Integrated Modeling for Road Condition Prediction Phase 4: Final Report

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U.S. Department of Transportation
Federal Highway Administration

FOREWORD

Integrated Modeling for Road Condition Prediction Phase 4: Final Report describes the phase 4 development, demonstration, evaluation, and assessment of IMRCP. It provides a summary description of the system design, study area of deployment and engagement, operations experience, evaluation, and recommendations for further study. The report is structured to help advance the body of knowledge related to IMRCP and how transportation agencies can use and deploy the system. This document is the final version of the first publication of this information.

This report will be useful to transportation agencies and academic researchers, operations and maintenance personnel, and systems and software developers working in operations, weather maintenance, and weather-responsive management strategies. The document is available on the research website at https://www.fhwa.dot.gov/research.

Mark Kehrli, Director
Office of Transportation Operations

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The Federal Highway Administration Road Weather Management Program started development of Integrated Modeling for Road Condition Prediction (IMRCP) in 2015 to provide data and decision support for transportation system management and operations in weather events. IMRCP gathers traffic and weather data and forecasts. It creates new forecast data for road weather and traffic conditions from the collected data. It provides tools for what-if analyses and views of the data from past, present, and future operational time horizons. It supports transportation system and emergency operations in decision-making and after-action reviews. Previous phases of IMRCP had developed the foundational traffic and weather data system components. IMRCP phase 4 has improved and deployed the system in Ohio and Louisiana, expanding system capabilities and applicability to extreme events while addressing functional gaps identified in earlier phases. The Ohio deployment focused on IMRCP as a tool for planning, monitoring, and postevent assessment of traffic management and operations during adverse, primarily winter-weather events. The Louisiana deployment investigated IMRCP use cases in tropical-storm-event preparation, response, and recovery. IMRCP enhancements and applications developed in phase 4 have been documented to support future deployments. The final report describes the phase 4 development, demonstration, evaluation, and assessment of IMRCP. It provides a summary description of the system design, study area of deployment and engagement, operations experience, evaluation, and recommendations for further study.</td></tr>
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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 ABBREVIATIONS

ATMS	advanced transportation management system
EOC	emergency operations center
FHWA	Federal Highway Administration
I–10	Interstate 10
I–12	Interstate 12
I–90	Interstate 90
IMRCP	Integrated Modeling for Road Condition Prediction
LaDOTD	Louisiana Department of Transportation and Development
MAE	mean absolute error
MDSS	maintenance decision support system
METRo	Model of the Environment and Temperature of Roads
mph	mile per hour
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
ODOT	Ohio Department of Transportation
OSADP	Open Source Application Development Portal
RAE	relative absolute error
RSME	root square mean error
RWIS	road weather information system
RWMP	Road Weather Management Program
TMC	transportation management center
TSMO	transportation system management and operations
USDOT	U.S. Department of Transportation
VSL	variable speed limit

EXECUTIVE SUMMARY

Transportation agencies face many challenges when working toward effective transportation systems management and operations (TSMO). Weather, incidents, and events outside the knowledge and control of transportation agencies and travelers can reduce a free flow of traffic to a snarled mess in minutes or seconds. Whether the focus is on traffic incident management, work zones, active traffic management, emergency evacuation routing, or weather, the intent of TSMO is to minimize and mitigate the impact of disruptions and to enable travelers to make better choices for safe and reliable travel.

The Federal Highway Administration Road Weather Management Program started development of the Integrated Modeling for Road Condition Prediction (IMRCP) in 2015 to provide data and decision support for these kinds of events. IMRCP gathers traffic and weather data and forecasts. It creates new forecast data for road weather and traffic conditions from those data. It provides tools for what-if analyses, views of the data from archives, and views of the data from near past, present, and future operational time horizons. It supports transportation system and emergency operations in decision-making and after-action reviews.

Previous phases of IMRCP developed the foundational traffic and weather data system components, including a machine-learning-based traffic model; deployed the system at the scale of a metropolitan area; operated the system for two winter seasons; evaluated the operational results; and updated the system documentation.

IMRCP phase 4 has improved and deployed the system in two new locations, expanding system capabilities and applicability to extreme events while addressing some functional gaps identified in earlier phases. The Ohio deployment focused on IMRCP as a tool for planning, monitoring, and postevent assessment of traffic management and operations during adverse, primarily winter weather events. The Louisiana deployment investigated IMRCP use cases in tropical storm event preparation, response, and recovery. IMRCP enhancements and applications developed in phase 4 have been documented to support future deployments.

The final report describes the phase 4 development, demonstration, evaluation, and assessment of IMRCP. It summarizes the system design, study area deployment and engagement, operations experience, evaluation, and recommendations for further study.

CHAPTER 1. INTRODUCTION

BACKGROUND

Transportation agencies face many challenges when working toward effective transportation systems management and operations (TSMO). Weather, incidents, and events outside the knowledge and control of transportation agencies and travelers can reduce a free flow of traffic to a snarled mess in minutes or seconds. Whether the focus is on traffic incident management, work zones, active traffic management, emergency evacuation routing, or weather, the intents of TSMO are to minimize and mitigate the impact of disruptions and to enable travelers to make better choices for safe and reliable travel.

The Federal Highway Administration (FHWA) Road Weather Management Program (RWMP) has researched the intersection of weather and TSMO for more than 20 years. The trend during that time has been to move from basic road weather research to closer integration of road weather information with TSMO. Research and development of the capabilities are now moving toward sustaining safety and mobility in even extreme weather events. The working hypothesis is that TSMO will be enhanced with access to diversified information about current and future travel conditions across the road network in extreme weather events. This broader and deeper view could enable operators to identify and highlight ongoing and forecast risks at particular locations. That knowledge could be put to work in decision-making for planning, event response, and recovery. Detailed knowledge of conditions increases situational awareness for operators and emergency responders during events, and it supports enhanced traveler information about conditions ahead and on alternative routes. The total effect would be to reduce safety risks to travelers and sustain mobility as much as possible before, during, and after extreme events.

Integrated Modeling for Road Condition Prediction (IMRCP) is intended to provide data and decision support for these kinds of events. After it gathers traffic and weather data and forecasts, it then creates new forecast data for road conditions from those data. It provides tools for what-if analyses, views of the data from archives, and views of the data from near past, present, and future operational time horizons. It supports transportation system and emergency operations in decision-making and after-action reviews.

The FHWA RWMP started development of IMRCP in 2015. The modeling and integration worked in two directions: first, to bring traffic and weather and events data into a common view of conditions and second, to extend that common view from now into the future and back into the past. Doing this requires getting real-time data, corresponding with archives, and generating results from an ensemble of forecast and probabilistic models. These data and models include atmospheric weather, road weather, hydrology, traffic, work zones, winter maintenance operations, incidents, special events, and demand models. IMRCP combines all of these data and models to predict the current and future overall road and travel conditions for transportation system operators, maintenance providers, and, ultimately, the traveling public to use.

The sum of IMRCP capabilities is greater than its enhanced awareness. Putting the broader and deeper view of conditions to use in decision-making can benefit all the transportation system's stakeholders. Operators, maintainers, and, ultimately, travelers could make better informed decisions for:

- Enacting controls (e.g., variable speed limits (VSLs), ramp metering, and gates)
- Deploying maintenance
- Providing traveler information
- Changing (e.g., delaying, rerouting) travel plans

Operators and maintainers together would have a basis for cooperative responses to storms and roadway conditions. Operators with more-informed control strategies and travelers responding to more-specific and actionable information could improve traffic flow. Improved safety and mobility would emerge from the aggregate impacts of better decisions across all the stakeholder groups.

The ongoing efforts toward a fully integrated view of road conditions have taken several stages. The foundational elements that characterize IMRCP were developed in the phase 1 which consisted of a concept of operations and requirements. IMRCP phase 2 specified, implemented, tested, and evaluated the IMRCP concept in a demonstration deployment with local agencies in the Kansas City metropolitan area. Phase 3 expanded the IMRCP deployment across the entire Kansas City metropolitan area, implemented a machine-learning-based traffic model, operated the system for two winter seasons, evaluated the operational results, and updated the system documentation.

PURPOSE

The objectives of IMRCP phase 4 have been to improve and deploy the system in two new deployment locations, expanding system capabilities and applicability to extreme events while addressing functional gaps identified in phase 3. One of these deployments focuses on IMRCP as a tool for planning, monitoring, and postevent assessment of traffic management and operations during adverse, primarily winter weather events. The other deployment investigates IMRCP use cases in tropical storm event preparation, response, and recovery. IMRCP enhancements and applications developed in phase 4 have been documented to support future deployments.

The purpose of this final report is to provide a detailed report of the project outcomes, evaluation, lessons learned, and recommendations for future improvements. The report is structured to help advance the body of knowledge related to the project and how transportation agencies can use and deploy the system.

DOCUMENT OVERVIEW

Chapter 1 provides background information as context for the rest of the document.

Chapter 2 describes the system concepts and interfaces, including the map interface, creating and viewing scenarios, and creating and accessing reports and subscriptions.

Chapter 3 describes the phase 4 deployments and applications.

Chapter 4 summarized the findings of the IMRCP deployment evaluation.

Chapter 5 describes the opportunity for additional deployments of the IMRCP system.

Chapter 6 summarizes the project accomplishments, lessons learned, and recommendations for future improvements.

