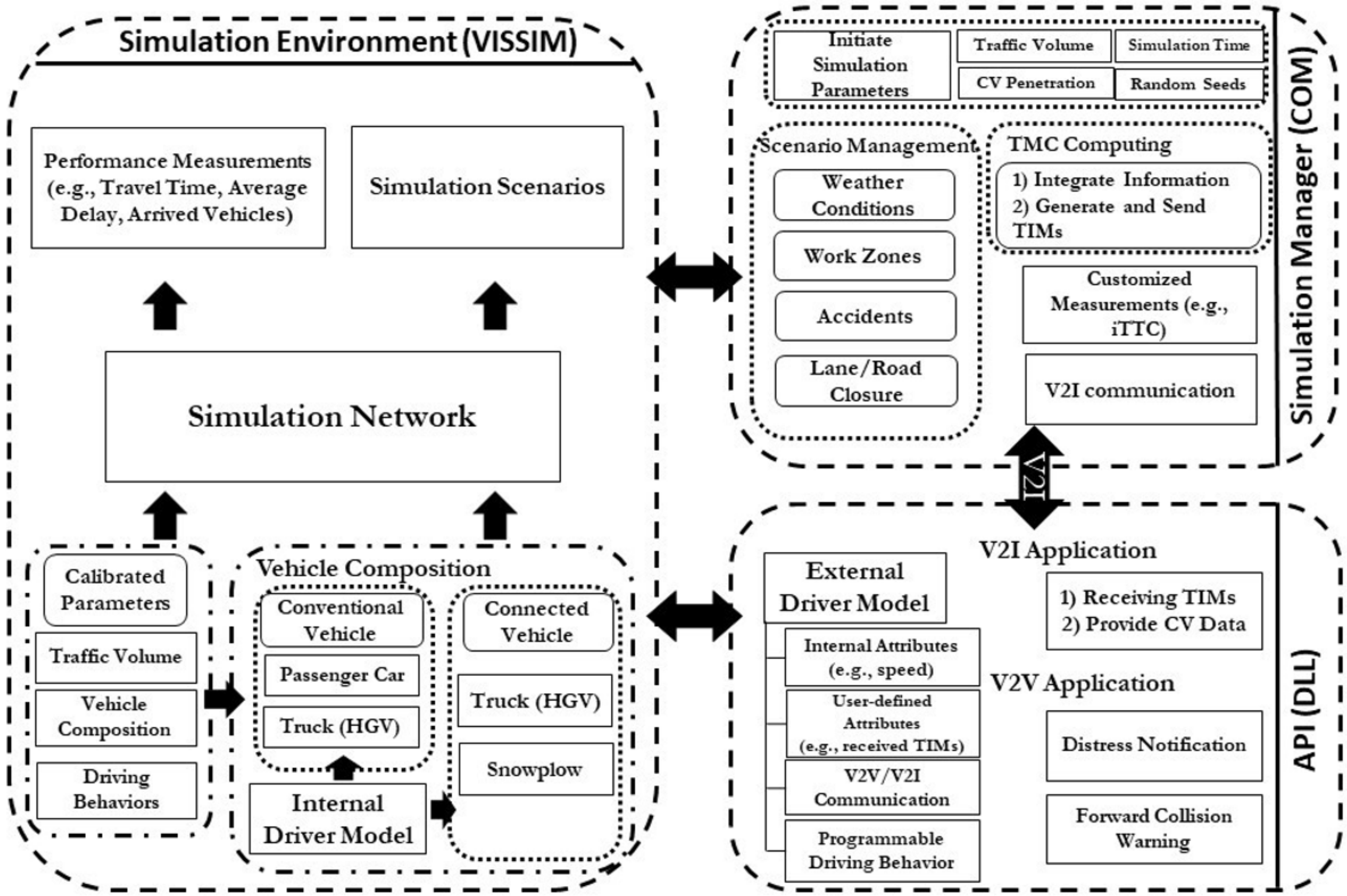
SIMULATION FRAMEWORK

A recent Federal Highway Administration (FHWA) Saxton Transportation Operations Laboratory (STOL) and University of California, Los Angeles (UCLA) platform development project using Vissim developed customized functions for CV and weather features. The tool has been used for CV/automated vehicle (AV) applications in multiple ongoing and previous FHWA efforts. To implement various CV applications, three major modules are needed in the AMS tool: the Vissim Network module, the Simulation Manager module, and the application programming interface (API) module. The detailed simulation framework, shown in figure 4, is explained as follows:

- Vissim Network is the underlying transportation network used for testing a large variety of CV algorithms. In this study, various Vissim networks must be constructed for different weather conditions, as reflected by various types of driver behavior.

- Simulation Manager is enabled through a component object model (COM) interface to support easy scenario building and system-level control. The Simulation Manager allows users to adjust control parameter values crucial for the implementation of CV applications in Vissim without directly accessing the Vissim driver model API source code. It also provides users with an interface to modify simulation scenario parameters, such as market penetration rates (MPR), traffic volumes, and simulation times. The Simulation Manager can be used to realize online or offline implementations of the AMS tool.

- The API module is a program that determines driving behavior by customized programs for corresponding parameters in different CV applications. Vissim is capable of not only conducting conventional simulations of transportation behavior in a network, but also implementing its external driver model through a dynamic linked library (DLL) interface. This substitutes the built-in Vissim driving behavior with a fully user-defined behavior for vehicles. In a proper framework, Vissim passes the current state of a vehicle and its surrounding traffic to the DLL, the DLL computes and determines the succeeding behavior of the vehicle as specified by an algorithm, and the DLL passes the updated state of the vehicle back to Vissim for the next simulation step. This feature allows the user to model (and test) various CV applications.



Source: FHWA.

API = application programming interface. COM = component object model. CV = connected vehicle. DLL = dynamic linked library. HGV = heavy-goods vehicle. *iTTC* = inverse time-to-collision. TIM = traveler information message. TMC = traffic management center. V2I = vehicle-to-infrastructure. V2V = vehicle-to-vehicle.

Figure 4. Diagram. Detailed simulation framework of Vissim© network, component object model, and application programming interface.

PERFORMANCE MEASURES

The main goal of the I–80 WRMS implementation is to enhance safety performance. While many surrogate safety measures have been proposed and adopted in the literature, in this case study, inverse time-to-collision (*iTTC*) is applied, as shown in figure 5, to measure longitudinal collision risks. Time-to-collision (*TTC*) is defined as the expected time for two vehicles to collide if they remain at their present speed and on the same path. We use *iTTC* to avoid infinity in numerical computation. Large *iTTC* values indicate large safety risks. *iTTCs* smaller than or equal to 0 imply no collision risk, and therefore will not be used in the summation calculations in figure 5.

$$iTTC = \frac{V_r - V_f}{P_f - P_r}$$

Figure 5. Equation. Calculation of inverse time-to-collision (iTTC).

Where,

P_f = position of the preceding vehicle (m).
P_r = position of the following vehicle (m).
V_r = current speed of the following vehicle (m/s).
V_f = current speed of the preceding vehicle (m/s).

However, the total *iTTC* usually does not reflect the real collision risk of a vehicle during the trip in the network, since the longer time a vehicle drives, the higher the total *iTTC* would be. Thus, *iTTC* for a group of vehicles, we use the time-weighted *iTTC* to reflect the average collision risk of all vehicles in the group and avoid the impact of the travel time of each single vehicle. This measurement uses the travel time of each vehicle as a weight to average each vehicle's unit *iTTC* in the network.

While the *iTTC* can serve as a good measure of the overall collision risks in the system, the aggregated values do not distinguish small collision risks with high or extremely high collision risks, which are more likely to cause actual crashes. Therefore, in this case study, the collision risks are further categorized into four levels by *iTTC*: small risk ($0 < iTTC < 0.1\ s^{-1}$), medium risk ($0.1\ s^{-1} < iTTC < 0.2\ s^{-1}$), high risk ($0.2\ s^{-1} < iTTC < 0.3\ s^{-1}$), and extreme risk ($iTTC > 0.3\ s^{-1}$). Within each risk level, the *iTTC* is divided into finer intervals with a resolution of $0.02\ s^{-1}$.

Several strategies in this report (e.g., VSL) improve safety performance by reducing vehicle speed in specific situations. Some research[(59)] proposed the negative mobility impact of this kind of strategy. While the primary performance optimization of the Wyoming CVP corridor is safety performance, it is also necessary to ensure that mobility efficiency is not significantly compromised. In this case, the average travel time is used to quantify mobility efficiency in order to provide a trade-off between safety and mobility.

ANALYSIS, MODELING, AND SIMULATION FOR TRAVELER INFORMATION MESSAGES

The simulation of TIM applications in this case study can be generally divided into two sections. The first is TIM data transmission, and the second is how drivers would react to the TIM messages. The data transmission includes both I2V and V2V communications. In this case study, with the use of an API, all CVs in the network calculate the distance between itself and the nearest front vehicle either in the current or adjacent lane at every simulation time step. If a nearby vehicle is a CV and the distance is within the DSRC range (i.e., 300 meters [m] in this case study), the V2V communication module will be activated to allow the TIM message to be transmitted between the two CVs.

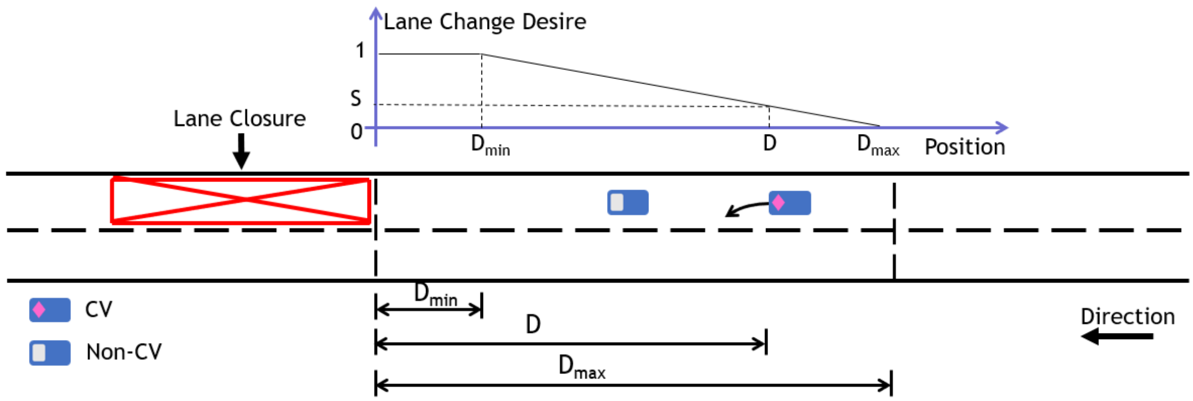
Road events included in the above-mentioned applications (e.g., crashes, work zones, spot weather) can lead to a temporary or long-lasting lane closure. All these cases could be included in TIM and delivered to CVs on the roadway. The simulation also needs to handle how drivers would react to the in-vehicle TIM advisories or warnings. In this case study, two applications enabled by TIMs are selected (i.e., early lane-change [ELC] advisory and FCW) to investigate the impact of TIMs on driver behavior and, subsequently, system performance. The ELC advisory and FCW applications are selected because they cause changes in choices of longitudinal acceleration/deceleration and lateral lane selection.

Early Lane-Change Advisory

When a vehicle approaches an event location on the same lane, it may run into slow or braking non-CVs or static objects at the event scene, particularly in low-visibility conditions, resulting in substantial safety risks. Therefore, it is beneficial to let the vehicle make a lane change when possible (i.e., no vehicles blocking the lane change on the adjacent lanes) in order to reduce rear-end crash risks. This ELC advisory message can be included as a part of the TIMs and delivered to each CV. The OBUs can then broadcast this message to the drivers (e.g., via auditory messages).

To model the details of this process, the lane-change behavior is controlled by lane-change desire. The lane-change desire is linearly determined by lane-change distance, defined as the distance from the vehicle to the lane-closure zone. The smaller the distance, the higher the lane-change desire will be. The upper and lower bounds of the lane-change distance are defined as maximum lane-change distance and minimum lane-change distance, separately. The maximum lane-change distance is set as the DSRC communication range. The minimum lane-change distance is a threshold distance that, once lower than this value, the vehicle will be facing high crash risks and will immediately make a lane change. This threshold is set to 100 m in this case study.