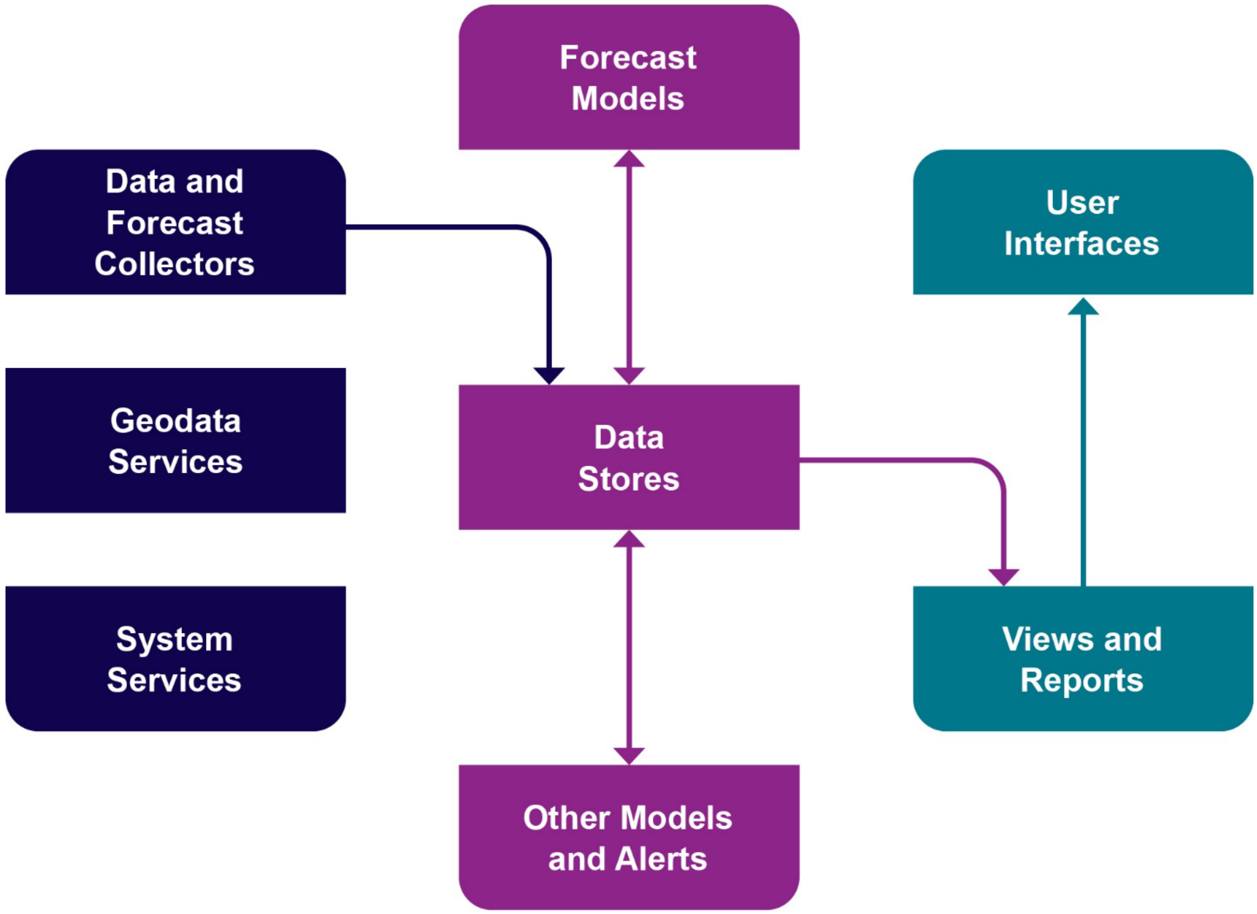
CHAPTER 2. SYSTEM CONCEPTS

Applications for IMRCP are ultimately driven by transportation system user needs. For example, travelers have an immediate need for information about conditions along their planned routes. They also contribute to aggregate travel conditions along their routes by their choices and behaviors. Winter maintenance crews may plan ahead for reducing the impacts of storms on roadway conditions based on weather forecasts and a sophisticated maintenance decision support system (MDSS). They also adapt to conditions on the roadway as they execute those plans. Operators in a transportation management center (TMC) monitor roadway conditions across a network with cameras and sensors accessed through an advanced transportation management system (ATMS). They also respond to conditions and events by generating alerts to be published on roadside dynamic message signs and pushed out to traveler information systems. In all of these examples, stakeholders are making and executing plans, monitoring and adjusting to current conditions, and potentially changing their plans based on their analyses of potential future conditions.

The IMRCP system provides a framework for the integration of road condition monitoring and forecasts data to support tactical and strategic decisions by transportation operators and maintenance providers. The IMRCP system performs six major functions:

- Collecting weather, traffic, operations, and hydrological data for use in predicting road and weather conditions
- Storing the collected and system-generated data
- Generating forecasts of traffic and road conditions
- Mapping the forecasts, current conditions, alert notifications, and archive data for system users
- Reporting on forecasts, current conditions, alerts, and archive data
- Enabling what-if analyses of operational and maintenance strategies for traffic and road weather conditions

The IMRCP system, shown in figure 1, consists of sets of modules to collect, store, analyze, and view the data. Collector modules are specific to the data and sources from which they are collected. Data stores provide a common set of geographical, temporal, and logical references that get used by other modules to access data and store the results of analyses. Forecast models generate future datasets from past and current/real-time data. Other models synthesize physical data types and categories (such as precipitation rate and type) and alerts from other data. Views and reports generated from the data are provided to users through maps and graphical interfaces or as downloadable files. These modules are all supported by a common set of mathematical and data management libraries and an extensive set of geographical data services. Phase 4 added new collectors and data stores to support tropical storm use cases.



Source: Federal Highway Administration.

Figure 1. Diagram. Integrated Modeling for Road Condition Prediction modules.

IMRCP leverages current and forecast data from national authorities as a basis for deriving roadway conditions. Traffic and operations information such as incident location and timing, work zones, and maintenance plans is provided by the State and local agencies or their traffic information service providers. The National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) provide real-time and forecast atmospheric and river gauge data. Phase 4 added new datasets to support tropical storm operations. Tropical storm path, intensity, and storm and tide-surge forecasts are collected from NOAA's National Hurricane Center (NHC).

IMRCP uses these data as input to forecast road conditions. Traffic speeds are forecasted from archive and real-time data by using machine-learning methods. Pavement surface conditions such as temperature and snow accumulations are predicted using an enhanced model otherwise used in MDSSs. Pavement flooding forecasts use river gauge levels and inundation maps overlaid on the road network and segment models. All of these data and forecasts are conflated at the level of individual road segments to provide a fully integrated view of road conditions in the past, present, and future. Phase 4 refactored data stores and interfaces to support larger road networks and reduce the processing time for forecasts on those networks.

IMRCP uses a modified Model of the Environment and Temperature of Roads (METRo) model based on the Environment Canada model to assess current and forecast pavement conditions. Modifications to the base code keep track of rain and snow accumulations at each location in the system over time. Initial estimates of conditions are based on measurement and statistical analysis. IMRCP takes advantage of data from agency road weather information systems (RWIS) and uses a Kriging analysis to provide initial-estimate conditions on roadways between sensor stations. The system then performs time-dependent energy and mass balances to predict pavement conditions up to 12 hours ahead. Resulting pavement condition predictions can be applied to winter maintenance scenarios.

IMRCP uses machine-learning models to forecast future traffic speeds. Training for the offline models is based on historical weather, event, and traffic speed data on particular road network links. Online modeling is adjusted to real-time speed and incident data. The IMRCP phase 4 deployments trained the machine-learning methods to 2 years of historical data with monthly updates as new real-time data were added. The results provide near-term, 5-minute predictions of speed for each network link up to 2 hours into the future. Similar models for tropical storm conditions are new in phase 4 and have been trained to multiple tropical storm events, for which data were available in 2020 and 2021. The tropical storm model provides 1-hour predictions of speed up to 8 hours into the future during tropical storm conditions.

The IMRCP system user interfaces are entirely Web based. The system administrator sets up user names and passwords for system users. Instructions are provided with the user credentials and can also be found on the help tab of the user interface.

IMRCP uses maps similar to those in transportation management and traveler information systems to provide situational awareness of road network conditions. It combines road network views with U.S. weather data for current and forecasted conditions. Roadway and regional view layers are user selected, and multiple layers can be overlaid. Events and alerts can be displayed over the roadway and regional layers to indicate specific locations. Data for any location are available directly from clicks on the regions, roadways, and points on the map. Once the views are set, users can save their map preferences to support their specific interests and applications. Phase 4 added new map layers to support tropical storm datasets such as paths, cones, and storm and tide surges.

Phase 4 expanded the time range supported on the map based on experience from the phase 3 deployment. Whereas phase 3 focused on real-time operations, the phase 4 multiday forecast supports planning for operations and maintenance, and the look back can be helpful in after-action reviews.

Time controls on the map interface can be used to view:

- Current observations by placing the time slider at the current time
- Future predictions up to 5 days into the future by sliding the time slider to the right
- Past observations up to 5 days in the past by sliding the time slider to the left

The map's calendar date and time function allows users to select a past reference date and time to get a view of the map and data at that time. The system keeps past predictions, so looking ahead from a reference time in the past enables users to recover the forecasts as the forecasts had existed at that time. Phase 4 system performance enhancements improved the response time for these data retrievals.

Users can export data from IMRCP in a report for offline analysis. The user selects road segments, data types, and a timeframe for the report. Submitting the report queues it up for processing. Reports are saved in the system for users to download at their convenience. Users can set up subscriptions as recurring reports. System-specified links to the subscription reports can be used by other systems to import the data for additional analysis and presentation. Phase 4 improved the performance of the reporting features relative to the phase 3 implementation.

Scenarios are new in phase 4 and used to run what-if analyses of potential operations and maintenance activities. Users create scenarios that consist of groups of road segments and actions to be performed on those segments during a 24-hour period. Actions can include changing speed limits, closing one or more lanes, opening (shoulder) lanes, snowplowing, and applying treatments for deicing and icing prevention. Users then specify a reference time for the start of the analysis, and the scenario is queued up to be run offline. Users can view results on a map anytime after the analysis has been completed. Users can save the scenarios to rerun them against future or past conditions, with weather and traffic inputs specific to that time.

CHAPTER 3. DEPLOYMENTS AND APPLICATIONS

Two phase 4 IMRCP deployments were selected to demonstrate a range of transportation system operating conditions and management strategies.

General criteria considered in the deployment selections included:

- Agency partner engagement and interest in IMRCP applications
- Potential demonstrations in transportation operations centers
- Potential for related and follow-on development with other local and related agencies or related types of events
- Severe and extreme weather events
- High availability of traffic data
- High availability of weather data
- High availability of hydrological data

The two deployments were intended to demonstrate use cases for two sets of extreme weather challenges to transportation operations: strong winter storms and severe tropical storms necessitating evacuations. Deployments in Ohio and Louisiana were selected for those use cases. The Ohio statewide deployment focused on IMRCP as a tool for planning, monitoring. and postevent assessment of traffic management and operations during adverse, primarily winter weather events. The Louisiana Statewide deployment investigated IMRCP use cases in tropical storm event preparation, response, and recovery.

The two deployments involved working with the respective State departments of transportation to:

- Help identify and provide access to resources (e.g., data, agency practice, operations personnel) as needed to support effective IMRCP deployment
- Provide feedback and instruction on systems development
- Help identify State and local subject matter experts
- Use and test IMRCP in operations
- Participate in project evaluations

OHIO DEPLOYMENT

The Ohio Department of Transportation (ODOT) agreed to work with FHWA in deployment for operations in severe winter weather conditions. Although ODOT already had significant weather and road condition information resources, IMRCP real-time traffic forecasts presented a novel capability and offered a complementary dataset. The ODOT engagement provided an opportunity to investigate the use of integrated forecasts as part of a larger suite of winter road maintenance and operations strategies.