In order to ensure the lane-change timing is randomly determined for each vehicle, a random number between zero and one is introduced and used to compare with lane-change desire to simulate the ELC behavior. Once the vehicle enters the ELC section, a random number will be generated and refreshed every simulation time step. The random number is compared with the lane-change desire at every time step. If the lane-change desire is equal to or greater than the random number, the vehicle starts lane changing; if the lane-change desire is less than the random number, the vehicle keeps driving on its current lane. The total ELC logic is shown in figure 6.



Source: FHWA.

CV = connected vehicle. D = distance. max = maximum. min = minimum.

Figure 6. Illustration. Early lane-change logic.

Forward Collision Warning

FCW systems provide visual, audible, or tactile alerts to warn a driver of an impending collision with a car or object in its direct forward path. The warning message can be included as a part of the TIM message and broadcast to drivers via DSRC and OBUs.

Under adverse weather conditions (e.g., heavy fog, snow), visibility distance is insufficient for drivers to promptly react to avoid crashes. FCW relies on I2V and V2V communications to obtain data of the front vehicle and calculate the headway and speed difference. During severe weather conditions, the communication distance is always longer than the sight distance, and therefore, CVs could receive the alert of the forward collision risk before drivers observe the front vehicle.

While FCW can also rely on vehicle sensors, such as vehicle front radar, this case study focuses on CV/DSRC-enabled FCW. That said, if at least one of the two consecutive vehicles is non-CV, the FCW function will not be activated. The front and rear vehicles must all have communication capability and be in the communication range of each other.

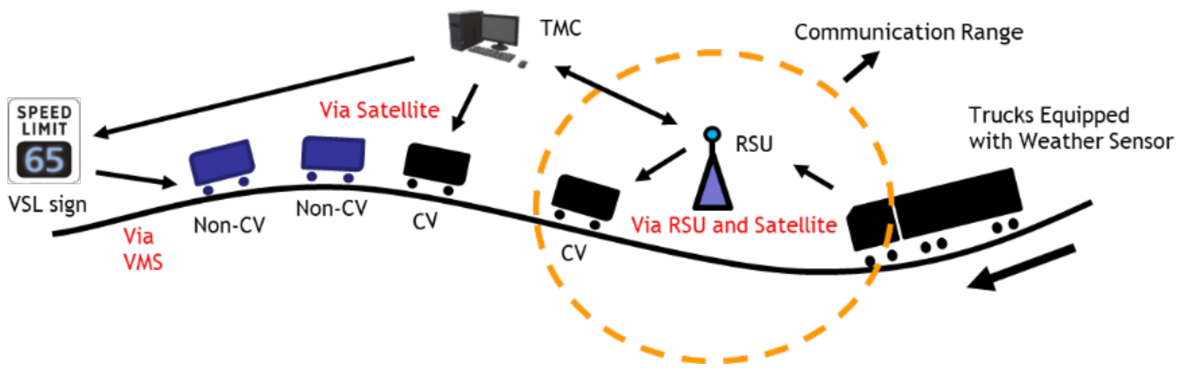
In this case study, FCW is categorized into two notification levels: cautionary level (yellow) when *iTTC* is between 0.2 s^{-1} and 0.1 s^{-1}, and alert level (red) when *iTTC* is more than 0.2 s^{-1}. In the cautionary level, there is still enough time for drivers to slow down with a reasonable deceleration. However, if the alert level occurs, the FCW system will provide decision-making to help drivers choose between changing their lanes (to the left or right, if there are multiple lanes) and applying the brake heavily. This decision is determined based on the condition on adjacent lanes.

Except for the lane-change decision, another parameter to be calibrated is driver deceleration choice after receiving the collision warning.[58] If the warning is at the alert level, the deceleration and lane-change behavior are determined by the Vissim default car-following and lane-change models because the drivers need to brake heavily or change lanes to avoid crashes. Vissim can generate reasonable behavior values under this condition. If at the cautionary level, the deceleration may not be directly affected by the front object, and cannot be accurately captured through Vissim's models. Therefore, the behavior is calibrated using a behavior data set collected by the University of Wyoming of a truck driving simulator with 25 professional truck drivers under adverse weather conditions.[54] The average deceleration under the cautionary level in this experiment is 1.31 feet per second squared (ft/s^2) (0.4 meters per second squared [m/s^2]). It is regarded as the constant deceleration in this case study when drivers receive cautionary level warnings.

ANALYSIS, MODELING, AND SIMULATION FOR CONNECTED VEHICLE-BASED VARIABLE SPEED LIMIT

In this case study, the speed limit information displayed on VSL signs can only be received by vehicles in the visual range. This range is the visibility of drivers under specific weather conditions. This presents spatiotemporal constraints to drivers to receive the information. CVs can also receive speed limit information via the HMI equipped on the vehicles. It is also possible to send this information through satellite or cellular technologies, since VSL is not time-sensitive information and some delay in VSL communication is tolerable, from the perspective of system safety and efficiency. Sending through the satellites will enable communication of dynamic speed limits to all CV drivers in a short time period to achieve more substantial system benefits.

In the former scenario of DSRC communication, the VSL information can only be transmitted from RSUs to CVs. In this situation, only CVs in the RSU communication range can receive the VSL information after the TMC sends the speed limit value information to RSUs. Connected vehicle-variable speed limit (CV–VSL) communicated through DSRC is similar to signed-based VSL, in that it can only inform drivers/vehicles passing the location of the RSUs or signs. The VSL information is included as a part of the TIM. Additionally, the VSL information can be sent through non-DSRC communication channels (i.e., satellite and cellular communication), which can enable immediate notification of dynamic speed limits to all CVs and, therefore, further improve system safety performance. The VSL information is not time sensitive and can be sent through these additional channels, subject to information delay and packet drops, in exchange for systemwide information dissemination. The Wyoming CV testbed also proposes to use satellite communication for this purpose,[53] as illustrated in figure 7. In this scenario, all CVs on the road can receive the VSL information after the TMC broadcasts the speed limit information. Meanwhile, non-CVs can continue to receive the VSL information from roadside signs. It is expected that the systemwide information dissemination can significantly enhance safety performance, and therefore this dissemination approach is targeted in this case study.



Source: FHWA.

CV = connected vehicle. RSU = roadside unit. TMC = traffic management center. VMS = variable message sign. VSL = variable speed limit.

Figure 7. Illustration. Connected vehicle-variable speed limit system using satellite communication.

In this case study, we use the same weather-responsive VSL decision strategies that are currently adopted in the Cheyenne TMC.(53) This road weather information system (RWIS) algorithm takes data from RWIS and field staff reports as inputs, and automatically calculates suggested speed limits under specific weather and road conditions. Key weather parameters included in the algorithm are road surface status, humidity, average wind speed, and visibility.

In microscopic traffic simulation, weather and road conditions are reflected using different driver behavioral models through the parameters such as look-ahead distance, desired following gap, and desired velocity. These parameters are frequently associated with roadway links of the simulation network, such that specific weather and road conditions can be reflected through driving behavior for different parts of the freeway. By referring to these parameters, a mapping between RWIS weather data and weather-sensitive driving behavior parameters was created in this case study. The AMS tool first receives data on weather and road conditions, and the mapping determines the specific set of driving behavior parameters to use in the simulation evaluation. In the meantime, the Cheyenne TMC algorithm is used to determine the speed limits and directly implemented in the simulation. An example mapping is shown in chapter 5 to enable the simulation evaluation for this case study.

ANALYSIS, MODELING, AND SIMULATION FOR SNOWPLOW PRE-POSITIONING

The snowplow pre-positioning strategy refers to deployment of snowplow trucks at key roadway segments ahead of severe weather events, such that accumulated snow on the road can be cleared as early as possible. This has two positive effects on traffic safety: (1) clearing the road to improve roadway conditions and (2) providing additional real-time weather and road condition data to the TMC.

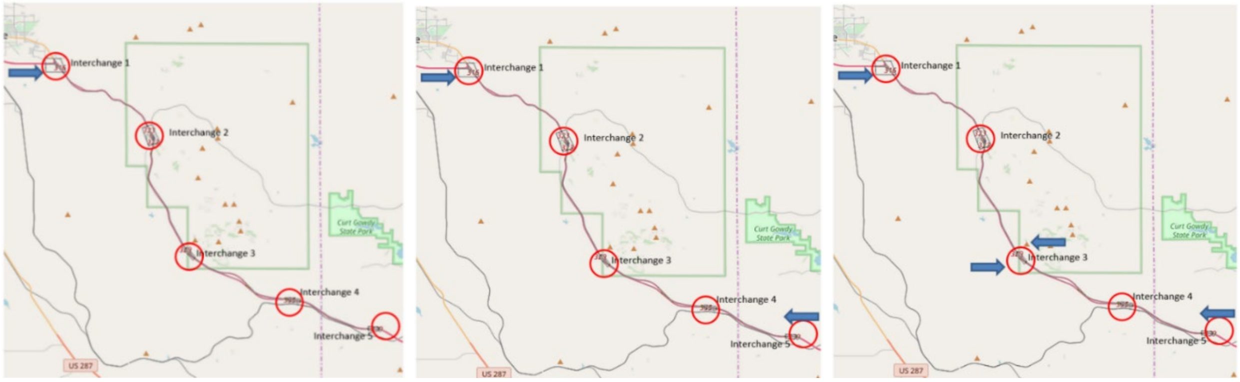
According to the Wyoming CVP, there are approximately 60 total snowplow trucks deployed along the 403-mile I–80 corridor. It is assumed that the number of snowplows that serves in this 23-mile segment for simulation can be proportionally scaled down by distance to four.

The application of snowplow pre-positioning aims to optimize the deployment strategy of snowplows. With the snowplow pre-positioning strategies applied, the roadway surface is expected to be improved so that the overall safety performance could be enhanced more quickly. Meanwhile, the operation of plowing should be completed as soon as possible, and the snowplow operations should cause the least amount of interruptions to the traffic.

Improving roadway conditions can be simulated in Vissim by changing the vehicle's car-following behavioral parameters. In Vissim, maximum and minimum accelerations are attributes of the link driving behaviors, and this behavior is associated with roadway links as an attribute of the links. In this case study, it is assumed that a link will be plowed by two snowplow trucks before the snowplowing job is completed for the link, and the corresponding driving behavior parameter set for better road and weather conditions will be used after the plowing is completed. This is considered reasonable because the driving condition can be much improved by the snowplow. However, it will require an additional calibrated parameter set to reflect this driving condition after the link is plowed. Since no such data are available to the research team, the parameter set of clear weather condition was used as a rough surrogate. Similarly, Vissim does not contain modules that directly simulate the road surface condition. To simulate the influence snowplows have on the surface, and their impact on traffic safety performance, different link driving behavior types are applied for the same roadway to represent the surface condition before and after plowing. All snowplow trucks drive at a relatively low speed while plowing the road (25 mph). Once a link is twice passed by snowplows, it is defined as a plowed link.

Because the route length remains the same (23 miles), the consideration becomes how to group the snowplows and where to pre-position them to achieve optimal system performance, in terms of safety and mobility. Because this test network is only a segment of the CV corridor, and the plowing operations may be conducted jointly with adjacent segments, the actual plowing strategies can be different from those discussed in this study. However, the focus here is to understand how two realistic pre-positioning strategies can improve system safety and what the magnitude of safety enhancements is. The base case and pre-positioning cases evaluated in this study are defined as follows:

- Base case (single-point positioning): in the base case, all snowplows enter the network from one end of the freeway segment, as shown in figure 8A.
- Pre-positioning case 1 (two-point positioning): four snowplow trucks are divided into two groups, and each group contains two trucks. The two groups of snowplows start plowing simultaneously from the end of the eastbound and the end of the westbound freeway segment (i.e., Interchanges 1 and 5 in figure 8B).
- Pre-positioning case 2 (multipoint positioning): four snowplow trucks are divided into four groups, and each contains only one snowplow. The snowplow trucks enter the network from Interchanges 1, 3, and 5 and start plowing simultaneously, as shown in figure 8C.



Original maps: © 2020 Google® Maps™. Map overlays: FHWA (see Acknowledgments).

A. Map. Base case. B. Map. Case 1. C. Map. Case 2.

Figure 8. Maps. Three snowplow pre-positioning scenarios.

SYSTEM PARAMETERS

In the Vissim network calibrated as a part of the Wyoming CVP, three weather scenarios are designed: normal/clear, snowy, and severe weather conditions. These scenarios can clearly distinguish between different weather conditions, pavement conditions, and visibility levels. Therefore, they are representative of varying weather conditions of I–80 during winter seasons. As previously indicated, three CV-based WRMS are introduced and evaluated for the I–80 study: TIM, VSL, and snowplow pre-positioning. The driver behavior differences under the three weather scenarios are in terms of speed distribution, look-ahead distances, and other behavioral parameters. For driving behavior, apart from some basic parameters such as visibility and look-back distance, Vissim's Wiedemann 99 model parameters (CC0–CC9) are calibrated, as shown in table 6.

Table 6. Car-following parameters used for clear, snowy, and severe weather in this study.

W99 Model Parameters	Clear	Snowy	Severe
CC0: standstill distance (m)	4.2	3.05	6.1
CC1: spacing time (s)	0.7	0.9	0.9
CC2: following variation, max drift (m)	12.7	16.1	6.1
CC3: threshold for entering following (s)	-24.6	-8	-8
CC4: negative following threshold (m/s)	0.0	-0.35	-0.35
CC5: positive following threshold (m/s)	0.9	0.35	0.35
CC6: speed dependency of oscillation (10^{-4} rad/s^2)	1.7	11.4	11.4
CC7: oscillation acceleration (m/s^2)	1.0	0.25	0.25
CC8: standstill acceleration (m/s^2)	1.4	3.5	3.5
CC9: acceleration at 80 km/h (m/s^2)	0.1	1.5	0.91

Source: FHWA.

m = meter. m/s = meter per second. m/s^2 = meter per second squared. km/h = kilometer per hour. rad/s^2 = radian per second squared. s = second.

Different CV MPRs are considered to understand the system performance sensitivity with varying percentages of CVs in the system. In this study, the CV MPR is defined as the proportion of CVs in all heavy-goods vehicles (HGV) (i.e., trucks). HGVs are the focus of the I–80 CV testbed, which aims to equip trucks with DSRC capabilities to enhance their operational safety. The CV MPRs of HGVs include 0 percent, 20 percent, 40 percent, 60 percent, 80 percent, and 100 percent. To eliminate the confounding effects caused by the traffic volume, traffic volume in all scenarios are set at the same level as in the severe weather conditions. The total simulation time is 7,800 seconds, including a 600-second warm-up period. For each scenario, results from five simulations using random seeds are averaged to account for the randomness in simulation.

To create external conditions on the network, four active lane-closure events (e.g., work zones, incidents, crashes) are used, including two for the eastbound and two for the westbound. In each of the four events, the right-most lane is closed for 646.17 feet (200 m), leaving the left-most lane open for vehicles to bypass the events. Each event starts and ends at different simulation seconds, and the duration of time is identical (1 hour) for all lane-closure events. Note that the proposed AMS tool can simulate any type of event with random start and end times.

The CV-based weather-responsive VSL is applied in the case study as follows. The weather change is assumed to take place at the 2,000th simulation second. The weather condition changes from normal weather to severe weather, which is expected to reflect the safety performance deterioration because of the apparent gap between speed distributions and driving behaviors of vehicles under these two weather conditions. Using the RWIS VSL algorithm, the determination of the speed limit under three weather scenarios, associated with three calibrated behavior sets (i.e., normal/clear, snowy, and severe) is listed in table 7. This is a customized mapping between three weather conditions (i.e., simulation behavior sets) and weather parameters used by the VSL algorithm for the purpose of simulation implementation.

Table 7. Speed limit determination of three weather scenarios.

Weather Condition (Corresponding to Driver Behavior)	Pavement Condition	Relative Humidity (percent)	Visibility (feet)	Surface Temperature (degrees Fahrenheit)	Speed limit Determination (miles per hour)
Normal	Dry	< 95	820	> 32	75
Snowy	Slick	< 95	500	< 32	54
Severe	Slick	< 95	200	< 32	35

Source: FHWA.

The speed limit value under severe weather can be regarded as 35 mph (approximately 55 km/h in the simulation). The speed limit under normal weather is determined as 75 mph (120.70 kilometers per hour [km/h]). In the Vissim network, to model the VSL sign, the desired speed distribution attribute in Vissim is modified when drivers see the VSL sign. The use of desired speed distributions, instead of a single deterministic value, is more realistic considering the randomness of driver behavior and compliance with the dynamic speed limits.

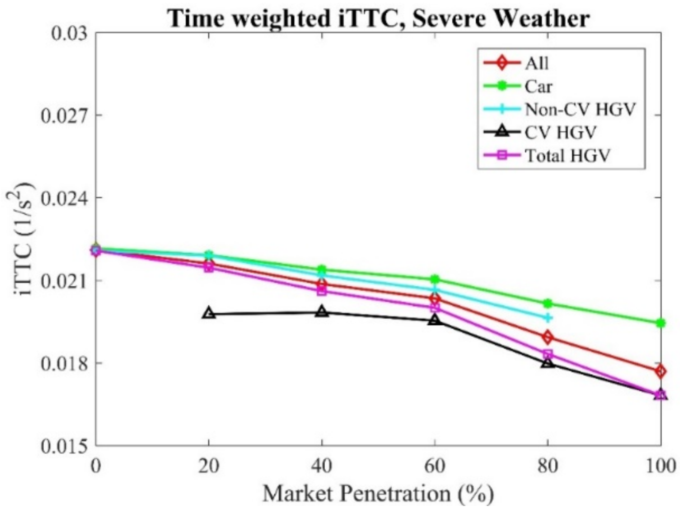
Apart from the VSL, the behavior of non-CVs may also be impacted by CVs that have slowed down due to the latest CV–VSL commands. In this case, the entire traffic can be smoothed by the CVs, even when the CV MPR is low. While this phenomenon has been reported in some literature,(57) no further information on the influence rate is reported. Therefore, in this report, a new parameter is adopted—traffic-smoothing rate (TSR)—to capture the percentage of non-CVs that can be influenced by slow vehicles and conduct sensitivity analysis to understand the effect of TSR. If a vehicle's front vehicle slows down, the vehicle with the traffic-smoothing characteristic will also slow down to continue the car-following maneuver (and the vehicle's desired speed is also changed). Vehicles without TSR will change their lanes to overtake the slow front vehicle because their desired speed is still high, meaning they will maintain high speed until they receive the speed limit information. Three levels of TSR selected for testing in the evaluation are 0 percent (no smoothing effect), 50 percent, and 100 percent (full smoothing effect).

The key process of simulating the impact of snowplow operation on the road surface is to use link driving behavior parameter sets to reflect the proper driving behavior for certain road surface conditions. In this case study, two adverse weather scenarios are studied on the snowplow operation environment: severe and snowy, respectively, either of which contains calibrated car-following parameter sets. After the surface of a link in these weather scenarios is passed by a certain number of snowplows (two, in this case study), the car-following parameters bounded with this link, except for the visibility-related parameters, are replaced by the parameter sets used for clear weather scenario. Then this link is regarded as a plowed link.

SIMULATION RESULTS

Traveler Information Messages

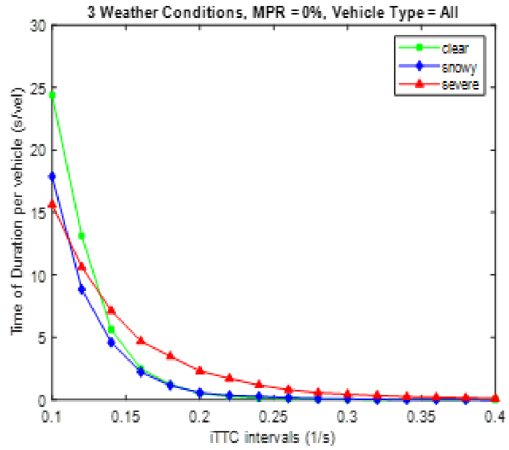
Figure 9 shows the performance of the $iTTC_{tw}$ of different vehicle types in severe weather scenarios. As shown in the severe weather scenario, when the CV MPR increases from 0 percent to 100 percent, the time-weighted $iTTC_{tw}$ of the passenger cars, HGVs, and all vehicles decrease by 12.24 percent, 23.82 percent, and 19.96 percent, respectively. When the CV MPR increases from 20 percent to 100 percent, the decrease of the $iTTC_{tw}$ is 14.92 percent for CVs and 11.04 percent for non-CVs. The safety improvement in terms of $iTTC_{tw}$ is the most significant in severe weather cases, less significant in snowy weather cases, and least significant in clear weather cases.

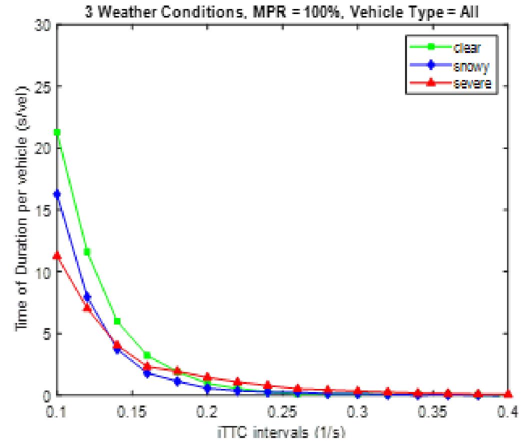


Source: FHWA.
% = percent. CV = connected vehicle. HGV = heavy-goods vehicle. *iTTC* = inverse time-to-collision. s = second.

Figure 9. Chart. Time-weighted inverse time-to-collision under severe weather scenarios.

Figure 10A and figure 10B show the average time distribution at each *iTTC* level during one trip in the network for the CV MPR of 0 percent and 100 percent. In all three weather scenarios, a vehicle spends most of the time under low-risk *iTTC* intervals ($0.1 < iTTC < 0.2$) and very little time under medium-risk ($0.2 < iTTC < 0.3$), high-risk ($0.3 < iTTC < 0.4$), and extreme-risk ($iTTC > 0.4$) intervals. The clear weather case involves more time at low-risk levels than that in snowy and severe weather cases, but involves the least time at the medium-to-extreme risk levels. In contrast, the severe weather scenario involves less time at the low-risk *iTTC* level, but much more time at the medium- and higher-risk levels than that in snowy and clear weather cases. In figure 10, when the charts are compared with the CV MPR of 0 percent and 100 percent, it is clear that, in addition to the overall safety risk reduction, the medium and higher risks with $iTTC > 0.2$ also significantly decrease. This indicates that implementation of TIMs can avoid many high-risk near-crashes, therefore considerably improving the overall system safety. Results also show the limited impact of mobility in terms of when the CV MPR increases. For all three weather scenarios, the increase in travel time when the CV MPR rises from 0 percent to 100 percent is only by 1.85 percent, 1.81 percent, and 1.12 percent, respectively. This indicates the effects of TIMs on mobility efficiency are limited.





Source: FHWA.

% = percent. *iTTC* = inverse time-to-collision. MPR = market penetration rate. s = second.

A. Chart. Connected vehicle market penetration rate = 0% scenario.

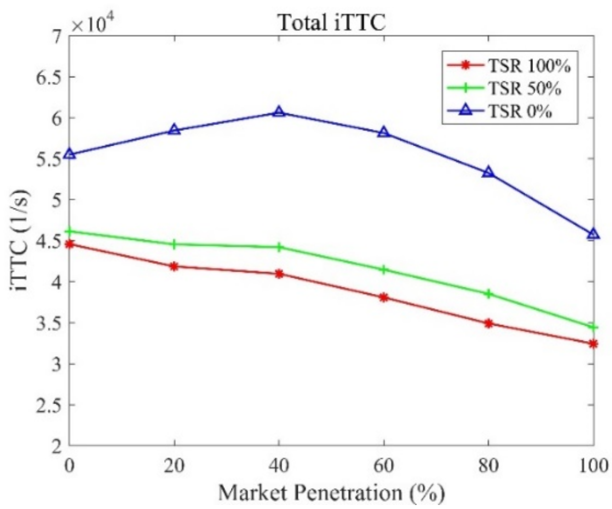
B. Chart. Connected vehicle market penetration rate = 100% scenario.