The Ohio IMRCP deployment created a road network model of all interstate roadways and selected other U.S. routes and State routes within the State. Traffic and operations data were provided through the Statewide ATMS and the OHGO traveler information system.[1] Operations data for training the traffic models were generated from ODOT archives. This enabled the machine-learning predictions to capture the impacts of operational strategies such as VSLs and hard shoulder running.

Winter Storm Applications

Winter weather conditions present operational challenges for the transportation system and its stakeholders. For example, travelers want information about conditions along their planned routes, and as a group, they create the aggregate traffic conditions as they drive along their routes. Winter maintenance crews plan for reducing the impacts of storms on roadway conditions based on weather forecasts and may use an MDSS, but they also may adapt to roadway conditions as they execute those plans. Operators in a TMC monitor roadway conditions and implement weather-responsive management strategies that may include using VSLs; limiting access to roadways through lane or road closures; and providing traveler information online, on roadside DMSs, on smartphone applications, and through the media.

IMRCP provides information and tools to support many of the needs driven by winter weather impacts on the transportation system. It enhances situational awareness by gathering, synthesizing, and integrating information about current and forecast traffic, weather, and hydrological conditions across the road network. It provides Web interfaces, reports, and data subscriptions for operations stakeholders and for other systems that might benefit from the data integration. IMRCP can assist in planning and operations decision support with scenario analysis of weather-responsive management strategies, such as implementing VSLs.

As a winter storm approaches, IMRCP will collect atmospheric weather condition information and forecasts. Those weather data will be used with data from the RWIS to model current and forecast pavement conditions across the road network. IMRCP's scenario tools can be used to investigate the road condition impacts of pretreatment and plowing, although IMRCP does not provide treatment or plowing plans that can be generated by an MDSS.

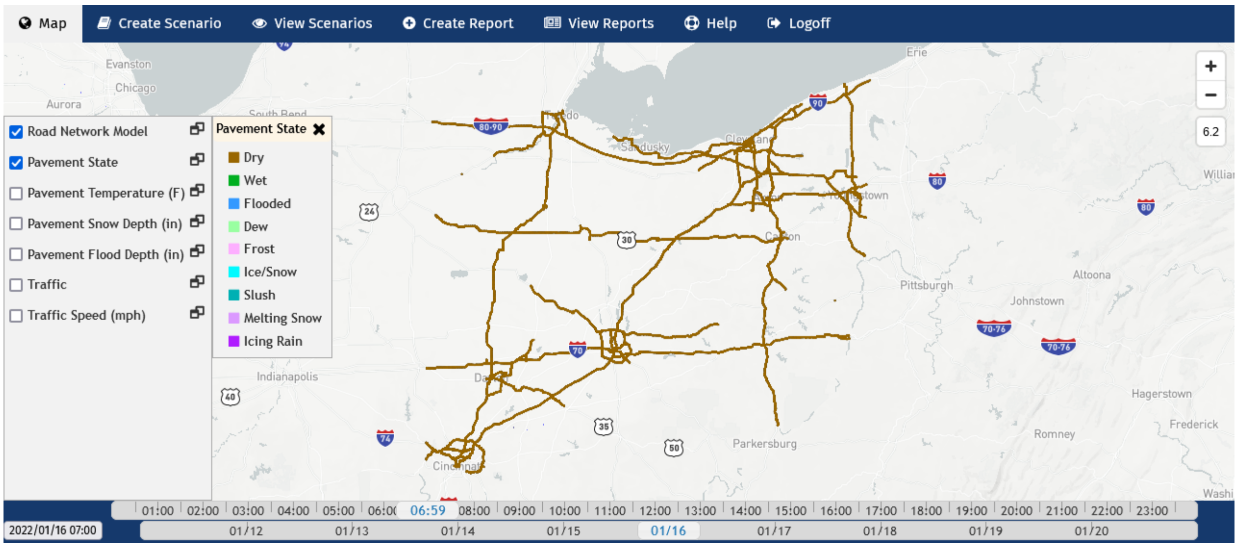
As winter storm conditions are affecting the road network, IMRCP integrates traffic and weather views of current road conditions. This enables maintenance staff and operators to see the impacts of actual weather conditions across the network as the conditions develop. TMCs can get views of conditions beyond specific locations seen through traffic cameras. Maintenance supervisors can monitor conditions in real time—beyond reports from plow vehicles or the RWIS. Road weather condition forecasts reflect the accumulated real-time weather conditions. Traffic predictions include the impacts of road weather conditions and the incidents that may occur as a result of those conditions.

After the storm has passed, IMRCP provides a record of weather and traffic conditions and forecasts throughout the storm. This record provides operations and maintenance staff with a richer and more integrated view of events for after-action reviews. The data might also be used to feed storm indices or performance measures.

[1]ODOT. n.d. "ODOT" (webpage). https://www.ohgo.com/, last accessed November 28, 2022.

Example Ohio Winter Storm—January 16–17, 2022

A winter storm was forecast to move from the southeast (unusually) into Ohio on Sunday, January 16, and Monday, January 17, 2022. As shown in figure 2, conditions across the State were normal during the morning hours on January 16, with dry roads across the State. ODOT was marshaling road winter maintenance crews in preparation for snow-fighting activities throughout the storm.

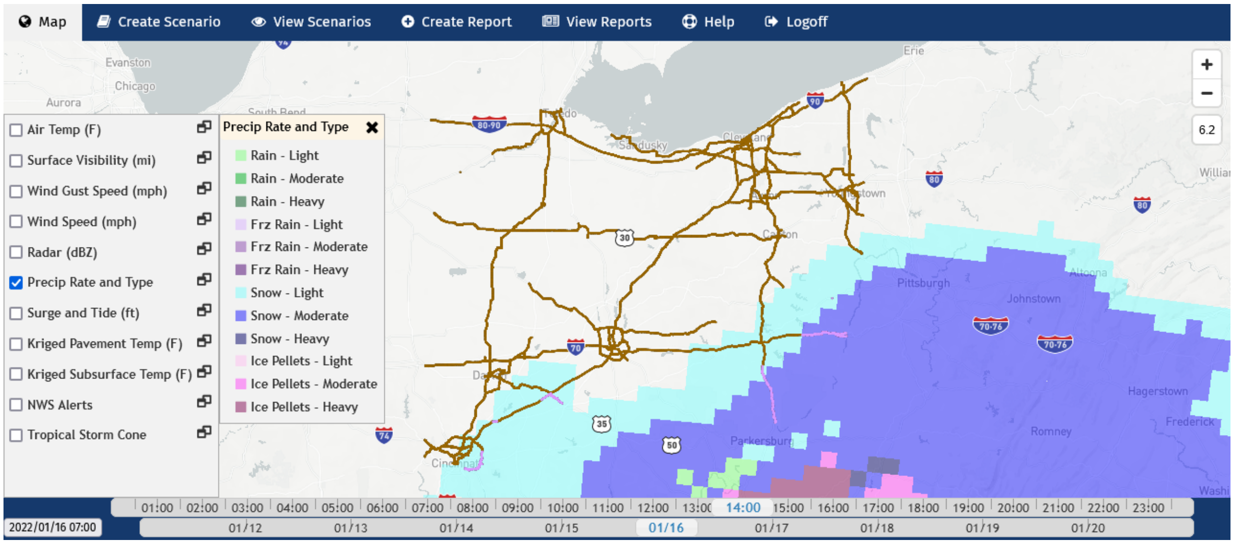


Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 2. Screenshot. Ohio road conditions, January 16, 2022, 8 a.m. eastern standard time.

On the morning of January 16 (figure 3), the forecast from NWS as presented by IMRCP showed snow beginning to fall in midafternoon in far southeastern Ohio.

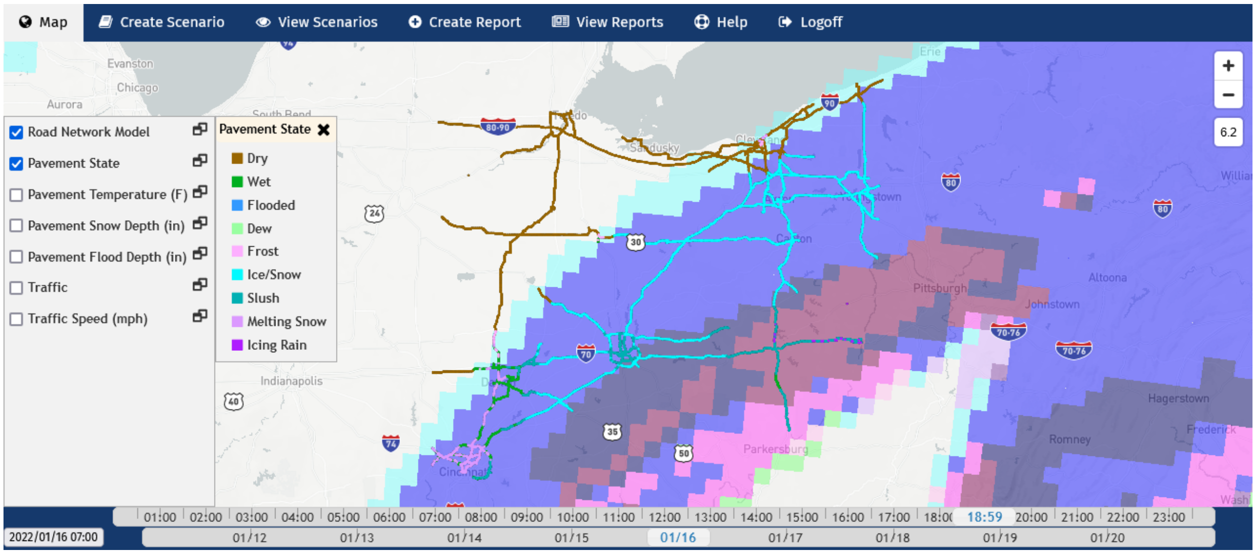


Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 3. Screenshot. Ohio forecast weather conditions, January 16, 2022, 3 p.m. eastern standard time.

The morning 12-hour forecast on January 16 showed more-widespread winter precipitation and worsening road conditions across the State in the midevening (figure 4). The forecast pavement conditions did not, in this case, include the effects of any pretreatment or plowing operations.