Figure 10. Charts. Performance of inverse time-to-collision distribution from applying connected vehicles in different weather scenarios.

Variable Speed Limit

Figure 11 illustrates the results of the total *iTTC* for various scenarios when the CV MPR grows from 0 percent to 100 percent. The results show that for 0 percent TSR (i.e., non-CVs are not smoothed by CVs), the total *iTTC* increases when the CV MPR grows from 0 percent to 40 percent, indicating that system safety risks become higher. This is mainly because majority of the traffic on the roads is still non-CVs, and they will continue to drive fast before they see the VSL signs. Therefore, the interaction between fast non-CVs and slow CVs and maneuvers of lane changes and overtaking of non-CVs may result in many instances of high collision risks. Based on the results in this case study, the peak of the safety risks is reached at 40 percent of the CV MPR. After 40 percent, the *iTTC* curve of the 0 percent TSR starts to decline. This is because a sufficient number of CVs is on the road, and the CVs are able to block the overtaking maneuvers of upstream non-CVs. Therefore, the non-CVs are forced to follow CVs slowly, and the entire traffic is smoothed. Overall, when the CV MPR rises from 0 percent to 100 percent, the total *iTTC* of the 0 percent, TSR case decreases by 17.59 percent. When the TSR is 50 percent and 100 percent, the total *iTTC* drops with the increase of the CV MPR. The decreases in the total *iTTC* for 50 percent and 100 percent TSR cases when the CV MPR grows from 0 percent to 100 percent are 25.37 percent and 27.24 percent, respectively. The result indicates that CVs can induce the deceleration of non-CVs that follow the traffic-smoothing rule when the TSR is high. In high TSR cases, when a preceding CV slows down, the following non-CVs will drive more conservatively and tend to follow the new driving behavior of the front CVs. Such phenomena can then spread to the surrounding conservative non-CVs. Therefore, the overall trend of the total *iTTC* is downward with the growth of the CV MPR in the 50 percent and 100 percent TSR scenarios.

It is worth noting that when the CV MPR equals to 0 percent, the total *iTTC* under three TSR scenarios is different. As shown in figure 11, when the CV MPR is 0 percent, the total *iTTC* decreases with the growth of TSR. This is due to the difference in car-following modes between three TSR cases. Assume a vehicle slows down when observing a VSL sign (in all scenarios of this report, the assumed compliance rate with the VSL is 100 percent). If the following vehicles are conservative, they tend to follow the deceleration behavior of the preceding vehicle, even though the VSL sign is not yet within the sight distance. With more conservative vehicles in the network (i.e., higher TSR levels), the overall car-following behavior is smoother. Therefore, the collision risk of the traffic system can be mitigated with the rise of TSR even if CV MPR equals to 0 percent.



Source: FHWA.

% = percent. *iTTC* = inverse time-to-collision. TSR = traffic smoothing rate. s = second.

Figure 11. Chart. Total inverse time-to-collision of all vehicles, cars, and heavy-goods vehicles under different traffic-smoothing rate percentages.

Table 8 shows the decrease rate of the total *iTTC* of passenger cars and HGVs when the CV MPR rises from 0 percent to 100 percent under three TSR scenarios. Note that the total time-weighted *iTTC* shows similar trends. The decrease in the total *iTTC* for HGV is more significant than that of passenger cars because some HGVs are CVs, while all passenger cars are non-CVs. The decrease in the total *iTTC* of passenger cars indicates that when the TSR is at a high level, CV–VSL can also provide safety benefits to aggressive non-CVs whose behavior will not be smoothed unless they are blocked.

Table 8. The inverse time-to-collision reduction for cars and heavy-goods vehicles under three traffic-smoothing rate scenarios.

Traffic-smoothing rate	0%	50%	100%
Car	8.00%	17.02%	18.28%
Heavy-goods vehicle	21.96%	29.27%	31.50%

Source: FHWA.

% = percent.

Results also show that under three TSR scenarios, the increases in travel time as the CV MPR rises from 0 percent to 100 percent are limited. This indicates the limited impact of CV–VSL on system mobility efficiency.

In most scenarios in this case study, the increase of the CV MPR and TSR can both improve the safety performance of the traffic system, except when the CV MPR is at a low level and TSR is 0 percent. The changes in CV MPR and TSR cause no deterioration on the travel time performance, indicating that system mobility efficiency is not compromised.

Snowplow Pre-positioning

Table 9 shows the comparison of traffic performance between the base case and two pre-positioning cases. The weather condition is set to be severe in the simulation. To show the differences in performance under both low and high CV MPR, the results from two CV MPRs (20 percent and 80 percent) are compared in this case.

As shown in Table 9, both case 1 and case 2 pre-positioning outperform the base case in terms of $iTTC_{tw}$ and average travel time in either low or high CV MPR scenarios. Case 2 reduces the $iTTC_{tw}$ and average travel time more significantly than case 1. When the CV MPR is 20 percent, case 2 decreases 9.85 percent of $iTTC_{tw}$ of all types of vehicles, while case 1 only reduces 8.6 percent. When the CV MPR increases to 80 percent, the decrease in $iTTC_{tw}$ in case 2 rises to 10.38 percent, still larger than the 7.09 percent reduction in case 1. This is because case 2 distributes four snowplows far apart from each other and causes smaller impacts on other vehicles in the network.

Case 2 also leads to a decrease in average travel time as compared to the base case and case 1. The only measurement that case 1 outperforms case 2 is snowplow operation time. Case 1 reduces the operation time by 33.07 percent, while case 2 only decreases by 26.16 percent as compared to the base case. This is mainly because the snowplows in case 1 drive continuously along the freeway from start to end, while snowplows in case 2 change direction through interchanges during the plowing operation, and the times elapsed to traverse the interchange are included in the total operation time.

Table 9. Results of base case, case 1, and case 2 in severe weather.

Case	Base Case (20% CV)	Case 1 (20% CV)	Case 2 (20% CV)	Base Case (80% CV)	Case 1 (80% CV)	Case 2 (80% CV)
$iTTC_{tw}$ of all types of vehicles (1/s^2)	0.02145 (0.00%)	0.01960 (-8.60%)	0.01934 (-9.85%)	0.01018 (0.00%)	0.00945 (-7.09%)	0.00912 (−10.38%)
$iTTC_{tw}$ of passenger cars (1/s^2)	0.02181 (0.00%)	0.02099 (-3.78%)	0.02019 (-7.44%)	0.01342 (0.00%)	0.01266 (-5.65%)	0.01232 (-8.22%)
$iTTC_{tw}$ of non-CV HGVs (1/s^2)	0.02200 (0.00%)	0.01935 (−12.03%)	0.01956 (−11.06%)	0.01251 (0.00%)	0.01213 (-3.01%)	0.01195 (-4.45%)
$iTTC_{tw}$ of CV HGVs (1/s^2)	0.01849 (0.00%)	0.01763 (-4.64%)	0.01681 (-9.10%)	0.00799 (0.00%)	0.00734 (-8.10%)	0.00705 (−11.77%)
$iTTC_{tw}$ of All HGVs (1/s^2)	0.02128 (0.00%)	0.01900 (−10.69%)	0.01896 (−10.89%)	0.00878 (0.00%)	0.00818 (-6.88%)	0.00786 (−10.48%)
Average Travel Time (s)	1,786.65 (0.00%)	1,765.41 (−1.19%)	1,760.26 (−1.48%)	1,988.20 (0.00%)	1,947.55 (-2.04%)	1,954.58 (−1.69%)
Maximum Travel Time (s)	2,076.34 (0.00%)	2,102.83 (1.28%)	1,957.57 (-5.72%)	2,570.81 (0.00%)	2,359.91 (-8.20%)	2,322.84 (-9.65%)
Snowplow Operation Time (s)	5,149 (0.00%)	3,446 (-33.07%)	3,802 (-26.16%)	5,149 (0.00%)	3,446 (-33.07%)	3,802 (-26.16%)

Source: FHWA.

% = percent. CV = connected vehicle. HGV = heavy-goods vehicle. $iTTC_{tw}$ = time weighted inverse time-to-collision. s = second. s^2 = second squared.

SUMMARY

The simulation results show that effectiveness of all three CV WRMS strategies depends on weather conditions, CV MPRs, and the levels of impact of CVs on non-CVs (as quantified by using TSR in the study). Based on the simulation results, the following key observations and implications are summarized:

- AMS tools based on a microscopic traffic simulator have developed and proved effective in capturing realistic traffic and driving behavior under different weather conditions. It is also possible to implement and evaluate different WRMS that use RWIS and CV data as input, through a mapping between weather conditions, which is characterized by weather-related parameters (e.g., pavement condition, visibility, heavy snow) and various sets of driving behavior parameters (e.g., car-following gaps, look-ahead distance).

- For all scenarios, individual CV-based WRMS applications can improve traffic safety performance, as measured by *iTTC*. The effectiveness is most dramatic under severe weather conditions.

- TIMs can help improve the safety performance of the traffic system by reducing the risk of collisions and the occurrence of pileup crashes near the lane-closure event zones. In the I–80 case study, the CVs receive TIMs that include multiple advisories for the driver to decelerate or make lane changes to avoid potential collision with the preceding vehicles or objects in the lane-closure zones. The simulation results indicate that safety benefits provided by CVs continue to increase as the CV MPR rises.

- VSL can provide suitable speed limit advisories under different weather scenarios to keep vehicles driving at safe speeds. The weather information and road conditions can be obtained by RWIS stations, as well as vehicles equipped with weather sensors, to determine the safe speed limits correspondingly. The effectiveness of CV–VSL is influenced by both CV MPR and TSR. The safety performance improves as the rise of CV MPR at each TSR level. Meanwhile, the high TSR cases outperform the low TSR cases in safety performance, as measured by the $iTTC_{tw}$ of the traffic system under the same CV MPR.

- Snowplow pre-positioning is an effective strategy for winter surface maintenance that helps improve operation efficiency, reduce collision risks, and increase the mobility efficiency of the traffic system. Two pre-positioning strategies are designed and tested as compared to the base case. The multipoint positioning strategy is recommended for severe weather because it provides more performance benefits to the system, in terms of *iTTC* and travel time, than the other strategies. Either a two-point or multipoint pre-positioning strategy is acceptable for snowy weather because the performance difference is not significant for the two cases, indicating the average significant benefits if the pre-positioning of snowplows is implemented.

- For all three CV strategies, the level of safety benefits to the traffic system significantly depends on the weather scenarios. All three CV strategies tend to perform most effectively in severe weather. This is because when weather conditions are more severe (e.g., lower visibility, lower acceleration, and deceleration rate), there are more crash risks, and the advantages of CVs preventing large safety risks become more significant. With the TIMs updated continuously, the CV drivers can perform safer driving maneuvers under conditions in which non-CVs may be exposed to more substantial crash risks.

- The I–80 case study shows that when the CV MPR increases, though *iTTC* decreases in most cases, the travel time is not significantly impacted. In cases of snowplow pre-positioning in severe weather, the travel time performance even shows a non-negligible improvement with the growth of the CV MPR. This indicates that introduction of CVs to WRMS, which may even consist of strategies that slow down CVs, will at least maintain the same level of mobility efficiency of the system.

SUGGESTIONS FOR ADDITIONAL RESEARCH

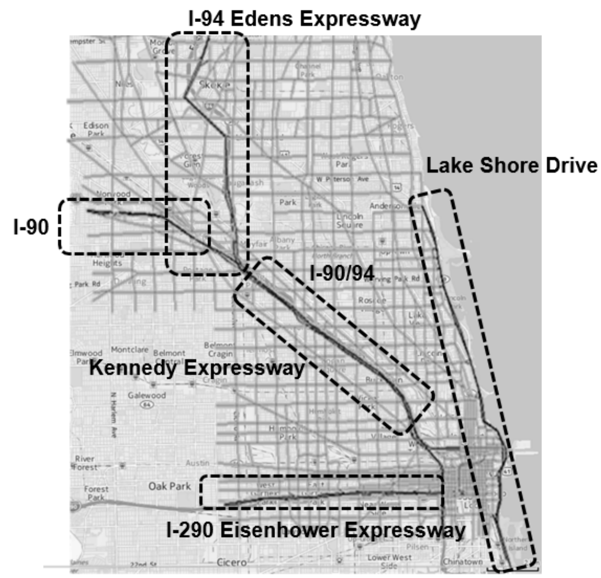
To further enhance the state of the practice and state of the art in using AMS tools for WRMS decision-making, the following future work, including research and deployment, are suggested:

- The AMS tool development in this project is designed as an framework to model CV technologies for traffic management, and three modules were developed and customized for specific WRMS. It is suggested to apply this framework to evaluate additional weather-responsive strategies in the future.
- The selected testbed in this case study has a traffic safety focus, and mobility-related performance is not as important. For congested traffic networks with adverse weather events, it would be necessary to fully implement the framework and develop customized simulation solutions, including additional modules such as online estimation and prediction of traffic demand. However, to ensure safety analysis at driver behavior level, microscopic simulations are still required.
- This case study uses a calibrated network from the Wyoming testbed. The simulation network is calibrated using weather and traffic detector data and can simulate three weather conditions: clear, snowy, and severe. It is recommended to use richer data sets, such as naturalistic driving data, to calibrate driver behavior models for a wider range of weather events. For example, WYDOT categorizes weather events into nine different types, and it is necessary to obtain nine sets of driving behavior parameters for each weather category to fully integrate such AMS models into the daily traffic management and maintenance operations.
- In this case study, the CV-based WRMS strategies are implemented and simulated in a virtual world in Vissim. All strategies are implemented in real time of the simulation. It would be of interest to directly test the simulation in selected TMCs. Two types of TMC integration are recommended. First, the offline AMS tool can be used by TMC staff to generate, in advance, an initial set of weather- and traffic-responsive strategies that will be applied when weather or traffic events occur, and continuously refined with real data. Second, for congested traffic networks where online simulation and decision-making are necessary, the AMS tool, or a customized one with less computational load for online implementation, can be applied to guide TMC operations in real time or near real time (i.e., tactical decision-making).
- The AMS tools usually require predictions of future traffic and weather conditions as inputs to simulate and evaluate the potential performance if certain strategies are implemented. It is suggested to integrate such systems with existing or new road condition prediction tools.

CHAPTER 5. CHICAGO CASE STUDY

CHICAGO TESTBED NETWORK CHARACTERISTICS

The Chicago testbed network is extracted from the greater Chicago metropolitan area to evaluate the impact of citywide weather-related strategies (figure 12). This partial network includes the Chicago Loop in the bottom right, O'Hare International Airport (O'Hare) in the far left, and Evanston, Illinois, at the top. The road network in the area consists of Kennedy Expressway on Interstate 90 (I–90), Edens Expressway on Interstate 94 (I–94), Eisenhower Expressway on Interstate 290 (I–290), and Lake Shore Drive. The testbed network is bounded on the east by Lake Michigan and on the west by Cicero Avenue and Harlem Avenue. Roosevelt Road and Lake Avenue bound the testbed network from the south and north, respectively. Table 10 summarizes characteristics of the network.



Original map: © 2017 Google® Maps™. Map overlay: FHWA (see Acknowledgments).
I–90/94 = Interstate 90/94. I–290 = Interstate 290.

Figure 12. Map. Network of Chicago testbed.

Table 10. Network characteristics for Chicago testbed.

Chicago Testbed Network	
Link	Total 4,805 links: 150 freeways, 47 highways, 247 ramps with 59 metered, 4,361 arterials
Node	Total 1,578 nodes: 545 signalized intersections
Zone	Total 218 zones
Demand	24 hours: ~1,100,000 total vehicles 5-minute interval demand matrix

ROAD WEATHER CONNECTED VEHICLE APPLICATION IN ROAD WEATHER RESPONSE

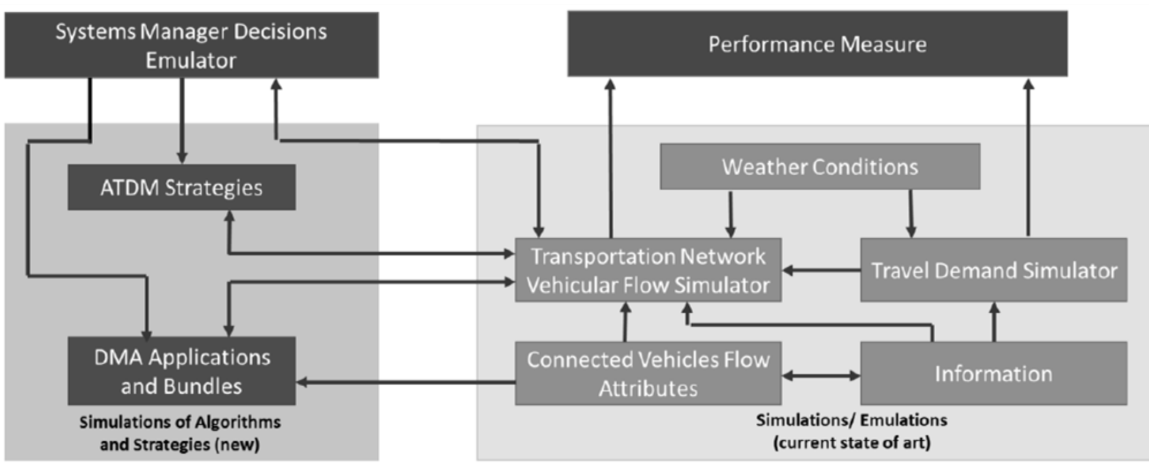
This section describes the analysis framework and a proposed framework of road weather connected vehicle (RWCV) application in snowplow operations.

Analysis Modeling Framework of Road Weather Connected Vehicle Application

Analysis, modeling, and simulation (AMS) implementation for RWCV applications is designed to address the following questions of this study:

- What is the marginal benefit of integrating information from connected vehicles (CV) into winter road maintenance plans?
- How can data from CVs be combined with data from other sources for real-time traffic estimation and prediction?
- Can integrating data from CVs to a legacy system improve current road weather response strategies?

In the proposed modelling framework for RWCV applications, CV data provide additional input of real-time localized traffic information in the decision support system of road weather response. Figure 13 presents the analysis framework, guiding the application of AMS tools to CV-enabled WRMS. The analysis framework is designed to simulate operational strategies and decision-making processes in the traffic management center (TMC) under winter weather conditions, and describe main process detection; CV data collection, communications, and control/advisory information dissemination technologies; and system management decisions.



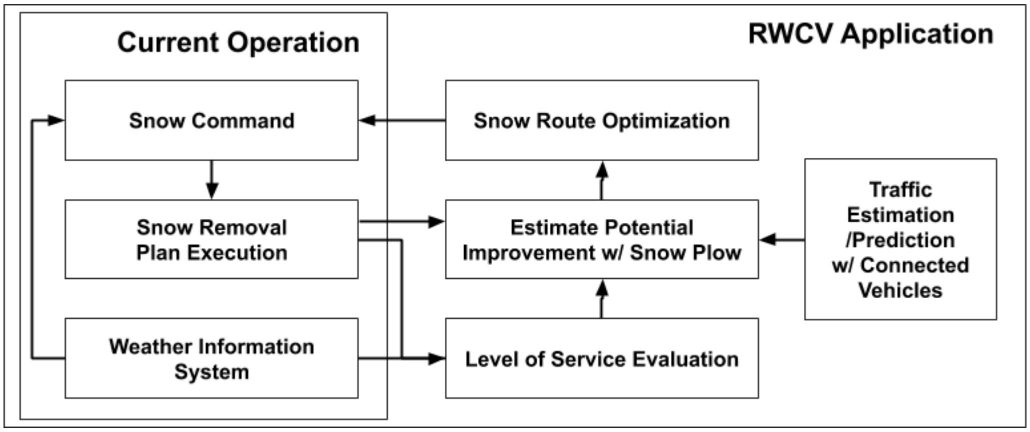
Source: FHWA.

ATDM = active traffic demand management. DMA = dynamic mobility application.

Figure 13. Diagram. Analysis framework.

Road Weather Connected Vehicle Application in Snowplow Operation

In the Chicago testbed, AMS tool development and application are not limited to traffic operations; they also extend to various control strategies that can leverage the predictive capabilities of the tools and vehicle-to-infrastructure (V2I) connectivity under adverse weather. For implementing AMS tools for the RWCV application in snowplow operation, additional modules were developed to estimate and predict conditions and capacities of road sections across the testbed network affected by snow accumulation. The network traffic states are estimated and predicted by processing data from CVs running in the network. The Snowplow Command module uses the information to generate snowplow routes to minimize the weather impact on traffic. Figure 14 shows the RWCV application framework specialized for snowplow operations in the current operation scheme.



Source: FHWA.

RWCV = road weather connected vehicle.

Figure 14. Diagram. Snowplow framework of current operation (left) and road weather connected vehicle application (right).

To evaluate the marginal benefit of additional layers of CV data input and route optimization, three scenarios of snowplow operation under identical weather conditions are evaluated: (0) do nothing, (1) execute predefined snowplow route plan, and (2) execute snowplow route plan optimized with CV data. While a predefined snowplow plan is initiated based on network-level evaluation of snow severity, an optimized snowplow plan is generated by utilizing link-level traffic states and weather conditions. For a meaningful comparison, both snowplow operations are bounded by the same constraints of vehicle-working hours, number of vehicles, depot locations, and plow capacity.

DATA DESCRIPTION

This section describes the data used for setting up quantitative input of weather scenarios and snowplow route plans in this project. The remainder of this section outlines a list of data in use and sources, followed by data analysis results.

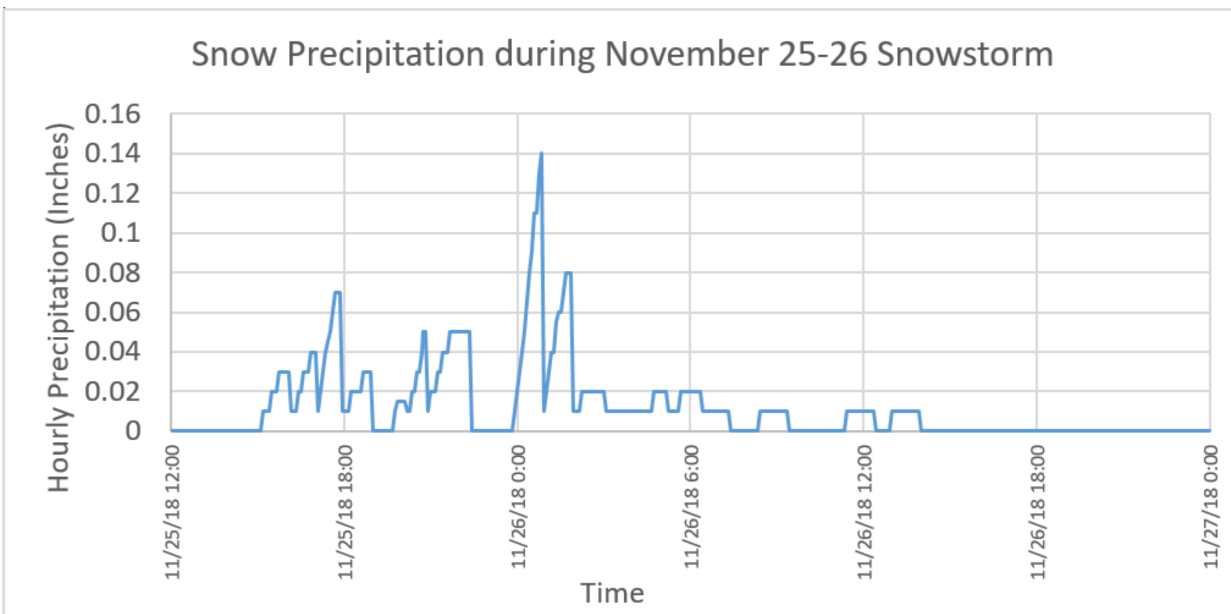
Data Sources and Description

Data on traffic and weather conditions, as well as real-time data from CVs are needed for the implementation of AMS tools for RWCV applications. Specific weather-related and CV applications, such as snowplow routing and variable speed limits (VSL), require additional data from CVs that can complement data from legacy systems to allow for improved performance. To reproduce a network condition affected by adverse weather conditions and an impact of an actual snowplow plan executed by the City of Chicago, a real-world weather data and snowplow route tracker are used in the project. For the purpose of integrating CV data into weather-related strategy, traffic data was synthesized from DYNASMART.