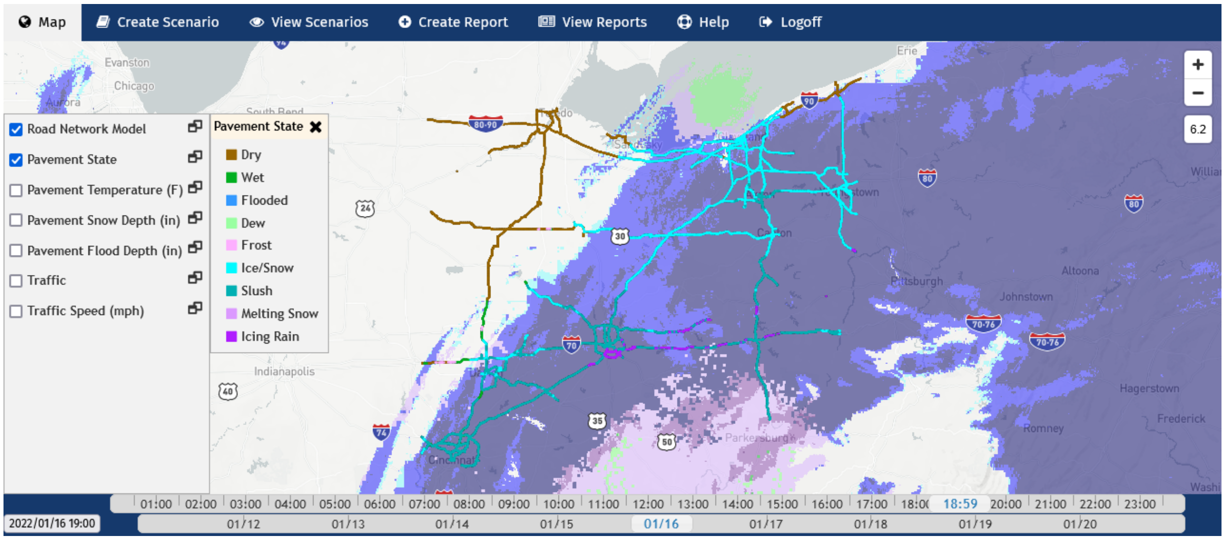


Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 4. Screenshot. Ohio forecast road conditions, January 16, 2022, 8 p.m. eastern standard time.

The 12-hour weather and IMRCP road condition forecasts across the State were proved to be reliable, as conditions in the evening (figure 5) closely resembled the earlier forecast. The road condition model showed the result of precipitation accumulations and melting and refreezing cycles but did not include any pretreatment or plowing operations that may have occurred during the day.

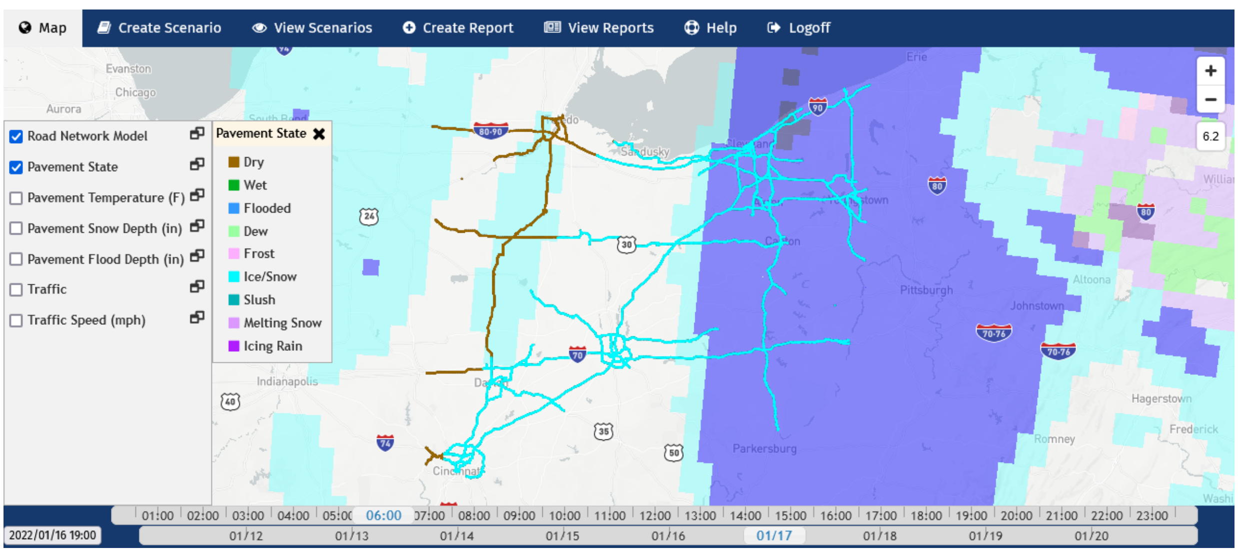


Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 5. Screenshot. Ohio road conditions, January 16, 2022, 8 p.m. eastern standard time.

The Sunday evening forecast for the Monday morning commute indicated a potential for continued snow and icy conditions over the eastern half of the State (figure 6).



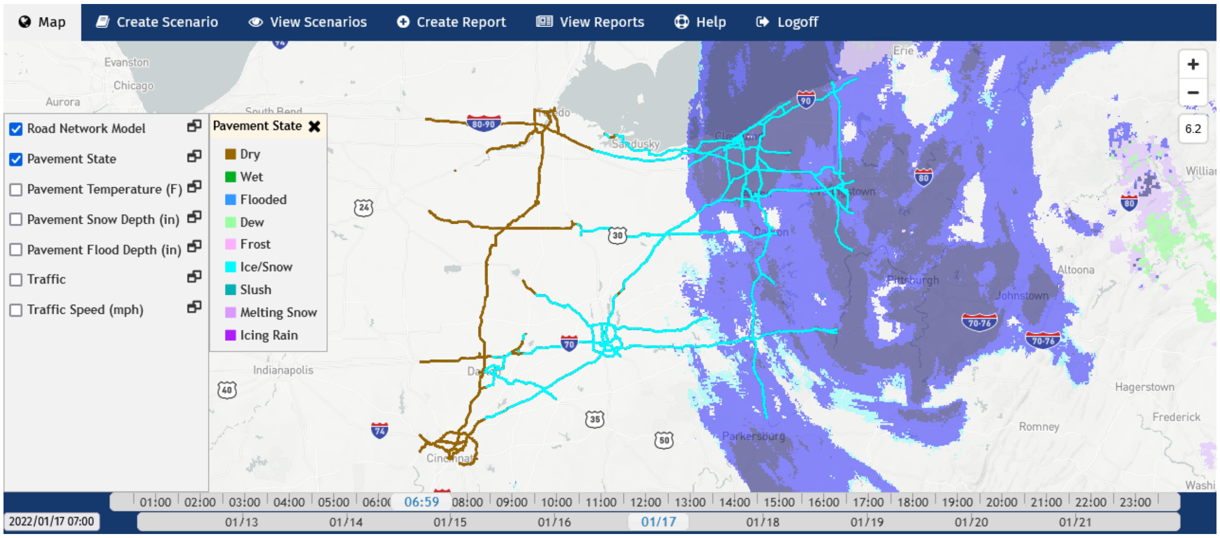
Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 6. Screenshot. Ohio 12-hour forecast road conditions, January 17, 2022, 7 a.m. eastern standard time.

With the storm expected to cover the far northeastern part of Ohio along Lake Erie, ODOT decided to activate the VSL corridor on Interstate 90 (I–90) northeast of Cleveland. The statewide TMC reduced the speed limit along the corridor in increments—from the normal

70 miles per hour (mph) to 50 mph, then to 40 mph, and finally to 30 mph for the Monday morning commute. Weather and conditions on the roads during the commute demonstrated the relative accuracy of the IMRCP road condition forecasts relative to the real-time models (figure 7). Indicated pavement conditions did not include effects of any plowing operations.

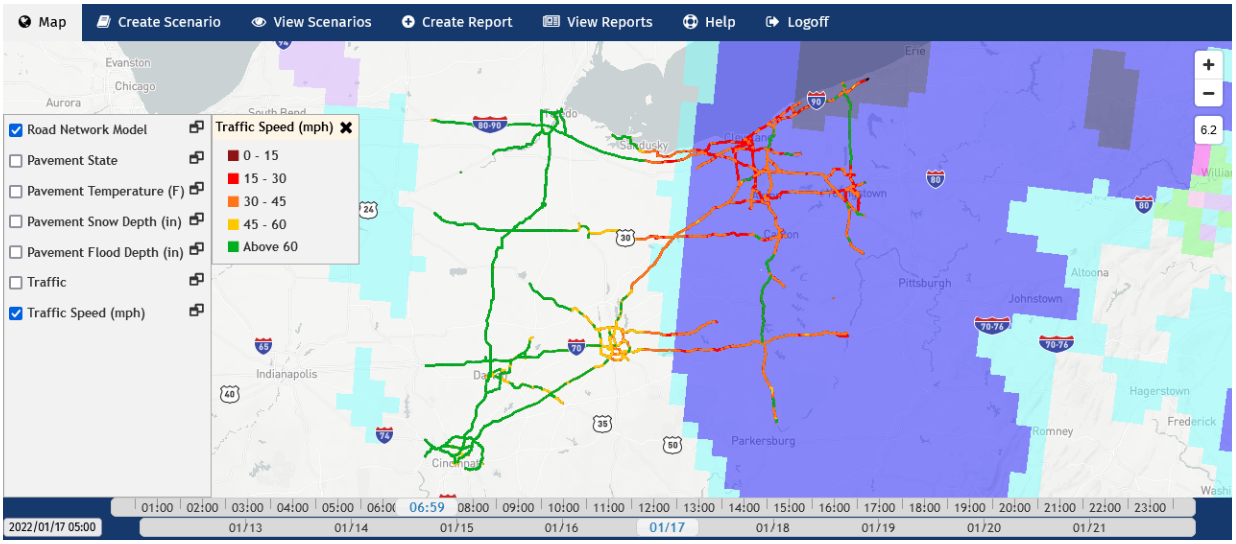


Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 7. Screenshot. Ohio road conditions, January 17, 2022, 8 a.m. eastern standard time.

The 2-hour early-morning traffic condition forecasts predicted very slow speeds almost everywhere on the modeled road network during the commute hours (figure 8). ODOT under these conditions used VSLs on the I–90 corridor between Cleveland and the Pennsylvania State line to reduce traffic speeds and the risk of incidents from heavy snowfall and accumulations.