An interval from 00:00 to 23:59 on November 26, 2018, was selected as a test period in consideration of adverse weather conditions that initiated a citywide snowplow plan. A major early season winter storm affected the Midwest November 25–26. The City of Chicago released the snowplow tracker data including the locations of road treatment vehicles from November 25–28. Snow precipitation and visibility measurement data collected during the snowfall were used for generating input of weather and the predetermined snowplow route plan.

Weather Data

The Automated Surface Observing Systems (ASOS) data with resolutions of one minute and five minutes are available at the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) FTP server (ftp://ftp.ncdc.noaa.gov/pub/data/). Weather observation data from the ASOS station at O'Hare (International Civil Aviation Organization [ICAO] code KORD), which is six miles west of the center of test network, are used for this report. Weather observation data from 2000 to today are available from the station. In real life, the severity of snow events is the complex outcome of air/pavement temperature, snowfall, and wind speed; however, for the sake of simplicity, only the precipitation rate was used to estimate cumulative snow depth in this project. The November 25–26 snowfall that had started late in the night on November 25 had let up in the following afternoon. The snow precipitation measurement from the ASOS station at O'Hare is plotted in figure 15.



Source: FHWA.

Figure 15. Graph. Snow precipitation measured at ASOS station located at O'Hare International Airport during November 25–26, 2018, snowstorm.

City of Chicago Plow Tracker

The City of Chicago's snowplow trucks are equipped with global positioning system (GPS) trackers that share on the web the location of trucks in operation (https://www.chicago.gov/city/en/depts/streets/supp_info/plowtracker.html).

The data released by the City of Chicago in the plow tracker app include information on the location specified in terms of latitude and longitude, date and time of the observation, and track number. In addition to tracking real-time vehicle locations, predetermined snowplow route patterns can be extracted from the archived data sets. The snowplow data archive collected contains plow activity for 54 snow events in Chicago since January 2012.

It is reported that the City of Chicago had dispatched 287 large trucks and 26 pick-ups to respond to the November 26, 2018, snowstorm. GPS data from active snowplow trackers had been recorded from the late night of November 25 to the afternoon of November 28. To generate DYNASMART input, GPS points collected within the network coverage were extracted and analyzed to find the executed snowplow routes, depot locations, number of vehicles operated in the range of the test network, total vehicle operation hours, and plowing vehicle speeds.

INTEGRATION OF CONNECTED VEHICLE DATA INTO ROAD WEATHER CONNECTED VEHICLE APPLICATION

One of the main research questions is how data from CVs can be combined to a legacy system for real-time traffic estimation and prediction. This section explains possible integration of data from CVs and roadside detection systems in an AMS implementation and illustrates the integration plan of CV data in real-time traffic estimation and prediction.

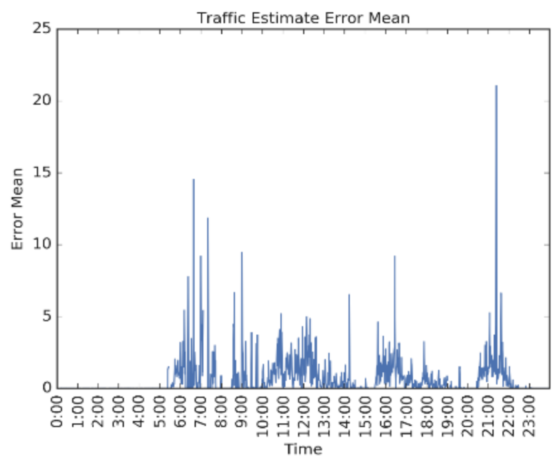
Integration of Traffic Data for Real-Time Traffic Estimation Prediction

Timely observations of unfolding traffic conditions are an important input in operating a prompt weather-responsive traffic management (WRTM) system. Most common traffic surveillance systems collect data from stationary detectors mounted on/above the selected road sections. Relying on this type of traffic monitoring system for real-time traffic state estimation introduces two problems: uncertain data reliability and limited network observability. First, transmitted sensor data may be temporarily or permanently missing or corrupted. Second, in general, detector stations are sparsely located due to budget constraints, providing only limited network observability. The sparse data coverage can be compounded by temporary or permanent failure of detectors. The primary benefit of CV trajectories is that traffic measurements become available on every road section a CV is traversing. This additional source of data can boost real-time network observability of traffic management systems. However, it can be challenging to estimate traffic parameters only with CV data if CV market penetration rate (MPR) is not high enough to represent the overall traffic population. This study developed a method to use data from CVs and stationary detectors to estimate and predict real-time network traffic conditions using low CV MPR and the limited number of available detectors in the network of interest. In the AMS tool for RWCV application, this networkwide traffic estimation is the primary input for diagnostic assessment that initiates traffic control strategies or road management plans.

Real-Time Traffic Speed

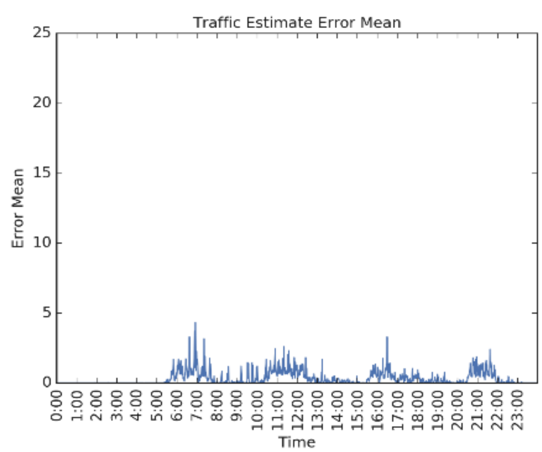
Traffic speed is defined as a ratio of total length that vehicles travel in a spatial range of interest to total travel time of the vehicles. At a fixed point, vehicle speed is estimated by measuring how long it takes for the vehicle to pass the target point. If multiple vehicles travel the location, traffic speed is a harmonic mean speed of the vehicles. On the other hand, speed of a vehicle trajectory is measured by how far the vehicle traveled for a given time range. Thus, traffic speed of multiple trajectories becomes space-mean of the speed of all corresponding vehicles.

To measure the accuracy of the traffic state estimation with data from CVs that account only for a fraction of the total vehicle population, traffic estimation with various CV MPRs were compared to traffic estimation with full information (figure 16). Figures 16A, 16B, and 16C show the traffic speed estimation error with 1, 5, and 10 percent CV MPR, respectively. The estimation error is compared in table 11. According to the results, traffic estimation with more than 5 percent CV MPR can provide an acceptable level of accuracy.



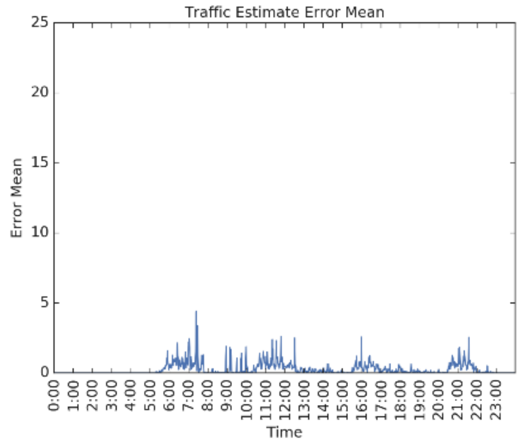
Source: FHWA.

A. Chart. Traffic speed estimation error with 1 percent connected vehicle market penetration rate.



Source: FHWA.

B. Chart. Traffic speed estimation error with 5 percent connected vehicle market penetration rate.



Source: FHWA.

C. Chart. Traffic speed estimation error with 10 percent connected vehicle market penetration rate.

Figure 16. Charts. Traffic speed estimation error with market penetration rate of 1 percent, 5 percent, and 10 percent.

Table 11. Average relative error of traffic flow estimation with connected vehicle.

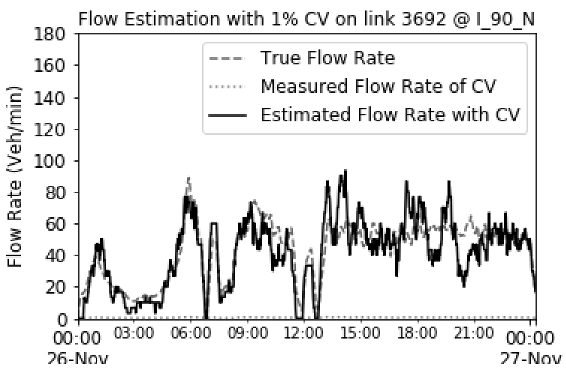
	Mean		
MPR	1	5	10
I–94 N	3.1	0.7	0.5
I–94 S	4.3	1.1	0.8
I–90 S	4.5	2.0	1.8
I–90 N	7.6	2.3	1.9
LSD N	1.9	0.6	0.4
LSD S	1.0	0.4	0.3
I–290 E	2.8	0.7	0.6
I–290 W	4.7	1.3	0.7
The rest	11.6	7.6	6.5

Source: FHWA.

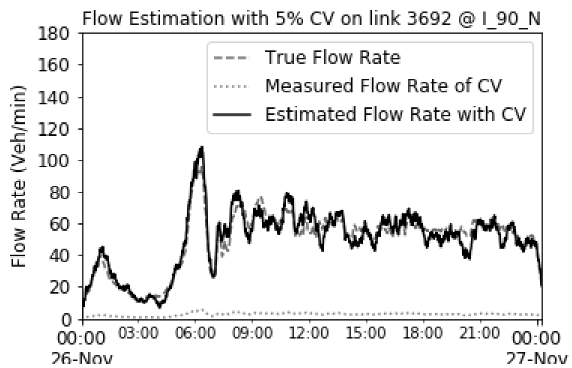
E = east. I–90 = Interstate 90. I–94 = Interstate 94. I–290 = Interstate 290. LSD = Lake Shore Drive. MPR = market penetration rate. N = north. S = south. W = west.

Real-Time Traffic Flow

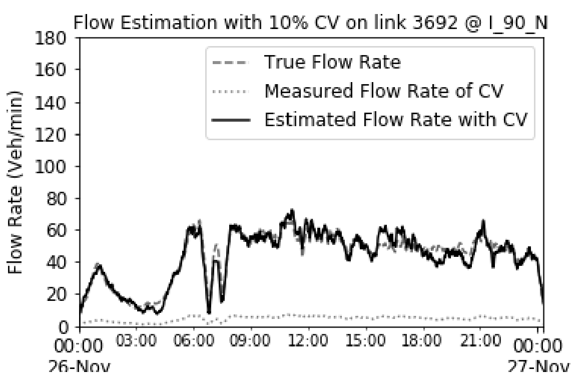
As for traffic flow, a roadside detector can directly measure traffic flow as the number of vehicles that pass the detector per unit time. However, traffic surveillance systems are mainly implemented on freeways rather than arterial roads, although the latter account for a significant portion of the overall lane-miles to be managed in weather-responsive programs. Meanwhile, CV data with low MPRs may not be sufficient to provide complete and accurate information on prevailing traffic states. In this study, statistical information about the CV population is extracted where data from both sources are available; this information provides the basis to use CV data to estimate traffic flow rates where no roadside detectors are installed. If CVs are randomly mixed in traffic, the ratio of traffic volume of CVs to traffic volume of total vehicles on the same link would be the expected value of probability that a randomly selected vehicle in traffic is a CV. If statistical properties of this probability are identical across the network, total traffic flow rate can be inferred in any part of the network as long as the CV traffic flow rate is available. In the study, it is assumed the inverse CV ratio is a random variable for which the probability distribution is unknown in advance. The CV ratio was estimated on 87 preselected links where stationary detectors are located, and the estimation is updated as new data are collected. The ratio is applied to all 4,805 links to estimate traffic flow with CV data. To understand the accuracy of the method, three scenarios with different MPRs are compared: 1 percent, 5 percent, and 10 percent. In each scenario, CVs are randomly generated with the given MPR. The estimation results are presented in figure 17 and table 12. Figures 17A, 17B, and 17C show the traffic flow estimation with 1, 5, and 10 percent CV MPR, respectively.



A. Graph. Traffic flow estimation with 1 percent connected vehicle market penetration rate.



B. Graph. Traffic flow estimation with 5 percent connected vehicle market penetration rate.



C. Graph. Traffic flow estimation with 10 percent connected vehicle market penetration rate.

Source: FHWA.

% = percent. CV = connected vehicle. I–90 N = Interstate 90 North. Nov = November. veh/min = vehicle per minute.

Figure 17. Graphs. Traffic flow estimation with connected vehicle for market penetration rates (1 percent, 5 percent, and 10 percent).

Table 12. Average absolute error of traffic flow estimation with connected vehicle.

	Mean		
MPR	1	5	10
I–94 N	10.9	5.0	3.6
I–94 S	12.8	6.6	5.3
I–90 S	15.1	8.5	6.9
I–90 N	15.7	9.9	8.6
LSD N	9.3	3.7	2.4
LSD S	8.7	4.0	2.8
I–290 E	11.1	4.9	3.6
I–290 W	12.1	5.9	3.6
The rest	7.4	3.3	2.2

Source: FHWA.

E = east. I–90 = Interstate 90. I–94 = Interstate 94. I–290 = Interstate 290. LSD = Lake Shore Drive. MPR = market penetration rate. N = north. S = south. W = west.

SOLVING THE DYNAMIC SNOWPLOW ROUTE PROBLEM

This section describes the snowplow route optimization problem and the algorithm to find the solution. Figure 18 shows the objective function and constraints for the snowplow routing problem formulation. Objective functions for a snowplow route optimization might be to minimize total working hours or total salt consumption to plow all links in the network in order to meet annual snow program budgets. In this project, working hours are assumed to be given by the predetermined route plans. The goal is to determine snow routes that maximize the snowplow impact in terms of minimizing traffic flow disruptions during and after the snowfall (equation 2). With traffic information from CVs, the optimization problem is designed to prioritize the road sections with higher traffic demand in the order of plow routes. The formulation recognizes that weather forecasts and link traffic flow predictions from CV data are available for each planning horizon. When new forecasts and predictions are available, the snowplow plans are extended with additional road routes to maximize snowplow impact in the next planning horizon. The process repeats until the end of the simulation horizon.

As for snowplow capacity, it is assumed the snowplow vehicle can plow one lane at a time, even if a link may have multiple lanes (equation 7). After a lane is plowed, the post-effect of plowing can vary with several factors, such as road surface temperature, wind speed, precipitation rate, etc. Modelling the post-effect of plowing is out of scope of this report. In this problem, an expected duration of plowing effect is given as a networkwide constant in order to estimate snowplow impact on a given link. Therefore, a certain lane of a link would desirably be plowed once in a given prediction horizon, but multiple times during the whole simulation period. At each iteration, snow depth on each link is calculated considering the effect of snowplowing planned up to the time. If a link has multiple lanes, snow depth on each lane is calculated independently (equation 3). Link capacity is determined by the snow depth on the specific link. When a snowplow vehicle traverses a link, it follows the link-specific speed. In order to penalize unnecessary U-turns, additional travel time is added if a vehicle needs to turn around. As a result, total working time of a snowplow vehicle is equal to the sum of link travel time of all the links the vehicle needs to traverse, additional turnaround time, time to reach the first link to be served from the closest depot, and time to come back to the closest depot from the last link to be plowed. The total working hour duration cannot exceed predetermined working time window of the vehicle (equation 4). The problem solution determines whether or not a vehicle plows a lane of a specific link at a given time (equation 5) and whether or not a vehicle needs to turn around in order to move to the next link (equation 6). The mathematical model of the optimization problem is described in the following section.

Mathematical Model

Notation

$x(i,j,k,t)$	Decision variable – indicator if j^{th} lane of link i is plowed by vehicle k at time t
$z(i,k,t)$	Decision variable – indicator if vehicle k has to take U-turn on link i at time t
t	Current simulation time
T	Simulation horizon
h	Prediction length
A	Set of arcs in the network, $A=\{1,2,..,N\}$
$n(i)$	Number of lanes of link i
$l(i)$	Length of link i
$v(i)$	Average snowplow speed on link i
$ST(k)$	Scheduled time that vehicle k begins plowing
$ET(k)$	Scheduled time that vehicle k finishes plowing
$CT(k)$	Time that a determined route of vehicle k ends
V	Set of all vehicles
$V(t)$	Set of active vehicles at time t, for $\{k: k \notin V \text{ if } ST(k) \leq t \text{ and } ET(k) > t\}$
U	Set of vehicles to be assigned
$s(i,j,t)$	Snow depth on j^{th} lane of link i at time t
$p(t)$	Snow precipitation at time t
h_p	Duration of snowplow impact
$r(s)$	User-defined road capacity reduction rate for snow depth level s
$st(k)$	Travel time to the first link to be served from the closest depot where a vehicle k can depart
$et(k)$	Travel time to the closest depot from current location of vehicle k
ρ	Turnaround penalty
$q(i,t)$	Traffic flow rate per lane on link i at time t

Objective Function:

$$\min_{X,Z} \sum_{t=t}^{t+T} \sum_{k=1}^{|V|} \sum_{i=1}^{|A|} \sum_{\tau=t}^{t+h} \sum_{j=1}^{n(i)} r(s(i,j,\tau))\ q(i,\tau) \qquad (1)$$

Where $X = \{x(i,j,k,\tau): for\ \forall i\ \in A, \forall j\ \in \{1,\dots,n(i)\}, \forall k \in V, \forall \tau \in [t, t+h]\}$ and $Z = \{z(i,k,\tau): for\ \forall i\ \in A, \forall k \in V, \forall \tau \in [t, t+h]\}$

s.t.

$$s(i,j,\tau) = s(i,j,t) + \sum_{t'=t}^{\tau} p_{t'} \left(1 - \sum_{t''=t'-h\_p}^{t'} \sum_{k=1}^{|V|} x(i,j,k,t'')\right) \qquad (2)$$

$$\sum_{t=1}^{T} \sum_{i=1}^{N} x(i,j,k,t) \cdot \frac{l(i)}{v(i)} + \rho \sum_{t=1}^{T} \sum_{i=1}^{N} z(i,k,t) + st(k) + et(k) \le ET(k) - ST(k) \qquad (3)$$

$$x(i,j,k,t) = \begin{cases} 1 & \text{if } j \text{ th lane of link } i \text{ is plowed by vehicle } k \text{ at time } t \\ 0 & otherwise \end{cases} \qquad (4)$$

$$z(i,k,t) = \begin{cases} 1 & \text{if vehicle } k \text{ has to take U} - \text{turn on link } i \text{ at time } t \\ 0 & otherwise \end{cases} \qquad (5)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{n(i)} x(i,j,k,t) \le 1, for\ \forall i\ \in A, \forall k \in V, \forall t \in [0,T] \qquad (6)$$

$$\sum_{i=1}^{N} z(i,k,t) \le 1, for\ \forall i\ \in A, \forall k \in V, \forall t \in [0,T] \qquad (7)$$

Source: FHWA.

Figure 18. Equations. Objective function and constraints for snowplow routing problem formulation.

Heuristic Algorithm

This section describes the heuristic algorithm developed to find the solution of the snowplow optimization problem. The algorithm is designed to globally search the road segments that can maximize snowplow impact from a current vehicle location and extend its route plan while it meets time window constraints for every vehicle in operation.

<Heuristic Algorithm for Real-Time Snowplow Route Optimization Problem>

0) Read current time t

For time $t<T$

1) Read input
   - 1-1) Read the list of vehicles $U = V(t)$ in operation and their locations at time t
   - 1-2) Read accumulated snow depth $s(i,j,t)$ for $\forall i \in A$
   - 1-3) Read weather information $p(\tau)$ for $\tau \in [t, t+h]$
   - 1-4) Read determined snowplow route plans for $\forall k \in V$ up to time t, if any
   - 1-5) Read traffic flow prediction $q(i,t)$ from CV data for $\tau \in [t, t+h]$
2) Find the link that maximizes snowplow impact

   Do while vehicle list U is not empty

2-1) Calculate road capacity reduction rate *r(s(i,t))* with predetermined snowplow route plan for $\tau \in [t, t+h]$

2-2) For $\forall i \in A$ with positive weighted road capacity reduction
-Find the vehicle *k** that can arrive to link *i* the quickest from the current location
-Find the shortest path from the current location of vehicle *k** to link *i*
-Re-calculate road capacity reduction with the snowplow path and its estimated travel time (Add penalty time for turnaround if vehicle needs to take U-turn)
-Calculate snow impact of the path to link *i*, which is measured by road capacity reduction per unit travel time
-Add link *i* to the list of tasks of vehicle *k**

2-3) For $\forall k \in U$
-Find link *i** in the list of tasks of vehicle *k* with the largest snow impact
-Add the path to link *i** to the plow route of vehicle *k* and update the end time of snowplow route of vehicle *k*, *CT(k)* with estimated travel time
-Exclude vehicle *k* from *U* if the end time of its schedule passes *t+h*
-Return vehicle *k* to a depot if $CT(k) + et(k) \geq ET(k)$
-Update *et(k)*, travel time to closest depot location from ending point of the updated route

TEST RESULTS

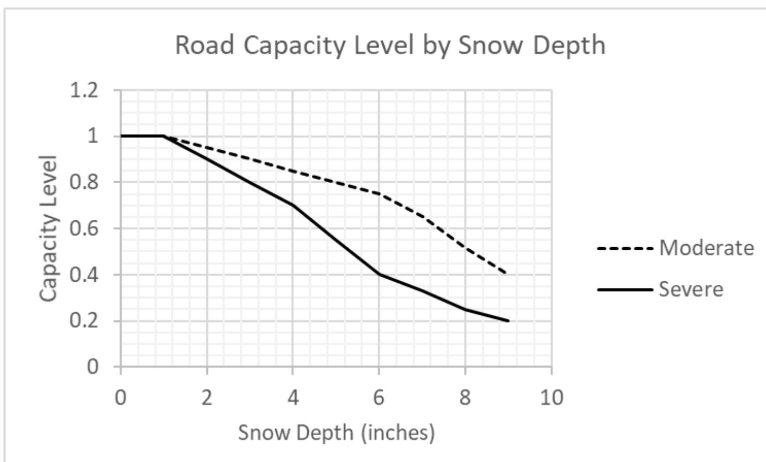
In this section, simulation results under three different plowing strategies are presented: (1) do nothing, (2) plow with predetermined routes (snowplow GPS tracks), and (3) plow with routes optimized with CV traffic information. Three simulation runs were executed under the same snowstorm scenario emulating November 26, 2018, but with different plowing strategies. For a fair comparison between strategy two and strategy three, the same number of plow trucks and the same total operation hours are used in both strategies. For strategy three, the snowplow route for each truck was determined by the heuristic algorithm in the previous section. The values given to predetermined variables are presented in table 13.

Starting points and ending points of GPS tracks were used as depot locations. Capacity reduction in an adverse weather event is an outcome determined by complex interaction of road surface temperature, air temperature, wind speed, snow intensity, duration, etc. In this demonstration, snow capacity reduction rates were arbitrarily determined in proportion to snow accumulation. To see the impact of the capacity reduction rates on plowing effect, the moderate reduction scenario and severe reduction scenario are both tested to compare the snowplow impact of predetermined routes and optimized routes.