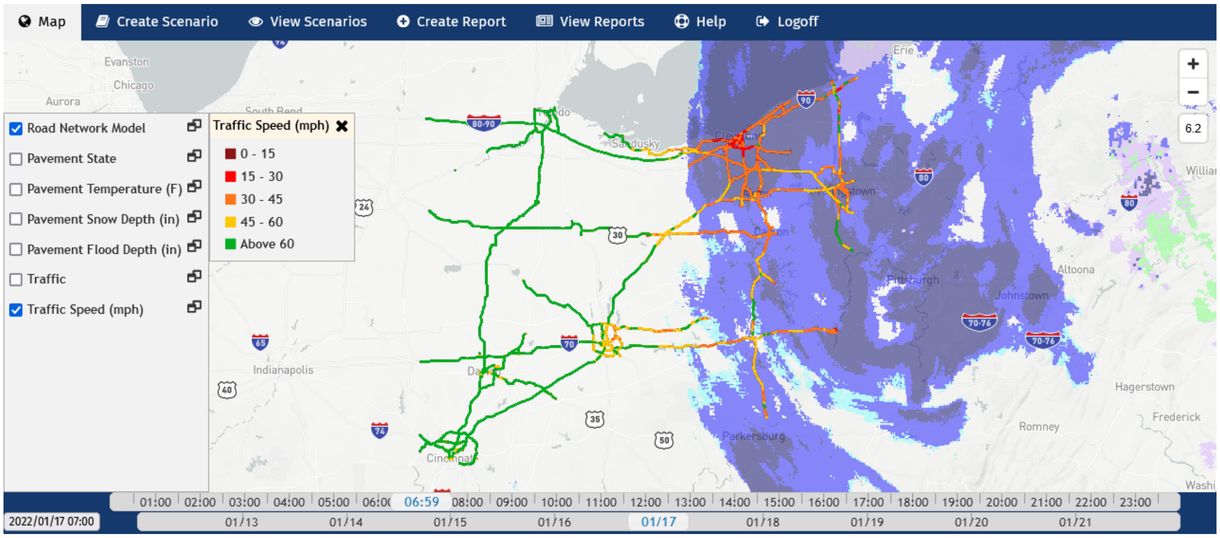


Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 8. Screenshot. Ohio 2-hour forecast traffic conditions, January 17, 2022, 8 a.m. eastern standard time.

Conditions monitored and displayed by IMRCP during the commute showed a stark slowdown in traffic conditions under the storm (figure 9). Actual traffic conditions demonstrated the accuracy of the traffic forecast (as shown in figure 8) consistent with the underlying relative accuracy of the weather forecast.



Source: Federal Highway Administration.

Note: The times on the time controls are central standard time rather than eastern standard time.

Figure 9. Screenshot. Ohio traffic conditions, January 17, 2022, 8 a.m. eastern standard time.

LOUISIANA DEPLOYMENT

The Louisiana Department of Transportation and Development (LaDOTD) agreed to work with FHWA in IMRCP deployment for operations in tropical storm conditions and other severe weather events, including winter storms. Traffic conditions during evacuations for hurricanes are difficult for evacuees and can vary based on the particular characteristics of a storm. The LaDOTD engagement provided an opportunity to investigate the use of machine-learning models for traffic prediction during the preparation, response, and recovery phases of tropical storm events.

The Louisiana IMRCP deployment created a road network model of evacuation routes throughout the State. This model included interstate, national, State, and local roadways. Traffic and operations data were provided through the Statewide ATMS. Traffic speeds for training the traffic models were extracted from archives corresponding to tropical storm events that had affected Louisiana in 2020. The machine-learning models were exposed to tropical storm predictions and characteristics, such as landfall location and intensity as well as traffic speed behaviors on evacuation routes over time.

Tropical Storm Applications

Tropical storms create ongoing threats to transportation system operations, to life, and to property as they approach land and move onshore. Emergency procedures focus on planning for evacuation and on preparedness for the storm's landfall and are dependent on the increasingly more precise forecasts of expected storm conditions and potential consequences. Operations as the storm moves onshore are somewhat limited to monitoring conditions and receiving damage reports. The poststorm recovery stage focuses on assessing damage and moving as quickly as possible to restore access and essential services to affected areas.

Transportation agencies play a support role throughout the storm planning, event, and response phases. While roadways are essential to preparing for and responding to tropical storms, emergency operations and public safety agencies manage most of the storm-related activities on the road network. Transportation agencies continue to maintain normal operations throughout, participate in emergency operations center (EOC) decisions and public information dissemination, support evacuations and contraflow, and provide resources to extraordinary operations in flood control, response, and service restoration.

IMRCP provides information and tools to support transportation agencies in tropical storm planning, response, recovery, and review. Hurricane events that trigger mass evacuations affect multiple agencies, jurisdictions, and levels of government. Although IMRCP is a transportation tool, it can help with decision support for all of these entities—not just transportation agencies. IMRCP's situational awareness capabilities support environmental and forecast monitoring as a storm progresses. IMRCP's traffic models predict conditions to assist in planning for evacuations and operations. The scenario analysis tool can assist in assessing weather-responsive management strategies such as VSLs, managing lane use, road closures, and, potentially, contraflow.

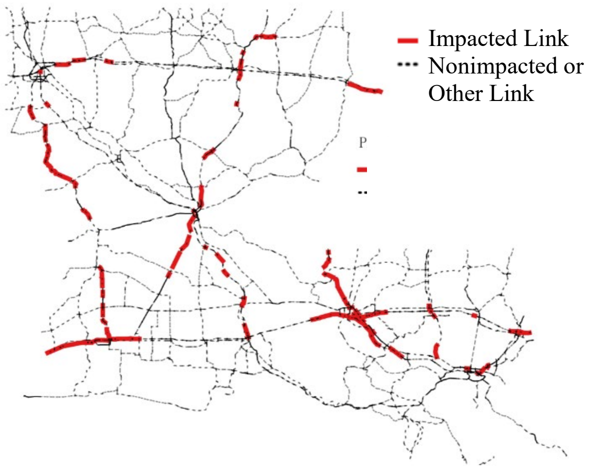
Tropical storms are closely monitored and modeled by NOAA's NWS and NHC. State EOCs and transportation agencies similarly monitor the NHC and NWS forecasts for potential impacts on their States. IMRCP collects NHC and NWS data products for integration with its own traffic and pavement condition models. Forecast datasets collected by IMRCP include:

- Tropical storm path forecast cones
- Wind and precipitation forecasts
- Storm-tide surge
- NWS watches and warnings
- River and stream levels

IMRCP traffic models use machine-learning techniques to predict speeds across the network based on prior similar network conditions. For tropical storms, setting up the traffic model involved getting data for as many storms as possible that had previously affected Louisiana road conditions. The years since 2017—at least, prior to 2022—have included more storms affecting Louisiana than in many years prior. In the Atlantic Ocean and the Gulf of Mexico, 2020 was a very busy tropical storm season, and traffic and weather data records from 2020 were collected and processed into machine-learning algorithms to build tropical storm traffic predictions for IMRCP. The resulting traffic speed model consists of three major machine learning components:

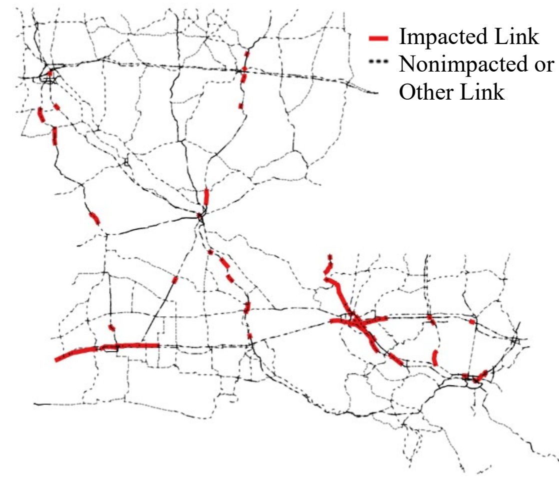
- A support vector machine model that predicts whether traffic on a link will be influenced by the approaching storm in a given day
- A Markov chain model for predicting speeds on affected links within a given period
- A time series model for predicting speed based on real-time observed traffic speeds

Figure 10 is a comparison of the affected links predicted (figure 10-A) and observed (figure 10-B) 1 day before landfall for 2020 Hurricane Delta, which was not part of the training dataset. The prediction model was designed to identify all actually impacted links to the maximum extent while tolerating some levels of false positives.



Source: Federal Highway Administration.

A. Hurricane Delta predictions 1 day before landfall.

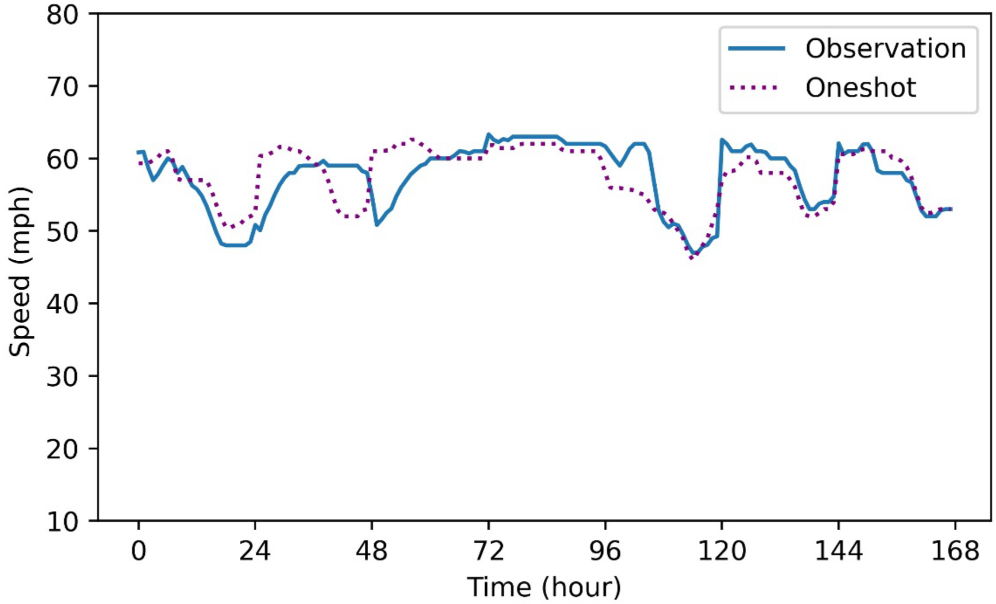


Source: Federal Highway Administration.