Table 13. Pre-determined variables and given values in the optimization problem.

Pre-determined Variables		Values
T	Simulation horizon	1,440 minutes (24 hours)
h	Prediction length	30 minutes
N	Number of links of the network	4,805
n(i)	Number of lanes of link *i*	Given from the Chicago network information
l(i)	length of link *i*	Given from the Chicago network information
v(i)	Average snowplow speed on link *i*	Lake Shore Drive: 25 miles per hour (mph); rest of links: 10 mph
ST(k)	Scheduled time that plowing starts	Minute 60
ET(k)	Scheduled time that plowing ends	Minute 528 (plowing hours are set to 468 minutes [7.8 hours])
h_p	Duration of snowplow impact	60 minutes (1 hour)
ρ	Turnaround penalty	3 minutes

Source: FHWA.



Source: FHWA.

Figure 19. Chart. Level of road capacity affected by snow depth.

As shown in figure 19, in the test, road capacity drops 40 percent at the worst condition of moderate reduction scenario (dashed line in figure 19) while it declines 80 percent in severe reduction scenario (solid line in figure 19). To evaluate the performance of the network under different strategies and scenarios, link speed and flow are compared by time. For spatial comparison, all links are classified into one of seven groups: eastbound of main freeways (Interstate 90 North [I–90 N], Interstate 90 South [I–90 S], Interstate 290 East [I–290 E], Interstate 290 West [I–290 W]), northbound and southbound of Lake Shore Drive, and arterials.

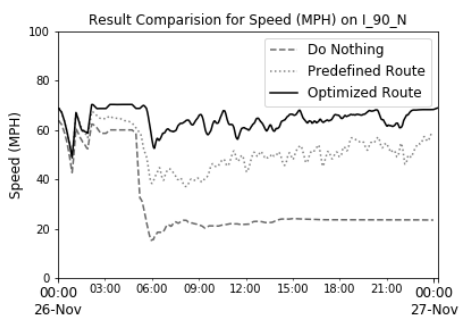
Performance Comparison

Simulation results are plotted in figure 20 and figure 21. Each subfigure shows the simulated traffic of DYNASMART with three different plowing strategies: do nothing, plowing with predefined routes, and plowing with optimized routes. The traffic results are presented for corridor groups (from top to bottom) I–90 N and I–290 E. The results with severe and mild road capacity scenarios are presented on the left and right columns, respectively. Lower traffic speed values mean the traffic in the corridor experienced more severe speed drops. In the same sense, lower traffic flow after the beginning of peak hours (5:30) implies the traffic in the corridor experienced more severe capacity drops. Despite different extents, the network managed with the optimized snowplow plan consistently performed better than two other cases of doing nothing and running a predefined plan in every part of network. Under severe capacity reduction scenario, network traffic without any snowplow eventually comes to a near standstill while the network remains functional with snowplow operations. In comparison of the two capacity reduction scenarios, the snowplow optimization impact in improving the default plan is more substantial if the accumulated snow on a road network reduces its capacity by a larger extent. With the test results, it can be concluded that if snowplow routes are optimized with incoming weather and traffic information, disruption of the network traffic can be effectively prevented, and the network can maintain its capacity to serve demand with more desirable levels of service even during severe weather events.

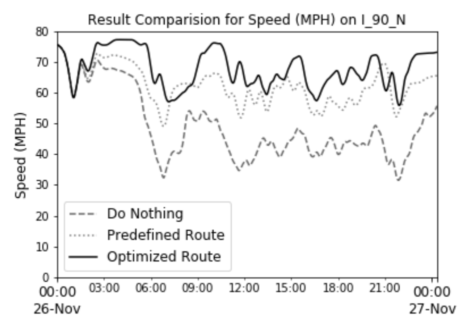
Speed Comparison

Severe Reduction Scenario

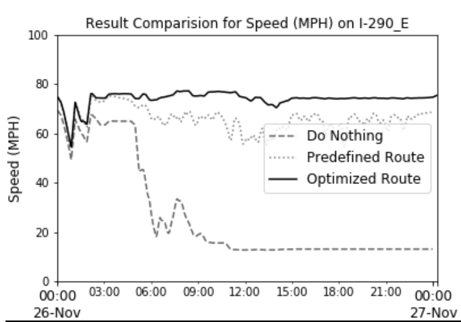
Moderate Reduction Scenario



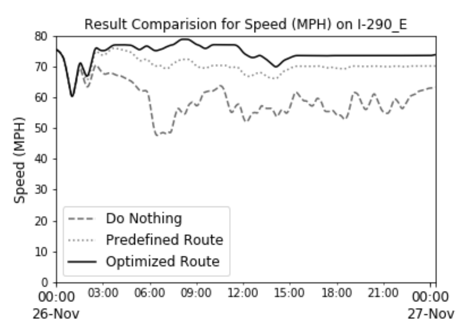
A. Graph. Traffic speed of DYNASMART results on I–90 N for three plowing strategies with severe capacity reduction scenario.



B. Graph. Traffic speed of DYNASMART results on I–90 N for three plowing strategies with moderate capacity reduction scenario.



C. Graph. Traffic speed of DYNASMART results on I–290 E for three plowing strategies with severe capacity reduction scenario.



D. Graph. Traffic speed of DYNASMART results on I–290 E for three plowing strategies with moderate capacity reduction scenario.

Source: FHWA.

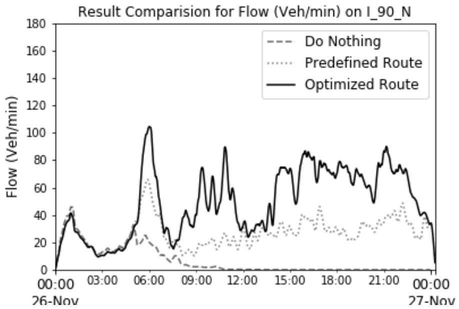
I–90 N = Interstate 90 North. I–290 E = Interstate 290 East. mph = mile per hour. Nov = November.

Figure 20. Graphs. Traffic speed of DYNASMART simulation results for three plowing strategies.

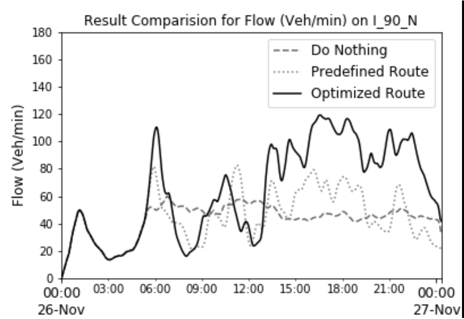
Flow Comparison

Severe Reduction Scenario

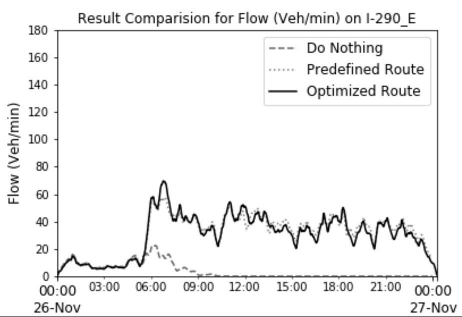
Moderate Reduction Scenario



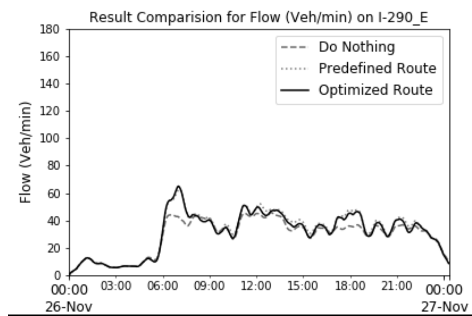
A. Graph. Traffic flow of DYNASMART results on I–90 N for three plowing strategies with severe capacity reduction scenario.



B. Graph. Traffic flow of DYNASMART results on I–90 N for three plowing strategies with moderate capacity reduction scenario.



C. Graph. Traffic flow of DYNASMART results on I–290 E for three plowing strategies with severe capacity reduction scenario.



D. Graph. Traffic flow of DYNASMART results on I–290 E for three plowing strategies with moderate capacity reduction scenario.

Source: FHWA.

I–90 N = Interstate 90 North. I–290 E = Interstate 290 East. Nov = November. veh/min = vehicle per minute.

Figure 21. Graphs. Traffic speed of DYNASMART simulation results for three plowing strategies.

CHAPTER 6. CONCLUSION AND DISCUSSION

The project was designed to evaluate marginal benefit of combining information from connected vehicles (CV) to a legacy system for weather-responsive traffic management (WRTM). The study demonstrated road weather connected vehicle (RWCV) applications in snowplow operations. In the framework, the Snow Command system utilized incoming traffic data from CVs and weather forecasts to prioritize road sections to maximize the benefit of snowplow route operations. A mathematical model and algorithm to find the solution were described and test results presented. Performance of weather-related strategies was quantitatively evaluated with measurements of traffic speed and flow on the network. The performance measures were compared to the results under the two scenarios of (1) doing nothing, and (2) executing a predetermined plan extracted from global positioning system (GPS) data.

When a traffic management system decides to do nothing, the road network under a severe snowstorm becomes impassible; however, with active snowplow operations, the network can serve its demand effectively. For a meaningful comparison to predetermined routes, the optimization problem was constrained with the same conditions as the original routes in terms of vehicle route, vehicle working hours, and depot locations. The comparison results show that snowplow operations can significantly improve by using real-time or predictive road-specific information, possibly collected from CVs, while still using the same amount of resources required by the current weather-response operation scheme.

The simulation results support the potential benefit of two different types of CV technology in WRMS practice. First, the traffic estimation results verify that data from passenger vehicles with connectivity can be a great source of timely disaggregated information on traffic conditions, even with low market penetration rates (MPR). Many American cities have installed roadside detectors and have extended their traffic surveillance systems with emerging technologies. However, the coverage of current implementation is concentrated on highway facilities, rather than arterials that require winter maintenance services as much as highways. By integrating various data sources including private CVs, local transportation agencies may be able to overcome the current issue of limited coverage and to monitor the network traffic states with a high resolution.

Second, local agencies can monitor the current WRMS performance by tracking CVs acting as agents or probes, estimate road surface condition with the executed winter maintenance plan, and generate real-time plans for remaining road sections by using incoming information to maximize the WRMS performance. Current WRMS practices are primarily predetermined on the basis of past traffic patterns and weather observations. The maintenance plans are developed for a few levels of weather severity and, in an inclement weather event, one of them is executed based on a qualitative decision supported by weather forecasts and near real-time road weather observations. By using CV technologies, the ongoing operations can be tightly monitored, assessed, and modified, if better service plans exist for the unfolding road network environment.

The findings from the present study have certain limitations due to assumptions made regarding the diagnosis of road surface condition:

- It is assumed road surface conditions would be clear for a certain time window after the section is plowed. The post-impact of plowing can vary with several weather factors, traffic conditions, and types of spread materials.
- It is assumed that snow depth on a road surface is the product of snow precipitation rates and duration of the precipitation without considering pavement temperature. In the real world, snow accumulated on a road surface could be blown by wind, either naturally or chemically melted, or bonded to pavement as ice.
- Weather data from a single source were used for the entire network during test periods because only one valid weather data source was accessible for the corresponding time period. True road weather conditions could have been significantly different from one location to another even within the test network area.

More disaggregated weather information and more sophisticated assessment model of road surface under adverse weather would be necessary for advanced WRMS in practice. This may be a direction for future study. These limitations do not alter the general conclusions about the value of CV data for traffic state prediction and WRMS application. The framework and methodology developed as part of the study could readily accommodate improved relations about snow-pavement interaction as those become calibrated for particular locations.

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ACKNOWLEDGMENTS

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Figure 8

The map overlays showing deployment of snowplow trucks at key roadway segments were developed as a result of this research project. The overlays include red circles denoting snowplow entry locations along the network.

Figure 12

The map overlays showing the Chicago testbed network were developed as a result of this research project. The overlays include dotted lines and text labels denoting the road network in the area.

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November 2020
FHWA-HOP-20-060

U.S. Department of Transportation
Federal Highway Administration