B. Hurricane Delta observations 1 day before landfall.

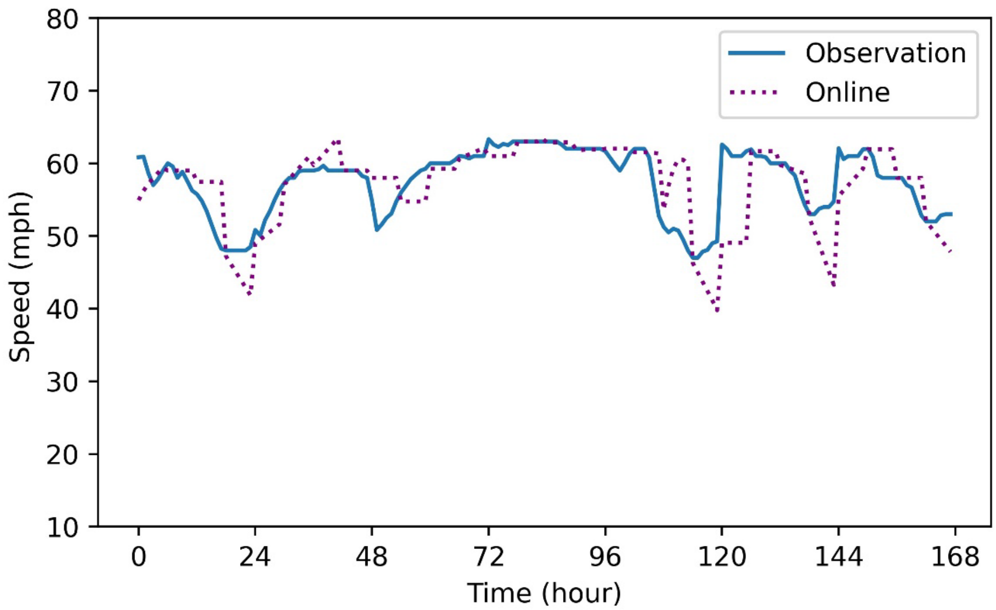
Figure 10. Illustration. Comparison of Hurricane Delta observations and predictions 1 day before landfall.

The three-part machine-learning model also predicted traffic speeds at particular locations along evacuations that were validated against observations for Hurricane Delta. Traffic on Interstate 10 (I–10) eastbound approaching Lafayette was predicted based on a Oneshot model that is trained using historical hurricane impact data and takes forecast landfall location and category (figure 11) as inputs. Oneshot refers to the prediction that is calculated at the beginning of a time series—the length of which is the prediction horizon—and uses information available only at the beginning of the time series. The purpose of the Oneshot prediction is to instantaneously project the overall traffic trend in the next hours and days after an event occurs. Further combined with real-time hurricane path and local traffic conditions, predictions on traffic on I–10 can be updated periodically via an online model (figure 12). Both results show substantial agreement with observations.



Source: Federal Highway Administration.

Figure 11. Diagram. Oneshot prediction based on Hurricane Delta path.



Source: Federal Highway Administration.

Figure 12. Diagram. Online prediction based on 6-hour real-time updates.

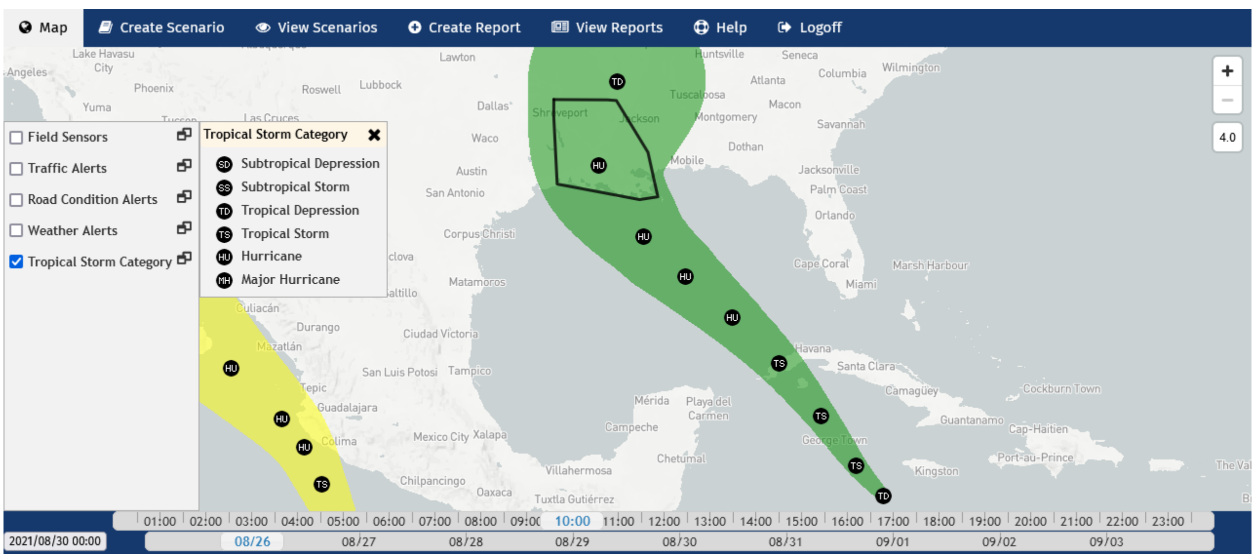
Transportation operations are constrained by necessity and practice to those important to safety as a tropical storm moves through an area. IMRCP in this phase of a storm's lifecycle monitors wind, storm surge tide, and precipitation for potential impacts on the roadway and collects incident and event data as they become available to the TMC. Data collections and monitoring may be limited during the storm by power and communications outages and infrastructure damage from the storm.

The focus of transportation operations after a tropical storm has moved across a State turns to potential ongoing flooding and to recovery of infrastructure services. TMCs monitor roadway closures and other service outages in power and communications from wind and water damage. Roadways and bridges may be damaged and need emergency repairs or routing around longer closures. Storm debris may need to be removed from roadways over large areas. IMRCP can assist in monitoring weather conditions and, to the extent that road condition data are available from agencies, support postevent traffic analysis.

Example Louisiana Tropical Storm—Hurricane Ida, August 26–31, 2021

Integrated weather and traffic models for tropical storms are highly dependent on the specific storm characteristics and the emergency operations response. Although IMRCP was not fully deployed for Louisiana at the time, poststorm analysis of Hurricane Ida, which made landfall in Louisiana on August 29, 2021, illustrates the challenges in traffic modeling for tropical storms.

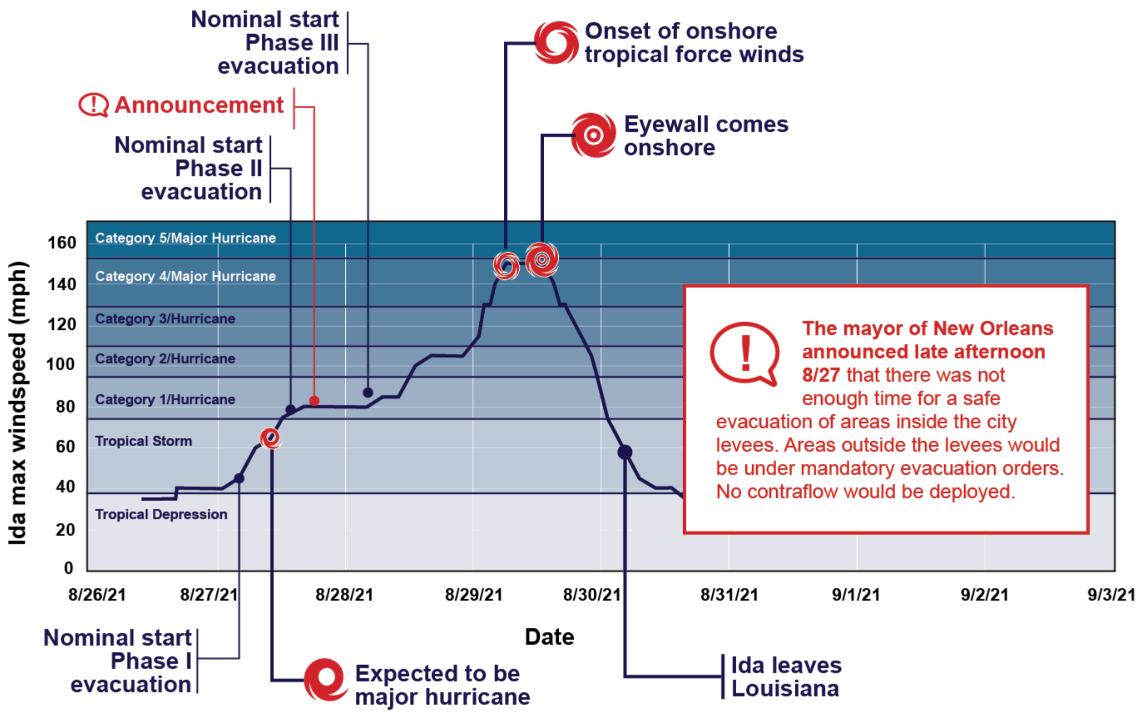
The first indications of a tropical system that might affect Louisiana were released by NHC on Thursday morning, August 26, 2021. The storm was identified as a tropical depression located southwest of the island of Jamaica. The entire coast of Louisiana was within the forecast cone of potential storm tracks, with landfall forecast as hurricane (figure 13). The Governor of Louisiana declared a state of emergency and activated the Governor's Office of Homeland Security and Emergency Preparedness EOC. The storm was upgraded from a tropical depression to a tropical storm named Ida within a few hours.



Source: Federal Highway Administration.

Figure 13. Screenshot. Forecast tropical storm Ida track and category.

Ida's development timing created problems for preparations and evacuation. Figure 14 shows the intensification of Ida in terms of windspeed over time from Ida's formation as tropical depression to its exit from Louisiana. The *Louisiana Emergency Preparedness Guide*[2] identifies three evacuation phases in the event of a major hurricane. Phase 1 evacuates the coastal parishes south of the Intracoastal Waterway beginning 50 hours before the onset of tropical-force winds. Phase 2 evacuates areas south of I–10 beginning 40 hours before the onset of tropical-force winds. Phase 3 evacuates areas in New Orleans east of the Mississippi River 30 hours before the onset of tropical-force winds. As noted in the New Orleans mayor's announcement, there was not enough time to safely execute normal evacuation plans.



Source: Federal Highway Administration.

Figure 14. Diagram. Hurricane Ida intensification time line.

Nonetheless, large numbers of residents did evacuate the southeastern Louisiana urban areas, moving, for the most part, west toward Texas, north into Mississippi, or farther east toward Alabama and Florida. Chokepoints appeared along I–10, Interstate 12 (I–12), and Interstate 59 at major interchanges and bridges. As noted earlier, the IMRCP machine-learning models for hurricane traffic were not completed prior to Hurricane Ida. Post event analysis of traffic speeds during Ida nonetheless demonstrated good agreement with observed traffic speeds, as illustrated in figure 15, for traffic westbound on I–10 over the Atchafalaya Basin Bridge.

[2]State of Louisiana. 2022. Governor's Office of Homeland Security and Emergency Preparedness, *Louisiana Emergency Preparedness Guide,* Baton Rouge, LA: State of Louisiana. http://gohsep.la.gov/Portals/0/Documents/Prevent/Emergency%20Guide%20v65_5-24-2022.pdf. Last accessed 08 03 2023.

LADOTD = Louisiana Department of Transportation; MLPH = machine learning prediction hurricane model; WB = westbound.

Source: Federal Highway Administration.

Figure 15. Graph. Observations and Integrated Modeling for Road Condition Prediction forecast of traffic speed on the Interstate 10 Atchafalaya Basin Bridge during Hurricane Ida.

Traffic management strategies for improving traffic flow during evacuations focus on increasing the number of lanes available for traffic moving away from areas to be evacuated. Contraflow adds lanes by reversing the flow of traffic in existing lanes that would normally flow into those evacuation areas. Authorizing traffic on shoulders during evacuations could also be used to increase the traffic capacity.

IMRCP's scenario-modeling tools theoretically can be used to simulate the effects of contraflow and shoulder running in evacuations. Data from prior instances of contraflow and shoulder running would be needed to train the traffic models. The scenario tools could then be used to indicate how many lanes would be opened and closed in each direction of travel over a time period for the evacuation.

Flooding from storm surge and tide can cause damage to roadways in low-lying coastal areas. IMRCP gets forecast storm and tide surge data from NOAA and computes potential roadway inundations by using high-precision roadway elevations from its pavement management systems. Data for storm surge during Hurricane Ida were not captured by IMRCP.

CHAPTER 4. EVALUATION

BACKGROUND

The IMRCP phase 4 evaluation investigated IMRCP accuracy and user experiences and perspectives. Staff from ODOT and LaDOTD participated in either interviews or walk-through activities. They provided insights and shared perspectives on IMRCP usability, usefulness, capabilities, and benefits.

The focus of the Ohio evaluation was the 2021–22 winter season (i.e., December 2021–April 2022). The evaluation team examined speed predictions and pavement temperature accuracy at locations in Cleveland and Columbus during a winter weather event on January 16–17, 2022. The evaluation team used questionnaires, interviews, and discussions with staff to assess experiences and perceptions.

For Louisiana, the focus was the hurricane/tropical storm season (i.e., May–August 2022). However, due to a lack of major storms, the evaluation team examined speed predictions and road condition accuracy during the Hurricane Ida event, which occurred on August 28–30, 2021, at locations in New Orleans and Baton Rouge. The evaluation team used guided walk-through sessions with LaDOTD staff, where they completed a variety of tasks and activities, to gather and assess user experiences and perceptions.

This chapter summarizes the IMRCP findings and addresses two questions:

- Did IMRCP provide accurate information during adverse weather conditions?
- What were staff perspectives about IMRCP's usability, usefulness, capabilities, and benefits?

The complete details and results of the evaluation are documented in the Ohio and Louisiana evaluation reports.[3]

INTEGRATED MODELING FOR ROAD CONDITION PREDICTION ACCURACY

The evaluation of IMRCP system accuracy examined:

- Reported speeds versus historical observations
- Speed forecasts
- Pavement temperature forecasts

Reported Speeds Versus Historical Observations

For the Ohio deployment, IMRCP appeared to be capable of providing reliable real-time speed predictions versus historical ODOT speeds most of the time during the major snowstorm.

[3] The evaluation reports may be viewed at OSADP/IMRCP, GitHub, https://github.com/OSADP/IMRCP.

Although the predictions were sometimes not as accurate, the occurrences usually happened in early morning around 2 a.m., which is prone to more fluctuations given the low traffic volume.

Similar findings were observed for the Louisiana deployment. IMRCP appeared to be capable of providing reliable real-time predictions for the majority of time after Hurricane Ida made landfall on August 29, 2021. During the day before the landfall of Hurricane Ida, there appeared to be more times when the predictions were inaccurate. This might indicate factors that had not been considered that could potentially have affected the speed. The road and weather conditions reported by IMRCP appeared to be useful and valuable, since they often corresponded to the speed data the team examined—especially after Hurricane Ida arrived.

Speed Forecasts

The investigation of speed forecast accuracy examined 15-, 30-, 60-, and 120-minute IMRCP speed forecasts. Three metrics—mean absolute error (MAE), relative absolute error (RAE), and root square mean error (RSME)—were used to assess the deviation between forecast speeds and the actual (historical) speeds.

In general, the results from Ohio and Louisiana analyses indicated that shorter-term forecasts tended to have smaller errors than longer-term forecasts (i.e., the shorter-term forecasts tended to be more accurate). Since the machine-learning traffic model learns from historical data, further investigation of the model and the training data may be helpful to improve the accuracy of speed forecasts.

For Ohio, speed forecast error analyses showed that the traffic model provided more accurate predictions when forecasting for the nearer future. The segment from Interstate 670 westbound had the largest deviations for 60-minute lead time. Nonetheless, all the other observed errors were still reasonable and tolerable. For the pavement temperature forecasts, the METRo model was able to provide accurate predictions regardless of the lead time lengths that were examined. However, the segments from I90 had relatively larger deviations compared with the other selected locations.

For Louisiana, speed forecast error analyses showed that the traffic model provided more-accurate predictions when forecasting for the nearer future, which was expected. Based on the results, speed forecast performance for I10 East in the eastern New Orleans area segment and for I12 West near Amite River segment appeared to be relatively poor compared with the two other segments.

Pavement Temperature Forecasts

Pavement temperature forecasts were examined in Ohio from January 16, 2022, 3 p.m. eastern standard time, to January 17, 2022, 3 p.m. eastern standard time. The investigation of pavement temperature forecasts examined MAE, RAE, and RSME for 15-, 30-, and 60-minute METRo pavement temperature forecasts.

The three metrics indicated that the deviations appeared to be minimal regardless of the lead time length. The pavement temperature forecasts were able to provide accurate 15-, 30-, and 60-minute predictions regardless of the lead time lengths. Segments from the adjacent location had similar results. In general, the road conditions reported by IMRCP appeared to be useful and valuable, since they corresponded well to the speed data that were examined.

STAFF PERSPECTIVES

The evaluation team conducted interviews with ODOT staff and an IMRCP walk-through exercise with LaDOTD staff to collect their perspectives about the usability, usefulness, and capabilities and benefits of the IMRCP decision-support tool.

The walk-through participants indicated that IMRCP was easy to use and easy to understand. A majority of participants indicated that IMRCP was useful for decision-making and provided suggestions to improve the user interface and functionality. All participants were novice IMRCP users, and none had used IMRCP for operations or analyses. Despite participants' lack of familiarity with IMRCP, their ratings were generally positive for the IMRCP topics covered in the walk-through (i.e., setup, map layers, data tables, traffic speed, and weather forecasts).

When asked whether IMRCP was easy to use, all participants agreed and a majority strongly agreed. When asked whether IMRCP was easy to understand, all participants agreed and half strongly agreed. When asked whether IMRCP was useful for decision-making, about two-thirds of participants agreed and about one-third was unsure. These results were unsurprising, given some participants did not have decision-making responsibilities and remarked they were not involved in decision-making, so they were not sure. When asked whether IMRCP could be improved, about half the participants agreed (no one strongly agreed) improvements could be made to IMRCP.

Staff roles and responsibilities influenced what aspects of IMRCP are used and useful. For example, in Ohio, a TMC project manager was interested in using IMRCP forecasts to help anticipate upcoming changes to traffic and weather conditions. A snow and ice coordinator, who had been plowing during an event, looked at IMRCP afterward to compare the tool's predicted road conditions with what he had experienced while plowing the road. The snow and ice coordinator also reported that the weather and pavement conditions were valuable assets of the system and could be used to monitor icing conditions and make decisions for treating roads.

Perspectives from Louisiana cited that IMRCP could be useful for public information requests and for after-action reviews. Having the ability to adjust the date and time can be useful to view and assess the road condition, weather-related details, and traffic conditions at the time of a crash or situation under review.

LaDOTD users also mentioned that IMRCP may be useful for winter weather predictions and flooding. Traffic operators want to know which areas of the network will be impacted and usually get information from calls, experience, emergency operations, and people out scouting. Having weather and flooding information from weather sites, gauge sites, and traffic sites in one presentation would simplify access to the data. Also, since LaDOTD is concerned about flooding, IMRCP could be useful to monitor water levels to help with sending out crews and putting out message signs. Staff also noted a variety of user interface recommendations to improve user experience, which are documented within the evaluation reports.

Other recommended improvements include:

- Providing for the ability to upload or integrate IMRCP or parts of IMRCP into other maps (i.e., merging what the users know and use with the additional IMRCP data)
- Considering limiting the number of sources for some data (e.g., several options have ranges of values for air temperature)

Overall, the accuracy of IMRCP data and information is important to ensure users continue to use the system. IMRCP needs to show it is adding value, and users need to have confidence in the system.

CHAPTER 5. DEPLOYING IMRCP

The Integrated Modeling for Road Condition Prediction (IMRCP) system was developed under a U.S. Department of Transportation (USDOT) open-source software license and is available to interested agencies for deployment in their operations. IMRCP documentation and code are available on the USDOT Open Source Application Development Portal (OSADP).[4] All of the code libraries IMRCP uses are similarly available under open-source licenses. The IMRCP system takes extensive advantage of existing data sources and forecast methods. All of the base weather and water data and forecasts come from NOAA and NWS sources. Traffic data come from agency transportation management systems or from traffic data service providers used by the deploying agency. Some system configuration settings and the road network model need to be set up for each deployment, and local data sources (e.g., agency traffic data or stream gauge data) may need custom collectors to be developed. Traffic models should be trained to deployment-specific networks using archived traffic data.

Setting up the road network model is fundamental to an IMRCP deployment, and an IMRCP automation tool helps. The resulting road network model nonetheless needs detailed review and confirmation. While the weather data and forecasting components of the system are configured for the continental United States, the traffic models may require significant development and system configuration to local data sources and traffic networks. Training the traffic prediction model similarly requires substantial effort and is not fully automated. At a high level, agencies would need to consider deployment activities, including:

- Gathering stakeholders and defining the scope and use cases
- Setting up the computing infrastructure and system software
- Building the road network model
- Identifying and building collectors for traffic, operations, and incident data
- Identifying and building collectors for work zone data
- Identifying and building collectors for local road weather and hydrology data, if available
- Identifying and building collectors for winter maintenance operations data, if available
- Calibrating the traffic model
- Planning for use in operations
- Training users
- Integrating with operations

The IMRCP documentation and code are available on the USDOT OSADP. The repository includes the system documentation and code. Information about installation and adaptation to a region is provided in the *Installation and Administration Guide*.[5]

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[4]GitHub. 2023. "OSADP/IMRCP" (webpage). https://github.com/OSADP/IMRCP, last accessed November 28, 2022.

[5]"OSADP/IMRCP," *Integrated Modeling for Road Condition Prediction: Installation and Administration Guide*, GitHub, accessed November 28, 2022, https://github.com/OSADP/IMRCP/blob/master/IMRCP_Admin_Install_Guide_FINAL.pdf.

CHAPTER 6. ACCOMPLISHMENTS, LESSONS LEARNED, AND RECOMMENDATIONS

IMRCP can extend operational awareness of road weather and traffic conditions from *now* to *what next*. It captures traffic operations and road weather data in real time, uses those data to make predictions of conditions in operational time horizons, and makes the data and predictions available to operators for event reconstruction and analysis. In phase 4, these capabilities have been deployed in Ohio and Louisiana—demonstrating traffic and weather models for tropical storms and evacuations—and have added scenario analysis and tools to support agency decision-making in operations and maintenance. Future development will enable deployments by transportation agencies in support of their own operational needs in tropical storm and other extreme weather events.

ACCOMPLISHMENTS

Previous phases of IMRCP developed the foundational traffic and weather data system components, including a machine-learning-based traffic model, deployed the system at the scale of a metropolitan area, operated the system for two winter seasons, evaluated the operational results, and updated the system documentation. IMRCP phase 4 has improved and deployed the system in two new locations, expanding system capabilities and applicability to extreme events while addressing functional gaps identified in earlier phases. The Ohio deployment focused on IMRCP as a tool for planning, monitoring, and postevent assessment of traffic management and operations during adverse, primarily winter, weather events. The Louisiana deployment investigated IMRCP use cases in tropical storm event preparation, response, and recovery. IMRCP enhancements and applications developed in phase 4 have been documented to support future deployments.

IMRCP systems improvements have included:

- Making data store enhancements to support multiple large networks. The enhancements required changes to the data indexes and interfaces to support faster access by other system components and user interfaces.

- Developing a tool for partial automation and editing of road network models. The tool reduced the effort required to generate, modify, and review the Ohio and Louisiana network models.

- Adding support for multiple road networks and user groups. The ability to support multiple networks was key to computing resource management and required user profile management that supported other user interfaces such as scenario analysis.

- Extending the forecast domain to support multiday applications. Prior-phase IMRCP use cases focused on operations out to 8 hours in the future. Winter maintenance and tropical storm scenarios needed wider operations windows, which in turn required more computing resources, higher computational efficiencies, and changes to user interfaces.

- Refining the pavement-condition models. Previous phases lacked the scale and data to effectively calibrate pavement condition predictions to RWIS data. Phase 4 added Kriging analysis of RWIS data as input to the pavement forecasts and updated the precipitation accumulation model.

- Adding traffic models for evacuation scenarios. Evacuation scenarios present traffic-modeling characteristics unlike other use cases considered in earlier IMRCP phases. New datasets and machine-learning models were developed to predict conditions from tropical storm histories in Louisiana and incorporate them into the IMRCP traffic models.

- Improving responsiveness of user interfaces. IMRCP manages and displays large datasets in its Web-based user interfaces. The size and complexity of the phase 4 deployments needed improvements to the IMRCP services and interfaces to reduce response times in retrieving and displaying data.

- Adding a scenario-modeling tool. Applications of IMRCP in operational decision-making in prior phases were limited to improving situational awareness and alerts. Phase 4 developed and deployed a tool for doing what-if analysis.

LESSONS LEARNED

The project team worked with ODOT in a statewide deployment to assess potential applications primarily for winter operations and maintenance.

In that context, it was observed that:

- Use of IMRCP in winter operations needs to complement the existing maintenance-focused toolkits. IMRCP predictions could be provided to the other systems as additional sets of overlays or in a simplified view that does not duplicate data available in the other systems.
- IMRCP traffic forecasting specific to degraded weather and pavement conditions and inference of local pavement conditions from regional sensors and forecasts may be unique offerings even in agency operations with other weather-responsive decision-support systems.
- Strategies such as VSLs are already in use for winter operations in Ohio but depend on dedicated intelligent transportation systems (e.g., RWIS and signs) for deployment. IMRCP may be more valuable in agencies seeking additional information without having to make those infrastructure investments.

The deployment with LaDOTD to understand the context for tropical storm events and evacuations was limited by a lack of opportunities for LaDOTD to use IMRCP during a tropical storm event. Postevent analysis of data from prior storms offers some insight for future applications:

- LaDOTD works with other State and local agencies in all stages of tropical storm operations—from planning to preparation, response, and recovery stages. TMC operations primarily provide a monitoring function in support of emergency operations.

IMRCP represents a new forecast and scenario analysis capability that could extend awareness from current to future conditions and provide decision support.

- From an operations perspective, recent storms are highlighting the limitations of prior practices and plans. The State of Louisiana and Louisiana DOTD have established emergency operations processes that look back to previous storm response performance as a guide. Storms such as Ida have developed more quickly and need more information and flexibility in evacuation planning and execution. IMRCP may provide tools to fill the information gap with integrated views and forecasts but is still dependent on hurricane forecasts.

- Congestion during Hurricane Ida was localized but persisted, raising the question of what operations strategies might be developed to alleviate that congestion and shorten evacuation route travel times. Contraflow takes about 24 hours to set up, but other strategies such as VSLs and hard shoulder running might be used to smooth flow and increase capacity on some corridors where the infrastructure supports those operations.

- In general, data availability is a significant limitation during extreme events. Data are needed from sources that might not otherwise be used during normal operations. Power outages reduce data availability and awareness as a storm comes onshore, suggesting that field sensor and infrastructure hardening might be beneficial. The recovery phase needs information about infrastructure conditions.

- Data systems for planning for, monitoring, and recovering from storms are not necessarily the same as those needed for normal operations. Low-volume high-storm-risk-area roads (e.g., through a bayou or out to a barrier island) are generally not monitored but are very important for evacuations and recovery.

- Transportation infrastructure conditions during and in recovery from tropical storms are impacted by storm surge and flooding as much as or more than by winds. Although the National Oceanic and Atmospheric Administration (NOAA) and its partners have improved the accuracy of and access to hydrological forecast data, application of the water forecasts to infrastructure monitoring and operations is in its early stages.

RECOMMENDATIONS

Recommendations for next steps focus on capabilities and applications supporting agency-driven deployments in operations. First, the system should be deployed by and for agencies to demonstrate applications in operations. Operational validation would discover and highlight practical operational needs and opportunities for improvement. In anticipation of those deployments, other high-level objectives would be to improve the forecasts for hurricanes and other evacuation-type events (e.g., wildfires); improve the hydrological models and deploy them more broadly; and get the IMRCP output data into forms where the data can more effectively support decision-making (e.g., into layers in ATMS, traveler information, and applications). The justifications for these objectives are similar to those established for IMRCP in its beginnings: to reduce the risk and mitigate the potential consequences of adverse weather and hydrological conditions on surface transportation.

Topics and activities to address in next-phase IMRCP objectives could include:

- Developing and demonstrating next-level evacuation models for decision support. This could include developing more extensive and more accurate evacuation traffic models to give continuous temporal views over a full week ahead. Such a model might address tropical storms, wildfires, and long-term areal flooding. The model could be trained and enhanced with:
  - More historical datasets, such as contraflow data from agencies other than deployment States
  - Nontraditional data (e.g., travel and truck stops, crowdsourced trip data, hotel vacancies, and social media) to supplement traffic data
  - More strategies and tactics, including demand management and active traffic management
  - Explicitly accounting for operational decisions to evacuate so as to better predict spatiotemporal demand
- Providing multi-State support for evacuation and freight corridors. This capability would support traveler and public information systems, freight dispatch and information systems, and, potentially, route planning services to avoid dangerous weather conditions
- Incorporating roadway flooding models to assess risk and operational mitigations. This could include forecasting infrastructure flood locations from precipitation and storm-tide surge, which could bridge the gap between existing NOAA/NWS hydrological products and consequences for the road network.
- Enhancing event recovery support. Assessing the impacts of flooding, road closures, and infrastructure damage on traffic patterns could support recovery efforts such as prepositioning of recovery assets and routing services.
- Demonstrating integration with TMCs and ATMS either as part of an agency deployment or conceptually through a standard interface. Integration into a TMC could provide new layers on existing maps, such as pavement conditions and forecasts, traffic forecasts, and weather data layers, if not otherwise available in the TMC.
- In a related concept, getting agency input to determine what kind of interfaces and systems might benefit from importing IMRCP data. ATMS, maintenance systems, and 511 traveler information systems could be potential IMRCP data users.
- Further developing decision support for weather-related traffic safety and mobility. Preserving mobility and reducing risk of crashes and crash severity in bad weather (e.g., winter storms, fog, rain, hurricanes, and dust) could leverage data and the scenario analysis methods developed in phase 4—primarily for near-term forecasts and operational strategies. Activities could further investigate traveler information strategies as methods complementary to VSL, hard shoulder running, and access control.
- Investigating use cases for other types of natural disasters to assess evacuation strategies and traffic models. Wildfire evacuations and earthquake recoveries share many characteristics with tropical storm scenarios.
- At strategic planning and programming levels, using data in the IMRCP repository to support infrastructure investment analyses for resilience to disruptions by natural disasters. The severe storm data collection in Louisiana and in any future deployments provides a diverse but integrated view of environmental and traffic conditions across the road network.

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